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Improved aquifer characterization and the optimization of the design of brackish groundwater desalination systems

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ABSTRACT

Many water scarce regions possess brackish-water resources that can be desalted to provide alternative water supplies. Brackish groundwater desalination by reverse osmosis (RO) is less expensive than seawater systems because of reduced energy and pretreatment requirements and lesser volumes of concentrate that require disposal. Development of brackish groundwater wellfields include the same hydraulic issues that affect conventional freshwater wellfields. Managing well interference and prevention of adverse impacts such as land subsidence are important concerns. RO systems are designed to treat water whose composition falls within a system-specific envelope of salinities and ion concentrations. A fundamental requirement for the design of brackish groundwater RO systems is prediction of the produced water chemistry at both the start of pumping and after 10–20 years of operation. Density-dependent solute-transport modeling is thus an integral component of the design of brackish groundwater RO systems. The accuracy of groundwater models is dependent upon the quality of the hydrogeological data upon which they are based. Key elements of the aquifer characterization are the determination of the three-dimensional distribution of salinity within the aquifer and the evaluation of aquifer heterogeneity with respect to hydraulic conductivity. It is necessary to know from where in a pumped aquifer (or aquifer zone) water is being produced and the contribution of vertical flow to the produced water. Unexpected, excessive vertical migration (up-coning) of waters that are more saline has adversely impacted some RO systems because the salinity of the water delivered to the system exceeded the system design parameters. Improved aquifer characterization is possible using advanced geophysical techniques, which can, in turn, lead to more accurate solute-transport models. Advanced borehole geophysical logs, such as nuclear magnetic resonance, were run as part of the exploratory test well program for a new 66,200 m^3/d (17.5 million US gal/d, MGD) brackish-water desalination plant for the City of Hialeah, Florida. Salinity and hydraulic conductivity data from the borehole logging program were used for both well design (determination of production zone) and groundwater modeling to optimize the production wellfield layout and predict future water quality. Advanced characterization techniques have general applicability for improving the design and predictability of well-based raw water supply systems, including alternative seawater intakes.

Keywords: Reverse osmosis; Brackish water; Desalination; Groundwater; Modeling

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1. Introduction

In arid, semiarid, and coastal regions throughout much of the world, freshwater resources are already being exploited and are close to or exceeding sustainable limits. Alternative water sources are necessary to meet growing demands. Many freshwater-scarce regions are underlain by aquifers containing brackish water that is not suitable for direct potable use because of its high salinity. Brackish groundwaters can be used as the raw water supply for reverse osmosis (RO) desalination facilities. Brackish groundwater desalination offers two major advantages over seawater desalination. The lower salinity results in a lesser energy requirement for RO desalination and greater recovery rates, which substantially reduces construction and operational costs. Also, groundwater is typically of better quality in terms of suspended solids and organic foulants, and thus requires less pretreatment, than seawater obtained from conventional surface-water intakes.

Brackish-water aquifers usually contain substantial spatial variation in salinity. The density of water increases with salinity. Brackish-water aquifers, therefore, tend to be salinity and density stratified, with salinity increasing with depth. Salinity within brackish aquifers also increases laterally from inland recharge areas towards the coast. Variations in salinity may also be related to the paleohydrologic history of the groundwater basin, rather than the current hydrological regime. Brackish and saline water within aquifers may have been trapped under past hydrologic conditions.

Brackish-water RO facilities are designed to treat water that has a chemistry falling within a specific compositional envelope. The composition of the raw water needs to be known both initially (at the time of plant design) and throughout the operational life of the treatment system, which is typically taken as 20 years. Due to the spatial heterogeneity of salinity within brackish-water aquifers, the composition of the produced water will change over time. A critical aspect of the design process for brackish groundwater RO desalination facilities is groundwater (solute-transport) modeling to simulate the evolution of the salinity and ion concentrations of the produced water over the operational life of the RO treatment facility.

The development of brackish groundwater supplies includes an additional level of complexity beyond that for fresh groundwater resources. In addition to bulk aquifer hydraulic properties (transmissivity, storativity, and leakance), accurate solute-transport modeling requires knowledge of the three-dimensional distribution of salinity (and any other parameter of specific local concern) within the aquifer, effective porosity, and aquifer heterogeneity with respect to hydraulic conductivity, particularly the presence of potential flow zones or conduits. An additional issue is whether the brackish groundwater is a renewable or non-renewable resource. Aquifer characterization is thus crucial for the development of brackish groundwater resources. Advanced techniques are available that can result in more detailed and accurate aquifer characterization and thus improved groundwater models and water quality predictions.

2. Data requirements for brackish RO system design

Reverse osmosis membrane treatment systems are designed to treat water with a specified salinity range. The raw water supply requirements for brackish-water RO systems were reviewed by Missimer [1]. Both membranes and high pressure pumping system equipment are selected based on the maximum salinity expected to be encountered over the operational life of the treatment facility. Potential consequences of unpredicted excessive salinity increases beyond the RO treatment design parameters include reduced system efficiency and water production, the need to replace membranes and high pressure pumps, and to install new production wells.

Prevention of membrane fouling by mineral precipitation is another important water quality consideration. The concentrations of some ions or complexes (e.g., $CaCO_3$, $BaSO_4$, H_2SiO_4, $Fe(OH)_3$) must not exceed system-specific thresholds. If the raw water chemistry is conducive for chemical clogging, then pretreatment will likely be required to reduce the ion or complex concentration below thresholds. The pretreatment will typically involve reduction of pH, addition of a polymer, or addition of a process (e.g., iron removal). A thorough evaluation of current raw water chemistry is, therefore, a basic element of the design of RO desalination systems. Prediction of future changes in water chemistry is more complex. It is often assumed that ion and complex concentrations are correlated with salinity, which may or may not be completely accurate. Ideally, chemistry data should be obtained from waters that may eventually migrate into the production zone, which would include underlying and overlying aquifers or aquifer zones.

3. Groundwater modeling

Solute-transport modeling is the primary tool for predicting long-term salinity changes in brackish-water aquifers. The model code used should be density dependent. A variety of models have been developed that can simulate density-dependent solute transport. As a general principle, open-source codes are preferred over proprietary codes, unless the latter has additional features or capabilities that are germane to the specific project. The US Geological Survey MODFLOW family of models is now widely used for groundwater investigations because they are open source, have been greatly tested by numerous workers, and are generally accepted by regulatory agencies. SEAWAT [2] has become the preferred code for simulations of brackish-water aquifers.

The aquifer characterization program should focus on the specific data requirements for the model development. This is a key distinction that is often not considered. It has been common for the modeler to become involved in a project only after the aquifer characterization has been already completed, when the opposite should be the case.

The basic data requirements for the development of a solute-transport model of a brackish groundwater system are illustrated in Fig. 1. Key data are the three-dimensional distribution of salinity (and other ions or complexes of specific concern), the vertical and horizontal distance of the production zone from lesser quality water, aquifer hydraulic properties, and aquifer heterogeneity that can result in more rapid flow of lesser quality water towards the production well. Fig. 1 is based on salinity, but a similar approach can be taken for ions or complexes of specific concern for a project.

It is important to recognize that there will always be an element of uncertainty in predicting the long-term evolution of water quality because natural systems are inherently, to a degree, unpredictable. The amount of data obtainable from aquifer characterization programs will always be limited relative to the size of the aquifer. A key part of the modeling process is to reduce and define the uncertainty through the sensitivity analysis process. A most likely scenario for salinity change over time can be made based on professional judgment for the conceptual model design and values for hydraulic parameters. By varying the values of critical model parameters (within hydrogeologically feasible ranges), a set of possible salinity versus time curves can be generated to develop a "cone of uncertainty," which is conceptually illustrated in Fig. 2. The water treatment system should be designed to treat water with a salinity at least as high as the upper limit of the cone of uncertainty and, ideally, with an additional safety factor.

Undetected hydrogeological conditions can result in water quality falling outside of the cone of uncertainty. One scenario is that water quality trends above the cone of uncertainty, but stays within the design limits, at least until the latter part of the planned operational life (curve A, Fig. 2). A more ominous situation is the breakthrough of more saline water, which results in a sudden rapid rise of salinity (curve B, Fig. 2). In a breakthrough situation, there is little time for corrective action, whereas under a curve A scenario, substantial advance warning is available that salinity will eventually rise above the design limit at some relatively distant time in the future. Plans could be made for a more expedited upgrading of the treatment system to handle the greater salinity.

Gradual rises in salinity are, fortunately, the more common situation. However, breakthrough of saline water has been documented in a brackish raw water wellfield. The production wells at the west end of the Collier County, Florida, North County Regional Water Treatment Plant (NCRWTP) wellfield experienced a very

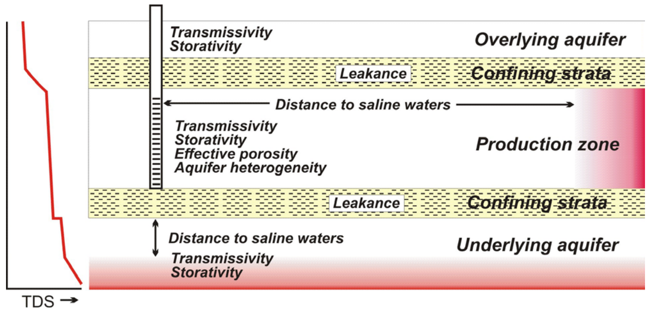

Fig. 1. Basic data requirements for the development of solute-transport models of brackish-water aquifers.

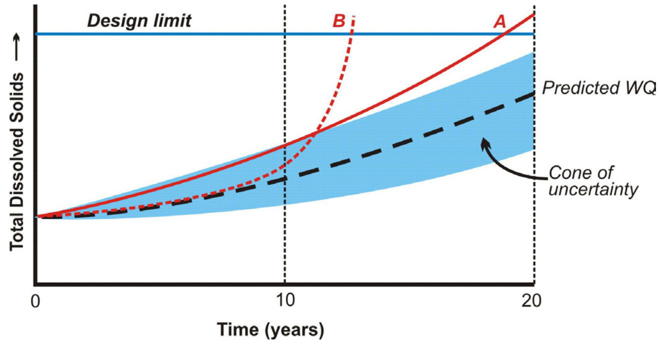

Fig. 2. Schematic illustration of the modeled cone of uncertainty (shaded blue) in the total dissolved solids (TDS) concentration of the raw water over time. The dashed black line represents the most-likely scenario. The plant design limit is a TDS concentration selected above the cone of uncertainty after 20 years (operational life period). Unexpected departures from the cone of uncertainty may be gradual (curve A) or sudden (curve B) in the case of breakthrough.

rapid rise in salinity shortly after the start of production, which resulted in the total raw water feed exceeding the plant design limits. Groundwater flow at the NCRWTP is dominated by fractured dolomite beds whose geographic extent and orientation are not known [3]. It is believed that the fractured dolomite encountered some type of vertical conduit that allowed the upwards migration of more saline water [1]. A high-pressure RO skid was subsequently designed for the plant and will be fed by the high-salinity wells.

An example of an actual sensitivity analysis used to determine a cone of uncertainty is provided in Fig. 3 using data from the Palm Beach County Lakes Region Water Treatment Plant (LRWTP) in the City of Belle Glade, Florida. Variables considered in the sensitivity analysis include initial salinity (to account for spatial variability in wellfield area) and production zone transmissivity and leakance. The plant was designed to accommodate a salinity increase at least up to the highest simulated TDS value.

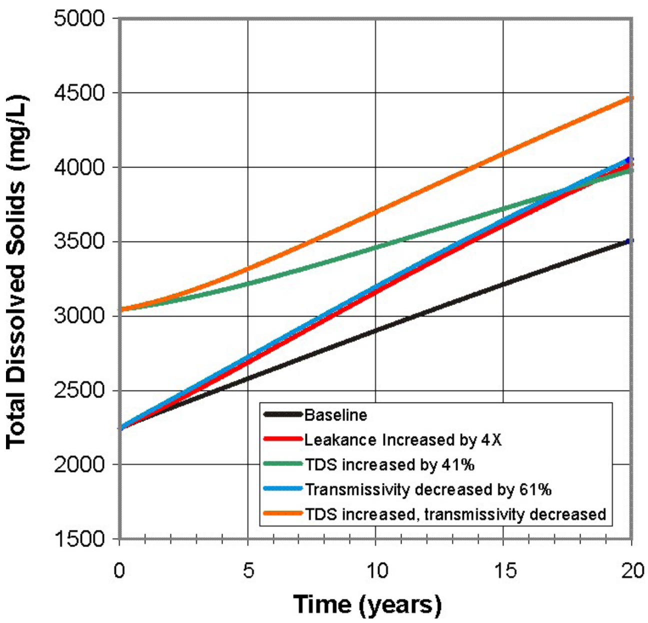

Fig. 3. Sensitivity analyses performed for LRWTP brackish-water supply. The baseline curve represents the best-estimated hydraulic and water quality values.

Groundwater modeling should not end with desalination plant construction. Actual salinity vs. time data from the operational plant should be continuously compared to the predicted trend. If the data start to depart from the predicted trend, then the model should be recalibrated in order to develop an understanding of the cause of the unexpected changes and to obtain an updated, more accurate projection of future salinity changes. Re-evaluation of the salinity trend is important in providing advanced warning if salinities are likely to exceed plant design parameters and if so, the time in which the exceedance will likely occur. Such advance warning would provide a plant owner and operator time to plan and budget for a response to the salinity change. For example, recalibration of the groundwater model used for the design of the Kill Devil Hills, Dare County, North Carolina, BWRO facility allowed for an effective corrective response to a more rapid than expected increase in salinity.

Groundwater monitoring is also critical for the prediction of future water changes. Sentinel monitor wells should be installed between the production wells and poorer-quality groundwaters in order to provide early warning of the movement of the poorer-quality waters towards the wellfield. Water quality data from the monitor wells should also be compared against modeled changes in water quality at the well locations.

4. Aquifer characterization

Aquifer characterization is used to identify the brackish-water production zone and to provide data to develop groundwater models. Determination of the optimal production zone interval involves balancing two objectives: maximization of the productive capacity of wells (i.e., well yield or specific capacity) and managing the salinity of the produced water. Well yields may be increased by increasing the well depth in order to produce from a greater thickness of the production zone (i.e., including more potentially productive strata). However, deepening the production zone may include aquifer zones containing higher salinity water and/or decrease the vertical separation from underlying zone that contains more saline water.

An important, and very cost-effective, element of the aquifer characterization for an RO raw water supply is a desktop investigation. The term "desktop" signifies that fieldwork is not involved. In many areas of the world, a considerable amount of data is available in various forms on local and regional hydrogeology. Borehole geophysical logs from oil and gas production may also be available that can be reprocessed to extract information on shallower aquifer strata. Typically, the data are available in bits and pieces, and the desktop investigation involves "data mining," (i.e., extracting small items of useful information from multiple sources). The desktop investigation may be able to identify a target brackish production zone and its likely depths, salinity, thickness, and horizontal extent.

Groundwater flow may also be affected by natural flow conduits (e.g., fracture zones, faults, karst features) and man-made flow conduits, particularly poorly constructed and abandoned wells. Conduits that intersect the production zone and underlying more saline water may allow for the rapid upwards migration of saline water during production. A records search for deep wells and evaluation of structural geology maps should also be part of the desktop investigation.

Surface geophysical surveys, such as DC resistivity and time domain electromagnetic induction (TDEM), can provide information on salinity changes with depth, which can facilitate the initial source water investigation. The great advantage of TDEM is that it is, by far, a less expensive means of obtaining estimates of water-quality changes with depth compared to drilling and testing of a well. However, the cost and time savings come at the expense of accuracy. TDEM data should be ground-truthed with salinity-versus-depth data from a well within the study area.

A basic requirement for the characterization of a brackish-water aquifer for RO raw water supply is the drilling of a least one exploratory well and a test production well. The latter is often constructed to serve as an actual production well for the RO plant, and thus does not represent an additional cost. The former is typically completed as a production zone monitoring well, to be used as an observation well for subsequent aquifer testing. The exploratory well should be drilled through and below the target production zone in order to also obtain information on the hydrogeology of underlying confining zones and aquifers. Multiple exploratory wells are desirable (and necessary for very large wellfields), but they represent a significant cost and may not be economically feasible for some systems.

Borehole geophysical logging is an integral element of exploratory well programs. At a minimum, a suite of basic geophysical logs should be run, which includes caliper, natural gamma ray, resistivity (dual induction), spontaneous potential, and sonic porosity. If borehole conditions and local regulatory conditions allow, flowmeter, borehole video, neutron and density logs may also be run. Borehole geophysical logs are often only qualitatively evaluated. Quantitative analysis of the logs can enhance aquifer characterization by providing continuous profiles of both salinity and porosity versus depth and, when used in conjunction with aquifer performance tests, the distribution of hydraulic conductivity.

The technological level of borehole geophysical logging employed in typical groundwater investigations is literally decades behind that currently employed in the oil and gas industry. The technological gap is largely due to economics. Where new water is readily available and inexpensive, there is little technological or economic justification to employ higher and more expensive levels of technology [4]. For complex groundwater projects in which solute transport is critical, advanced logs can cost-effectively provide useful information and thus improve aquifer characterization. The costs of logs represent a very small percentage of the total project cost.

Advanced borehole geophysical logs, such as nuclear magnetic resonance and microresistivity imaging, for example, can provide a continuous profile of porosity (total and size distribution) and hydraulic conductivity and visualization and quantification of secondary porosity that may dominate groundwater flow (Fig. 4). Advanced borehole geophysical logs have been used as part of the aquifer characterization program for aquifer storage and recovery (ASR) systems [4,5] and can also assist in the design and modeling of brackish-water supply wellfields for RO plant and alternative intake designs.

Advanced borehole geophysical logs, such a nuclear magnetic resonance, were run as part of the test well program for a new 66,200 m^3/d (17.5 MGD) brackish-water desalination plant for the City of Hialeah, Florida [6]. The advanced logs include Combinable Magnetic Resonance (CMR), Formation MicroImager (FMI) and Elemental Capture Spectroscopy (ECS). Data from the advanced geophysical logging were used to determine the production zone for the brackish-water production wells and for the development of the solute-transport model used for the prediction of future water quality.

A critical element in brackish groundwater investigations is the performance of an aquifer performance (pumping) test (APT), which can provide data on large-scale aquifers. In order to obtain a leakance value, which affects the susceptibility of the aquifer to the up-coning of saline water, a multiple well (pumped well and at least one observation) test must be performed. Multiple well tests also have a greater volume of investigation and thus provide data that are more representative of local aquifer conditions than single well tests. The aquifer characterization can be improved by installing additional observation wells and extending the time-duration of the test. The additional observation wells should be located varying distances and directions from the production well. At least one well should be located at a distance from the production well equal to or greater than the preliminary estimated production well spacing to allow for direct evaluation of the likely magnitude of well interference.

While several days of pumping the test production well at the projected operation rate may provide enough information to calculate aquifer hydraulic parameters, longer periods are always recommended because they may allow for the detection of saline-water intrusion and the more accurate measurement of hydraulic parameters. Durations of several weeks should be considered if practical. However, it is recognized that long-duration tests may not be practical because of environmental concerns related to the disposal of saline water and cost considerations if a gasoline or diesel powered pump is used that needs to be continuously monitored.

5. Discussion

The effort and financial investment made in hydrogeological investigations must be commensurate with overall system capacity and costs. Larger capacity RO systems place a greater stress on the aquifer and are thus more prone to inducing significant movement of poorer-quality (more saline) water. Large-capacity RO systems also have greater project budgets that can accommodate more hydrogeological testing. For example, the aquifer characterization needed for a 40,000 m^3/d (10.6 million MGD) system will necessarily be greater than that needed for a 2,000 m^3/d (0.52 MGD) or lesser capacity system. However, even small capacity systems can experience large changes in salinity if the production wells are completed near an interface having higher salinity water.

An emerging technical concern is the potential for interference and cumulative impacts between systems. Where multiple brackish-water desalination facilities are constructed in a given area, the cumulative impacts of their groundwater production in inducing the movement of saline waters may be greater than the individual impacts of each system. Increased saline-water intrusion from cumulative impacts of multiple existing and planned brackish-water desalination facilities has been raised as a potential concern in southeastern Florida (USA), although such impacts have not yet been documented.

Aquifer characterization and groundwater modeling,

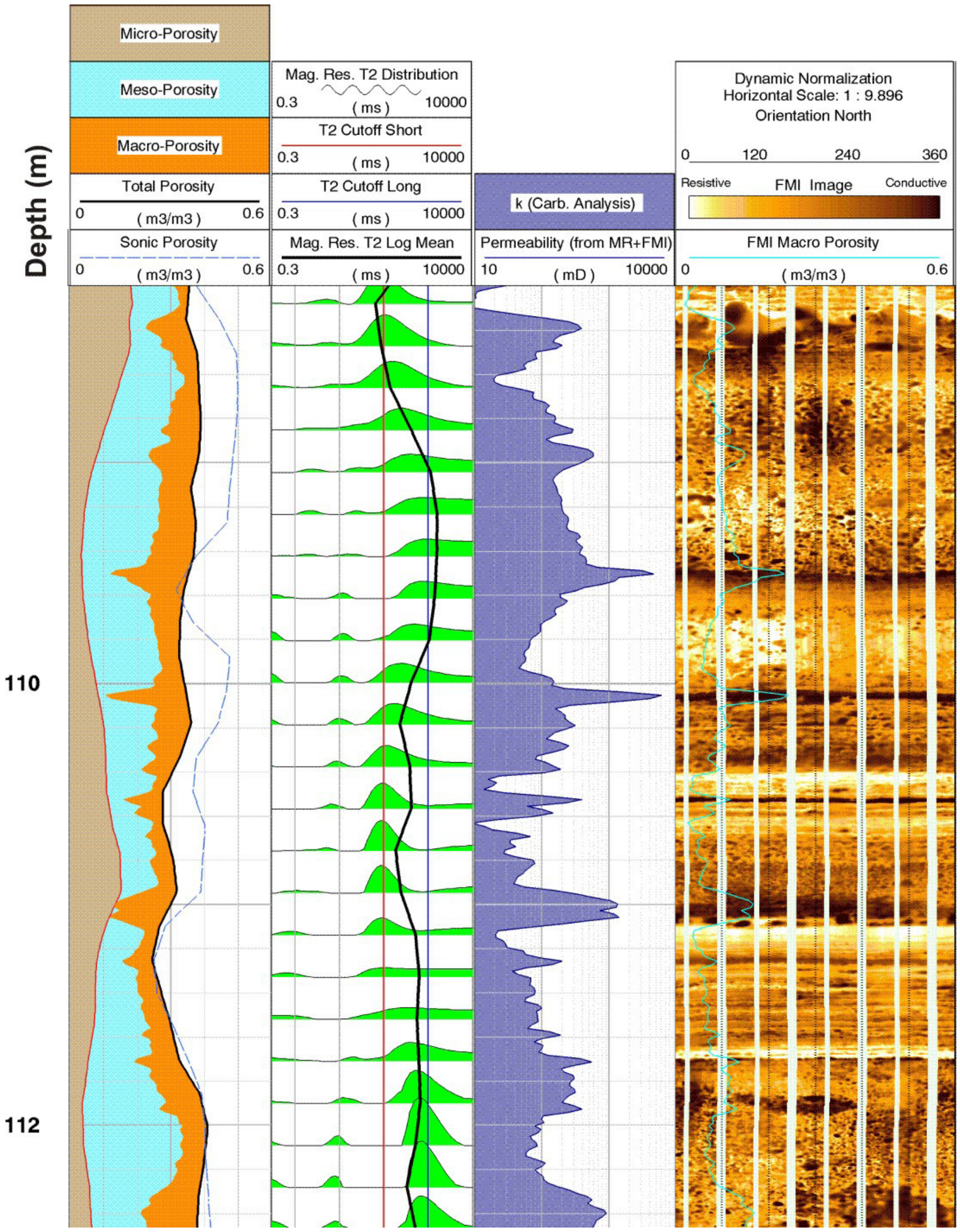

Fig. 4. Advanced borehole geophysical logs, nuclear magnetic resonance and Formation MicroImager (FMI) run on a brackish-water test well in Daytona Beach, Florida. The logs provided fine-scale data on porosity (total and size distribution) and hydraulic conductivity.

in essence, serve as a risk reduction function. Collection of more and higher quality hydrogeological data can result in more accurate groundwater models, which in turn, can provide more accurate predictions of future water quality. However, there will still always be an element of unpredictability in long-term water quality projections because natural systems are inherently not fully predictable. A cost-benefit evaluation needs to be made considering the costs of hydrogeological investigation, their benefits in terms of improving water quality predictions, and the consequence of unexpected increases in salinity (or other water quality parameters) beyond the plant's design parameters.

Engineers are under pressure (and by training are inclined) to not over-design RO plants such, as designing them to treat waters more saline than expected. Outside engineers are often retained by project owners to perform a value engineering review to identify measures that can reduce project costs. However, the inherent uncertainty in predicting water quality 10 or 20 years in advance needs to be considered in project planning and design.

The costs to use higher pressure pumps and membranes rated to higher pressures to accommodate greater increases in raw water salinity may be modest relative to the overall plant costs. The additional costs to provide the RO plant with greater flexibility to handle unexpected large increases in salinity may be money well spent if it will provide for greater plant reliability. For a small plant, it may be more cost-effective to over-design the treatment system so as to be able to handle higher salinities than invest in more extensive hydrogeological investigations to reduce the uncertainty in future water quality. The question arises as to how much flexibility is prudent? A key element of brackish groundwater RO projects is to obtain a realistic estimate of the worst conditions that need to be accommodated in the treatment system design.

6. Conclusions

Desalination of brackish groundwater may be the most effective alternative source of potable-quality freshwater in areas where substantial brackish groundwater resources are present. Brackish-water aquifers very often experience significant changes in water quality as the result of long-term, continuous pumping. A critical design issue of brackish RO desalination facilities is the prediction of water quality over the planned operational life of the treatment system. Such prediction of groundwater quality is performed by groundwater modeling. The hydrogeological investigation for brackish-water desalination facilities represents a small fraction of the total project design and constructions costs, but can be the "weak link" in the entire project if not thoroughly performed. Improved aquifer characterization, which may include advanced borehole geophysical logging, can provide needed data to develop more refined and accurate models and assist in the design of the production wellfield.

Acknowledgments

CMR, FMI, and ECS are the marks of Schlumberger Limited, Inc.

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