srk news

Mine Water Management

Overview

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Newsletter



Managing a scarce resource in arid conditions

As the mining industry focuses on improving productivity, reducing operating costs, and venturing into ever more challenging and remote locations for new projects, there is an increased need to look upon water as a whole-project issue.

Add broader perspectives such as stakeholder considerations and effects of a changing climate and water can present a significant risk to a mining project if not fully understood and managed. In this newsletter, we look at diverse aspects of water in the mining industry where SRK has added value and expertise to clients' projects. There are several strong themes that come through in the articles:

A changing climate: many mines and projects are located in regions where climate patterns are already changing. The way water is managed on mine sites needs to adapt accordingly; from effective flood risk mitigation through to ensuring operational continuity under drought conditions.

Integrated water management: whole-operation water management begins with effective mine site water balances but also requires a joined-up approach between the various functional teams running the mine. Interactive dashboards are just one example of how diverse water management activities at an operation can be more effectively managed.

…continued

Overview *(continued)*

Focused studies: clients often want specific issues investigated, or solutions developed for a particular problem. The diverse range of technical water-related studies profiled here demonstrates the strength and depth of SRK's experience which we apply to respond to our clients needs. Our understanding of mining operations and clients' objectives and priorities enables us to design and implement studies in a focused and effective manner.

Groundwater management is one area where very specialised, niche studies are required to fully understand the conditions at a particular project site before appropriate solutions can be evaluated and designed.

Tailings facility management is another focus area for targeted studies. In both cases, the combination of targeted field investigations and testwork, careful data analysis and appropriate modelling are essential in delivering a successful outcome.

Water care and good governance: employing water re-use and minimisation methods in mining operations not only reduces costs but also reduces risks and improves corporate governance indicators. Mine operations are becoming increasingly aware of their water 'footprint' and the benefits this approach delivers.

Good neighbours: the increasing recognition of water as a finite resource to be safeguarded, managed and shared with the wider community is driving mining companies more and more to improved mine water management throughout the design, operational management and closure lifecycle of projects. The other way of looking at this is conflict-mitigation; working alongside and with local communities and being recognised as good neighbours.

In summary, SRK helps identify, manage and mitigate risks in mine water management while also highlighting opportunities through innovative thinking and embracing a whole-project approach.

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Auditing an underground mine dewatering system

Predicting groundwater inflows at the Yaramoko Gold Mine, Burkina Faso



The Yaramoko project in 2013

Groundwater flow in crystalline rock environments with poorly developed or unsaturated saprolite is dominated by fracture flow, whether this be within the upper weathered/fractured zone or deeper in the bedrock where structural discontinuities are present. Predicting flows in discrete fractures can be challenging but by using all available data – hydrogeological, geological, structural and geotechnical – an integrated evaluation can provide enhanced characterisation.

In 2013, SRK undertook a hydrogeological assessment of the high-grade, shear-zone hosted gold deposit at Yaramoko's 55 zone in Burkina Faso as part of a multi-disciplinary Feasibility Study. A field investigation included downhole wireline impellor logging ("spinner testing"), pumping tests, infiltration testing and laboratory core analysis.

The field investigation demonstrated that the fissured, weathered zone was permeable, and that faults identified in the structural interpretation also had the potential to be permeable.

Not all the faults could be tested in the field and so their hydrogeological significance was, initially, not well understood. In the absence of such data, a detailed hydro-structural interpretation completed by SRK hydrogeologists and structural geologists assisted with the hydraulic parameterisation of faults. This included a review of structural parameters such as RQD, fracture frequency and infill composition. This allowed the magnitude of groundwater inflow from each fault intersected by the planned mine workings to be evaluated in greater detail.

A numerical groundwater flow model was constructed using MODFLOW with domains and layers modelled in Leapfrog geological modelling software. The model was calibrated on a limited basis due to limited groundwater level observations and site specific hydraulic parameters. Detailed sensitivity analysis was performed instead with base case and worst case sensitivity scenarios developed, with a focus on the hydro-structural interpretation and identified uncertainties. The base and worst case scenarios presented a range of inflows that were used conservatively depending on the scenario being investigated (i.e. base case which investigated water shortfalls, and worst case for designing the dewatering system). Such an approach was acceptable to the study team, and it is noteworthy that even worst case inflows were insensitive to the financial model.

The zone 55 mine has been operational since late 2015, and dewatering rates at this early stage are broadly comparable to base case predictions. Further review of operational data over the coming years will be important to evaluate the accuracy of the groundwater model.

This study has shown that a hydrogeological feasibility study may be completed successfully without comprehensive in-situ hydraulic testing by using supplementary geological and structural data. However, the risk posed by uncertainties must be incorporated by worst-case scenarios, and this may not be an appropriate approach for all projects.

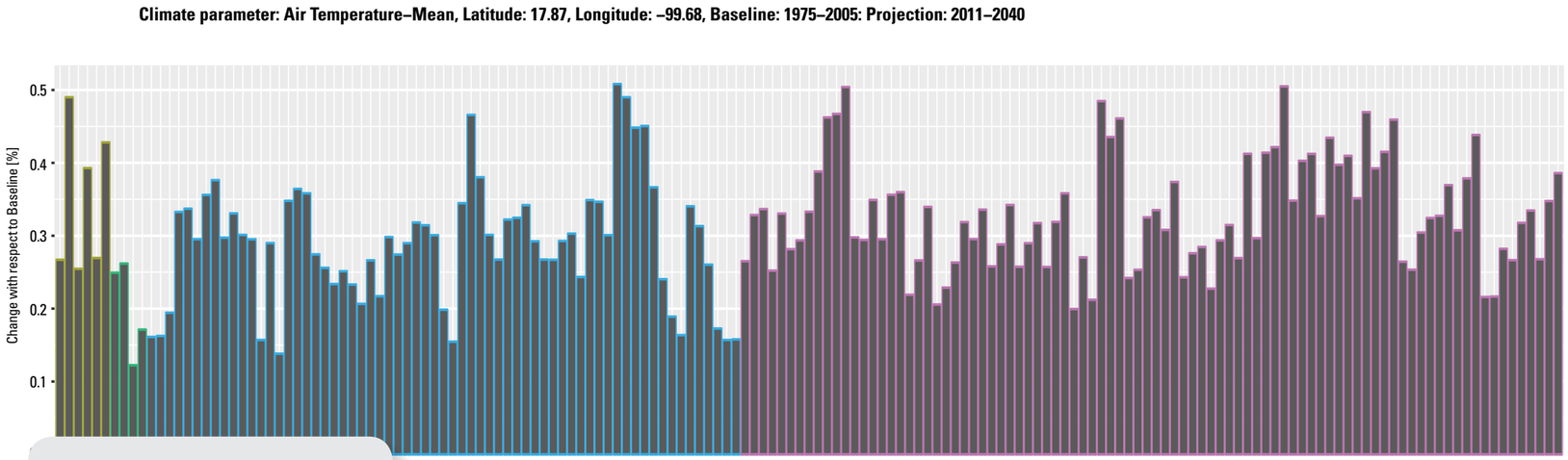
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MICHAEL PALMER

Michael is a Consultant Hydrogeologist with over 8 years' experience having worked in Australia, the UK, Western Europe, the Middle East, Africa and Asia. Michael's area of expertise includes field investigation design and management, numerical modelling for dewatering, depressurisation and impact assessments and the design and costing of groundwater dewatering systems. Michael has developed particular expertise characterising fracture-dominated hydrogeological environments for shear-hosted gold projects.

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Integrating climate change into engineering design



Example outcome scenarios for Yellowknife, Canada, showing projected air temperature relative to baseline conditions for individual climate change models associated with each of the five Assessment Reports for the 2011-2040 projection period

During the last several decades, global climate change (GCC) has emerged as a key driver of environmental processes. However, hydrologic analyses assume local climate is constant and can be directly understood from historical records. To meet the challenge of incorporating GCC into predictions of meteorological events and trends, this article presents a combination of methods that uses publicly available historical records to determine meteorological engineering design values under climate change conditions.

Environment and Climate Change Canada (ECCC) is a database for GCC data. They provide access to information from Intergovernmental Panel on Climate Change (IPCC) assessment reports (ARs) 1 to 5 which contain a wide range of variables (e.g., precipitation, temperature, and wind speed). A purpose-built script was developed using R statistical computing language.

The script compiles all available GCC models from EC that included scenarios from AR1 to AR3 (i.e., A2, B1, A1B, GA, GG) to representative concentration pathways or RCPs (i.e., RCP 2.6, RCP 4.5 and RCP 8.5) from AR4 and AR5. These were selected to show the respective rate of change in multiple climate variables for a given longitude, latitude, and time (up to year 2100).

The available GCC models are weighted equally during statistical evaluation of the cumulative results. Results are then compared to trends in historical data associated with the selected climate change parameters obtained from ERA-Interim reanalysis, which is produced by the European Centre for Medium-Range Weather Forecast and encompasses more than 30 years and the entire planet.

The engineering design value is chosen as the maximum value between the median obtained from the cumulative probability curve that describes the GCC models and related scenarios and the mean of the historical regression trends obtained with a statistical significance higher than 95% (p-value<0.05).

This procedure marries the most conservative result between the GCC and the historical values at the defined geographical place. This overall procedure combines analysis of GCC models and historical data to define appropriate design values.

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Victor, Civil Engineer, is a Hydrotechnical Senior Consultant with fifteen years of work experience. His well-developed combination of academic pursuits and experience includes a focus on: hydraulics, hydrology and water management problems in areas related to modelling, design, and construction. Along with his SRK Vancouver experience, Victor has focused on surface water, data mining, and climate change at mine sites located in Canada, USA, Mexico, South America, PNG, Russia, and Africa.

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Assessing flood hydrology in data scarce tropical regions

A robust hydrological assessment can be a challenging task in regions where a lack of data, of a sufficient quality, is available to fully validate both hydrological assessments. This level of uncertainty is heightened in studies of flood hydrology for tropical regions, where spatio-temporal variation in rainfall can be significant and the associated timing can be challenging to determine. In 2014, SRK undertook a hydrological assessment as part of a multi-disciplinary Feasibility Study for an open pit phosphate mine situated within the Republic of Congo. Due to the progression of the pit through the main floodplain of the Tchivouba catchment, characterising the flood hydrology in this data scarce region was key to ensuring the accuracy of the resulting water management design.

A bottom up approach was applied, with the baseline hydro-meteorological monitoring network reviewed and improved, establishing a stronger representation of rainfall-runoff response in the area. A detailed review of climatic influences in the region was performed, with remotely sensed TRMM data (Tropical Rainfall Measuring Mission) used to support the analysis. A quasi-distributed hydrological model (below) was built using a gridded ModClark transform and SCS-CN loss methodology (Soil Conservation Services - Curve number) to better represent the spatial variability in catchment characteristics influencing runoff processes. The model required developing unique site specific design hyetographs. Uncertainty within the modelling was reduced by validating simulated outputs in response to measured events.

This study highlighted the many issues associated with hydrological analysis in areas with little data, and explored solutions to what is a common problem for many studies in tropical regions. It is by no means a definitive study, however it explored the application and limitations of advanced techniques available for hydrologists working as consultants with limited time and resources, to determine the magnitude, timing and impacts of flooding events.

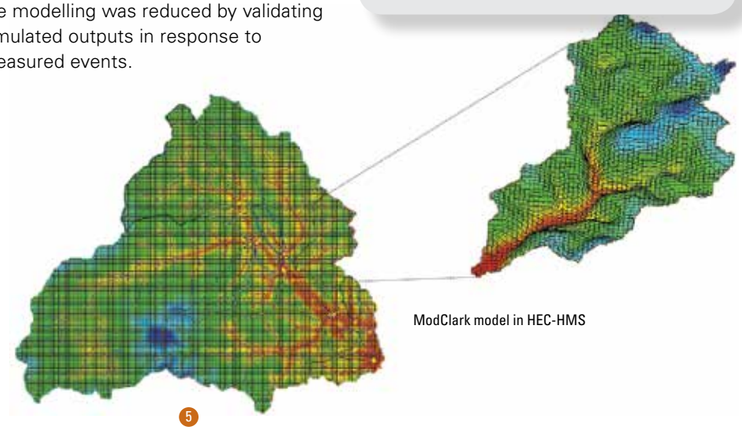
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Francis is a Hydrologist with international experience in the mining industry, specialising in evaluating and interpreting surface water hydrology and meteorology. He addresses environmental engineering issues through environmental and social impact assessment, due diligence, expert witness and scoping, and detailed feasibility studies. Francis' technical expertise lies in hydrological and hydraulic modelling, flood mapping, extreme event and climate change analysis and hydrometric surveys.

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ModClark model in HEC-HMS

Infiltration study in a thickened tailings deposit

In 2007, SRK Chile was involved in designing the first large-scale facility for thickened tailings in Chile. The project included a pilot plant to provide data on the beach angle of the tailings, and tests to estimate infiltration from the tailings into the ground. The soil water characteristic curve was determined in the laboratory and the water content was measured during the operation of the pilot plant. Based on the collected data, a 1D model of unsaturated flow was built to simulate, layer by layer, the deposition of tailing over time and predict infiltration. The results of that model predicted that infiltration would occur only as a non-saturated front, 2m below the contact between tailings and soil.

Mine operation and tailing deposition started in 2011 without being able to achieve the design thickening, i.e. a solids content of 67%. In January 2015, SRK ran a complete field program to evaluate infiltration from the tailing deposit and compare it with the predictive model.

Geophysical exploration, test pits, sonic drilling for sampling tailings and the foundation soil were undertaken within the tailings deposit and underlying soil. The water content within the deposited tailings was found to be around 17%, whereas in the soil, it was around 5%. Both tailings and soil are low permeability materials, a condition that minimised the extent of flow between both materials. If tailings are saturated, water is moving to the soil.

Due to the high evaporation rate, field data showed that five days is enough to reduce the average water content in the tailings when deposited in layers of 20cm to 60cm. This is supported by results of the water balance analysis indicating that infiltration into the underlying soil would be negligible, consequently tailings water should not affect the groundwater of the area.

The field data were used to update the 1D unsaturated model (Feflow). Modelling using the updated SWCC for both soil and tailing reproduced the observed water content for both materials, with simulated water content of tailings at 18.6% and the soil at 4.9% below 2m of depth.

After validation, new scenarios were run to simulate future operating conditions. Results indicate little variation on the current soil water content as the tailings layer works as an impermeable barrier, and due to the high evaporation rate.

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Track-mounted sonic drill at the tailings facility

Mine water management: recent experience from India



Formation of pit lake in one of the limestone quarries

One of the largest cement manufacturing companies in India, OCL India Limited, produces limestone from its open-cut Lanjiberna mine. With increases in mining depth, the mine is facing significant inflow of water, resulting in the formation of pit lakes. The area experiences significant rainfall during the monsoon months. OCL retained SRK India to help advise on potential water inflows with the deepening of the limestone pits and to develop a cost-effective mine water management solution.

Currently OCL operates three adjacent limestone pits with a fourth used to store pumped out water. During the initial phase of the study, SRK noticed that some water management practices had been overlooked causing high levels of inflow to the pits. The presence of large unlined water bodies and garland drains close to pit edges could be responsible for recirculating water. There were no interception or diversion structures to minimise the impacts of recirculation. Similar oversights were noted at some of the other projects that SRK India is presently involved in. For example, the pit at the Mangampet barytes mine is closely surrounded by unlined garland drains and water impoundment structures. To identify connections between water features, SRK suggested simple fluorescence-based tracer tests and accretion surveys along these drains.

To understand the water management issues at Lanjiberna mine, SRK developed a water balance model. It indicates the split between surface and groundwater inflows: about 5% is from direct rainfall onto the pit lakes, 45% from surface runoff, and the remaining 50% from groundwater seepage.

The Lanjiberna deposit belongs to a Precambrian metasedimentary sequence with multiphase folding and faulting. Landsat 8 satellite images and walk over surveys indicate large-scale lineaments intersect the Lanjiberna pits. Such narrow, elongated fracture zones may act as hydraulic pathways for groundwater flows into the pits. While overall groundwater inflows contribute about 50% of the pit lake water, a good proportion could be due to recirculation from nearby unlined water holding facilities.

Subsequently, SRK mapped the perennial (and seasonal) seepages inside the pit, which indicate reasonable correlation with narrow, linear structures and the regional groundwater flow pattern. Based on the preliminary water balance, SRK developed numerical models to estimate potential groundwater inflows. The results, though preliminary in nature, predict significant water inflows with progressive deepening of the pits.

Overall, it appears that restricting potential recirculation, improving existing storm water management and intercepting groundwater seepages by peripheral dewatering wells along the narrow fracture zones are key solutions for this operation. To validate this, SRK suggested further site-specific data gathering, including detailed fracture mapping, Electrical Resistivity Tomography along selective transects, pumping tests, tracer tests and accretion surveys along the unlined garland drains.

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Sujit is a Senior Engineering Geologist in the SRK India office with more than thirteen years of academic and mining consulting experience. Sujit's broad background includes designing and managing site investigation projects, geological and structural mapping, rock mass characterisation, site hydrological and hydrogeological assessment and numerical modelling. He analysed slope stability in anisotropic rock and assessed post failure dynamics of moving debris mass for his doctorate. Sujit's international experience includes projects from Indonesia, Malaysia, Somaliland, Sudan, Tanzania, Kenya, Mozambique and Oman.

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BEATRIZ LABARCA



Beatriz is a Geologist specialising in Hydrogeology with 18 years of experience in groundwater issues. She heads the hydrogeology area of SRK Chile. Beatriz is expert in simulating groundwater flow models and drainage aspects of fractured media in mines, tunnel hydrogeology and pore pressure in rock mass and geophysical methods applied to hydrogeology. She is experienced in hydrological data management and basin balances, and is skilled at obtaining permits regarding water rights.

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Effective dewatering and depressurisation at operational mine sites







PLANNING → CONSTRUCTION → OPERATION & MONITORING → ANALYSE, LEARN & ADAPT → PLANNING

The highly iterative dewatering/depressurisation planning cycle

JAMES BELLIN



James is a Principal Hydrogeologist with 12 years' experience in mine water management working in both consultancy and industry. His experience encompasses water management projects in a broad range of hydrogeological settings and commodities around the world. In industry, James led various operational and planning teams responsible for site groundwater and surface water management, technical studies, regulatory engagement and water risk and strategy.

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When it comes to dewatering and depressurisation at operational mine sites, getting the technical understanding right is only half the story. The other key to success is in maintaining and operating equipment effectively, as well as dealing with a constantly evolving mine environment. The best dewatering or depressurisation system in the world will only be as effective as the way it is operated. If pumps are down for maintenance, refuelling, or damage from mining, they will quickly become limiting factors to success. Furthermore, the system must stay relevant throughout the inevitable changes in mine design that come as a mine moves through the development cycle.

Dewatering and depressurisation planning should be integrated with the many mining disciplines which it interacts with or it will fail. However, these interactions, and the operational decisions that result, should be well-informed with timely, reliable, operations-specific monitoring data. Good data may require significant cost and effort but good water management decisions will almost certainly deliver many times more value back. Data capture need not be complex but the consistency and quality of the data requires a well-designed monitoring plan with clear justification for every measurement, honing in on key risk areas. This not only enables the monitoring and subsequent analysis to be as cost-efficient as possible, but also prevents dilution of key messages from "data overload."

Presenting data in an easy-to-understand format that can quickly inform discussions and tactical changes is also paramount. Problem solving should proceed logically from aquifer response to abstraction rate to equipment effectiveness using universally understood metrics. For example, if groundwater levels are higher than planned, but abstraction rates achieve plan, then the conceptual hydrogeological model should be investigated; but if abstraction rates, availability, and utilisation are all lower than plan, infrastructure maintenance would come into question.

Should we wait until the operational stage of a mine to consider these challenges? Dewatering and depressurisation planning and operation is an iterative process that follows the typical Plan-Do-Check-Act cycle, necessarily taking data and learnings from construction and operation as an input into the next plan iteration. Although this seems like a simple concept, often systems are designed in a one-off, linear way so that changes in hydrogeological understanding, mine plans, or operational efficiency render the system ineffective. If systems are not phased, flexible, and unobtrusive from the outset, these mistakes can be extremely costly to correct once built. Innovative solutions to avoid mining interactions, like angled wells, horizontal directional drilling, and targeted pre-blasting, may cost more initially but can often reap significant financial benefits over the project life.

Understanding the challenges of dewatering and depressurisation upfront can produce flexible solutions that integrate seamlessly with operations, are easy to operate and maintain, and ultimately reduce costs and maximise dewatering or depressurisation effectiveness.

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Managing saline groundwater

Mining operations frequently encounter saline groundwater below permafrost on the Canadian Shield. Saline groundwater on the shield is primarily a calcium chloride brine. Management options need to meet compliance limits for total dissolved solids (TDS) and chloride in receiving waters.

TDS concentrations in groundwater increase with depth below the permafrost and can exceed 50,000 mg/L. The Canadian Council of Ministers of the Environment long term chloride limit for protection of aquatic life is 120mg/L. A TDS limit of 1,000mg/L has also been set for some mines in the north. Treatment options are limited, expensive, and energy intensive. Conventional treatment involves a concentration step (typically a membrane process). At TDS concentrations over 30,000mg/L, most membrane processes are not feasible. Evaporation and crystallisation is cost prohibitive for mine operations. This leaves two feasible options for managing saline groundwater: discharge to the environment or storage in completed pits or underground workings.

Discharge to the environment requires enough assimilative capacity (dilution) in the receiving water to meet compliance limits. The assimilative capacity varies seasonally in the north, which may require mine water storage during low flow periods of the year. Discharge to a lake may initially meet compliance limits but if the loading to the lake exceeds the rate at which TDS is flushed from the lake, concentrations may eventually exceed the compliance limit. Discharge to the marine environment is a viable option but depends on proximity.

Saline water can also be disposed of in completed underground workings and pits. This requires integrating water management and mine planning. Disposal in underground workings isolates the saline water from the environment but sufficient volume needs to be available when saline inflows begin. Saline water can be stored in a pit by forming density stratified lakes where the saline water is deposited first and overlain with less dense freshwater. Creating this type of lake in a pit is challenging, but has the potential for the long-term storage of saline water without impacting the environment.

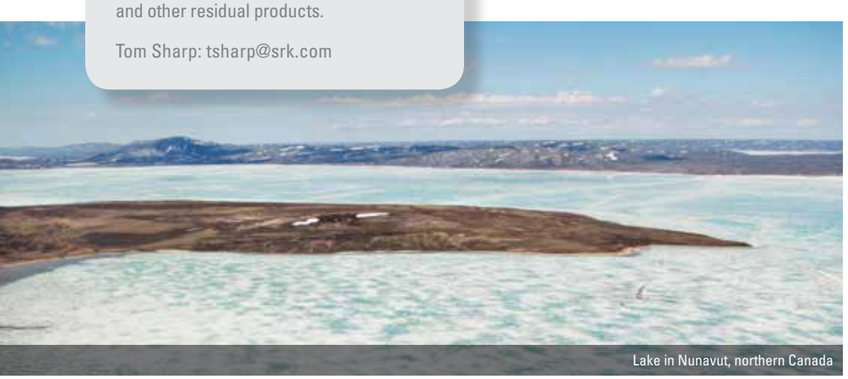
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TOM SHARP



Tom, PhD, PE, PEng, is a Civil/Environmental Engineer focusing on integrating mine water management and treatment into mine planning. Tom joined SRK in 2011. He has prepared numerous site water, load balances and water management plans for mines and metallurgical facilities. Tom has significant experience in the testing, design, operation and cost estimation of mine water treatment systems as well as evaluating management and disposal alternatives for water treatment sludge and other residual products.

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Lake in Nunavut, northern Canada

Predictions of mine waste geochemistry in arctic conditions



Winter conditions in the Fennoscandian region

The management and use of water is a critical concern for mine project viability and profitability. This is especially true of mining in arctic environments where water issues are compounded by too little water (lack of seasonal water availability) and periods of too much water (snow melt). These extreme issues have implications for water management, treatment and discharge to pristine environments.

Acid rock drainage and metal leaching can be a major environmental liability that greatly complicates and adds to the expense of site water management. Predicting source term water quality from mine waste facilities is becoming a pre-requisite for the ESIA and permitting process. It facilitates the implementation of efficient waste rock management plans, and can help determine if mitigation measures are required during life of mine (LOM) and post-closure, to prevent environmental impacts.

To make meaningful predictions of long-term leachate quality, a detailed knowledge of site-specific hydrologic, climatic and geological conditions is required. Quantitative parameters are needed from systematic laboratory studies on waste materials and representative field measurements. SRK typically modifies testwork and predictive methods to account for lower temperatures, spring snow melt and slower weathering kinetics in Arctic conditions, in addition to other input parameters including, oxygen supply and grain size.

SRK completed predictive numerical calculations to assess long-term leachate chemistry from a proposed waste rock dump (WRD) at an iron ore deposit in Northern Sweden. Annual temperatures at the site range from -30°C in winter months to 25°C during summer, with a period of spring snowmelt (April-June). The calculations were undertaken to support the environmental permitting process.

SRK worked with the client to develop an effective waste management strategy to minimise potential environmental impacts.

Source terms for LOM and post-closure were developed from static and kinetic testwork carried out on lithologically representative drillcore samples. The WRD material consists of:

(i) Potentially acid forming skarn (sulfur content >1%), ~30% waste; and

(ii) Non-acid forming material types (sulfur content <1%), ~70% waste.

Modelling results demonstrated that predicted metal loading from the WRD is greatest during spring snowmelt for LOM, when seepage through the WRD is greatest and the material is uncovered. Segregating high sulfur waste material and applying a qualified cover proved to be the most effective strategy for minimising water quality impacts on the adjacent water course post-closure.

As global resource demand increases and mining techniques advance, mining in arctic regions becomes ever more feasible. Robust mine water management plans from site-specific seepage quality predictions are vital for permitting such projects in these pristine environments. By incorporating arctic environmental conditions (low temperatures and spring snow melt) in modelling, SRK can outline potential environmental impacts and define mitigation measures in the early phases of project development.

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Jessica is a Consultant Geochemist with a Master's degree in Environmental Geology. Her areas of expertise include the geochemical characterisation of mine wastes and waters; field based analytical geochemistry; and ARDML assessment. She provides input into environmental baseline and hydrogeological review studies. Jessica has been involved in numerous field programs including: XRF analysis at exploration sites, and mine waste sampling for feasibility studies.

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Hydrogeologic characterisation and modelling for block cave mine vs open-pit mine dewatering

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Roger, PG, is a Principal Hydrogeologist with over 30 years of experience in mining hydrogeology, exploration geology/ geochemistry, and environmental engineering. His areas of expertise include design and management of mine dewatering and mine-water disposal projects, geological synthesis and development of conceptual hydrogeologic models, and integrating hydrogeology with exploration drilling and development programs.

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Dr Vladimir Ugorets, Principal Hydrogeologist, has more than 38 years of professional experience in hydrogeology. He has been involved in numerous mine dewatering projects for pre-feasibility and feasibility studies, mine construction, and mine operation. Vladimir's experience includes hydrogeological data analysis, developing conceptual and numerical groundwater flow and solute transport models for mining projects, optimising well fields and other dewatering systems for open-pit, underground and ISR mines and predicting pit-lake infilling and underground mine flooding during post-mining condition.

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Drilling a large diameter test well

At a large Cu-Au deposit in the Philippines, mineralised porphyries occur below an erosional surface buried by post-mineralisation volcanic and lake-bed deposits (cover sequence); ore lies below the river stage in hilly terrane where rainfall totals 4.8 meters annually. Inter-volcanic muds in the cover sequence, including a thick basal unit, caused the loss of numerous drillholes during exploration. Consequently, hydrologic drillholes were hastily "telescoped" to as deep as 700m into the basement, leaving few opportunities for hydraulic tests or monitoring wells in the upper units. Groundwater flow in the confined basement aquifer was deemed more crucial to dewatering studies than flow through overlying volcanics, based on a block-cave mine plan.

Three basement pumping tests (10L/s to 136L/s) were insufficient to define boundaries or resolve vertical recharge rates. As a result, early dewatering predictions for a laterally-unbounded, high transmissivity basement were very high. However, dewatering a basement decline, which affected water levels throughout the hydrologic program, was increased late in the program to 200-300L/s, thus providing an opportunity to passively monitor a large stress of the aquifer for a long period (10-months). Boundary effects were eventually seen, which reduced numerical predictions of block-cave dewatering by two-thirds. Partial recovery in the decline allowed an estimate of groundwater storativity, and net recharge through leaky lateral and vertical boundaries.

An iterative approach was used to evaluate the robustness of model calibrations and to validate alternative conceptual models. In total, the groundwater model was reasonably well recalibrated five times to account for new data. This required revising the conceptual model with regard to transmissivity, vertical hydraulic conductivity, groundwater storage, recharge, and boundary conditions—in the basement only. Throughout the process, the cover sequence was assigned generic properties, to which model predictions of dewatering the block cave were largely insensitive.

Post pre-feasibility, the mine plan was changed to an open pit design. The existing data and block-cave model accurately defined inflows from basement rocks, but those flows now constituted less than a third of potential pit inflows, and would occur later in the mine development. The poorly-constrained volcanic sequence, however, now transmitted another third (direct precipitation the remainder) of potential mine inflow, immediately upon development, and posed significant slope-stability risks. Major data gaps relative to open-pit mining, included:

- Intermediate circulation of meteoric recharge through the cover aquifer
- Water levels and gradients within the volcanic sequence
- K values in pit-wall material, critical to both slope stability and inflows
- Layering and vertical K in volcanics, critical to dewatering strategies

An entirely new phase of field and numerical investigation was required to assess these gaps and the feasibility of the open pit mine.

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Surface water management in high rainfall environments

Water management at sites generating excess impacted water can result in high costs and risks if the development concept is advanced without consideration of certain key aspects. SRK developed a conceptual design for surface water management related to a project in Papua New Guinea (PNG) which included large open pits. The region's mean annual precipitation is approximately 8m.

The primary objective of the surface water management system is to divert clean water, as well as direct contact water, around the open pits to appropriate transfer facilities and, from there, to the water treatment plant. Contact water that is not collected by diversion channels is collected at the pit base and pumped to the transfer facilities.

The surface water management system comprises:

- Clean water diversion channels/ bunds
- Contact water channels
- Drop structures
- Treatment plant transfer points (TPTPs)
- Pumping line from the base of the open pit to the TPTP

The clean water diversion structures collect runoff from the catchments upstream of the open pit and discharges this water to the natural stream system downstream of the pit. Ideally, as much clean water as possible should be diverted; however, due to the steep topography, it was difficult to find suitable sites for the surface water infrastructure. SRK suggested minor modifications to the pits' layouts to improve water management; clean runoff from approximately 40% of the total catchment area is diverted.

The contact water diversion structures collect runoff that has been in contact with the walls of the open pits, and discharges it to the TPTPs, from where it is sent to the water treatment plant.

Contact water diversion structures (drains) are installed on the pit benches; the minimum bench width allows for the bench width and drain components. Drop structures are installed to direct water from drains on the upper benches to lower bench drains.

Where possible, the contact water diversion structures are placed along mine access ramps. Contact water runoff from approximately 42% of the total catchment area is diverted by gravity towards the TPTPs.

Finally, contact water that cannot be diverted is pumped from the base of the open pit to the TPTPs, i.e. runoff from approximately 18% of the total catchment area.

The conceptual surface water design and analysis resulted in a significant cost saving, as less water needs to be pumped to the TPTPs and a smaller water treatment plant is required.

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JUANITA MARTIN



Juanita has over 20 years' experience in design, coordination and supervision of projects for the mining and civil engineering industries. Juanita's key areas of expertise are in water management for mining infrastructure in diverse environments; the design of hydraulic elements – channels, ponds, culverts, spillways; the design of embankments for tailings and water dams, storage capacity evaluation, water balance and hydrology studies, catchment areas and basin characteristics, climatic evaluation and determination of storm events. Her experience includes various engineering levels from conceptual through detailed designs.

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User friendly dashboards for dynamic water management

SRK conducted the water management aspects of a Feasibility Study for the Tete Pig Iron and Ferro-Vanadium Project in Mozambique. The project is located in the north of Mozambique, approximately 40km north east of the town of Tete, in the Tete province, one of the region's fastest growing mining and industrial centers.

Water supply and management were the client's key concerns as the area is characterised by a long, dry winter and a short but extremely wet summer. The site is located on the eastern bank of the Rio Revuboe, one of the last major tributaries, which flows into the Zambezi River before it reaches the Indian Ocean. Other mining projects are planned for further down river, presenting competition for water resources. The client recognised the need for a proactive water management strategy and the value of a decision support tool to help make informed decisions about the impacts of operation decisions on water demand and availability.

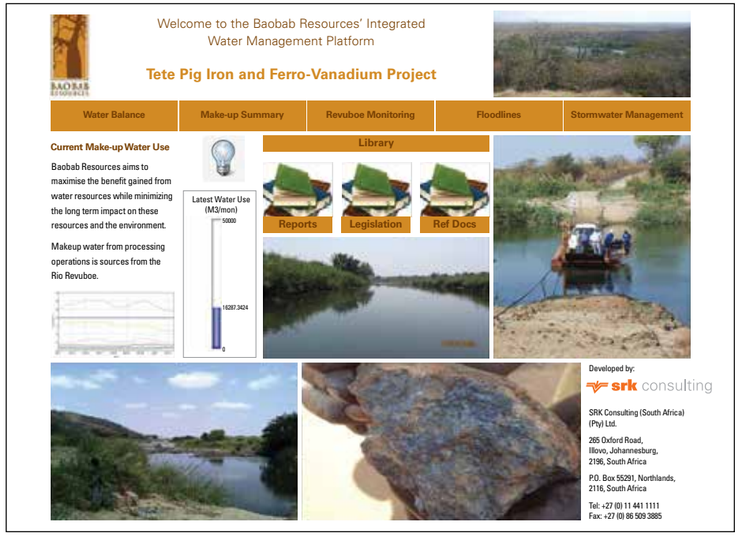
The author, Lauren Bulcock, formerly with SRK, developed an integrated water management dashboard, which is used for planning and presenting water data, using Goldsim software.

The dashboard incorporates stormwater information, floodline information and, more importantly, a dynamic water balance which allows the user to test water intervention or environmental scenarios that can impact water demand and availability. This allows the client to model the implementation of strategies and make decisions instantly, to prevent interruptions to operations due to water constraints. These intervention strategies include slurry densities, scenarios of increased or decreased production and water routing options, while the environmental scenarios include different rainfall and evaporation scenarios.

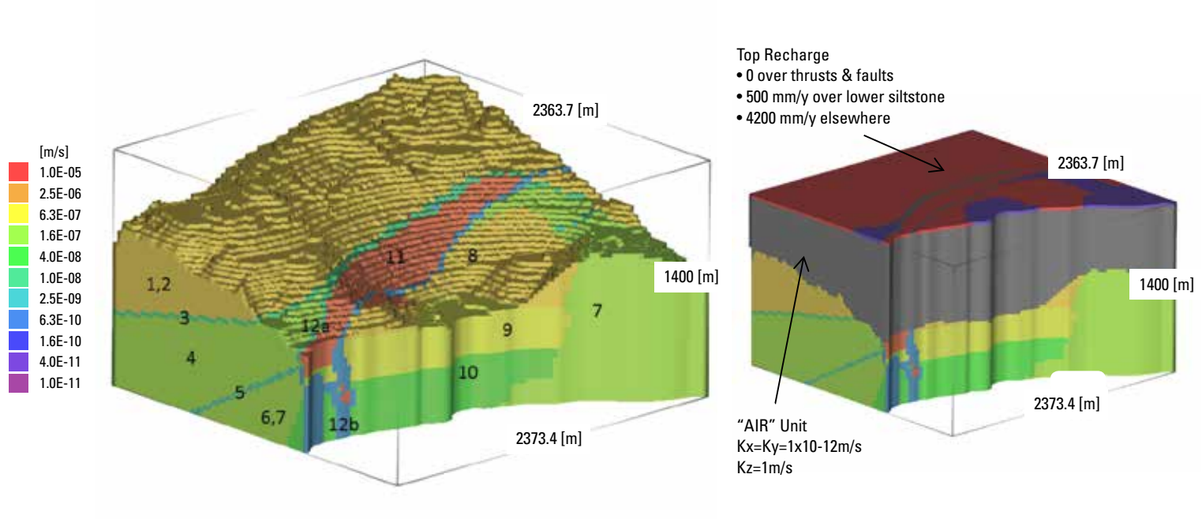
This dashboard was well received by both the environmental agencies and authorities as well as financial advisors who were assisting with the bankable feasibility study and mentioned the increasing emphasis being placed on the availability of water for future investment projects.

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Samples of interactive dashboards which provide near real time feedback to the client on water supply and availability and allow for testing of operational decisions



Integration of pore pressure modelling with slope design



Integrating groundwater pressures into slope stability modelling is an evolving process in mine design. The goal is to carefully match the slope modelling requirements with a somewhat conservative and plausible groundwater scenario while keeping things as simple as possible. The simplest approach is to use 2D cross sections of the pit slope and assess the stability assuming either a hand-drawn or a simulated 2D hydrostatic water table. In some cases, this approach may be sufficient and deemed conservative, but more often it ignores the geological complexities that affect slope performance and cannot correctly represent the potential high pressures found at the toe of pit slopes. The Holy Grail consists of modelling the transient excavation of the full scale pit in 3D, predicting the pore pressures coupled with the geomechanical changes in the rock mass due to unloading (rock mass dilation, etc.). While we never have the data to accurately conceptualise and calibrate full pit scale models to this level of complexity, opting for 3D modelling significantly increases the effort and must be therefore chosen cautiously. Specific site conditions may be required such as the influence of a dominant orientation of fractures producing anisotropic flow/depressurisation, pit geometry, localised sources of recharge, etc.

A major limitation for the 3D modelling used to be the ability of groundwater modelling codes to construct complex geometries such as a pinching geological layer or pit slopes changing over time. The recent advances in commercial software make it possible to provide 3D pore pressure distributions, in both, static or transient conditions, that match the slope geology at limited cost (i.e. time and computer power). The construction of meshes is more flexible and efficient with "unstructured" grids. The geology geometry can be more accurately modelled and again transferred back more accurately to slope modelling to ensure geotechnical and hydrogeological domains match. The alternative block method SRK utilised to allow for geometry matching with complex stability codes such as 3DEC (SRK, 2013) still has some advantages but may quickly become obsolete.

As with much of the modelling we can do today, the codes allow for ever higher complexity to be brought into the analysis. However, the key is still to understand where the groundwater and geomechanical models need to most accurately interact, what portions of the slope are most sensitive to pore pressures (and this will change with time due to natural or induced depressurisation), and what are the data uncertainties and resulting limits of the models. Model sensitivity is an important part of the modelling, and must be used to determine potential uncertainty/probability in whether acceptable depressurisation rates can be achieved to produce stable slopes, or identify the need for more proactive measures (enhanced drain installation programmes, drainage adits, etc.).

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Michael is a Principal Hydrogeologist with over 25 years' experience with projects in Canada, Africa, Australia, PNG, USA, China, and Turkey. Michael manages multidisciplinary programs to PFS level, under difficult conditions in Australasia or the Canadian Arctic. His mining and geological experience, plus instrumentation knowledge, have guided the planning and investigation of groundwater projects. His project experience includes slope stability investigations and depressurisation, mine dewatering, rock mass characterisation, mine closure, tailings dam seepage, environmental monitoring, and contaminant hydrogeology.

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Peter is a Partner, Director and Principal Hydrologist in SRK's Johannesburg office. With a BSc (Hons) in hydrology from the University of Natal, he has been with SRK since 1992. His specialisations include floodlines, dam hydrology, mine water management, river hydrology, water supply and flood management. Peter's recent mining projects, based in various African countries, focused on stormwater management and developing water management plans for mines in dry and wet areas. Dealing with variable climatic conditions is critical for mine water management and SRK is at the forefront.

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Improved conceptualisation of shallow weathered groundwater flow using surface geophysics

PAUL HUBBARD



Paul is a Senior Consultant (Hydrogeology) with over ten years' experience in mining hydrogeology and groundwater solute transport assessment. His expertise includes groundwater impact assessment for mine developments, solute fate and transport assessment for tailings seepages and mine dewatering programs. Paul's work has primarily been focused in West Africa and Northern Europe.

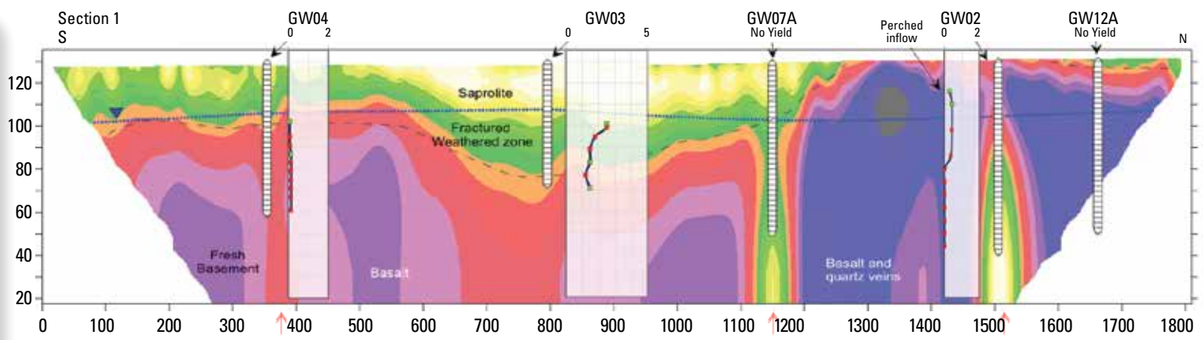
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HOUCYNE EL IDRYSY



Houcyne, MSc, CGeol FGS, is a Principal Hydrogeologist with SRK UK and a Chartered Geologist. With a PhD in Hydrogeology and MSc in Hydrology, Houcyne is particularly skilled in water resources studies. He has worked on numerous mine projects around the world, including support for operating mines and feasibility studies on various projects in diverse and complex settings from permafrost to tropical environments.

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Integrated visualisation of geophysical profile with control boreholes

Shallow groundwater flow in weathered hard rock areas typically focuses on fractured weathered zones, which are often simplistically conceptualised with a uniform thickness and permeability. This 'transition zone' is typically encountered as a horizon of increased, then decreasing, hydraulic conductivity occurring between the base of the weathered saprolite and the underlying fresh bedrock.

However, this fractured zone is not always a simple, laterally extensive layer with uniform depth. In metamorphic terrain it can be formed from a number of weathering events at different elevations. Weathering around sub-vertical features like faults and dykes can cause localised variation in depth and associated hydraulic properties.

Over simplifying the weathered zone into a layer of uniform depth and hydraulic properties using only limited hydraulic measurements can lead to misleading interpretation resulting in ineffective remediation designs and monitoring programmes.

In recent projects, SRK has combined targeted hydraulic data with surface geophysical data to improve our concept of the weathered fractured zone. The primary surface geophysical technique used has been Electrical Resistivity Tomography, although other methods have been tried with less success. Geophysical results have been combined with drilling data (core logs and geotechnical logs) and compared with the results of vertical hydraulic profiles derived from packer tests, spinner tests or drilling airlift results. Leapfrog™ 3D geological modelling software has typically been used for compiling data. This approach enables the resistivity tomography sections, borehole data and hydraulic test data, as well as other geological interpretation, to be combined for subsequent interpolation of the weathering interfaces.

The variability in hydraulic conductivity results can be related to local variations in the weathered fractured zones when adopting this approach. The improved conceptualisation and understanding of the spatial variability of the weathered zone in-turn provides a more realistic representation of the system in subsequent numerical groundwater modelling.

Integrating geophysical data with geological and hydrogeological information has been instrumental in recent contaminant transport investigations of leaking tailings facilities. The approach allowed us to identify and characterise laterally extensive pathways of deeper weathering that act as permeable channels for solute migration.

Careful selection of the geophysical method is required, based on the local geology and groundwater depth, with initial field trials at each site before the main investigation. Additionally, ground-truthing the geological and weathering profiles from boreholes along geophysical survey lines has proved highly effective for accurately interpreting geophysics profiles.

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Water supply for a permafrost mine project in northern Russia

Mine project Feasibility Studies (FS) usually require the involvement of various consultancies and process design companies where cooperation between the involved parties is critical to the success of the study. Lack of communication between the parties and/or understanding of the study requirements can lead to gaps in the scope of work and hinder the study's quality.

Recently, SRK UK was involved in a FS for the Mangazeisky Silver project in the permafrost region of northern Russia, for which parallel International and Russian Standard studies had to be undertaken to satisfy both the local and international requirements for the project. SRK's scope of work comprised, among other disciplines, the hydrogeology and dewatering study for the proposed mine, which consists of two shallow pits and underground workings. Also, SRK was commissioned to review the water supply study, which had been undertaken by a local contractor.

Despite the fact that the water supply study was part of the local contactor's scope of work, SRK designed the mine hydrogeology and dewatering investigations to take into account the potential need for boreholes by the water supply study. The main aim was to collect data for modelling the permafrost, and estimate the sub-permafrost aquifer parameters and use these in a groundwater model to estimate the potential inflow of groundwater into the mine.

The water supply investigations (surface geophysics and borehole drilling) by a local contractor resulted in low yielding boreholes unable to fulfil the plant water demand requirement. However, the boreholes SRK designed encountered aquifer zones with higher flow rate that could fulfil the plant water demand.

The groundwater model that has been developed primarily to estimate inflows of groundwater into the mine was used to simulate pumping from water supply wells and assess the aquifer potential and sustainability of the water supply. SRK's involvement, therefore, minimised the water supply risk to the project and the potential cost of additional investigation.

The client appointed SRK to remain involved in the drilling and testing of the actual water supply wells. SRK UK involved SRK RU in supervising the hydrogeological investigations in the FS and the testing of the actual water supply wells.

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Photo courtesy of Silver Bear Resources.

Helicopter transport illustrating the challenging conditions due to cold weather and remoteness of the site

Seepage estimates from tailings impoundments

SRK has a long history of evaluating tailings dam hydraulic and hydrological processes. These studies inform water balance estimates, flood control design, seepage predictions, and stability analyses.

Recently, the Department of Water and Sanitation in South Africa issued a Proposed Amendment to the Regulations Regarding the Planning and Management of Residue Stockpiles and Residue Deposits, enabling the use of risk-based design of pollution control barrier systems in mine tailings. In order to address a risk-based design, detailed analysis of the infiltration, evaporation and redistribution of rain and slurry water within the tailings impoundment is required.

This has become particularly necessary with cyclone deposition, where coarse, underflow tailings are deposited on the perimeter of the impoundment and the overflow fines are deposited onto the beach. In addition, the level of the phreatic surface throughout the deposit needs to be accurately established so that stability analyses can be performed. The drawdown due to drains and the potential seepage through barrier systems at the base of the tailings also require detailed analysis.

To address the requirements for risk-based design, HYDRUS-2D, a 2-dimensional, finite element soil-water physics model has been used.

HYDRUS-2D was used initially to simulate the behaviour of saturated and unsaturated zones in an existing tailings impoundment. The hydraulic characteristics of the impoundment were measured in-situ and derived from piezocone analyses. Simulated fluxes from drains were compared with monitoring records; the simulated phreatic surfaces were compared with observed piezometer water levels, and hydraulic pressure gradients extracted from the 2-D model were compared with those observed in piezocone tests.

The successful representation of the existing hydraulics in the model has allowed for the evaluation of barrier systems for a new tailings storage facility with similar tailings material. Here, specific boundary conditions have been invoked to represent the non-Darcy characteristics of seepage losses through a geomembrane barrier system. Theoretical and experimental flux estimates for geomembrane performance under various conditions, reported in the literature, were used to develop an envelope of possible boundary responses. These were simulated to derive potential seepage fluxes into the footprint.

The simulations were also effective in the positioning and design of the drains, as well as deriving conditions for stability analyses.

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Conducting Guelph permeameter tests on an existing tailings impoundment

Optimising mine pollution control measures



Palabora Copper's open cast mine is Africa's widest man-made hole at almost 2000 meters

Palabora Copper (PC) operated an open pit to recover copper ore (and secondary metals) from 1964 until 2002, and has since mined the ore by underground block caving.

Portions of the mine complex, particularly the tailings impoundments and magnetite stockpiles, are located within 1km of Kruger National Park (KNP). The primary Waste Rock Dump and Return Water Dam are located within 500m of the Selati River, a tributary of the Olifants River, which also flows through KNP. PC has installed a comprehensive network of groundwater and surface water sampling sites to monitor the impacts of their activities and has implemented some remedial actions. However, subsurface contaminant flow does move across the KNP boundary.

The objectives of this project were primarily to update the conceptual and numerical groundwater model and subsequently to assess the current and proposed remedial options.

However, SRK applied a multidisciplinary approach to assess not only groundwater, but also surface water and vadose zone pathways to identify and quantify contaminant migration. Key results from the study include:

Upper & Lower Aquifer Interaction. The site is underlain by a semi-confined Upper Aquifer and a confined Lower Aquifer, almost entirely driven by flow within dyke contact zones. These aquifers have not been previously defined in borehole logs, and screens or open holes through both aquifers exist. With statistical analysis and studying old borehole logs, however, water quality and levels in 'dyke contact' boreholes showed very different signatures to those of 'granite only at depth' boreholes. Many of the proposed pollution control boreholes have previously been sited within dyke contacts where yields are highest. However, this SRK project proved that the Lower Aquifer is largely protected from contamination in the Upper Aquifer by a naturally upward vertical hydraulic gradient and distant recharge zone.

If the Lower Aquifer is pumped for 'groundwater remediation', however, the Aquifers' drawdown may reverse this vertical hydraulic gradient, inadvertently spreading the contaminant plume, and unnecessarily pumping uncontaminated water from the Lower Aquifer.

Preferential Pathways for Contaminant Flow. Contaminant flow near the source is often fairly diffuse and only later converge into sandy drainage channels flowing towards the rivers. Thus, the cost-effectiveness of the currently proposed pumping of the Upper Aquifer requires re-evaluation to prevent selecting boreholes with poor long-term yield rates and localised contaminant mass capture. The drainage channels form the prime location for effective cut-off trenches and pollution control boreholes.

Surface Water and Interflow Contribution to River Loads. The contributions of sulfate to the Selati River reveal a significant discrepancy between groundwater and the loads from flow and water quality in the river. We assumed a significant sulfate load from sporadic, rainfall induced discharges. However, this mechanism needs to be confirmed before remedial measures can be recommended, necessitating further study during 2017.

With the application of SRK's fresh eyes, critical data review and cross-disciplines (geohydrology, hydrology, hydropedology) and office collaboration, various traditional concepts were challenged, thus bringing to light important new conceptual thinking, backed up by numerical modelling, and forming a key-pin of future remediation management and associated studies at the site.

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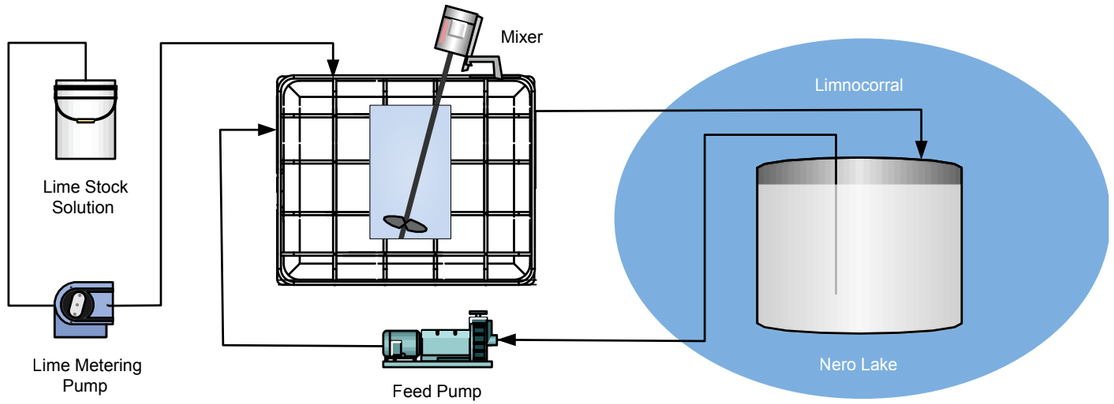
SIMON LORENTZ



Simon, BSc (Civil Engineering), MS and PhD (Bioresources Engineering), is a Principal Hydrologist in SRK's Pietermaritzburg office. He has 40 years' experience, in hydrology with a specialisation in vadose zone hydrology. During 27 years in academia, he researched hydraulic and contaminant transport processes in numerous mining and industrial waste materials and contributed to the development of hydropedology in southern Africa. Currently, he is involved in near-surface contaminant mobility and water quality studies for mining and industrial clients.

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Design of in-situ water treatment of acid contaminated lake



Pilot trial schematic

SOREN JENSEN



Soren, PEng, Environmental Engineer and Senior Consultant, focuses on mine water management and treatment. He has developed and implemented mine water management plans and modelling assessments, and designed, commissioned and operated water treatment processes for mining operations across the Canadian North including on-going engineering support services. Soren has produced detailed water management studies, feasibility and engineering design to manage ammonia, nitrate, metals and selenium. He is particularly interested in developing low-cost, in-situ or batch treatment processes with the aim of reducing operating costs and closure liabilities.

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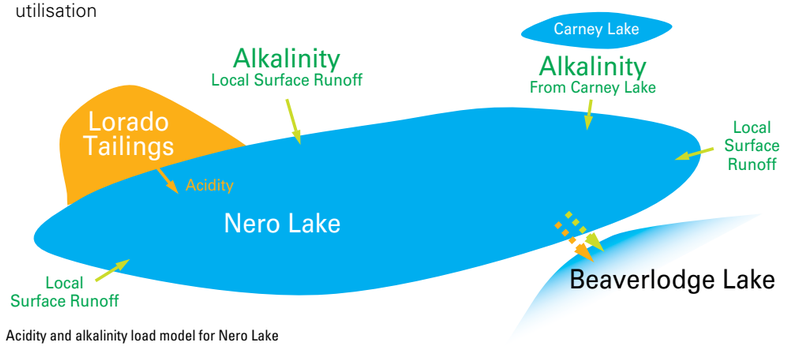
The Lorado site is an abandoned uranium milling operation located on the western shore of Nero Lake in northern Saskatchewan. The mill was constructed in 1957 and operated until 1960. Tailings and acidic waste produced by the milling operation were deposited near the western shore of Nero Lake and some tailings were submerged in the lake. Although not abandoned, the Lorado site was neglected as ownership changed hands.

In 2007, responsibility was transferred to the Saskatchewan Ministry of Economy, with funds for site remediation. The ministry retained the Saskatchewan Research Council to develop a Risk Reduction Plan and an Environmental Impact Statement. The goal: to reduce risk from acid contamination at the site to human, terrestrial and aquatic populations.

The plan included: covering surface tailings in-place, and treating Nero Lake by batch neutralisation of the lake water using lime. SRC retained SRK Consulting to design the tailings cover, carry out a pilot-scale trial to test in-situ batch treatment and ultimately design the full-scale water treatment system for Nero Lake. In addition, SRK developed a water and load balance model for determining whether acidity from the historical tailings would necessitate neutralising treatments in the future.

The purpose of the pilot trial was to inform the full scale design by:

- Determining the lime dose required to neutralise the lake water
- Assessing the effect on water quality in Nero Lake
- Evaluating the long-term stability of the precipitated solids
- Evaluating the effect of mixing on lime utilisation



Acidity and alkalinity load model for Nero Lake

Prediction of cyanide draindown in arid environments

The pilot trial was carried out using closed-bottom limnocorrals (large, impermeable plastic bags) submerged in the lake. A circulation pump delivered water from the bottom of the limnocorrals to the shore where lime slurry was injected inline before flowing back to the surface of the limnocorrals. Precipitates formed in the treatment process were collected from the bottom of the limnocorrals and analysed.

Results from the pilot trial were used as a basis for designing and implementing a batch neutralisation campaign of Nero Lake the following year. Overall, the pilot trial results were in excellent agreement with the full-scale neutralisation of the 11 Mm^3 of water in Nero Lake both in terms of mixing and water quality improvement.

The modelling water and load balance modelling study relied on monitoring data collected between 1978 and 2013. The modelling study concluded that that no further neutralising would be needed after the initial batch treatment. Two years' of subsequent monitoring data has confirmed this conclusion.

This project showed that short-term in-situ treatments can be a low-cost alternative to conventional treatment, particularly in cold climates with short open water seasons and high operating costs during cold weather.

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Heap leach pads are continuously irrigated with raffinate solution during their operational life; typically cyanide solution for gold ore, and sulfuric acid for base metal leaching such as copper or nickel.

At the end of the active leach operations, once the volumes or grades of recoverable solution diminish, there remains the problem of long-term draindown of a solution that is unsuitable for discharge to the environment, and therefore requires containment and management. Reducing the period of active management and fast-tracking closure is therefore of clear benefit to the operator.

In a recent study of a leach pad in an arid setting, a multi-disciplinary team from SRK Vancouver and Cardiff developed a complex unsaturated flow model to evaluate the length of the active closure period required to reduce the solution inventory. The early-period draindown volumes were too large to be contained in the existing raffinate ponds. Unable to discharge the water, the best closure option was to re-circulate the solution to the top of the pad – but this time the aim was not to leach gold, but to utilise the arid climate to reduce the solution inventory. As the solution inventory declined, the draindown volume would reduce to a point where it could be managed within passive evaporation cells. The arid climate, which had previously been an operational constraint, would now be a benefit - allowing the leach pad to close with no long-term discharge.

Numerical modelling was used first to assess and then to optimise the closure options while accounting for the inherent uncertainties of climate and heterogeneity of hydraulic behaviour. Geochemical modelling of the re-circulated solutions was used to assess the long-term chemistry and potential corrosive and scaling properties.

Using this approach, SRK was able to provide a range of options to shorten the period of active management and achieve zero discharge at closure, as well as provide the client with the basis for assessing which option would be most cost-effective to implement.

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DAVID TAIT



David is a Hydrogeologist and Environmental Geochemist in the SRK Cardiff office with over 11 years' experience in consulting. Prior to that he spent 4 years working in public and private sector chemistry laboratories. David's background and experience provides the skills and knowledge for evaluating complex hydrogeochemical systems and developing solutions for environmental issues. Since joining SRK in 2013, David has worked on mine-related water management and environmental studies in Africa, Europe, Russia and Asia.

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The application of satellite remote sensing in the mining sector

It is becoming increasingly important for mines to stay up-to-date with the latest monitoring technology to ensure water resources are monitored efficiently on site, both from a water management point of view and from a compliance and legislative point of view. One of the technologies gaining rapid traction in water resources is the use of satellite remote sensing technology to measure and monitor evaporation across a broad spatial scale. Remote sensing satellites that contain both visible and thermal bands can measure energy emitted from the Earth's surface. Using surface energy balance models, such as SEBS (Su, 2002), total evaporation (ET) of the land surface can be calculated across a landscape at a variety of different scales.

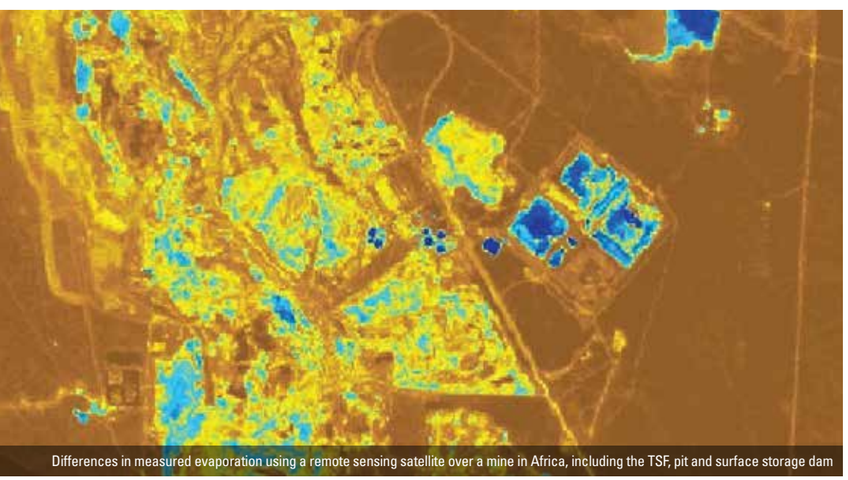
Remote sensing allows for the remote (from any computer with internet connection, from anywhere in the world) monitoring of the presence and surface distribution of moisture on Tailings Storage Facilities (TSFs) on a regular time scale (in this case every 2 weeks – weather depending) and at a sufficient spatial scale (30m resolution for free, higher resolution images incur a cost). Remote sensing will allow for monitoring the surface seepage, position patterns, evaporation and the persistence of surface moisture on the TSF. This provides valuable data to better inform water balances and TSF designs.

Remote sensing has been used on several mines in South Africa, and particularly over the tailings storage facilities, to measure evaporation as an indicator of seepage and to monitor the persistence of moisture deposited with the slurry. Lauren Bulcock, formerly with SRK, introduced this finding through her doctoral work in South Africa. Already this information has proven useful to our clients to identify if and where surface seepage is occurring, allowing them to concentrate their efforts in drilling recovery boreholes to contain those pollution plumes. This has saved clients unnecessary expenditure in developing exploratory boreholes and assists in targeting boreholes where seepage is identified.

The use of remote sensing to measure and monitor evaporation is a relatively new scientific field worldwide and has mostly been applied to agricultural applications. Very little to no applications have been done in the mining sector.

There is great potential for remote sensing to complement TSF monitoring programs into the future to measure and monitor the spatial distribution of slurry surface moisture, surface drying time and leak detection, which will allow for the better management of tailings dams and improved input into water balances.

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Differences in measured evaporation using a remote sensing satellite over a mine in Africa, including the TSF, pit and surface storage dam

Elandsfontein, Western Cape: groundwater predictive numerical modelling



Removing overburden in the first boxcut of the pit, made possible through both borehole and pit sump dewatering

The proposed Elandsfontein phosphate open pit mine is located on the south-western coast of South Africa, 8km inland from the environmentally sensitive Langebaan Lagoon, and bordering the West Coast National Park. SRK was commissioned to develop the numerical groundwater model for the design of the dewatering scheme. This sparked several subsidiary projects including geochemical analysis, engineering design for dewatering, and modelling and design of the mine pit.

The project has successfully overcome many challenges, including the hydrogeological setting which features an upper aquifer (where the ore body resides) composed of quartz grains and calc-arenites from marine deposits. Under it is a few-metre-thick unit of 'running' quartzose sands, a strong preferential pathway for groundwater flow, as local pumping tests proved. A confining clay aquitard, is situated below this sand, and under this an alluvial aquifer, comprising basal gravels/quartz sediments and gravel-filled palaeochannels with an upward hydraulic pressure head bearing on the aquitard. In this framework, SRK Cape Town undertook:

- Early consultations on hydrogeological and modelling approaches with SRK Cardiff, who had undertaken similar dewatering models for a phosphate mine in the Republic of Congo.
- Consultations with SRK Cape Town's team to address clay heave concerns from the lower aquifer, and slope stability issues within the upper aquifer.
- Integration of the hydrogeological model and the geotechnical stress analysis models.
- Detailed groundwater modelling and calibration of the hydrogeological system.

The South African Department of Water Affairs demanded that all water abstracted should be routed through a closed system and re-injected into the aquifer down-gradient (towards the lagoon) to mitigate potential reduction of baseflow. Challenges included:

- Rendering mine planning data (from others) into usable formats for the hydrogeological model.
- Calculating and modelling the continually altering flow rates for dewatering and re-injection.
- Controlling mounding at the re-injection site and managing the mounded water that partially flows back to the pit area.
- Considering potential geochemical alterations and risks within the closed (but vigorously pumped) dewatering system.
- Providing design input to the engineering design team (before drilling, dewatering and re-injection boreholes).

The mine is located in a highly sensitive environment, with multiple stakeholders and media actively challenging the continuance of the mine. SRK was instructed to:

- Develop clearly defined model objectives up-front to control complexities related to the sensitivity of the project and client expectations.
- Manage and respond to extensive external review and queries.
- Present clear and defensible explanations of the groundwater assessment and model results at challenging public stakeholder meetings.

As of February 2017, pit mining the overburden and dewatering (and re-injection) has begun. The mine is meeting tight timelines and regularly consulting SRK during implementation. Dewatering success depends on this continuing close relationship.

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SHEILA IMRIE



Sheila, MSC, PrSciNat, is a Principal Hydrogeologist in SRK's Cape Town office, has over 18 years' experience in groundwater resources and IT in Southern Africa and the UK. She specialises in conceptual and numerical modelling, generating flow and transport models for mining, industry and government. With a strong background in applied mathematics, databases, statistics and processes, Sheila dissects data, challenging conceptual thinking, and defining clear objectives to meet client requirements.

Using analogs to predict future pit lake chemistry

RUTH WARRENDER



Ruth is a Senior Geochemistry Consultant specialising in the application of environmental geochemistry to a range of mining projects. Ruth's areas of expertise include the geochemical characterisation of mine wastes, waters and soils and the application of geochemical modelling to mining environments. She is a Chartered Geologist and has over seven years' experience working on mine waste characterisation projects in base and precious metals worldwide.

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JOSÉ GARCIA



José is a Geologist from Universidad de Chile, specialising in underground hydrogeology. He has 15 years of professional experience in hydrogeology and environmental work, developing projects in Chile and Spain. Jose has conducted various hydrogeological studies for mining and civil works that include interpreting hydrogeological data, chemical and isotope information for conceptual models, EIA and environmental resolutions. He has performed environmental investigations and remediation projects in various industrial and mining installations.

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Existing pit lake at the Copper Flat project, Southern New Mexico

Predicting pit lake chemistry after closure is integral for demonstrating compliance during the Environmental Impact Assessment and mine permitting process. Water quality predictions rely on multidisciplinary information from geochemists, ecologists, hydrologists, hydrogeologists and mine engineering teams to assess potential ecological risks and identify options for closure, mitigation and reclamation.

Pit lake chemistry depends on multiple factors, including geology, mineralogy, climate, and hydrogeology. Despite using state-of-the-art numerical modelling, predicting future pit lake chemistry is often a 'best estimate' based on the information and tools available. Furthermore, it may not be possible to verify these estimates until decades later once a pit lake has formed. To develop more accurate predictions, SRK uses water quality, limnology and mineralogy data from analogue pit lakes, where available, to refine geochemical models.

This method was successfully applied at the Copper Flat project in southern New Mexico. The project is a porphyry copper-molybdenum deposit that was mined briefly in the early 1980s before low metal prices halted mining operations. New Mexico Copper Corporation is currently undergoing permitting activities to re-open and expand the project facilities. To support the environmental studies, SRK oversaw an extensive geochemical characterisation program, including developing a predictive geochemical model to assess future pit lake chemistry.

The existing pit lake provides a valuable analogue of likely future chemistry and characterisation of precipitated mineral salts along the lake shore allows for a more detailed understanding of mineral precipitation and adsorption processes.

Calculated estimates of pit lake chemistry were developed from the results of humidity cell tests, coupled with mine plan, geologic, mineralogic, hydrogeologic, climate and hydrogeochemical information and applied in the USGS software PHREEQC. The model was calibrated to the existing pit lake to account for all active geochemical processes. Good calibration was achieved, with predicted concentrations for most constituents being within the range of chemistry measured in the existing pit lake. This verifies the modelling method and demonstrates that future pit lake chemistry can be predicted with a good degree of accuracy.

Although the Copper Flat project is unusual in that it has an existing pit lake for comparison, published data from analogue pit lakes in a similar geologic and climatic setting can be used to indicate the expected range of pit lake chemistry for projects without a site-specific analogue. Pit lake geochemical predictions can thus be refined, allowing appropriate management and mitigation options to be identified to prevent impacts to human, environmental and ecological receptors.

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Isotopes to define natural water

Water isotopes (2H and 18O) are stable compounds and their principal fractionation comes from the evaporation and condensation process. In groundwater, the isotope variations and changes just come from the mixing of water of different origins.

In this project, a three-year quarterly water sampling program was oriented to know the presence and the percentage of natural water pumped by the hydraulic barrier downstream of a leaking tailings dam. The isotope content and water chemistry were analysed from water pumped by wells, surface water and tailings in order to characterise the natural, tailings, and mixed water. This definition is required to estimate the amount of natural groundwater that is being pumped without water rights.

The isotope content shows that the water stored in the tailings dam has evaporated, so its isotopic content is more enriched than the natural water (figure below). This situation allows differentiating the isotopes end members from the dam (PR3A) and natural groundwater (ABQ6A1), which will be used to estimate the natural water proportion downstream of the tailings dam.

The figure below shows the end members and the "mixing line". The groundwater isotopic content between both end members and near the mixing line indicates the existence of a mixture in the groundwater sampled. The proportion of the natural water is calculated using an analytical equation of the binary mix.

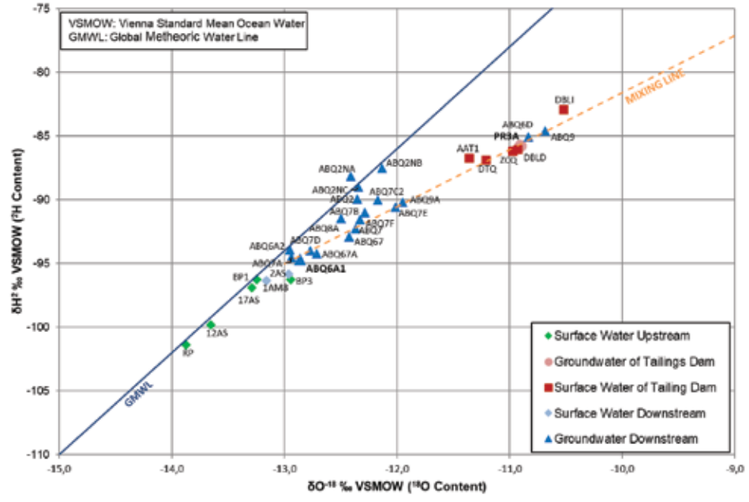
Results show that the percentage of natural water is higher when the distance to the dam increases. Water samples taken near the dam (ABQ6D and ABQ9) have no natural water because their isotopic content is similar to the groundwater stored in the dam.

The isotopic content of some groundwater samples (ABQ2, ABQ2NX, ABQ6AX) is in a line parallel to the Global Meteoric Line (GML); therefore, these points have not received any flow from the dam. This result indicates the hydraulic barrier is preventing the advance of water filtration from the dam to the downstream where public wells are located.

Water chemistry is used to support the percentage of the natural water in each point. The natural water is fresh water, calcium bicarbonate type, and 40% sulfate in anions. The water dam is slightly saline, calcium sulfate type, and 90% sulfate in anions. The mixing water is between these water types and sulfate percentage.

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ISOTOPIC CONTENT



Mine water risk management: an integrated approach

When it comes to water, the requirements of mining operations vary enormously, and the risks associated with water are different from site to site. This difference in risk factors is partly a function of the nature of the operation (above water table mining versus below, for example) and partly a function of climate and local hydrologic setting.

Wherever a particular project sits in a generic risk framework however, effectively identifying, defining, and managing the project-specific risks associated with managing mine water comes down to a few fundamental factors in SRK's experience:

- Understanding the hydrologic setting and conditions. In the majority of reviews we undertake, we highlight weaknesses in characterisation whether in the meteorology, the surface water hydrology or the hydrogeology. The characterisation needs to be supported by high-quality, representative data followed by data analysis and modelling. This knowledge, together with the supporting assessment, is fundamental to informing the effective design of water infrastructure (including dewatering systems, water abstractions, etc.), understanding specific project risks, developing water management plans and defining environmental and social metrics.
- Taking a joined-up approach. Because water management for a mining operation is a whole-mine consideration, the associated risks are heightened if the various functions responsible for aspects of water are not working as an integrated, communicating team. Water management plans are essential but so is effective management.
- Thinking about local communities. Social aspects of water and the perception of related impacts and issues are often under-estimated by clients. Water stewardship strategies linked to wider social and community initiatives can mitigate potential problems and disputes.
- Ensuring on-going monitoring and management. From pre-development baseline condition monitoring, to monitoring of, for example, water pressures in pit slopes during operations to closure monitoring of water quality, the importance of robust, high quality monitoring data collection and data management is critical in supporting management decisions and adding value to a project.

SRK helps define, manage and mitigate risks in mine water management, but also highlights opportunities through holistic and innovative thinking.

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Testing groundwater adjacent to a tailings facility

Post-closure groundwater impact assessment - Olympic Dam



BHP Billiton's Olympic Dam evaporation ponds, December 2007

The current BHP Billiton Olympic Dam operation comprises underground workings and a number of surface facilities, including the tailings storage facility (TSF) and processing plant. Mined out stopes are backfilled using cement amended tailings and aggregate fill. At the end of mining, dewatering will cease and the underground workings will re-flood. To support development of closure plans for the mine site, SRK assessed the potential impacts the operation could have on the regional hydrogeology (comprising the bedrock and Andamooka Limestone aquifers) and groundwater quality in the intermediate and long term post closure.

The approach combined hydrogeological modelling (using a FEFLOW platform*) with modelling for potential solute release from contaminant sources. The two primary sources identified were the: (i) above ground TSF, which releases percolate to the underlying groundwater table, and (ii) backfill and wall rocks within the underground workings.

The underground workings are connected to the overlying Andamooka Limestone aquifer via raise bores.

The model was used to assess the current extent of groundwater drawdown and calibrated against monitoring bore observations. The model was then used to predict the life-of-mine drawdown (3 to 11km) and the post-closure rebound, including the times required to re-flood the underground workings (several centuries). The model was also used to predict the groundwater mounding during tailings deposition (operational) and times for the mound to dissipate following closure (decades).

The TSF source was based on geochemically characterising existing tailings products and field evidence. These studies indicated that the percolate is neutralised within underlying soils and sediments, and that most metals and trace elements are attenuated, either within the tailings or immediately below the TSF.

The underground source comprised exposed (sulfidic) wall rocks and the cement-amended tailings backfill. Models were developed to describe the geochemical evolution of both components. The water quality predicted for the underground source components was similar to that observed for the neutralised TSF percolate. However, the flow from the underground workings is significantly lower than from the TSF, and in comparison, the underground workings represent a minor source.

The overall assessment showed that:

- Hydrogeological impacts would be acceptable within the near vicinity of the mine workings, with predicted water level changes at environmental and third party boreholes to be less than 3m.
- In the long term (post closure), no significant impacts on baseline groundwater quality are predicted at the lease boundary.

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* Hydrogeological modelling was undertaken by Sylvie Ogier-Halim.

CLAIRE LINKLATER

Claire has 22 years' experience in interpreting geochemical data and applying geochemical modelling codes. Her early career focused on managing radioactive wastes and understanding the geochemical behaviour of radionuclides for a proposed underground repository. More recently, she has focused on managing sulfidic materials; assessing acid rock drainage; predicting water quality and pollutant mobility from waste rock dumps, tailings storage facilities, underground workings and pit walls; and assessing mine closure strategy.

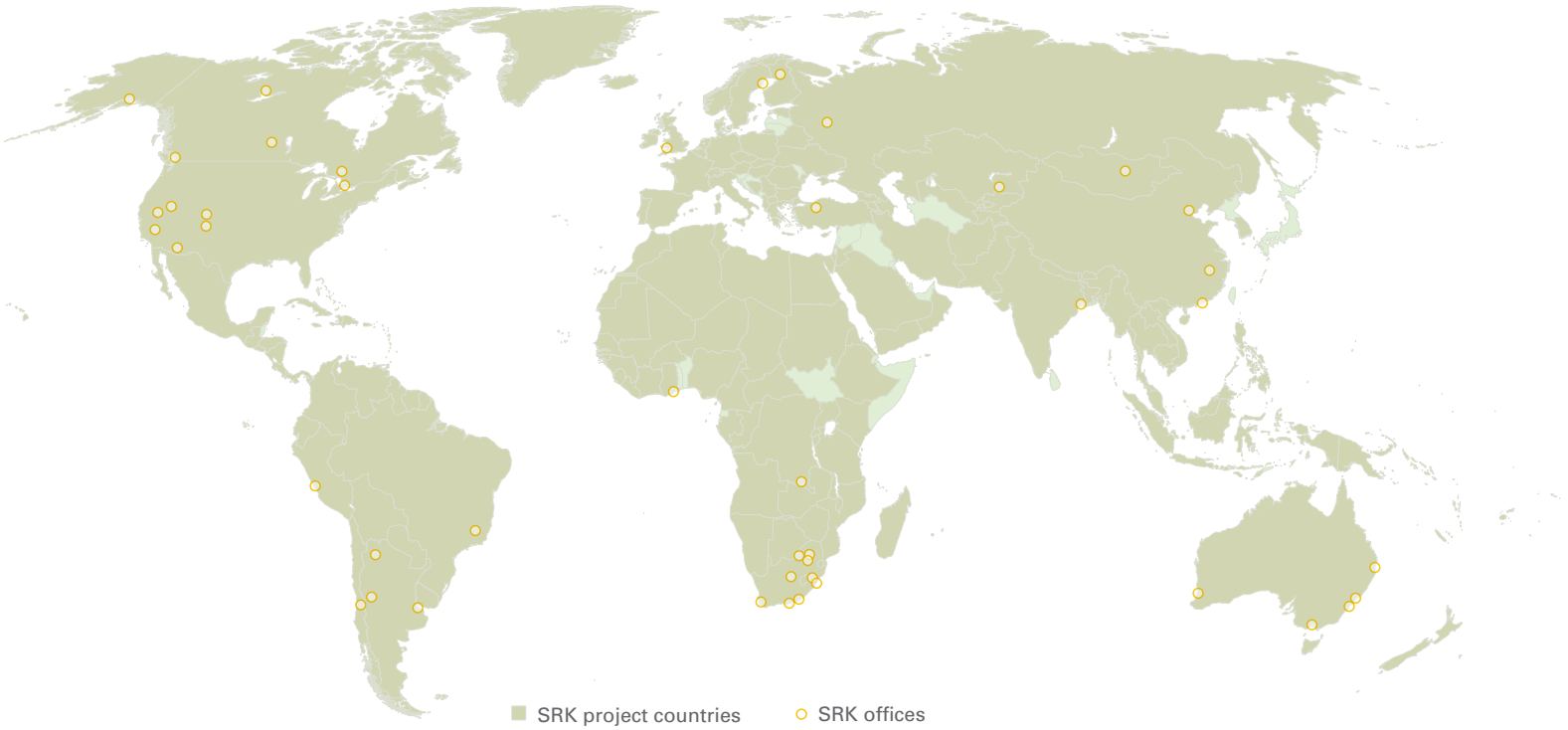
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TONY REX



Tony is a Corporate Hydrogeologist with over 30 years' professional experience in hydrogeology and water management. He specialises in mine water management including mine dewatering, groundwater evaluation and characterisation, water supply and water resources impact studies. Tony advises clients on water management issues both on development projects and operational assets mainly across Europe, Africa, Russia and CIS countries.

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