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## VILLAGE-SCALE ELECTRODIALYSIS DESALINATION: FIELD TRIAL VALIDATION

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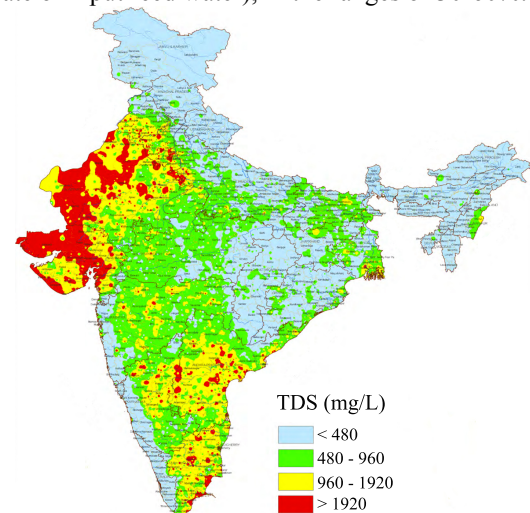
### ABSTRACT

This paper presents the design and initial testing of a village-scale photovoltaic (PV) powered electrodialysis reversal (EDR) desalination system for rural India. The system was built by the authors and tested at the Brackish Groundwater National Desalination Research Facility in New Mexico. EDR has the potential to be more cost effective than currently installed village-scale reverse osmosis (RO) systems in off-grid locations due to the lower specific energy consumption of EDR versus RO at high recovery ratios. Lower energetic demand leads to lower solar power system costs for off-grid areas. The system tested in this study is designed to validate that energetic, product water quality, and water recovery requirements can be met. An analytical model of the system that accounts for the composition of natural groundwater is presented and compared to initial experimental results. Additionally, results from the USAID Desal Prize are presented showing the system's performance in regards to recovery ratio and product water quality. This paper presents the design methodology, resulting system parameters, and experimental results for an initial village-scale PV-EDR field trial.

### INTRODUCTION

Small-scale desalination systems that produce water at a rate of approximately 10 m<sup>3</sup>/day, cost-effectively and with little water waste, are of growing interest in India due to the high prevalence of brackish groundwater (Figure 1) and the increasing demand on groundwater for both potable and agricultural water supply. At present, most village scale desalination systems use reverse osmosis (RO), a process in which a pressure that is greater than the osmotic pressure of the feed water is applied, forcing water through a

semipermeable membrane. Tata Projects, a company that has installed over 2000 plants in rural India using RO, has found the systems to be cost prohibitive in off-grid locations, however, primarily due to the high pumping power requirement of RO and resulting size of the solar power system [5]. Additionally, the existing small-scale rural RO plants currently installed have low water recovery (defined as the volume flow rate of product water divided by the volume flow rate of input feed water), in the ranges of 30-60%.



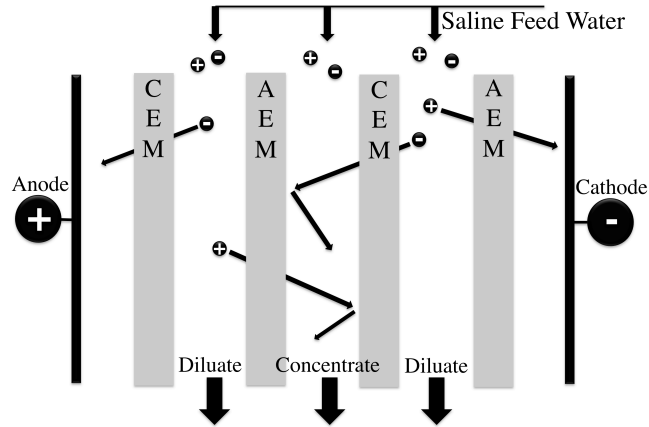
**Figure 1:** Map of groundwater salt concentration across India [2]. Groundwater with a salinity level greater than 480 mg/L underlies 60% of the land area in India. The WHO recommends a dissolved salt concentration of less than 500 mg/L [13] to avoid poor aesthetic quality and potential health problems related to long-term high salt intake, such as kidney stones.

Our previous work defined a series of critical design requirements for village-scale water desalination systems for

potable water production in rural India through a combination of literature review and engagement with end users, manufacturers, NGOs, government officials, and industry leaders in India [4]. The work concluded that several benefits of electro dialysis reversal (EDR) over RO make it a strong candidate for rural water desalination. These benefits include: lower specific energy consumption at the salinity levels present leading to lower capital cost for the photovoltaic (PV) power system, greater recovery ratio (up to 95%), and lower sensitivity to chlorine and feed water changes.

In the electro dialysis (ED) process, saline water is pumped between a series of alternating anion and cation ion exchange membranes (AEM, CEM). A voltage potential is applied at an anode and cathode located at either end of the membrane stack (Figure 2). Anions move toward the anode and cations move toward the cathode due to the potential difference at the electrodes. However, anions are blocked when they reach the first CEM and thus remain in the concentrate compartment. Similarly, cations moving towards the cathode are blocked when they reach the first AEM. In a commercial ED stack, there are many alternating CEM and AEM membranes (each set is called a “cell pair”), resulting in alternating streams of diluted and concentrated saline flow.

EDR uses the same stack arrangement as ED but reverses the polarity of the stack at certain time intervals. Polarity reversal increases membrane life by reducing fouling and allows for higher water recoveries to be achieved.



**Figure 2:** Electro dialysis (ED) process. A voltage potential applied across a series of alternating anion and cation exchange membranes (AEM, CEM) separates ions into dilute and concentrate streams.

This article describes a prototype PV-EDR system, designed, built and tested as part of the USAID Desal Prize. The goal of the prize aligned well with our research objectives: to design and characterize cost-effective, energy efficient, environmentally sustainable desalination technologies. Our system was designed to enable testing of a variety of groundwater compositions, with a production rate of 1.6 m<sup>3</sup>/hour. The goal of building and testing the prototype was: 1) to validate the technology’s ability to achieve the

desired water recovery and product water quality, 2) to validate the theoretical performance model, and 3) to identify potential challenges in making a commercially feasible solution for villages.

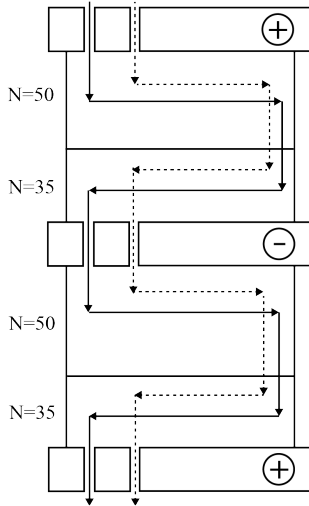
To our knowledge, no published literature exists on the field-testing of village-scale PV-EDR systems. While work has been completed on the use of ED in remote areas [6, 7] and on pairing ED with PV power [8], the work has thus far remained at the laboratory scale only. Adiga et. al. completed a pilot PV-ED project with a production rate of 0.12m<sup>3</sup>/hr in the Thar Desert (1987) [9]. With improvements in solar panel performance and cost as well as the introduction of EDR (the reversal operation) since that study, however, investigation into the use of PV-EDR systems at the village-scale is warranted. This work additionally aims to compare theory to field-testing results for real groundwater (multi-ion feed water).

## PROTOTYPE STACK REQUIREMENTS AND SELECTION

The system was designed for testing at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, NM as part of the USAID Desal Prize. Benefits of testing at BGNDRF include solar insolation levels similar to those found in India (~5.5 kWh/m<sup>2</sup>/day) and same-site access to wells with different salinity levels and ion compositions. The Prize required production of 8 m<sup>3</sup>/day of agricultural water and 0.25 m<sup>3</sup>/day of potable (drinking) water. This total production rate falls within the range that we have previously reported as ideal (6-15 m<sup>3</sup>/day) for a village-scale potable water plant in a community of 2000-5000 people. Our partner, Jain Irrigation Systems Ltd., designed the solar power system for the competition, and recommended an operating time of seven hours to balance the cost of solar panels versus battery storage. This results in a target flow rate for a median village in India of 0.86 - 2.14 m<sup>3</sup>/hour, or at least 1.18 m<sup>3</sup>/hour to meet the prize competition requirements. The maximum expected feed water concentration at BGNDRF is 6000 mg/L [12]. A commercially available EDR stack was selected for the trial with these production rates and feed salinity limits in mind.

An individual EDR stack may contain multiple hydraulic and electrical stages. The number of hydraulic stages refers to the number of passes the water makes along the membranes within a single stack. A single hydraulic stage typically provides 50-67% salt removal [14]. Thus for a feed concentration of 6000 mg/L with a desired product water quality of less than 500 mg/L, a first order analysis would suggest that four hydraulic stages would be required (Stage 1: 6000 → 3000 mg/L, Stage 2: 3000 → 1500 mg/L, Stage 3: 1500 → 750 mg/L, Stage 4: 750 → 375 mg/L). The number of electrical stages refers to the number of electrode pairs in the stack. Including more than one electrical stage in a stack allows for independent control of the current at each stage, increasing the efficiency of salt removal.

Figure 3 shows the flow path for the smallest multiple stage industrial EDR stack available from GE Water (Model Number AQ3-1-2-50/35). The stack contains two electrical stages, each with two hydraulic stages, making four total hydraulic stages. The first and third hydraulic stages contain 50 cell pairs while the second and fourth hydraulic stages contain 35 cell pairs [15]. The reduction in cell pairs for the second hydraulic stage in each electric stage is used to increase the linear flow velocity and thus the limiting current density (LCD) of the already partially desalinated water (see description of LCD in the following section). This stack was selected for the design of our experimental system as it meets the desired production rate and allows us to quickly switch between testing lower and higher salinity feed waters by applying voltage to one or both electrical stages. Each membrane in the stack has an active area of  $0.36 \text{ m}^2$ , for a total effective membrane area of  $57.8 \text{ m}^2$ . A full flow diagram for the test system is shown in Figure 4.



**Figure 3:** Schematic of the EDR stack for field trial. The stack contains two electrical stages, each with two hydraulic stages.

### ANALYTICAL MODEL: INCORPORATING WATER COMPOSITION

At the BGDRF test facility the natural groundwater wells have different total salinity levels and ion compositions. Our previous analytical model assumes a NaCl feed water solution [22] and thus is expanded in this study to include the affect of multiple ions found in natural groundwater. Equations 1, 2, and 3 are the basis of the Matlab model developed to predict the desalination rate and energy consumption of standard EDR stacks. The model is an expansion upon that published in our previous work in that it allows for individual analysis of each ion present in the feed stream. The model also allows for performance prediction of a system in which one stream (the feed stream) operates in continuous mode while the second stream (the concentrate stream) operates in batch mode.

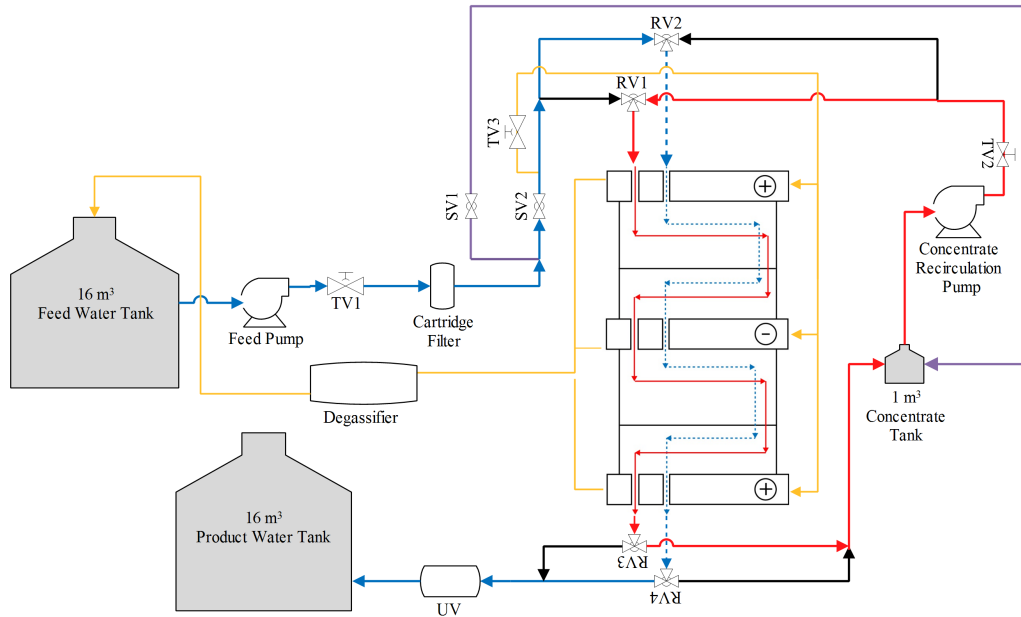
Equation 1 describes the time rate of change of the concentration of ion  $x$  as a function of hydraulic stage inlet

and outlet concentrations, the applied current density, the number of cell pairs in the hydraulic stage, and the active area of each membrane. It is derived from the fundamental continuity equation and the Nernst-Planck equation [16], which is used to describe the motion of ions under the influence of both an ionic concentration gradient (resulting in diffusion) and an electric field (resulting in migration). On the right hand side of Eq. 1, the first term represents the moles of ion  $x$  entering and exiting the compartments at the inlet and outlet of a given hydraulic stage, the second term represents the migration of ion  $x$  from diluate to concentrate compartment due to the electrical potential gradient, and the third and fourth terms represent the back-diffusion of ion  $x$  due to the concentration gradient across each membrane. A parallel equation can be derived for the concentrate stream.

$$\frac{dC_{x,dil,h}^{out}}{dt} = \left( Q_{dil}(C_{x,dil,(h-1)}^{out} - C_{x,dil,h}^{out}) - \frac{N\phi t_{m,x} i_e A}{z_x F} + \frac{NAD_{a,x}(C_{x,conc,h}^{AEM} - C_{x,dil,h}^{AEM})}{l_a} + \frac{NAD_{c,x}(C_{x,conc,h}^{CEM} - C_{x,dil,h}^{CEM})}{l_c} \right) \left( \frac{1}{N\nabla_{cell}} \right) \quad (\text{Eq. 1})$$

Here  $C_{x,dil,h}^{out}$  is the concentrations of ion  $x$  in the diluate stream at outlet of a given hydraulic stage ( $\text{mol/m}^3$ ),  $h$  is the hydraulic stage ( $h = 1 - 4$  for the stack tested in this study),  $N$  is the number of cell pairs,  $Q_{dil}$  is the flow rate of the diluate stream ( $\text{m}^3/\text{s}$ ),  $\phi$  is the current efficiency,  $i_e$  is the current density of a given electrical stage ( $\text{A/m}^2$ ),  $z$  is the ion charge,  $F$  is Faraday's constant ( $\text{C/mol}$ ),  $l_a$  and  $l_c$  are the thicknesses of the anion and cation exchange membranes ( $\text{m}$ ),  $D_{a,x}$  and  $D_{c,x}$  are the diffusion coefficients of the given ion in the anion and cation exchange membranes ( $\text{m}^2/\text{s}$ ), and  $C_{x,dil,h}^{AEM}$ ,  $C_{x,conc,h}^{AEM}$ ,  $C_{x,dil,h}^{CEM}$ ,  $C_{x,conc,h}^{CEM}$  are the concentrations of ion  $x$  in the diluate and concentrate streams at the interface with the anion or cation exchange membranes, in a given hydraulic stage (AEM, CEM)( $\text{mol/m}^3$ ). By evaluating Eq. 1 for each ion in the feed stream, and for each hydraulic stage, the total rate of desalination can be calculated in each hydraulic stage.

In this system design, high water recovery is achieved by first pumping a small percentage (for example 5% of the total feed water if 95% recovery is desired) into a concentrate recirculation tank via the purple flow line (Figure 4). Once complete, the concentrate recirculation pump and power to the stack are also turned on. The diluate stream (blue) passes through the stack only once, while the brine stream (red) recirculates through the stack and back into its tank throughout the day. This means that the concentration of the brine tank increases with time and that in the concentrate equation that parallels Eq. 1,  $dC_{x,conc,h}^{out}/dt > 0$  for every hydraulic stage. In this configuration, we say that the brine stream is operating in "batch" mode, while the diluate stream is operating in "continuous" mode. The concentration in the feed and brine tanks are given by Eqs. 2a and 2b, where  $C_{x,dil}^{tank} = C_{x,dil,(h-1)}^{out}$  and  $C_{x,conc}^{tank} = C_{x,conc,(h-1)}^{out}$  for the first hydraulic stage.



**Figure 4:** Flow diagram of the EDR system (TV=throttling valve, SV=one-way solenoid valve, RV=three-way valve used for hydraulic stream reversal, UV=ultraviolet disinfection).

$$\frac{dc_{x,conc}^{tank}}{dt} = \frac{q_{conc}(c_{x,conc}^{out}(t) - c_{x,conc}^{tank})}{V_{conc\ tank}} \quad (\text{Eq. 2a})$$

$$\frac{dc_{x,dil}^{tank}}{dt} = 0 \quad (\text{Eq. 2b})$$

Equations 1 and 2 define the concentration at each location in the system over time. In order to calculate the power required to desalinate a given quantity of water using ED, the system is analyzed as an electrical circuit, where power is equal to the product of the current through the stack and the voltage applied at the electrodes.

The maximum applied voltage is dictated by the limiting current density (LCD), the current density at which dissociation of water molecules would begin to occur in the boundary layer at the membrane surface. The LCD decreases with decreasing concentration and decreasing flow rate. Because the outlet concentration of the diluate stream is lowest for the final hydraulic stage in any given electrical stage, it is the linear flow velocity and outlet concentration in the 35-cell pair hydraulic stages that govern the limiting current for each of the two electrical stages. The decrease from 50 to 35 cell pairs in the 2<sup>nd</sup> and 4<sup>th</sup> hydraulic stages forces the linear velocity of the water to increase and allows a higher current density to be applied. Discussion on the calculation of the LCD is given in our previous work [22].

The relationship between the current and the applied voltage is given in simplified form in Eq. 3, where  $R_{dil}$ ,  $R_{conc}$ ,  $R_{AEM}$ , and  $R_{CEM}$  are the area resistances of the diluate stream, concentrate stream, AEM and CEM, respectively ( $\Omega\text{m}^2$ ).  $V_{elec}$  and  $V_{potential}$  are the electrode potential and

concentration potential, respectively.  $V_{total}$  is the total applied voltage (V).

$$V_{total} = V_{elec} + NV_{potential} + Ni(R_{dil} + R_{conc} + R_{AEM} + R_{CEM}) \quad (\text{Eq. 3})$$

Thus the instantaneous power consumption of an ED stack can be calculated if the applied voltage, number of cell pairs, and resistances are known. Membrane resistances and number of cell pairs are found in the electro dialysis stack manufacturer data. The resistance of the diluate and concentrate streams can be calculated by using empirical equations for the specific electrolyte aqueous solutions. In the present model, the Falkenhagen equation is used to predict the conductivity of each ion in solution at each time step. The total conductivity is given by the sum of the conductivities for each ion. We are able to achieve calculated conductivities within 10% of the measured values values by adapting the Falkenhagen equation (which is typically used for single monovalent electrolyte solutions) for use on this multi-ion sample. The constants required for the multi-ion model are shown in Table 1.

The conductivity is solved for simultaneously with the concentrations at each location: conductivity defines resistance, resistance defines current density (Eq. 3), and current density defines rate of ion removal (Eq. 1). The MATLAB *ode45* function is used to solve for the concentration of each ion over time. In this example where six ions are analyzed, there are sixty differential equations, ten for each ion. These ten include the tank concentration and the four hydraulic stage outlet concentrations, for both the diluate and concentrate streams.

**Table 1:** Values of limiting molar conductivity (Falkenhagen equation) and diffusion coefficient (Eq. 1) used for each ion.

Ion	z	limiting molar conductivity [Scm <sup>2</sup> /mol]	diffusion coefficient D <sub>a,c</sub> [m <sup>2</sup> /s]
Ca <sup>2+</sup>	2	59.47	1.18×10 <sup>-12</sup>
Mg <sup>2+</sup>	2	53.00	1.05×10 <sup>-12</sup>
Na <sup>+</sup>	1	50.08	1.64×10 <sup>-11</sup>
Cl <sup>-</sup>	1	76.31	1.27×10 <sup>-10</sup>
SO <sub>4</sub> <sup>2-</sup>	2	80.00	2.75×10 <sup>-11</sup>
HCO <sub>3</sub> <sup>-</sup>	1	44.50	1.03×10 <sup>-10</sup>

The equations in this section have a number of assumptions including that the concentrate and diluate compartments have the same flow conditions and are both considered well-mixed. Water transport through the membranes due to electro-osmosis and osmosis is ignored. Full derivations of these equations and sample calculations describing their use for continuous versus batch process operation are found in the references [18,19].

## DESAL PRIZE RESULTS

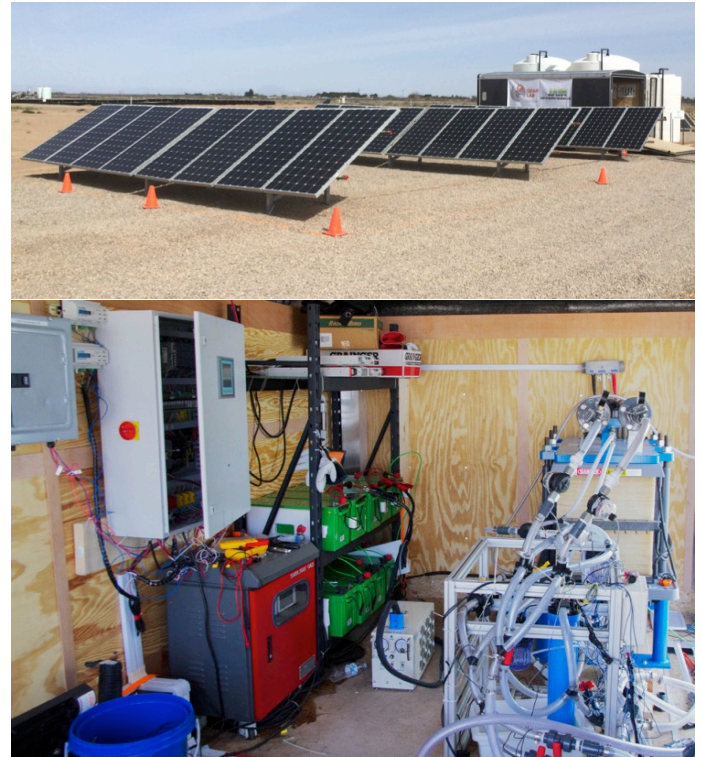
The USAID Desal Prize competition (Figure 5) consisted of two 24-hour test periods in which teams were judged on their ability to meet the following criteria:

- 8 m<sup>3</sup> product water of agricultural quality
- 0.25 m<sup>3</sup> product water of potable quality
- High recovery
- Use of chemical additions
- Maintenance and service schemes in developing world context
- Lifecycle cost

The system described in this study was able to meet the necessary quantity requirements on both competition days, with a recovery of 84%. The quality of the feed, agricultural and potable water is shown in Table 2. As can be seen by the Desal Prize requirements in the rightmost column, the specific composition of agricultural water is more stringent than that for potable water. Looking first at the recorded TDS values, the system was able to produce agricultural quality water that falls into the desired range of 450-500 mg/L as well as potable water with a much lower TDS of 172 mg/L by changing the voltage applied to the stack. For this feed water, pre-filtration was able to remove present coliform (bacteria) from the system without the assistance of the UV disinfection unit. This is clear since coliform was absent in both the agricultural and potable water samples, while UV disinfection was only applied to the potable water.

All requirements were met except for the Sodium Absorption Ratio (SAR) which was too high. SAR is a measure of the suitability of water for use in agriculture and is a function of concentration of sodium, calcium, and magnesium. The desire to better understand and control the removal of specific ions is one reason that we expanded our

analytical model to account for groundwater composition (as given in the previous section.)



**Figure 5:** The prototype system at BGNDRF showing full system with panels, trailer, and water tanks (top). All electronic control, battery storage, and hydraulic subsystems were installed inside the trailer (bottom).

**Table 2:** Final water quality testing shows composition of the feed water, agricultural product water, and potable water on the 2<sup>nd</sup> day of competition testing. (TDS=total dissolved salts, SAR=sodium absorption ratio, TC=total coliform)

Parameter	Feed Water	Ag. Water	Potable Water	Desal Prize Requirement
Ca <sup>2+</sup> [mg/L]	430	36	5	Ca/Mg > 1 [meq/L] (ag)
Mg <sup>2+</sup> [mg/L]	200	13	2.8	
Na <sup>+</sup> [mg/L]	360	99	48	
Cl <sup>-</sup> [mg/L]	660	110	44	
SO <sub>4</sub> <sup>2-</sup> [mg/L]	1600	120	15	
TDS [mg/L]	3470	462	172	450-500 (ag) <600 (potable)
SAR	3.6	3.6	4.3	< 3 (ag)
TC	Present	Absent	Absent	Absent (potable)

## MULTI-ION MODEL VALIDATION

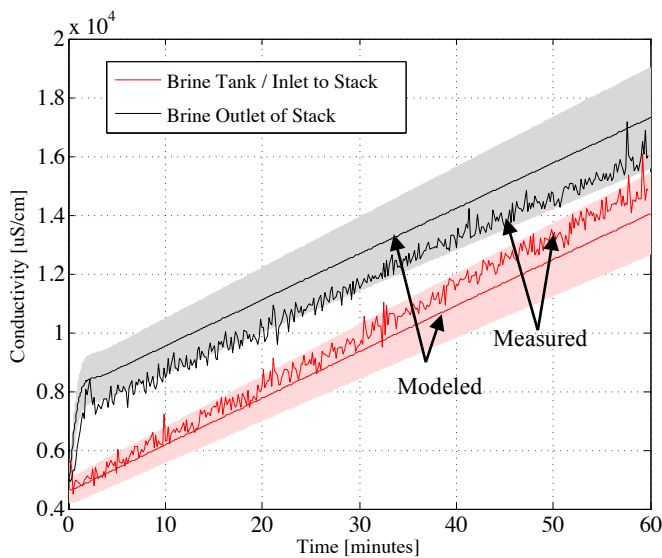
The concentrations of the major ion constituents in the feed water of one trial are shown in Table 3. Sodium chloride makes up less than 25% of the total TDS, confirming the need for a model that accounts for the specific groundwater

composition. This feed water was run through the experimental setup with applied voltages of 45V and 35V on the first and second electrical stages, respectively and a volumetric flow rate of 1.3 m<sup>3</sup>/hr in both the diluate and concentrate lines.

**Table 3:** Concentration of major constituents of feed water used in follow-up testing at BGNDRF and as inputs to the analytical model.

Parameter	Concentration [mg/L]
Ca <sup>2+</sup>	300
Mg <sup>2+</sup>	176
Na <sup>+</sup>	464
Cl <sup>-</sup>	411
SO <sub>4</sub> <sup>2-</sup>	2193
HCO <sub>3</sub> <sup>-</sup>	132

The red and black lines in Figure 5 show the conductivities in the brine tank and in the brine stream at the outlet of the stack, respectively. The solid red and black lines are the prediction from the analytical model; the lines with noise are the sensor-recorded values. The gray and light red bands are drawn around the former to show the 10% error we estimate to exist in using the Falkenhagen equation to calculate the conductivity of this multi-ion stream. Similarly, the recorded value, modeled value, and estimated error for the product water stream are shown in Figure 6.



**Figure 5:** Measured versus predicted conductivity for water exiting the brine tank (red) and the stack (black). Shaded area represents 10% error bounds on the predicted values.

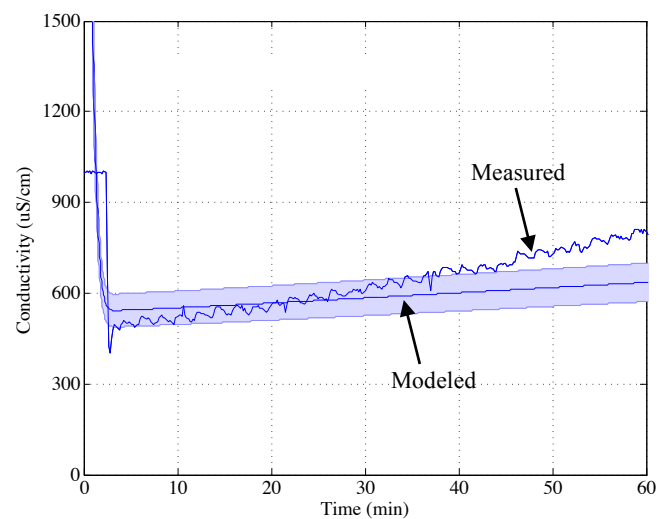
## DISCUSSION

Figure 5 shows that both the conductivity in the brine tank and the conductivity of the brine stream as it leaves the final hydraulic stage increase with time (as predicted) due to the fact that the brine is operating in a batch mode. Experimental

results also fall within the 10% error band at both locations, showing generally good alignment with the new analytical model incorporating feed water composition. Experimental results also show, however, that the rate of desalination decreases in time. This can be seen both by the narrowing gap between the red and black lines in the model and the experiment, as well as in the increasing conductivity of the product water stream in Figure 6. We expect the final product water concentration to change over time for two primary reasons:

- 1) as the brine tank increases in concentration and conductivity, the resistance of that stream decreases, resulting in a higher current being allowed to pass through the stack at a constant applied voltage and more salt being removed from the feed water/diluate stream, and
- 2) as the brine tank increases in concentration, the difference in concentration between the concentrate and diluate streams within the stack increases, resulting in higher rates of ionic back diffusion, and thus less salt being removed from the feed water/diluate stream.

Since the model predicts an increase in diluate concentration with time (Figure 6), we predict that factor (2) outweighs factor (1). However, the amount by which the diluate concentration increases is higher than the model predicts which tells us that we are either over predicting the effect of factor (1) or under predicting the effect of factor (2) in the analytical model. It is also important to remember the interdependency of Eqs. 1 and 3; if the model predicts a higher diluate conductivity (lower diluate resistance), then it will also predict a higher applied current, which will in turn allow more salt to be removed. This means that once error in the model is introduced it will grow over time, as can be seen in both Figure 5 and 6.



**Figure 6:** Measured versus predicted conductivity for diluate exiting the fourth hydraulic stage. Shaded area represents 10% error bound on the predicted values.

## FUTURE WORK

The prototype system presented here will continue to be tested at BGNDRF over the coming year, using the variety of feed water sources available to continue validation of the multi-ion model for both total conductivity trends as well as the removal rate of specific ions. Meanwhile, a prototype plant has been installed in India that will allow us to test in context and receive operator feedback on key concerns surrounding maintenance and service. Lastly, we continue to push for capital cost reduction. To address this issue, further research includes optimization of a stack design specific to the requirements of an Indian village (number of electric and hydraulic stages, membrane area, and potential manufacturers). Additionally a feasibility study will be conducted on the design and optimization of a system in which both the pumps and the stack are driven directly from the PV-power system. If feasible, this direct drive system would have the potential to decrease the capital cost of the power system by removing components (inverters and batteries) as well as minimizing energy conversion losses.

## CONCLUSIONS

This paper presents the design and initial test results of a PV-EDR system for village-scale brackish water desalination for potable water production in India. The system won first place at the USAID Desal Prize for its ability to reach high recoveries, meet quantity and quality requirements without the use of chemicals, and our partnership with Indian organizations in the development process. Since then, the pilot plant has been used to begin validating an analytical model that incorporates groundwater composition which will allow us to not only predict total TDS and conductivity of the product and brine water but also the major ion composition. The analysis and design presented in this work enables a system to be created that meets the potable water requirements for a typical Indian village, or the agricultural requirements for a small-holder farmer.

## ACKNOWLEDGMENTS

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