

Interpretation and application of hydrogeological concepts to commercial-scale brine extraction projects

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ABSTRACT

Brine extraction for surface process and recovery of potash, lithium and industrial salt requires the application of traditional hydrogeological theories to hyper-saline solutions. Such brines present additional technical challenges in comparison to fresh water due to density effects (*e.g.*, 1.2 gram/cm³), density driven multi-chemical composition flow on a large scale, and interaction between brines and fresh water over the course of the production period. Surface production facilities require estimation of brine composition over time. Therefore, the hydrogeologist is tasked with balancing extraction rates from multiple production wells, locating the production wells in space (and time), predicting chemical composition of the pre-pumping and extracted brines and monitoring depletion of a “dynamic” resource. Each of these parameters can have a significant impact on project economics. The parameters such as effective porosity, permeability (“hydraulic conductivity” adjusted by density and dynamic viscosity), anisotropy, aquifer configuration (extent, thickness and heterogeneity), and wellfield efficiency are key in the estimation of resources and reserves for a brine extraction project. During the stages of prefeasibility and feasibility, an accurately built numerical groundwater model is required in order to develop a production plan. Recent guidance from the Ontario Securities Commission provides an indication of how to disclose brine resource and reserve estimates according to the Standards of Disclosure for Mineral Projects, namely National Instrument 43-101. This paper examines the technical aspects of estimating extractable brine resources and reserves, and current public disclosure guidance.

INTRODUCTION

Brine extraction for surface processing and recovery of potash, lithium and various industrial salt products requires the application of traditional hydrogeological theories to hyper-saline solutions. The hydrogeologist is now the mine engineer and tasked with balancing extraction rates from multiple production wells, locating the production wells in space (and time), and predicting chemical composition of the pre-pumping and extracted brines. In terms of defining the recoverable resource or the mineable reserve, the resource geologist or the mine engineer require a different set of parameters and tools to define the economic extraction of selected minerals from hypersaline brines.

Within the context of this paper, the authors define brine extraction as the use of production wells to recover brine from aquifer storage. The authors are aware of other brine extraction methods which do not require a production wellfield. These alternate methods include shallow ponds or engineered trenches that intercept the top of brine and allow the extraction of brine. The authors note there are similarities in field investigation and interpretation activities described in this paper for resource characterization and exploitation under production wellfields and alternative extraction methods.

This paper references the National Instrument 43-101 disclosure standards for mineral resource and reserve reporting. Specifically, technical guidance provided by the Canadian Institute of Mining and Metallurgy for brine type deposits. The authors rely on the reader's familiarity with NI 43-101 Technical Reporting of Mineral Resources, Preliminary Economic Assessment, Preliminary Feasibility Study and Feasibility Study.

EXPLORATION CAMPAIGN

As indicated by Sonnenfeld (Sonnenfeld, 1984), water masses in evaporate deposits are always moving and precipitated crystals are subject to repeated alteration. Therefore, in contrast to hard rock deposits, exploration of brine deposits must focus on the characterization of hydrogeological parameters and definition of the brine hosting aquifer. Typical hard rock mining exploration methods focus on exploration drilling for geological definition and metallurgical testing, while brine extraction exploration focuses on the definition of hydraulic parameters via hydrogeological testing, as well as brine and core sampling.

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Site-specific parameters

The prediction of brine extraction rates must reflect the site-specific characteristics of a brine hosted deposit. Table 1 summarizes key basin-wide hydrogeological components that are relevant to commercial-scale brine extraction projects.

Table 1 Basin-wide hydrogeological concepts applicable to brine extraction projects

Water Balance	A quantitative accounting of estimated recharge and discharge, typically defined under steady state (or pre-mining) conditions
Lateral boundaries of the brine hosting aquifer	Can be geologic boundaries (e.g., bedrock, contrasting formations or faults) or hydraulic boundaries (e.g., fresh or brackish water)
Vertical distribution of hydrogeologically-distinct layers in the brine hosting aquifer	Typically defined by contrasting lithologies in horizontal layers (e.g., massive halite, dune sand, gypsum, clays)
Brine volume	Calculated within the vertical and lateral boundaries of the brine aquifer - can be estimated from specific yield

Table 2 summarizes the lithology-specific parameters that inform the brine resource geologist during estimation of measured, indicated and inferred mineral resource categories. These parameters allow the geologist to assess the physical extractability of the brine and the approximate chemical composition of the produced brine.

Table 2 Lithology-specific hydrogeologic properties applicable to brine extraction projects

Brine assays (targeted constituents, impurities)	Elemental analysis of brine samples collected from representative sampling depths
Hydraulic conductivity (lateral and vertical)	Estimated from in-situ testing (e.g., packer testing, short-term bore hole tests, pumping tests) or ex-situ laboratory testing (e.g., ASTM)
Specific yield (S_y) or specific storage (S_s) for each lithology	Approximated through in-situ testing (pumping tests) or ex-situ laboratory testing (e.g., relative brine release capacity)
Effective porosity (η_e) and dispersivity (longitudinal and transverse)	Used to estimate changes in brine composition as a result of advective transport

Between the lithology-specific hydrogeologic properties described in Table 2, the specific yield (S_y), specific storage (S_s) and effective porosity (η_e) are critical parameters used to estimate the volume of fluid which will gravity drain from the brine aquifer. The hydrogeologist will rely on a combination of different test methods and literature data to assign an appropriate S_y , S_s and η_e for each lithologic unit.

Steps for a brine hosted mineral exploration campaign

Surface exploration

Shallow pits, geochemistry surface distribution will help define the targets for further exploration. This initial phase involves brine samples collection and chemical assays. Geophysical techniques can also assist in delineating depth to basement rock as well as fresh water transition zones with the brine deposit.

Geological and structural information

Geologic core logs are the primary means for evaluating the distribution of lithologic facies in the host aquifer and subsequently grouping lithologic facies into hydrogeologic units (HGUs) and hydrostratigraphic units (HSUs).

The geologist interprets the stratigraphic sequence, depositional environment and conceptual 3-dimensional hydrogeologic framework of the aquifer. The geologist assigns lithologic facies based on drill samples and associated geologic logs. Core samples provide critical data regarding saturation, consolidation and detailed lithologic information.

Drilling targets

The drill density and drill method should reflect the differences in matrix conditions and stratigraphy between mature halite salars and immature clastic salars. The drilling technique should be conducive to recovery of samples for both porosity/permeability and brine chemistry determination. Core recovery is essential in locations where rapid changes in lithology likely correspond to similar changes in aquifer porosity/permeability and brine chemistry characteristics. Kunasz (Kunasz, 2013) emphasizes dual-wall reverse circulation drilling techniques to maximize recovery and quality of core samples for geologic logging and laboratory sampling.

Hydraulic testing

Houston (Houston et al., 2011) describes how brine extraction induces redistribution of the resource because the fluid is being dynamically stressed. The size and shape of the cone of depression created by the well field is a function of permeability and aquifer storage. Accordingly, the geologist must make realistic estimates of the 3-dimensional distribution of hydraulic conductivity as well as the specific yield of the brine aquifer.

CIM guidance (Canadian Institute of Mining, Metallurgy and Petroleum, 2012) indicates the estimates of hydraulic conductivity and specific yield should involve at least two different methodologies. Stormont (Stormont et al., 2011) describes the RBRC method as a surrogate for effective porosity and specific retention. This method also provides bench-scale estimates of hydraulic conductivity. Most brine geologists rely on a combination of laboratory analysis of core samples and in-situ brine aquifer testing.

A long term pumping test from a prototype production well should be conducted to demonstrate brine extractability from the aquifer's groundwater system.

Solute transport parameters (effective porosity and dispersivity) can be defined based on tracer test data, however, effective porosity is typically assumed to be equal to specific yield; dispersivity values are usually assigned based on literature data.

Sample collection

Core Sampling and Brine Sampling: Sampling protocols must be selected that can accurately determine the *in situ* location of the sampled intervals (Canadian Institute of Mining, Metallurgy and Petroleum, 2012). Kunasz (Kunasz, 2013) notes that the core sample program should focus on the hydrogeologies that will likely yield brine under commercial scale exploitation.

NUMERICAL GROUNDWATER/SOLUTE TRANSPORT SIMULATION AS AN EVALUATION TOOL FOR RESERVES

During brine extraction, brine assays at a given location will change based on the hydrogeological setting and the production schedule (well locations and pumping rates). Brine movement is the dynamic 3D process which could be easily over-simplified using analytical methods. The authors believe that numerical methods represent the best tool for prediction of brine composition, fresh water intrusions and well field design. The major advantage of a numerical model is its capability to combine the heterogeneous geologic setting, simulate density driven flow, and define the optimal production schedule under different scenarios.

Numerical groundwater and solute transport models of the Salar areas are usually built at a regional scale with significant sizes of finite-difference cells or nodal areas of finite-element mesh. Proper simulation of brine pumping wells requires use of special multilayer packages/features allowing simulation of well screens within multiple numerical layers, correct drawdown in large cells/elements to drawdown in real size of an extraction well, and application of a freeboard elevation below which pumping rate should be reduced in time to maintain operational conditions of the pump.

The impact of fresh water intrusion and dilution of the mineral resource should be evaluated properly. Evaporation commonly exceeds precipitation values at brine deposits; however, seasonal recharge introduces fresh water to the basin. Precipitation events usually happen during a limited time period during the year (2 to 3 months), and may include a snow melt event, generating significant fresh water fluxes to a Salar and causing accumulation of fresh water bodies peripheral to the Salar. The life-of-mine design of the production wellfield should consider the effects of density driven flow. This means that optimal location of the wells and their pumping rates might vary in time depending on intrusion of fresh water and/or lower grade brine.

MINERAL RESOURCE AND RESERVE REPORTING FOR BRINE DEPOSITS

The Ontario Securities Commission provided technical guidance for the disclosure of brine resource and reserve estimates according to the Standards of Disclosure for Mineral Projects, namely National Instrument 43-101. Figure 1 presents the progressive levels of study from the resource estimate to a preliminary feasibility study of a brine project.

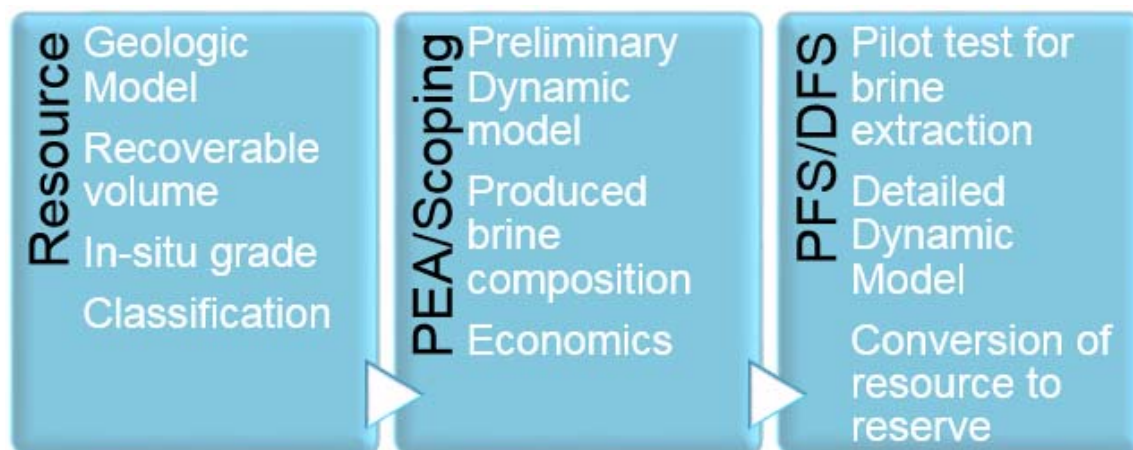


Figure 1 Progressive levels of engineering study for brine deposits

A brine deposit must have reasonable prospects for economic extraction in order to be declared a mineral resource. Economic extraction requires knowledge of the brine extractability, the composition of the produced brine, the process recovery for conversion of brine into the saleable product and the operating cost of doing so. At the declaration of a mineral resource, the brine resource geologist typically relies on comparisons to more advanced or operating projects with comparable geology.

Resource estimation

Starting at the PEA, the brine resource geologist and mine engineer can improve the basis for declaring a reasonable prospect for economic extraction when process recovery and operating costs are available. The physical properties of the brine aquifer allow the geologist and the hydrogeologist to develop a three-dimensional understanding of the brine deposit and to construct a “dynamic” numerical model to simulate a production schedule for the brine.

Historically, resource geologists examining conventional hard rock deposits examine the variogram of assay values to estimate appropriate sample spacing for resource classification. Brine deposits differ from hard rock deposits in that the resource classification is largely influenced by the hydrostratigraphic parameters and transmissivity of the units that comprise the Salar. The use of sequence stratigraphy and combining the static and dynamic models under one set of parameters gives a more workable and integrated system to calculate and classify the brine resource in the Salar.

Resource to reserve conversion

The dynamic model is a powerful tool to evaluate the physical aspects of brine extraction and should include 3-D density driven flow and solute transport. In the authors’ experience, the dynamic model is the preferred method to develop the mineral reserve estimate. Commercial programs such as MODFLOW-SURFACT (Hydrogeologic, Inc., 2006) and FEFLOW (DHI-WASY, 2009) provide adaptable and industry-accepted algorithms to conduct such modeling.

Using the hydrogeologic character and properties of a brine hosted deposit, combined with the well field design parameters, the rate and volume of brine that can be extracted from such deposit is

simulated using a numerical groundwater model. The model output generates a production profile appropriate for the deposit based upon the well field design assumptions and a targeted average finished product production rate.

The numerical model does not discriminate between brine derived from Measured, Indicated or Inferred resources. Therefore, an additional calculation is usually utilized which applies recovery factors to the Measured and Indicated resource to estimate the recoverable brine contained within these categories. The production profile generated by the model is then truncated based upon the calculation of recoverable mineral within the Measured and Indicated categories to effectively exclude production reliant upon Inferred resources.

Finally, the model output is checked against economic cut-off grades to confirm the reserve estimate maintains positive economics throughout the mine plan. The cut-off grade is less important in a brine operation as there is limited selectivity in pumping of the brine (i.e. there is no ability to designate low grade resource blocks as waste and avoid mining, or to selectively not process portions of the brine). However, it is a limiting factor to overall production as a raw brine stream that falls below the cut-off grade is no longer economic to process and production should be stopped.

As site specific data become available with increased exploration, the dynamic model is then used to simulate commercial scale exploitation of the brine deposit. As the project advances through the prefeasibility and feasibility stages with metallurgical and economic inputs, a robust dynamic model provides the basis for the production schedule. The model is also used to design the production wellfield layout and changes in the wellfield over time during depletion of the brine deposit.

Figure 2 presents an overview of the resource and reserve classification process, as applied to brine deposits. The authors provide examples of how mineral industry professionals interpret the conventional definitions of measured, indicated and inferred resources in terms of a brine deposit.

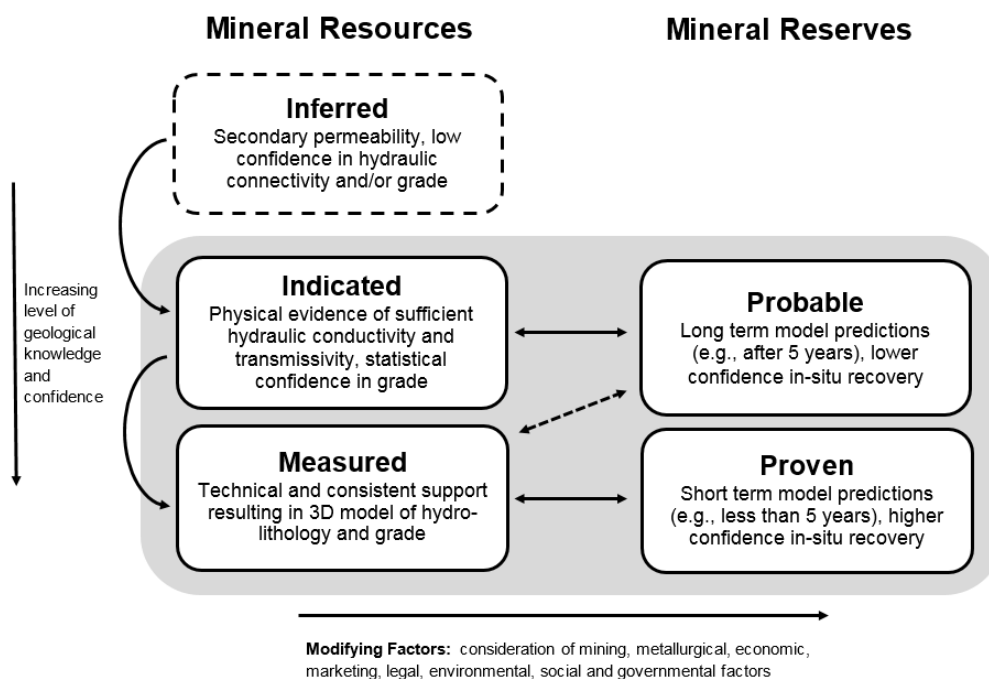


Figure 2 Overview of resource and reserve classification and conversion, brine deposits

RESULTS AND DISCUSSION

The authors evaluated the potential for brine extraction for the Salar de Diablillos project (SRK Consulting, 2011), located in Northern Argentina, to produce lithium carbonate, potash, and boric acid. The work was completed based on field hydrogeologic testing, development of a 3-D numerical groundwater and solute transport models, and included the assessment of:

- The number of extraction wells needed to meet production targets, their locations, the total pumping rate and the subsequent drawdown in surrounding areas; and
- Expected changes in lithium (Li), potassium (K), and boron (B) concentrations within the extracted brine over time given possible surface water dilution and dilution from surrounding areas containing lower concentrations of these components.

Hydraulic parameters of simulated hydrogeological units were based on the results multi-interval pumping tests. Production rate per individual well was assumed based on achieved rates during conducted pumping tests. Effective porosity and horizontal dispersivity of the brine-containing sediments were estimated based on tracer test results. Distribution of brine initial concentrations was made based on groundwater sampling and developed resource model of the project.

Figures 3 and 4 present an example of the results of the groundwater model developed for the project. Figure 3a presents predicted total pumping rate and average drawdown in extraction wells in time. Figure 3b shows Li, K, and B concentrations in extracted brines through time. Figure 3c illustrates simulated wellfield and drawdown at the end of mining.

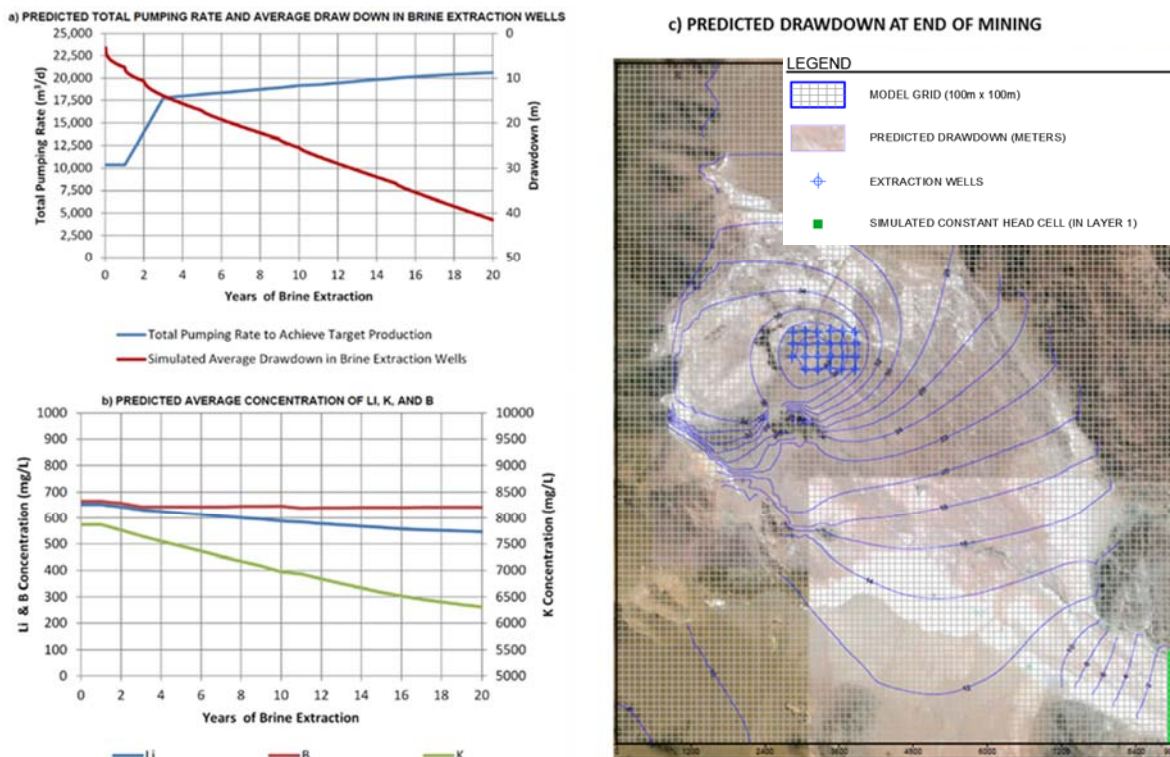


Figure 3 Predicted pumping rates, drawdown, and Li, K, B concentration in Time

Figure 4 presents a comparison of initial (a) and end of mining (b) simulated Li concentrations.

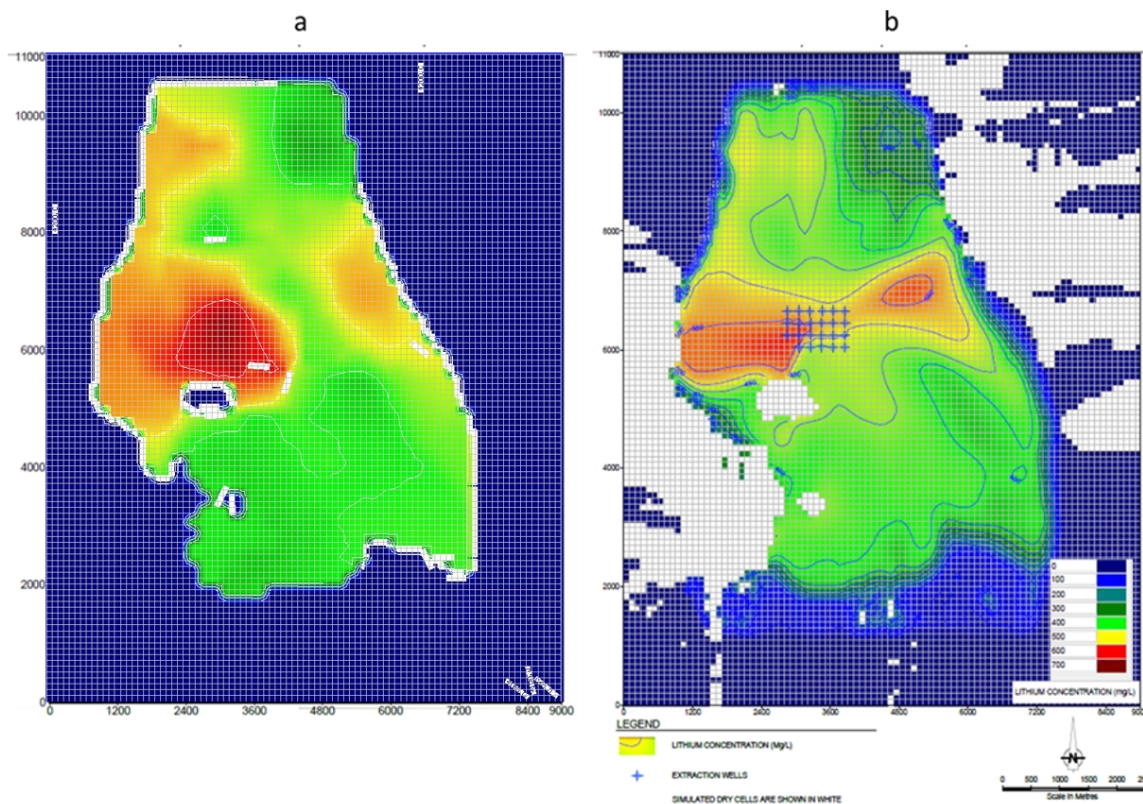


Figure 4 Initial (a) and end of mining (b) Li concentrations simulated by solute transport model

CONCLUSIONS

The brine hydrogeologist is tasked with balancing extraction rates from multiple production wells, locating the production wells in space (and time), predicting chemical composition of the pre-pumping and extracted brines and monitoring depletion of a “dynamic” resource. Each of these parameters can have a significant impact on project economics. The parameters such as effective porosity, permeability (“hydraulic conductivity” adjusted by density and dynamic viscosity), anisotropy, aquifer configuration (extent, thickness and heterogeneity), and wellfield efficiency are key in the estimation of resources and reserves for a brine extraction project.

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