Appropriate Catchment Management can Improve the Profitability of a Mine: A Case Study from Dallol, Ethiopia

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Abstract How do you secure a fresh water supply for a new mine where groundwater consists of brine located in "the hottest place on earth", in one of the most remote desert regions of the world, with very little pre-existing information? Catchment management principles provided the solution. YARA and the Ethiopian Government have invested substantial cost, effort, and time into investigation of the Sustainable Yield, Deployable Output, and environmental and local water supply needs in the Dallol region, which has allowed the design of a water supply for the proposed mine with a water quantity and quality that is likely to be both reliable and resilient and to save costs during the LoM (Life of Mine).

Key words catchment water management, groundwater investigations, mining costs

Introduction

Mine water supply has been considered historically as an engineering problem that can be developed as a component of the mine extraction and processing design after completion of the mineral exploration phase. This approach engenders mine profitability at the earliest opportunity, but due principally to the time required to investigate and understand the mine water supply catchments, will always leave substantial latent risks from the uncertainty in the reliability and resilience of the long-term water supply and the impact of the mine on the catchment. In order to address availability, use, management and sustainability of mine water resources, the mining industry has recently developed guidelines to promote implementation of catchment-based water management principles in new mines (ICMM 2017), which is especially relevant in desert regions (Anderson, 2015), or jurisdictions where these guidelines are not enforced, or are not already engendered in national law. However it is important to note that uncertainty in water supply reliability and resilience is also a substantial latent risk that often results in expensive legacy issues as mining progresses. These include moving costly wellfields or river dams built in the wrong place, and/or continuously investing in expensive additional treatment as water quality progressively deteriorates.

YARA Dallol (YARA) are currently developing a potash mine in the Danakil Rift in NE Ethiopia near the Mt. Dallol volcano (Figure 1). The study area is defined by surface water catchments that drain from the Lelegehedi/Ayshet Graben down to the centre of the Danakil Rift, and specifically the area bounded by the Regali River to the north, the Saba River to the south as far as Lake Assale, and the centre of the Danakil Rift. YARA have applied catchment management principles in the development of their proposed mine from the outset of their involvement in 2011, (well before the ICMM publication). This process required four years of investigation, so upfront costs were reduced by undertaking the catchment management investigations alongside the mineral extraction pilot testing program, and by partnership with the Government of Ethiopia, (who paid for and undertook the early water resources exploration).

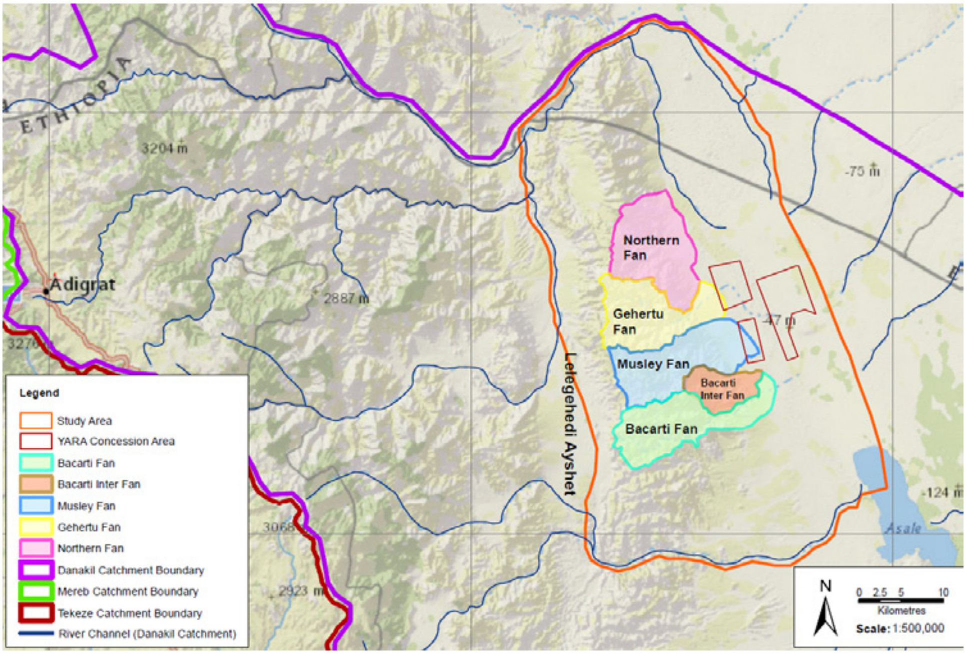

***Figure 1**: Yara-Dallol study area in the Danakil Depression, Ethiopia*

The Sustainable Yield is usually defined as the rate at which water may be removed from the groundwater hydrologic system without removal of water from storage over the medium term. In groundwater systems this is roughly equal to the combined average annual inflows and is often conflated with the sustainable water supply. However, the mine process requires a resilient supply with a reliable quality (in this case of fresh to brackish water), whereas the potash resources are associated with brines. The fresh and brackish water in the area of accessible groundwater floats on the brines and also interacts hydrodynamically with them, placing severe restrictions on the water quality that can be obtained. Thus in the Dallol environment, the deployable output (DO), which is the reliable flow rate at a particular required quality that can be delivered by a single well, or combined wellfield, will always be lower than the aquifer Sustainable Yield. This is due to the water quality mixing that occurs naturally in the system, and in response to the imposed pumping. Thus the imperative of a resilient and reliable water supply requires that the DO be a substantial percentage lower than the aquifer Sustainable Yield and by corollary, at least at a global level, will also be protective of catchment management principles. Thus both aquifer quantities need to be defined in a catchment management study. It is also useful to define three kinds of DO as follows:

- The minimum DO (MinDO) which is the DO that can be delivered during a design drought to provide the resilience required by the design specification.
- The mean DO (MDO) which is the DO available in average rainfall years. It is often the value used to define individual well and combined wellfield extraction licence quantities.
- The peak DO (PDO) which defines the capacity and reliability of the water supply system. It will always be 10 to 20% greater than the MDO to allow for individual pumps and wells to be temporarily switched off for maintenance whilst maintaining mine demand.

Historical Investigations

Mining of the substantial halite salt deposits in the Dallol area of the Danakil depression stretches back to antiquity, and artisanal mining operations continue to cut and transport halite by camel train to the salt market in Makelle to the present day. Commercial mining of potash salts began during the First World War, but ceased once the war ended due to competition from other sources, although it was intermittently restarted on a number of occasions in 1925-1929, 1951-1953, and most notably from 1960 to 1969 by the Ralph Parsons Company. Good regional geological information is available from this last period. This includes descriptions of magnetic and gravity geophysical surveys, lithology, stratigraphy, estimated thicknesses of the main geological units, and the general geological structure, (Holwerda & Hutchinson, 1968 and Bannert et al 1970), and a geology sketch map prepared by Brinckmann & Kursten (1970), that provides the detailed distribution of geological units in the study area. Despite this map being provisional, it is still the most reliable representation currently available. Furthermore the paper by Bannert et al (1969), was produced by the same group of authors as Brinckmann & Kursten (1970), and is effectively a memoir to the map. On the other hand very little groundwater data survives from these early operations. Further, the water supply wells in the Musley fan constructed by the Ralph Parsons Company in the late 1960s have nearly all since collapsed with only approximate locations and summary details of their well depth, groundwater depth and the water quality obtained.

Due to the rudimentary historical data available, four phases of groundwater investigations, undertaken over four years, were necessary to obtain the conceptual groundwater model (CGM). This defines the detailed understanding of the groundwater flow system, including reliable quantities for the annual water balance, Sustainable Yield, and DO available from each wellfield option. The CGM also defines the hydraulic properties of all the key hydraulic units, the groundwater potential gradients, the inflows from direct rainfall and runoff recharge and from regional through-flow, the locations of outflow from springs and predominantly soil evaporation, the locations and control of saltwater and brine density interfaces on groundwater flow and quality, and the modulation of the groundwater density by groundwater temperature (geothermal processes) and soil evaporation (saltwater to brine concentration processes). These steps were as follows:

i) Phase I: Regional water survey, groundwater exploration and drilling program to determine well yields and water quality of key formations. Commencement of baseline surface water, groundwater level and water quality monitoring.
ii) Phase II: Drilling of pilot wells, monitoring wells and piezometers and short duration well testing of pilot wells. Preliminary CGM development, targeted water en-

vironment surveys (socio-economic, vegetation, wildlife), and continued baseline monitoring.

iii) Phase III: Drilling of pilot wells in target aquifers, and short duration testing of pilot wells. Continued surface water and groundwater level and water quality monitoring.

iv) Phase IV: Drilling of final monitoring well network and long duration testing of pilot wells in potential wellfields. Continued water monitoring program.

Hydrological, Geological and Geophysical Surveys

One of the first steps in the catchment investigation included a spatially extensive transient electro-magnetic (TEM) geophysical survey undertaken in two phases with multiple survey lines parallel to the rift margin and along the target wadis. The TEM method was effective at delineating the fresh water thickness and the depth of the saltwater interface along each survey line. Above this interface, measured resistivity distinguished the major rock units, the water quality in these units, and the depth of the vadose zone. Results of the TEM survey indicated significant differences in freshwater and saline water thicknesses between different alluvial fans. In turn, this provided insight into the freshwater flow system, and the effect of density controls, which result in relatively light freshwater floating as a lens on top of the denser saline water.

An extensive inspection of the geological units at key locations throughout the study area was undertaken in Phase II to identify the geological distribution and succession. This survey confirmed the geology was mostly consistent with the sketch map and stratigraphy of Brinckmann & Kursten (1970). Precambrian massive sandstones, greenstones, volcanics and intrusives form the basement of the system and outcrop in the hills bordering the western margin of the rift. Jurassic limestone, (and locally Jurassic sandstone below), lie unconformably on the Precambrian. The Jurassic units are the best bedrock aquifers in the area, and the locations of the Jurassic inliers and down-faulted blocks control the groundwater flow system, by draining the flow in the Precambrian and redistributing the flow along the Rift margin. The proto-rift sediments of the Neogene Danakil Formation overlie the Jurassic units, and consist of marls, clays, silty sandstones, conglomerates, volcanics and intrusives that together form a confining layer of the Jurassic rocks below. Finally the Quaternary sediments of the current rift comprising sands and gravels in alluvial fans along the rift boundary, transition through sands into the silts and clays, and finally the halite in the centre of the rift playa, as indicated in Figure 2.

An extensive inspection of surface water features was also undertaken in Phase II throughout the study area at the same time as the geological survey. The water features survey, in conjunction with the TEM data, and the monitoring well and piezometer data, defined the key hydraulic features of the system and indicated the preliminary CGM: infiltration in the sands and gravels of the wadis and fans from flood run-off, groundwater throughflow within the bedrock, approximate flow directions, locations of saltwater interfaces, the water quality transition from deep fresh groundwater in the bedrock, to thick fresh water sequences in the alluvial fans, to very shallow brine groundwater in the playa. Soil evaporation from shallow groundwater in both the silt/clay and halite playa sections was identified as the dominant outflow from the system. The surveys also indicated the likely presence of a salt karst flow system within the silt/clay and halite playa, the brackish hot water upwelling along the rift boundary (regional geothermal water), and the superimposed hot brine convection in the volcano geothermal system beneath Mt Dallol. The preliminary CGM is provided in section and plan view in Figures 2 and 3.

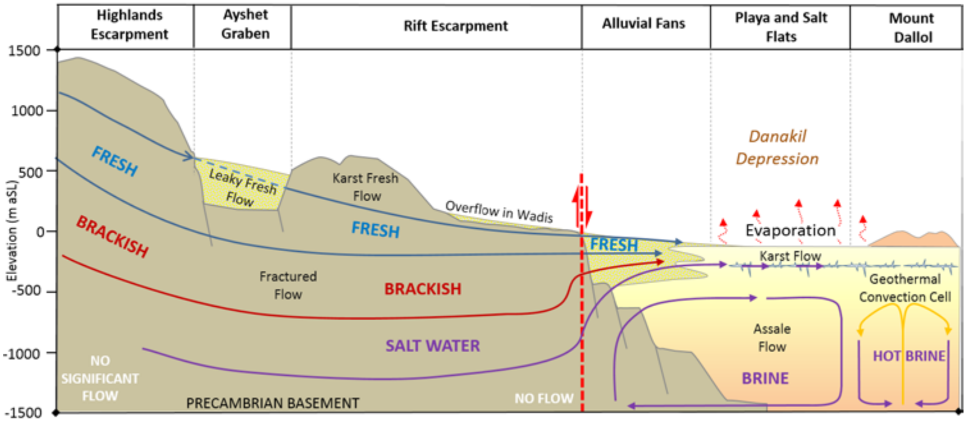

Figure 2: Provisional CGM cartoon section of the Rift Valley in the vicinity of Dallol

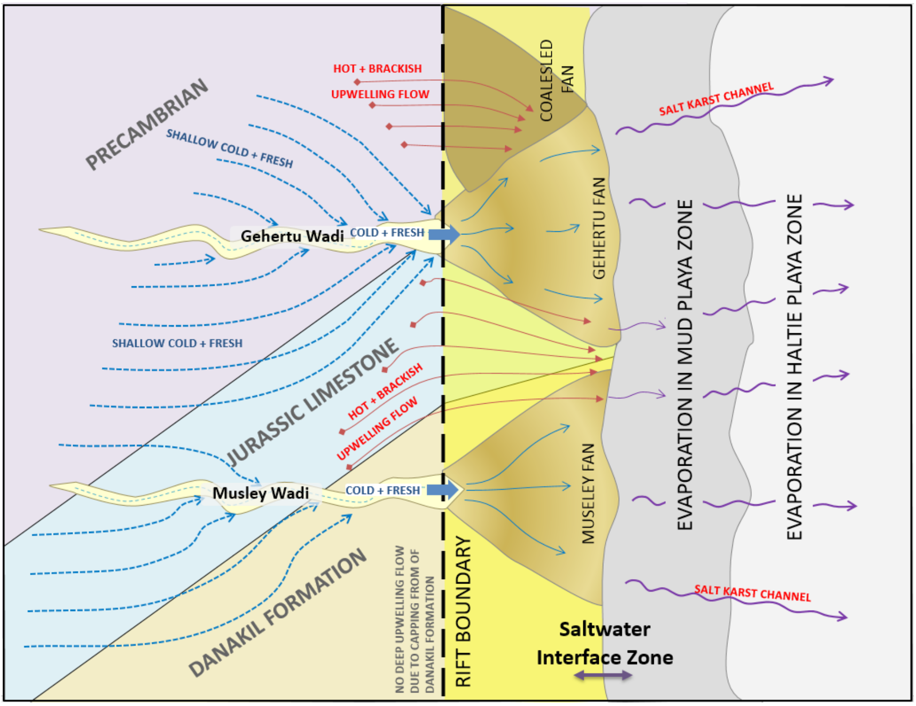

Figure 3: Provisional cartoon map of groundwater flow

Well Construction and Monitoring

An extensive pilot well, monitoring well and piezometer drilling program was developed in phases over the four-year time frame to validate the geology, hydrogeology and preliminary groundwater conceptual model. Hydraulic parameters (transmissivity, storativity, hydraulic conductivity, barrier boundaries, etc) of all key groundwater units were determined initially from short duration (1 to 6 day) tests of the pilot wells, which were then subsequently used as monitoring wells. Groundwater level monitoring (of up to three years) in each monitoring well provided dip and data logger measurements of the daily and seasonal groundwater fluctuations related to precipitation, flooding, and dry season and drought events. This data provided an essential baseline of the typical seasonal behavior of the regional aquifer system.

Water Balance and Sustainable Yield Estimates

The bedrock through-flows to the groundwater system (see Figure 2) are difficult to determine as the depth and thickness of groundwater flow in the rift escarpment bedrock was too deep (expensive) to prove from drilling. Similarly the fresh water through-flow through alluvial fans can't be calculated reliably as fresh water groundwater heads and gradients are affected significantly by their buoyancy on the brines below. However as groundwater inflow will equal groundwater outflow from the system during an average year, measurement of the soil evaporation outflows in the playa initially provided the only method of estimating total outflows and thus the total inflows and Sustainable Yield of the groundwater system. Innovative use of porous cup lysimeters determined the rate of soil evaporation at more than 9 locations across the silt/clay and halite playa. Rates of capillary rise at various locations, times, and depths below ground surface in the playa flats provided estimates of vertical groundwater flow moving out of the system by way of evaporation. Combined lysimeter measurements of soil evaporation rates fed into the CGM. However the rate of evaporation was found to be very sensitive to groundwater depth; doubling for every 10 cm reduction in depth, and although the playa is extremely flat, the potential error in the depth measurement was likely to be at least 10 cm. As a result, an alternative method was required to provide more reliable Sustainable Yield estimates.

Consequently a large number of monitoring wells were drilled during Phase IV in the bedrock in the western rift boundary above the fans, and most importantly above the saltwater interface zone. Thus groundwater elevations determined from well dip data, were largely unaffected by density and buoyancy effects, and were used to construct a flow net to identify groundwater flow directions and gradients, (as well as inflow, up-flow, recharge and discharge zones). The transmissivity and hydraulic conductivity data calculated from the packer, injection, and aquifer tests, along with aquifer thicknesses derived from the drilling and well construction program, and the groundwater gradients from the flow net, were used to calculate aquifer flux rates using the Darcy equation. As the monitoring wells were predominantly located outside the zone affected by saltwater density and buoyancy effects, the Darcy calculations provide the most accurate estimate of the aquifer Sustainable Yield. They also compared favourably with the lysimeter evaporation estimates, providing validation of these earlier estimates. Overall, both estimates confirmed that flood run-off provides an important augmentation, but only a minor contribution, to the groundwater balance, which is instead dominated by bedrock through-flow.

Well and Wellfield Deployable Output

The MinDO, MDO and PDO of individual wells (and combined wellfields) has been estimated from a numerical groundwater model predicated on the CGM, and calibrated against the water balance and large groundwater data set. The calibrated numerical model demonstrates its accuracy by how closely the steady state and transient model results match the observed conditions of groundwater elevation and water quality. Analytical methods (e.g. Schmorak & Mercado, 1969), were also used to validate and augment the numerical model results to determine the constraints on DO from saltwater upconing and saltwater intrusion.

Pumping tests of pilot wells determined the individual well PDO and validate the numerical model MDO and MinDO estimates. Initial tests of the order of several days established well production capacity (PDO) and water quality parameters in early phases. In phases 3 and 4, measurement of water quality against pumping rate and well depth demonstrated that the water quality was strongly influenced by well design in most of the aquifers. Tests of 2 to 3 months duration in the final phase provided insight into the sustainability, water quality, and MDO available from each location of the aquifer system tested. Water quality degradation was significant within one of the alluvial fan sites, where electrical conductivity (EC) during early tests was initially below 2000 µS/cm, but increased to 7,800 µS/cm without stabilising during the two month test. However, production rates were comparable in a second well location, where only minor changes in water quality occurred (from 1,900 to 1,970 µS/cm).

Discussion

The value of implementing the catchment management approach from the outset of the project can't be easily understated. The commitment to the thorough investigation of the groundwater and surface water systems had strong benefits in multiple spheres including the hydrological, environmental, engineering, water resources management and regulatory aspects of the water supply project. Desert hydrology is highly variable, and it is widely recognised that data periods of less than 5 years are wholly unreliable due to the large variations in precipitation each year. So it would have been impossible to define the design drought duration (a key element of a reliable and resilient engineering system) from say just 2 years of data. Even with the catchment management commitment, the 5 year rule of thumb will only have just have been achieved in the key data sets by the time the mine approval has been obtained and a construction start has been scheduled.

Secondly it is interesting to speculate what the outcome would have been if the 1969 Ralph Parsons' wellfield had merely been replaced after minimal investigation. The long duration test results clearly indicated that progressive and severe water quality degradation would have occurred over the first one to say 5 years. Over time the data from the catchment water balance and flow net (determined from the catchment management method), indicated that the water quality was likely to trend towards brine and become prohibitive, requiring a completely new water supply. Furthermore as the salination process is slow, mine construction would likely have been completed by the time a new water supply became an imperative. It is thus almost certain that wellfield development in the wrong location would ultimately have resulted in the requirement for a very expensive remote new water supply, the costs of which would substantially impact the bottom line, whilst the worst case scenario would cause termination of mine production.

More importantly, the other long duration test undertaken to date, indicates that stable and good quality water can be obtained from other aquifer locations. However without the knowledge gained from the 4 years of detailed groundwater investigation, allowing the development of a detailed flow net, it would have been impossible to infer the causes of the good and poor wellfield locations. Thus the commitment to detailed investigation provided a clear decision path to reliably select the proposed wellfields. Furthermore if there is insufficient data to define the fresh water MinDO and MDO reliably, then even in the right location, a wellfield water supply will be unreliable and prone to underperform the design. Thus in summary, a commitment to proper engineering investigation over a period of 4 to 5 years (and by corollary the catchment management approach) is the only way to derive a reliable and cost effective engineering design. This is especially the case in aquifers sensitive to water quality or in locations of highly variable rainfall.

In the environmental sphere, the greater accuracy of the CGM from the commitment to the catchment management methodology allows the impacts of the proposed wellfields to be determined with greater reliability. It thus allows the definition of the most suitable mitigation strategies and the avoidance of approaches that do not work.

In the governmental and permitting sphere, YARA worked closely with the Ministry of Water, Irrigation and Energy, the Department of Water Resources (DWR) and the Water Works Design and Supervision and Enterprise (WWDSE), the government engineering consultancy. During Phase I the works were directed by WWDSE and funded by the MWIE. From Phase II onwards, the investigations were funded by YARA, but the works for each campaign were submitted to the government in advance for approval and authorisation. Furthermore as the works were completed, YARA provided all the data and reports to the DWR and WWDSE for review, consultation, and agreement of next steps through workshops and consultation.

This collaborative approach was perhaps the greatest value of the catchment management approach. From the outset, it was agreed that the Ethiopian Government would own all the data and well infrastructure from the catchment management investigations located outside the YARA mineral concessions. This approach provided the critical data to allow the government entities to exercise regulatory oversight of the investigations, to retain the sole right to licence and control the extraction of any water supplies, whilst at the same time, providing the infrastructure required to monitor and manage any future wellfield developments. On the other hand, the funding of the investigation costs by YARA from Phase II onwards ensured that the programme was not held up whilst limited cash resources were procured by the government. The reduction in delays was therefore a substantial cost benefit to YARA. However perhaps the greatest value, was the development of trust between the various entities of the Government of Ethiopia and YARA that allowed the catchment management works to progress efficiently and without delays.

In other words in every sphere, it is possible to show the catchment management approach has saved costs in the short term, but should save substantial costs in the medium and longer term.

Conclusions

This brief case study shows that the catchment based water management approach provides cost savings for mine operations when implemented before mine construction. It not only enhances the bottom line in the medium to long-term, but also provides a "licence to operate" by identifying the resource reserve required to protect the water needs of the environment, wildlife and other water users. This study was undertaken in the Rift Valley of NE Ethiopia in a remote, largely undefined and challenging physical environment, so the approach is likely to be transferable anywhere. Key to the investigation was quantification of the Sustainable Yield of the groundwater system as well as the PDO, MDO and MinDO of alternative wellfields and individual wells. This approach has allowed the logical redevelopment of water supplies used by past operations to be recognised as an expensive mistake that needed to be avoided. Finally, early implementation of these investigations, in parallel with the mine process pilot stage (i.e. immediately following exploration) has proven largely successful. However start of water exploration during the mineral exploration phase would have been the best approach as this would have maximised the length of data beyond the minimum of five years required to complete the catchment investigations.

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