

Just Add Water: The Importance of Groundwater in Your Mine Feasibility Study

Paul D. Williams, PG, PH, M.Sc., SME-RM
SRK Consulting (U.S.), Inc., Denver, Colorado, USA

Geoffrey Baldwin B. Sc.
SRK Consulting (U.S.), Inc., Denver, Colorado, USA

Vladimir Ugorets, PhD. MMSA
SRK Consulting (U.S.), Inc., Denver, Colorado, USA

Scott Honan, M.Sc.
NioCorp Developments Ltd., Denver, CO, USA

Trevor Mills, B.A.
NioCorp Developments Ltd., Denver, CO, USA

ABSTRACT: The capital and operating costs of mine dewatering can appear negligible when combined with the overall project economics of the feasibility study (FS). However, groundwater issues can quickly become relevant, particularly in difficult permitting arenas where stakeholders are experienced and bound by thoughtfully crafted regulations. This case study highlights the need for early characterization of groundwater quality and quantity due to the impact these factors had on the technical economic model (TEM) for the project. Specifically, projected dewatering rates and poor groundwater quality resulted in high capital costs. Fortunately these items were identified and characterized relatively early in the project life cycle, allowing proper analysis of the data and collection of confirmatory information to keep the FS on track.

1 INTRODUCTION

The feasibility study (FS) is a critical milestone for any mining project in development. The FS identifies the key economic factors that will drive the operation, with a primary focus on the big ticket items such as the mining fleet, process plant, project infrastructure and mine waste management. Water issues for the average project can be overlooked in the scoping and prefeasibility stages, and sometime this leads to a lack of information at the FS level. If the dewatering and groundwater management costs are less than 5% of the total project cost, hydrogeology is often considered a non-factor, barring permit-driven issues.

A hydrogeologic characterization requires drilling and installation of wells or piezometers not only within the immediate vicinity of the deposit, but sometimes kilometers away laterally. The groundwater system does not stop at the edge of the ore deposit. Factors outside of the deposit govern the flow of groundwater through the prospective mine site, particularly in settings where the rock is relatively permeable (>0.5 m/day). In round numbers, and depending on the geologic complexity, no less than 10 to 15 exploratory boreholes and wells with a focus on hydrogeologic testing may be required to properly assess basic groundwater flow dynamics. The cost for field programs of this sort, combined with analysis and a predictive modeling effort, typically fall in the range of \$500,000 to seven figures. Furthermore, field programs can require significant time allotments. In the author's experience, hydrogeologically complex sites often require periods of two to three years to untangle, allowing adjustments for major changes to the initial conceptual model.

In the case study discussed here, Niocorp's Elk Creek Project in the southeast corner of Nebraska, the mine proponent initially planned to achieve a FS-level evaluation in a year's time. The hydrogeologic field program was initiated in concert with the geology and geotechnical core drilling programs, therefore most of the testing was achieved through packer testing and custom well installations in HQ and PQ diameter core holes. The initial program was planned

under the primary assumption that the host rock (carbonatite) for the deep underground mine would be of relatively low hydraulic conductivity and poorly connected to the surface due to 200 m of low-permeability limestone. The basic geology is shown on Figure 1.

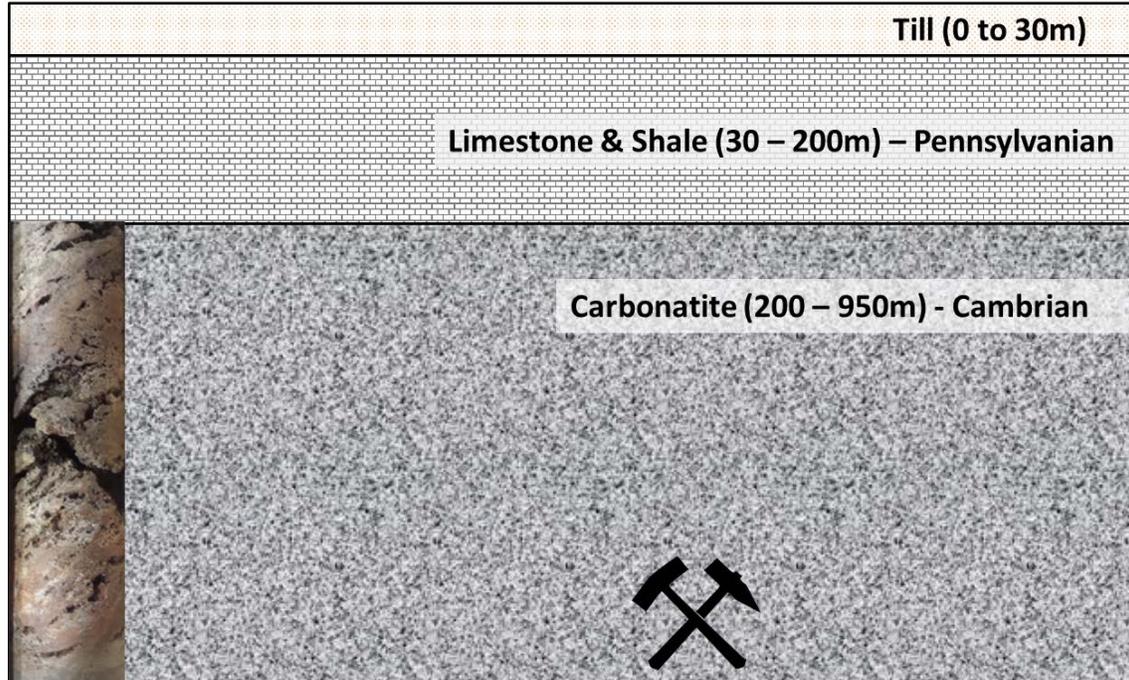


Figure 1. Site-scale geology

2 GEOLOGY

The basic geology consists of 0 to 30 meters of variably-saturated glacial till draped atop Pennsylvanian-aged limestone. In this part of Nebraska, a system of E-W trending paleochannels in the top surface of the limestone are filled in many instances with coarse till and are exploited in the area for center pivot irrigation systems. However, such channels do not exist in the immediate vicinity of the Elk Creek project. The bedded Pennsylvanian limestone is flat-lying and approximately 170 to 190 m thick. The host rock is an oval-shaped carbonatite “pipe” approximately 6 to 9 km across, surrounded by Precambrian-aged syenitic granite. The project is located on the Nemaha Uplift along the eastern flank of the mid-continental rift, less than 10 km west of the Forest City Basin and a large vertical offset of more than 1000 m.

The structural geology of the project area includes a regional-scale W-NW trending fault zone called the Central Plains Megashear that appears to run through the carbonatite host rock and extends east beyond the Missouri River. Locally, there is a system of N-NE trending faults sympathetic and parallel to the trend of the mid-continental rift; numerous faults with this N-NE orientation were mapped based on core inspection within the deposit, along with a set of faults generally parallel to the Central Plains Megashear.

3 FIELD CHARACTERIZATION – PHASE 1

The initial field program involved collecting hydrogeologic data from 13 angled HQ core holes, and installing long, open-hole standpipe piezometers over a period of about five months. Packer testing was completed on intervals of rock using the IPI SWIPs packer system; step pressure tests were attempted, but on most holes a packer-isolated airlift test was necessary to stress the test intervals (50 to 100 m). As the program progressed, it became obvious that the rock was more permeable than anticipated. Figure 2 presents the range of field-derived hydraulic conductivity values from the testing program.

The piezometers were constructed at significant depths (> 200 m) with schedule 80 PVC. Given the depths, vibrating wire piezometers were considered but discounted in favor of the sampling capability of standpipes. The open intervals were sealed off with cement baskets and flush-threaded, pre-packed bentonite sleeves. While the long open intervals isolated by the piezometers was not ideal, this design offered a good compromise given the fact that the HQ core holes were typically in excess of 850 m deep; cementing back the bottom of the holes proved time consuming and problematic, thus limiting opportunities for shorter screens. Lost circulation was an ongoing problem while drilling, and attempts to cement lengthy intervals of the hole resulted in several days of pumping cement into the void-riddled formation (see core photo Figure 1). In summary, the piezometers tended to be open to great lengths of the carbonatite. Fortunately, the primary pumping tests utilized fully penetrating production screens, allowing calculation of transmissivity from the test data.

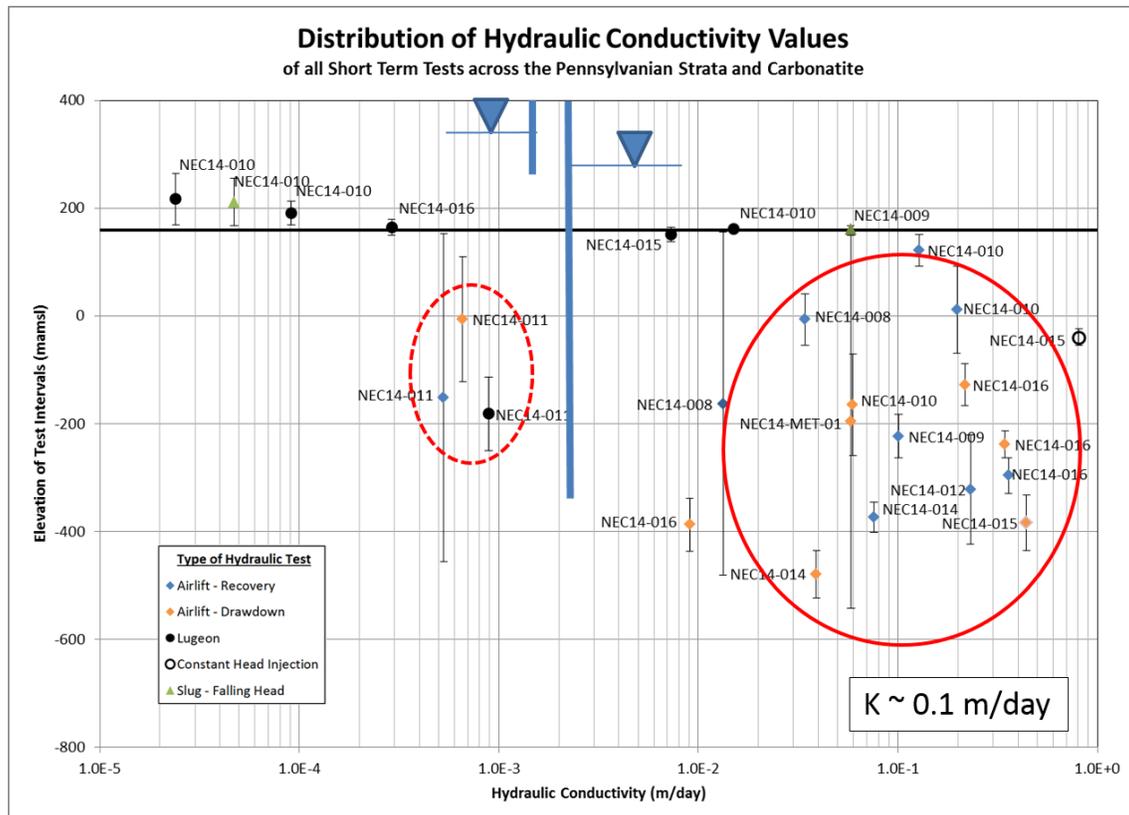


Figure 2. Hydraulic Conductivity Results from Short-term Tests Plotted vs. Elevation (meters amsl)

The first phase of data collection terminated with a 10-day airlift test from a fully penetrating 850-m deep vertical PQ core hole that was drilled for metallurgical bulk sampling purposes. Depth to water in the carbonatite (100 m), hole diameter (122 mm), and submergence limited the discharge rate to 2.2 l/sec (35 gpm). Drawdown from the test was monitored in the surrounding network of eight piezometers, and a transmissivity value of 65 m²/day was calculated. However, the zone of influence within the carbonatite was quite limited and resulted in a radial drawdown cone with a 0.5 m drawdown contour extending out 200 to 300 meters. Drawdown measured in the overlying limestone was negligible, suggesting this unit is a classic aquitard, as confirmed by K values on the order of 10⁻⁴ m/day. Water levels in the limestone are 50 m higher than the carbonatite, resulting in a surprising downward hydraulic gradient. Finally, the water quality in the carbonatite is saline, with TDS values as high as 18 g/L.

The data from Phase I were utilized to develop a conceptual model of the project site and to eventually allow simulation of the hydrogeology. The primary components of the site hydrogeology included:

- The overlying limestone is a low-K aquitard with elevated water levels;

- Variably saturated till overlies the limestone but appears hydraulically independent;
- The carbonatite is relatively high K (0.1 m/day), and exhibits voids (small karstic features);
- Water levels in carbonatite are 50 m lower than in the limestone;
- The carbonatite (ore host) is well connected laterally by fractures and faults;
- The underground mine will consist of stopes, declines and various ramps within carbonatite;
- Access from the surface by shaft through the limestone; and
- The ultimate depth of underground mine = 850 m (775 m below pre-mining water levels).

4 PRELIMINARY DEWATERING ESTIMATE BASED ON SHORT-TERM TEST DATA

A dewatering estimate was prepared following Phase I. The first round was based on an analytical model for active dewatering of the carbonatite. At this early stage of the project, production mining was to begin at the bottom of the deposit where the highest grades exist. However, this plan required rapid dewatering to the bottom of the mine over a short period of time prior to year zero of the mine, translating to significant mine dewatering and capital expenditures prior to production years (revenue).

4.1 *Dewatering Estimate – Round 2*

As a result of this first estimate, and the excessive CAPEX associated with drilling, dewatering, and water treatment two years prior to production mining, the mine plan had to be significantly altered to accommodate a more reasonable and less expensive dewatering scheme. The revised mine plan considered four production blocks mining up and down from the middle part of ore-body. It was assumed that installation of the dewatering well system (a number of wells drilled from surface) would begin two years in advance of production mining to allow dewatering of development workings such as the shaft, vent shaft and main access ramp.

To facilitate a more rigorous prediction of dewatering rates for the revised mine plan, a preliminary numerical groundwater flow model was built using *MODFLOW-SURFACT*. The model was constructed to replicate the basic groundwater flow features of the carbonatite based on testing (K) and water levels, and reasonable specific storage values (S_s). Because of the nearly perfect aquitard above, the groundwater within carbonatite was modeled appropriately as a fully confined system. The oval shape of the carbonatite pipe was implemented, surrounded by a different material representing the granite and the model was calibrated to the 10-day airlift pumping test. Because the properties of the granite were as yet unknown, the granite was modeled as an impermeable boundary (bounded deep groundwater system). The initial simulations with this model were provided in the initial preliminary economic assessment (PEA). The results of this first model were non-conservative due to the assumption that the granite was impermeable, and are not discussed in further detail here. However, the result from this exercise highlighted the need for an improved hydrogeologic conceptual model, the need for data that could provide insight about the behavior of the granite, and verification of the hydraulic parameters assigned to the carbonatite. Specifically, a large hydraulic stress within the carbonatite was needed, accompanied by observations and additional monitoring beyond the immediate vicinity of the ore deposit. Accordingly, another focused field program was proposed as discussed in Section 5.

5 PHASE II FIELD PROGRAM TO CHARACTERIZE GRANITE BOUNDARY

Upon determination that the properties of the regional granite surrounding the carbonatite would have the greatest long-term impact on mine dewatering rates, a second phase of field investigations was planned and implemented. The objective of Phase II testing was to better characterize the boundary conditions for the carbonatite, or specifically the properties and distance to where groundwater is either supplied or restricted from flowing into the carbonatite. Since the carbonatite-granite contact 3-5 km from the central ore body was the primary feature of interest as a likely boundary, testing would necessarily be designed to induce a measureable response at that distance. Furthermore, observation piezometers would be required outside of the immediate deposit to provide critical data on the rate and geometry of groundwater response.

Typically, a test of this magnitude is accomplished with a large pumping well which induces a cone of drawdown that propagates outward and is observed through a network of observation wells between the stress and the hydraulic boundary. Under normal conditions, this is a very effective method. However, permitting and disposal of brackish water can pose a significant challenge; the Phase I pumping test had produced 2.2 L/sec (35 gpm), a rate easily handled by trucking the water to disposal lagoons 11 km away. However, pumping rates on the order of 30 L/sec (500 gpm) required a different disposal approach. Treating the water before discharging to natural drainages would be complex and expensive, as well as requiring substantial time to secure a NPDES permit. Similarly, constructing storage ponds to contain the water for subsequent re-injection would require extensive earth moving and a UIC permit. After considering numerous options, it became clear that another approach was needed.

Instead of pumping water to induce drawdown, an alternative method was conceived whereby fresh water would be injected into the carbonatite via an injection well, resulting in the propagation of stress by groundwater mounding. Since the deep groundwater system was highly confined by the Pennsylvanian strata, the stress induced by injection would suffice as an equivalent to a pumping test. After surveying nearby drainages, a creek with adequate perennial flow was identified and a temporary pumping permit secured. A site for the injection well was selected in a central location in the ore deposit that intersected structural features which Phase I testing had identified as having elevated hydraulic conductivity. The well itself was constructed of 6-inch diameter steel in a 10.6-inch drillhole that was screened across the carbonatite to a depth of 832 m (2,730 ft). A temporary 8-inch pipeline was constructed from the creek to the injection well (2 km). The layout of the piezometer network is provided on Figure 3.

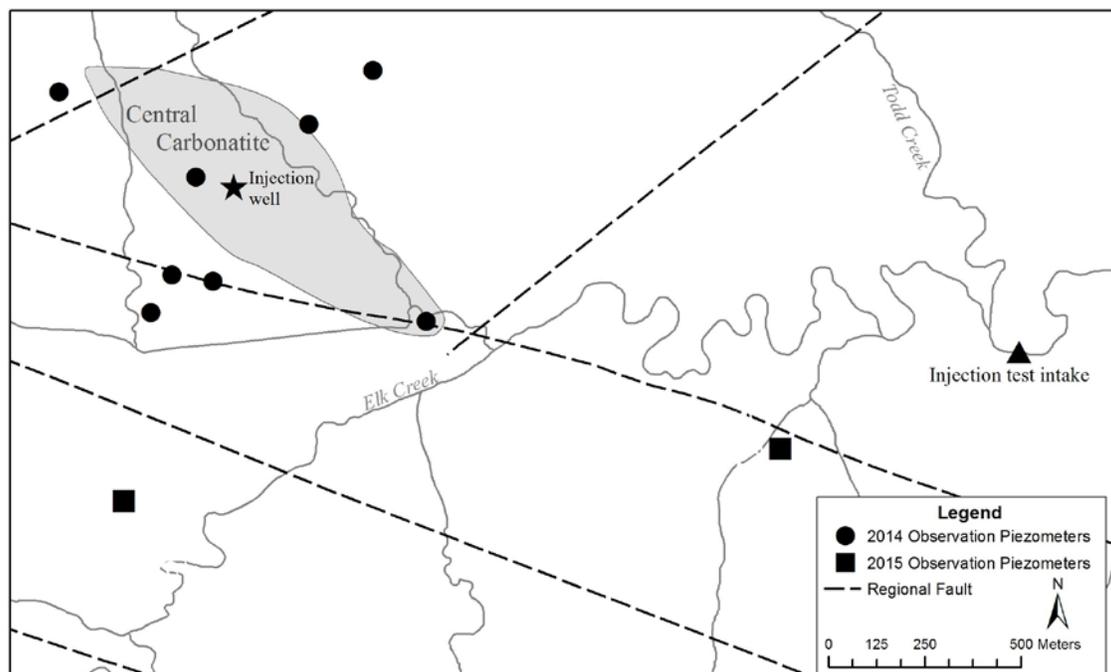


Figure 3. Layout of Wells and Piezometers

Four locations for additional observation piezometers were selected by considering the Phase I hydrogeologic test results along with the geophysical and structural models. After balancing time and budget constraints with the minimum necessary data needs, only two observation piezometers were funded. The piezometer sites were located: a.) 1.25 km from the central ore body and along strike (W-NW to E-SE) with the regional structural trends observed in the deposit, and b.) 0.6 km from the injection well, orthogonal to the primary structural alignment. The drillhole were cored to 850 m (2,790 ft) using PQ diameter diamond drill rigs and were tested approximately every 100 m interval in order to optimize the piezometer construction.

A standpipe design was used for the observation piezometers to enable the collection of groundwater samples, and were constructed from steel (B drill rods) due to the installation depths – PVC would have failed in tensile strength. The screened interval was left open since the narrow annulus did not provide adequate space to install a gravel pack, and was isolated from the grout interval using cement baskets. Additionally, each standpipe was equipped with two grouted-in vibrating wire piezometers placed at different depths above the screen to allow measurement of vertical variations in water levels and groundwater response to injection.

After securing the necessary permits and constructing the two additional nested piezometers, the injection well, and a pipeline, a nominal 30 day injection test was initiated. The response to injection was monitored in the Phase I & II piezometers. The injection test was briefly interrupted by flood events which necessitated pipeline repairs, but did not affect the final outcome of the test. The injection rate was managed at approximately 22 L/sec (350 gpm) for the first 15 days, and was increased to approximately 30 L/sec (475 gpm) for the remaining 17 days to maximize the stress. A total of 68.6 ML (18.1 million gallons) of water were injected over 33 days (including down time), resulting in nearly 2.6 m of mounding at the furthest observation piezometer 1.25 km away.

Mounding at the injection well was steady at 100 m – the water level in the injection well was at ground surface during the majority of the test. The water level in the nearest piezometer (NEC14-013) located 80m from the injection well increased by 13 m. A plot of mounded groundwater levels at the end of the test are shown in Figure 4.

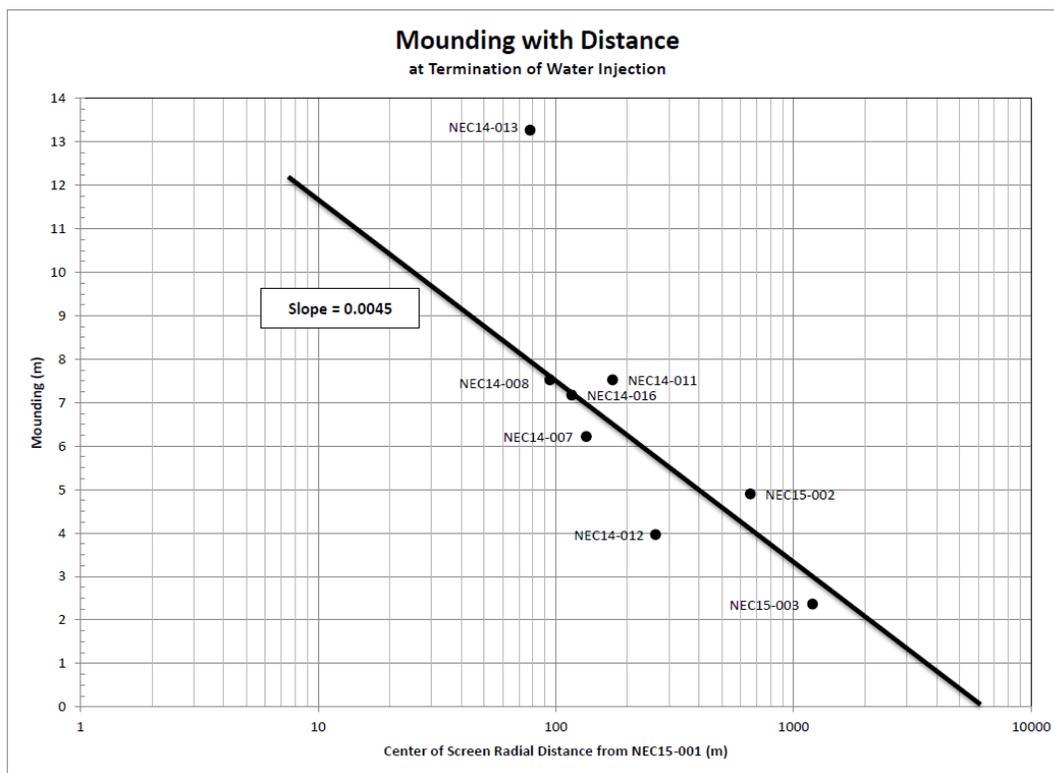


Figure 4. Groundwater Mounding in Selected Piezometers at End of Injection Test

After 30 days of water injection, the mounding response had diminished even in the distant piezometers, and the injection phase was terminated.

6 DEWATERING ESTIMATE BASED ON INJECTION-PHASE DATA – ROUND 3

At this point in the project timeline, the mine proponent needed to prepare a revised PEA, and time did not allow for full recovery of the injection test. Therefore, the data from the injection

phase was used to prepare a revised estimate of dewatering for the Elk Creek Project. Accordingly, the response data were analyzed and interpreted to update the conceptual model. The numerical model was used to converge on a revised set of hydrogeologic parameters and the model was re-calibrated to the injection-phase test data, since recovery was yet incomplete.

Hydrogeologic units and their hydraulic parameters as simulated by the numerical groundwater model are shown in Table 1. The hydraulic conductivity of carbonatite (including fault zones) within mineralized zone is in the range of 2 to 3 m/day. The carbonatite outside of mineralized zone is less permeable ($K=0.15$ m/d) with more permeable NE faults and NW regional faults ($K=0.5$ to 1 m/day). Specific storage – an important parameter defining a volume of water within carbonatite – was estimated as $S_s = 2 \times 10^{-6} \text{ m}^{-1}$. In the absence of more recovery data, the hydrologic role of the granite was unresolved and therefore two sets of simulations were conducted with different properties for the granite. The granite was modeled first as a highly conductive unit (unbounded deep groundwater system), and again as an impermeable boundary (bounded deep groundwater system).

Table 1. Revised Parameters for Conceptual Model

Hydrogeologic Unit	Hydraulic Conductivity, K (m/day)		Specific Yield (unitless)	Specific Storage (1/m)
	K_h	K_v		
Carbonatite within Mineralized Zone	2	2	0.005	2e-06
Faults within Mineralized Zone	3	3	0.005	2e-06
NE Faults outside of Mineralized Zone	0.5	0.5	0.005	2e-06
NW Regional Fault outside of Mineralized Zone	1	1	0.005	2e-06
Carbonatite outside of Mineralized Zone	0.15	0.15	0.005	2e-06
Granite ¹	0.15/0.001	0.15/0.001	0.005	2e-06

Note 1: Unbounded/Bounded deep groundwater system.

The model was used to generate a new prediction of mine dewatering based on the revised mine plan. Predicted dewatering rates for both bounded and unbounded cases, and the targeted water level elevation are shown in Figure 5. Their comparison indicates that in the unbounded case, the dewatering rate could be five times larger than for bounded conditions. Based on this model, and the inherent uncertainties, the “expected” dewatering rate for the preliminary economic assessment (PEA) was calculated by averaging the predicted flows for unbounded and bounded conditions. The maximum anticipated dewatering rate (~730 L/s) was expected to occur one year into production mining, following three years of active dewatering. The expected dewatering rate was projected to decline to 500 L/s in Year 13 and to 450 L/s at end of mining.

The approach used to define an expected dewatering rate was a significant improvement over the original model estimates, and the properties of the carbonatite had been defined as a result of the larger stress provided by the injection test. However, characterization of the granite boundary required a recovery period longer than 30 days to resolve the net gain in storage within the carbonatite. In fact, the carbonatite did not fully recover after 7 months.

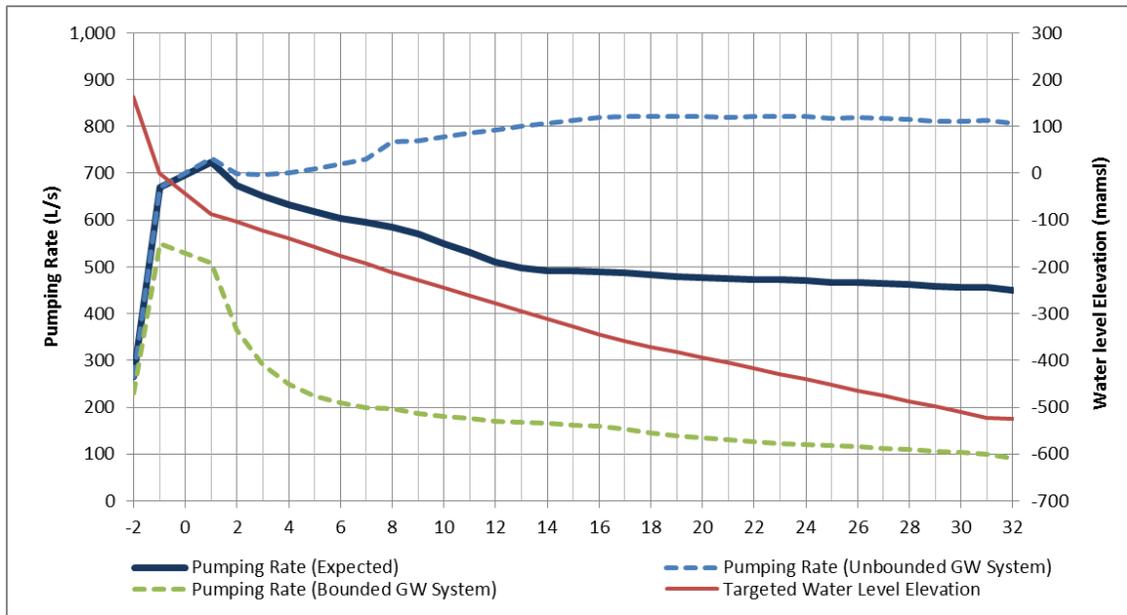


Figure 5. Predicted Dewatering Rates (Round 3) and Target Water Level Elevation

7 LONG-TERM RECOVERY OF WATER LEVELS FROM INJECTION TEST

As is often the case with pumping tests, the recovery phase of the test was critical to assess changes in storage. Notably, in many of the observation piezometers, the recovery curve nearly stabilized at about 1 m above the pre-test level then continued to recover at a much slower rate (shown in Figure 6). The recovery plot shows residual mounding in a selected number of piezometers plotted against t/t' , where:

- t = time since injection stopped, and
- t' = time since injection began.

It was obvious after more than 7 months of recovery from the nominal 30-day injection test that water levels had still not rebounded in many of the piezometers, indicating a temporary net-positive storage of water in the carbonatite. The recovery data were critical for assessing the storage properties of the granite, and thus the boundary conditions that will ultimately control groundwater flow into the mine. The data in Figure 6 suggests that the granite acts as a leaky boundary, although the exact nature and source of the leakage is unclear. The observed response could be interpreted to result from the granite being dissected by transmissive faults along which groundwater can enter or leave the carbonatite.

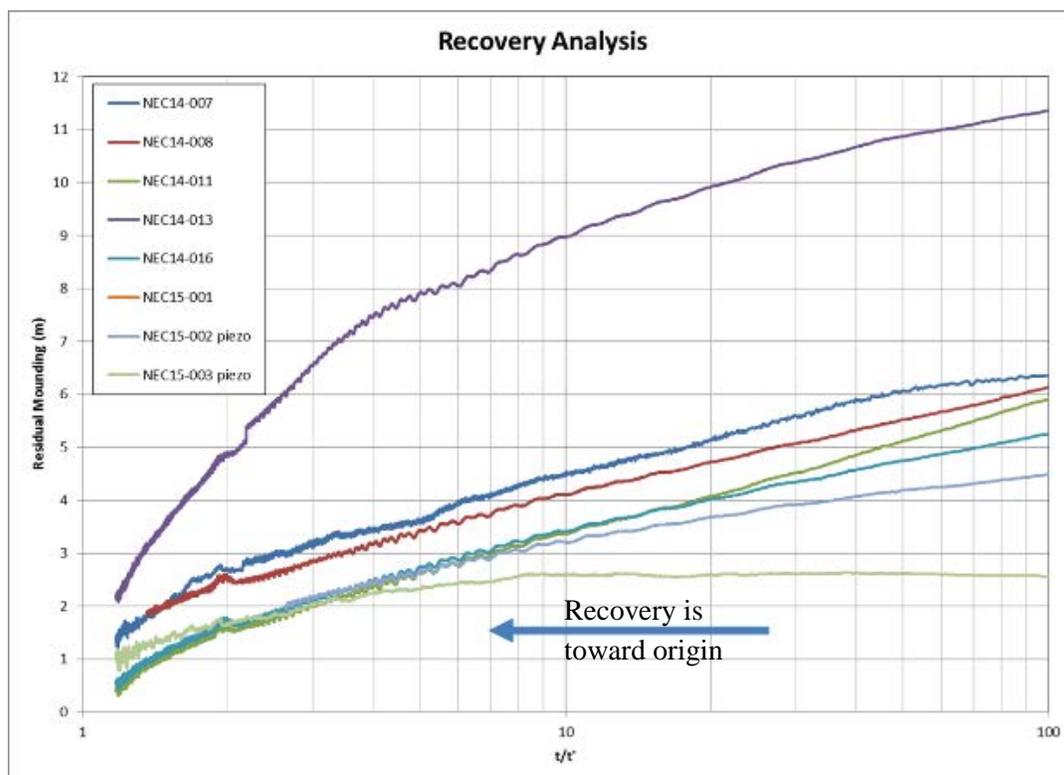


Figure 6. Residual Mounding vs. t/t'

8 DEWATERING ESTIMATE ACCOUNTING FOR TEST RECOVERY– ROUND 4

The model was re-calibrated and updated using the recovery data gathered seven months after the injection test, including the late-time recovery responses shown in Figure 6. The calibration process required limited changes to the original model which included:

- assignment of a low K for the granite (K was decreased from 0.001 to ≈ 0.0001 m/d);
- reduction of specific storage (Ss decreased from 2×10^{-6} 1/m to 1.2×10^{-6} 1/m; and
- incorporation of inferred geologic structure (Central Plains Megashear) that provides hydraulic connection between the carbonatite and a distant water source, as indicated by the uniformly low static heads found in the carbonatite (100 m below ground surface).

The structural changes to the model, depicted in Figure 7, allowed gradual release of injected water from the carbonatite during the recovery phase. The hydraulic connection was simulated by imposing a constant head to a model cell column southeast of the proposed mine at the carbonatite/granite contact along the general alignment of the Central Plains Megashear (Fig. 7). The leakage mechanism simulated in the model allowed a reasonable match to the transient hydraulic head response seen in the network of piezometers during injection and recovery.

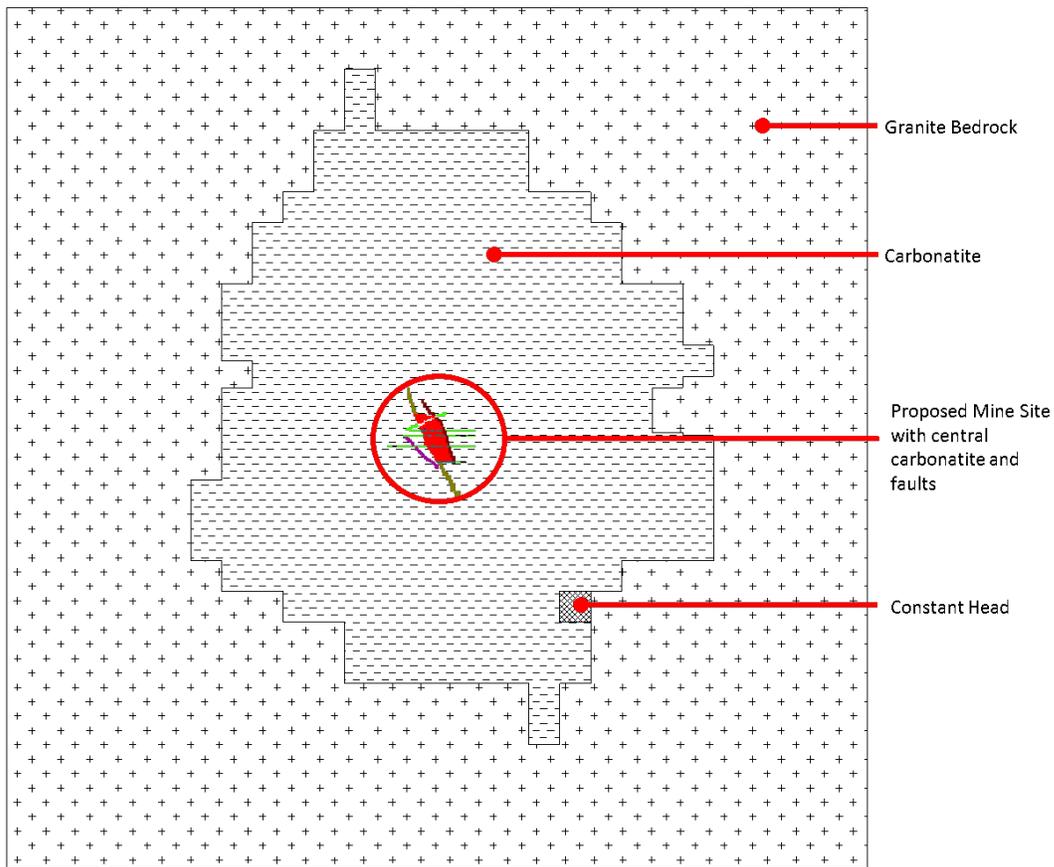


Figure 7. Model Grid Showing Location of Simulated Granite and Constant Head Boundary

Comparison of the measured and calibrated water levels observed during groundwater recovery in the most distal wells is shown in Figure 8.

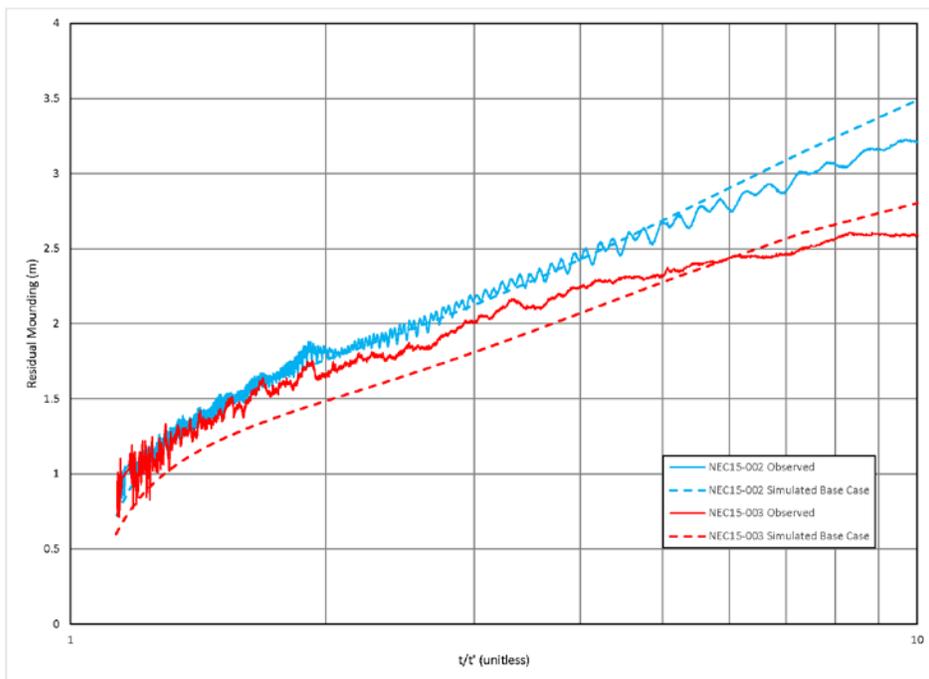


Figure 8. Observed and Modeled Recovery in Two Distal Piezometers

Following calibration, the model was used to predict dewatering requirements for the 32-year PEA mine plan using the hydraulic parameters from the calibration described above. The mine dewatering prediction is shown in Figure 9, along with the previous predictions. The average dewatering rate is predicted to be approximately 500L/s, remaining relatively steady for the LoM. The peak flow of 600 L/s occurs in project year 1, and will be the critical flowrate that drives the sizing and cost of the dewatering infrastructure that will be required to support the proposed mining operation.

The model simulated two primary sources of inflow:

- Groundwater storage within carbonatite, which contributes significant amounts of water at the beginning of dewatering; and
- Groundwater inflow from outside the carbonatite by way of a fault or faults that penetrate the granite (e.g., the Central Plains Sheer Zone), which contributes water in the later stages of mining.

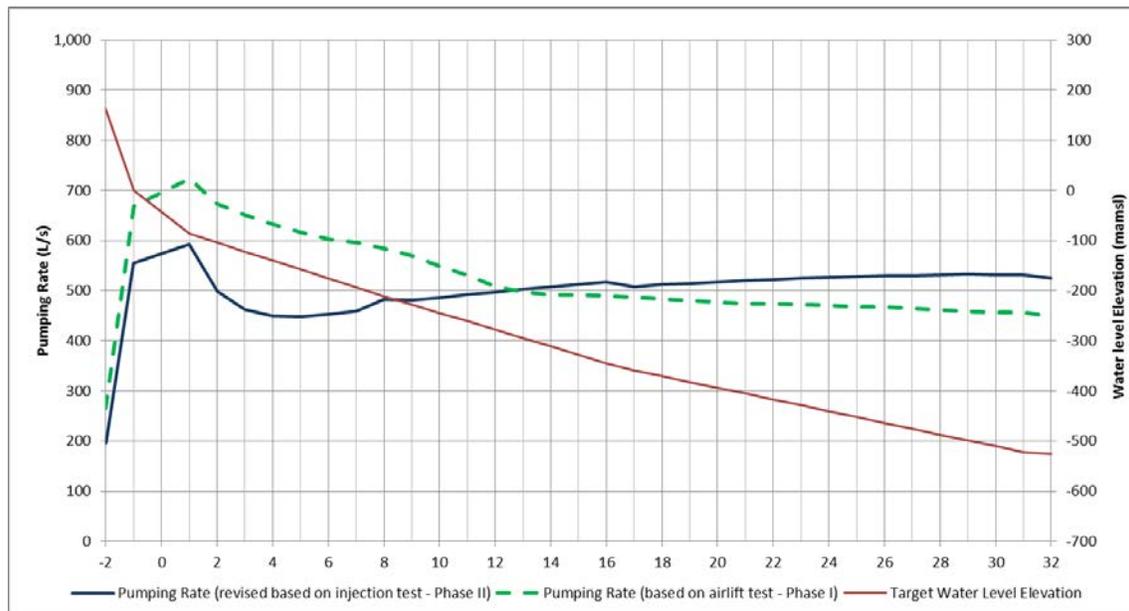


Figure 9. Predicted Dewatering Rates (Round 4) and Target Water Level Using Recovery Data.

9 CONCLUSIONS

A meaningful estimate of dewatering for a mine feasibility study can be a lengthy process, depending on the hydrogeologic nature of the deposit. In some cases, a proper characterization can be done in a matter of a few months if the rock is tight and the water is pure. For hydrogeologically complex sites, or deposits characterized by a high transmissivity rock type, a proper field characterization may take more than a few months.

This case study showed that the initial round of testing, while relatively comprehensive, did not produce enough information for a feasibility-level mine dewatering estimate. The host rock was permeable, and a large scale hydraulic stress test was needed to develop a reasonable understanding of the controlling hydrogeologic features, which extended the project schedule by at least 6 months. Comprehensive analyses and a good groundwater model, used in an iterative fashion to reduce uncertainty, were critical to development of a feasibility-level dewatering estimate. The combination of brackish groundwater and elevated dewatering rates contributed to water management costs that were significant components of the capital and operational costs for the project, yet much larger than originally anticipated.