Prevention of Saltwater Intrusion: A Laboratory-Scale Study on Electrokinetic Remediation

Abhishek A. Sutar and Veerabhadra M. Rotte

1 Introduction

1.1 Saltwater Intrusion and Conventional Ways of Its Prevention

Increased population along with improvement of living standard is forcing water demand to rise sharply in past few decades [1]. In coastal areas, for fulfilling the domestic, agricultural, industrial, and tourist water needs, groundwater is mostly overexploited [2]. Naturally fresh water flows from aquifers toward the sea and ground water flows from high level to low level, and this naturally occurring process prevents saltwater intrusion into fresh groundwater aquifers [3]. This phenomenon may get reversed due to long term climate change, sea level change, and tidal intensity fluctuations. Manmade activity like excessive pumping of fresh groundwater in coastal areas causes up-coning of transition zone as shown in Fig. 1, which has high impact on sea water intrusion. Saltwater intrusion can lower the potability of water and makes it difficult to use for other purposes like agricultural or industrial use [4]. Research has been going on to find out measures of controlling saltwater intrusion for protection of freshwater sources. The primary aim of these methods is to increase freshwater flow and reduce saltwater flow [5].

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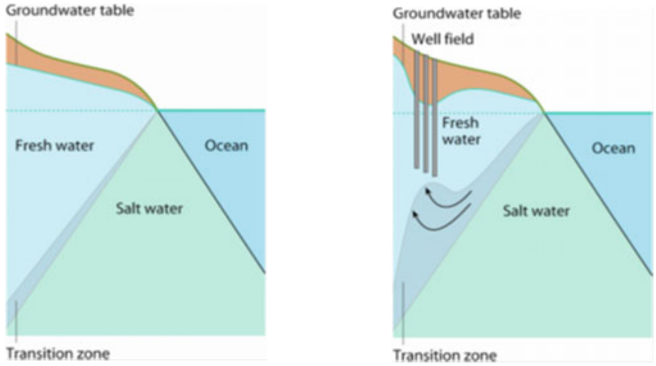


a. Natural situation without pumping wells

b. Upconing of the transition zone due to pumping wells

Fig. 1 Effect of excessive pumping in coastal areas (After Bereyso [18])

Hussain et al. [6] reviewed techniques for controlling saltwater intrusion and reported methods like reduction of pumping rate, relocation of pumping wells, permeable subsurface/surface barrier, hydraulic barrier, artificial recharge wells, abstraction barrier, and combination of any of these methods. It is very difficult to select the optimum control method due to limitations like performance efficiency, cost, etc. Due to high cost of installation, it is profitable to combine two or more methods to introduce efficient control technique [7].

1.2 Electrokinetic Remediation for Saltwater Intrusion

When direct current is applied to soil through electrodes, then pore water flows from positive to negative electrode. Electrokinetic treatment includes electro-osmosis, electrophoresis, electrolysis, and electro-migration, combining effect of all this phenomena causes movement of water. Malekzadeh et al. [8] reviewed electrokinetic dewatering of soil and reported that it is affected by soil type, zeta potential, pH, temperature, water content, soil salinity, electrical resistivity and conductivity, type of electrodes, etc. Electrokinetics plays an important role in different remediation applications. It has been used as an in-situ technique for contaminant mobilization and recovery. It is done by applying a low electrical potential between anode and cathode electrode array inserted in the soil [9]. This technology is applicable for containment of soils where conventional techniques are not applicable, and soils have very low permeability. Electrokinetic barrier or fencing is same type of application in which electrokinetics shuts the pollutants from moving into neighboring un-polluted ground. The hydraulically generated movement of ions is opposed by combined effect of electro-osmotic flow and electro-migration [10]. Electrokinetic barrier is an application of electrokinetic remediation technology. This technology has been developed for its practical use by Lageman and Pool [11] since 1980s. The main focus is given on electro-migration in case of remediation studies which includes movement of ions causing desalination of soils during the process [12]. In case of saltwater intrusion seawater flows in freshwater aquifers and contaminate the fresh groundwater source. Under the effect of DC field sodium and chloride ions which are major components of seawater are transported toward barrier and get trapped and deposited near to opposite electrode while fresh water passes toward other side of barrier. The deposited ions can be removed from ground periodically [13]. Electrokinetic remediation method is cost effective, easy to install, and operate [14, 15]. This method does not disturb the original nature of soil [16]. Electrokinetic remediation can be considered as eco-friendly and sustainable technique due to very less use of chemicals, and it can be given power by renewable energy sources like solar energy or wind energy [17]. Bereyso et al. [18] applied electrokinetic barrier in a lab scale setup for prevention of salt migration and allowed transfer of desalinated water through the barrier. The decreased conductivity on downstream side of barrier as compared to upstream side is the principal finding, but the scope was limited to a constant 12 V potential difference. The viability of this technology in practical use on field needs to obtain more insights into electrokinetic applications in the remediation area [19]. The main aim of the present study is to evaluate optimum efficiency of experimental parameters like spacing of electrodes and electrode materials for prevention of saltwater intrusion and integrating feasibility of the technique for its practical use. Further, it can be elaborated that the study aims to capture chloride and sodium ions present in salt water near the electrodes to some extent that the treated water on downstream side of the electrokinetic barrier can be used for drinking or agricultural use as per standards.

2 Materials

2.1 Soil

The experiments were carried out on river sand having specific gravity of 2.6 and passing through 600 micron sieve. Grain size distribution of the sand shows that the sand is poorly graded. The initial electrical conductivity of the sand was measured as 220 μS/cm. It was found to be same for all samples and need not be required to wash sand by deionized water before each test.

2.2 Water

Experiments were conducted by 75% saturation of the sand with potable water having conductivity 210 μS/cm. T.D.S. of the water was noted to be 110–115 with 8.7–9.2

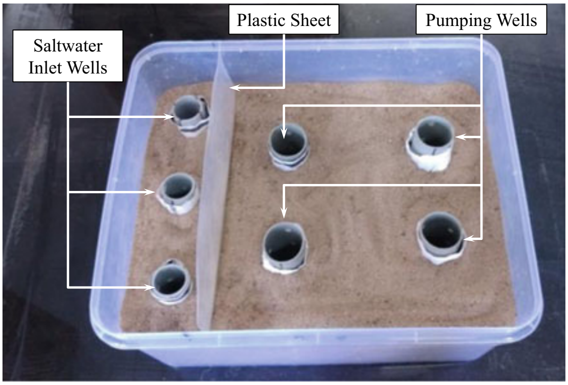


Fig. 2 Saltwater wells and freshwater pumping wells

pH. Seawater contains 75% of sodium chloride as major salt thus AR grade sodium chloride meeting ACS standards was used having 99% purity. 70 mg of NaCl was weighed and mixed thoroughly into 1 L water by using stirrer, and it was added on saltwater side of the setup. The electrical conductivity of the saltwater was found to be 1.625 mS/cm with T.D.S. of 747 and 9.2 pH. Sand on the right side of the vertical plastic sheet has been saturated by normal potable water through four perforated pumping wells (Fig. 2). Simultaneously, on left side of the sheet, saltwater was added into the perforated saltwater inlet wells to create actual seaside condition.

2.3 Electrodes

Based on the study by Malekzadeh et al. [20] stainless steel and graphite solid rods with 11 mm diameter and 105 mm length were used for supplying direct current to the sand.

3 Experimental Test Setup, Procedure, and Program

Experiments were carried out in a transparent plastic container box with dimensions 360 mm × 290 mm × 180 mm with reference of Tumalla et al. [21]. To prevent surface water losses, it was covered with lid from top. Two holes of 6 mm diameter were drilled on side edge to house electrical supply wires. The box was divided into two parts by a temporary plastic sheet having very less thickness making the saltwater side of area 70 mm × 295 mm and fresh water side of area 290 mm × 295 mm as shown in Fig. 2. The sheet was held vertically in between saltwater side and freshwater side of the box while filling the sand into box.

The sand was poured simultaneously on both sides and tamping was done to achieve uniform density of 1.365 gm/cm^3 having relative density of 80%. Flow characteristics of water depend upon the density of sand significantly. If the density of sand in the setup is different for each test then the flow characteristics of water will varie and affect the results of the experiments. In view of this, uniform density has been attained in all the tests. Total 16 kg of sand was filled in the box up-to 100 mm height. For measuring electrical conductivity and pH of water, two pumping wells were installed on the either side of electrokinetic barrier by using PVC hollow pipes with 37 mm internal diameter, 120 mm height, and 12 mm thickness. For allowing water inflow into these pipes 5 mm diameter holes with 30 mm center to center spacing were drilled on periphery of the pipes in staggered pattern. Similarly, for pouring salt water along the salt side of the setup three PVC pipes of internal diameter 30 mm and 120 mm height with 12 mm thickness were used. For prevention of soil particles into these perforated hollow pipes, cotton cloth around and from bottom side of these pipes was wrapped as shown in Fig. 3. The PVC pipes for pumping wells and salt wells were inserted by simply pushing without much disturbing the density of sand. Electrodes were installed in series with 40 mm center to center spacing between same polarity electrodes and required center to center spacing between opposite polarity electrodes as shown in Fig. 4. Potable water was poured in freshwater side through

Fig. 3 Details of perforated pipe and cotton cover

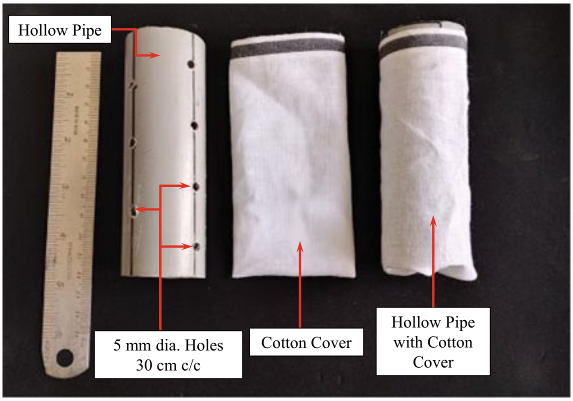
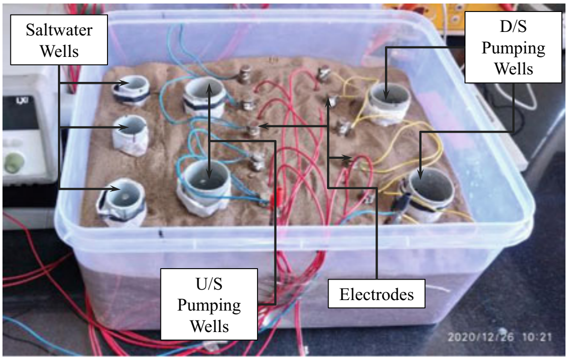


Fig. 4 Details of electrodes, U/S wells, and D/S wells



pumping wells and simultaneously salt water was poured in saltwater side of the box through saltwater wells. The sand in whole setup was saturated for 75% such that there should not be any freely flowing surface water to cause ill results by mixing of saltwater and freshwater. The vertical plastic sheet was removed slowly, and DC supply was started.

pH of water from wells was monitored manually by measuring it with WELL-TRONIX's AUTO pH System PM300 (Fig. 5). pH electrode was inserted in each well every hour and reading was noted to the accuracy up to 0.01 pH. Similarly, conductivity of the water was measured by using EQUIPTRONICS' Conductivity meter EQ667 (Fig. 6). For measuring T.D.S., handy T.D.S. meter was used. The details of complete setup are shown in Fig. 7. With these arrangements of electrodes, water was observed to flow from anode to cathode. Due to electrokinetic barrier only water and not the salts will flow from anode to cathode. Electrical conductivity, T.D.S., pH were measured manually at every hour for 24 h.

The experiments were performed to study the effect of Electrode Spacing and Electrode material on the electrical conductivity, total dissolved solids, and pH. All

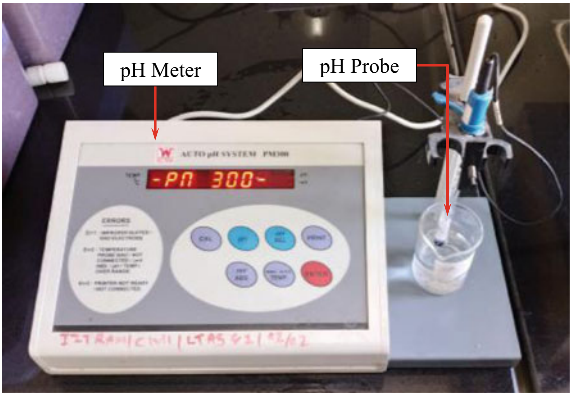


Fig. 5 pH meter

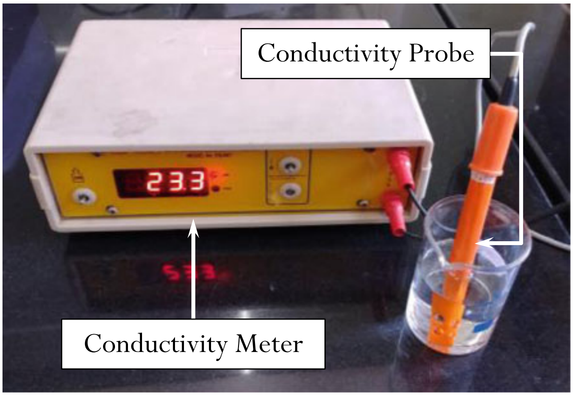


Fig. 6 Conductivity meter

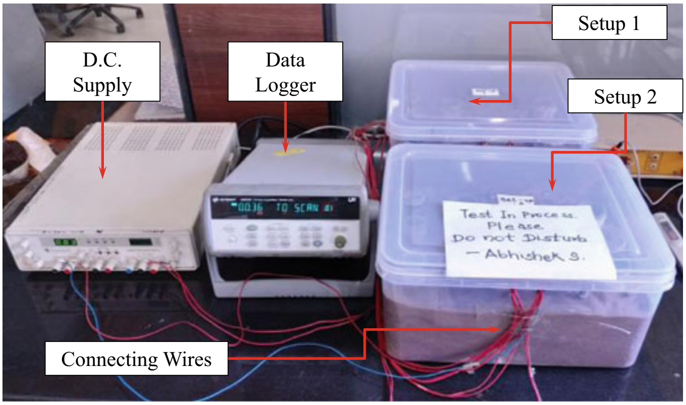


Fig. 7 Details of complete setup with D.C. supply and data logger

Table 1 Test program of the present study

Test name	Electrode spacing	Electrode material	Voltage
Control test	NA (cm)	NA	NA (V)
EKR-1	5	Graphite	10
EKR-2	10	Stainless steel	10
EKR-3	10	Graphite	10

the tests were continued up to 24 h. The test program with all details is shown in Table 1. Control test was also carried out in which no electrode was used and no potential difference has applied. The main purpose of control test is to compare the effect due to electrokinetic with control test and to find out efficiency of the electrokinetic barrier under different working conditions.

4 Results and Discussions

4.1 *Influence of Spacing on Electrical Conductivity and Total Dissolved Solids*

The electrical conductivity of soil water is measured to derive soil salinity. Electrokinetic remediation experiments were carried out by varying the center to center spacing between cathodes and anodes as 5 cm (EKR-1) and 10 cm (EKR-3). All cathodes were placed in a single row, and all anodes were placed in single row to form electrode array having c/c spacing as required. A potential difference of 10 V was maintained for all the experiments except control test in this series. Figure 8 shows

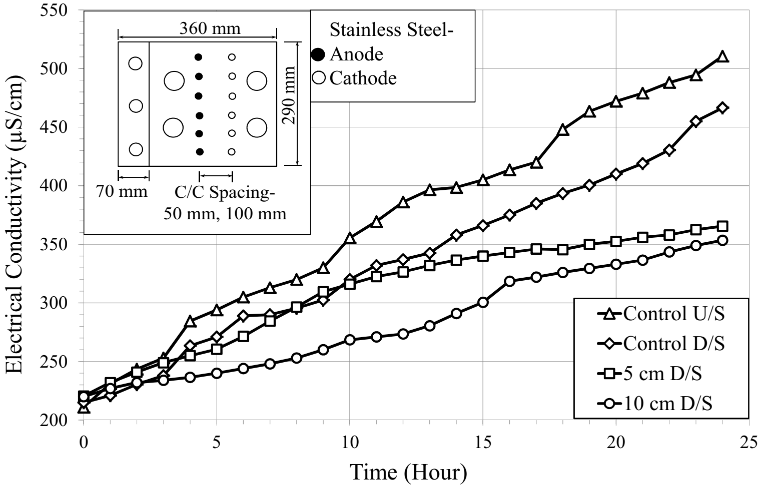


Fig. 8 Effect of spacing on electrical conductivity

variation of electrical conductivity of water with time for upstream and downstream wells of control test and only downstream wells of electrokinetic tests.

The rate of increase in electrical conductivity was observed to be more for control test as compared to electrokinetic tests. It was noticed for EKR tests, with an increase in center to center spacing between cathodes and anodes, rate of increase in electrical conductivity decreases with time. This is because of increase in spacing, an area under the influence of electric field increases causing efficient ions exchange with more absorbed ions on the large area of soil surface producing low electrical conductivity. Figure 9 shows variation of total dissolved solids with time for control test and electrokinetic tests. As time passes T.D.S. values were observed to increase. The T.D.S. values of upstream wells were noticed on the higher side as compared to downstream wells for control test. The figure indicates that with increase in spacing of electrodes, T.D.S. values decreases significantly. Chloride and sodium ions get prevented from flow at larger area under influence of applied potential for large spacing between the anodes and cathodes. Thus, only water is allowed to flow indicating less dissolved solids in downstream wells for more spacing in EKR tests.

4.2 *Influence of Electrode Material on Electrical Conductivity and Total Dissolved Solids*

Experiments were carried out to find out effect of electrode material on different parameters. Stainless steel (EKR-2) and graphite (EKR-3) electrodes have been used in current experiments. Electrode configuration was kept unchanged with 10 cm center to center spacing. A potential difference of 10 V was maintained for all

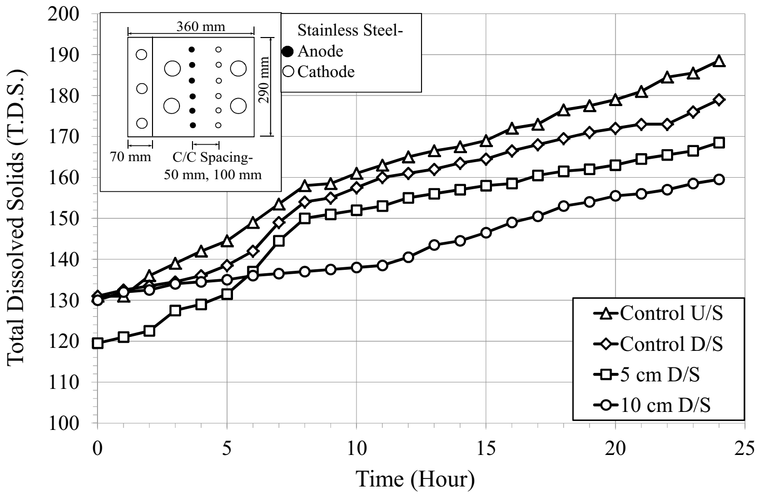


Fig. 9 Effect of spacing on total dissolved solids

experiments except control test in this series. Figure 10 shows variation of electrical conductivity of water with time. It is clear from figure that electrical conductivity for all tests increases with time. It was also noticed that stainless steel electrodes show lower values of electrical conductivity as compared to graphite electrodes. Variation of total dissolved solids with time has shown in Fig. 11. The graph for T.D.S. values for control test is much similar to electrical conductivity graph. The T.D.S. values are lower for stainless steel electrodes as compared to graphite electrodes. The stainless

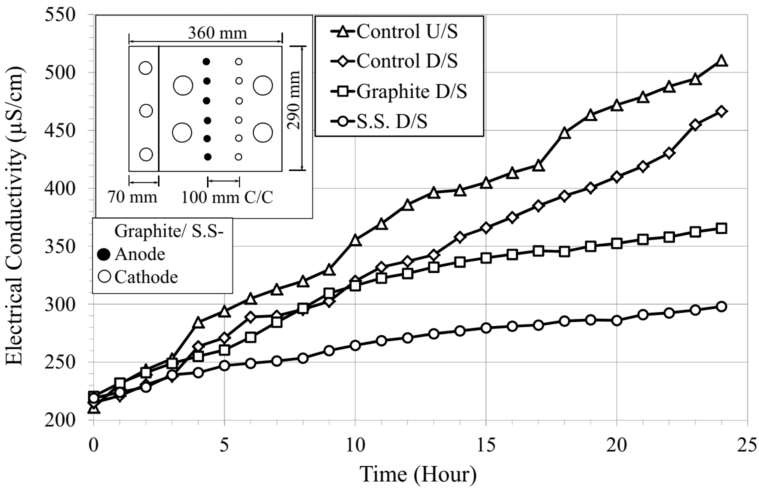


Fig. 10 Effect of electrode material on electrical conductivity

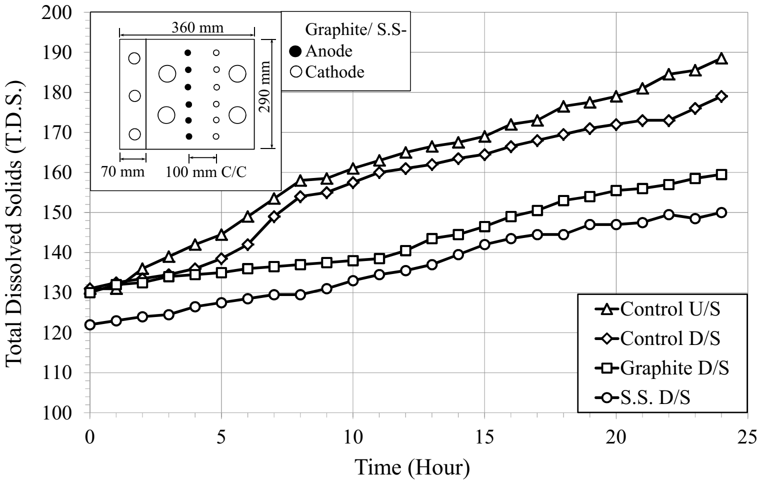


Fig. 11 Effect of electrode material on total dissolved solids

steel gives much better electro-osmotic effect over graphite electrodes. Graphite is carbon electrode which results in large voltage drop in later stages of experiments causing inefficient results as compared to stainless steel electrodes.

4.3 Effect of Different Parameters on pH

The manual tracking of pH was also done to find out effect of spacing and electrode material on pH. The change in pH directly relates to electrolysis occurring in soil. In all experiments the initial pH values from downstream pumping wells are in range of 9.2–10.2 which was not observed to change in a particular manner. The final values were also in the same range and did not follow any relation with time giving random variation. Rather the experiment duration was just 24 h which may need to be increased up to 72 h in order to obtain acidic and basic fronts due to oxidation reduction reaction to find out the effect of different parameters on pH of water in upstream and downstream wells.

5 Conclusions

Total two set of experiments were carried out for analyzing effect of spacing and electrode material on different parameters of the tests. Based on the results obtained from experiments, the following conclusions can be obtained.

1. Control tests show higher values of electrical conductivity and T.D.S. of water in downstream pumping wells as compared to EKR tests with increase in time. In case of EKR tests due to applied voltage the chloride and sodium ions of saltwater from upstream side got prevented from flow near electrodes which was not observed in the case of control test thus the values of electrical conductivity and T.D.S. are high in control tests.
2. For constant applied potential and electrode material as spacing between electrodes increases the electrical conductivity and T.D.S. values of water in downstream pumping wells decreases. It occurs due to an increase in spacing of electrodes, area under influence of an electric field increases. This causes efficient ion exchange over large surface area of soil giving decreased electrical conductivity and T.D.S. values.
3. Stainless steel showed lower values of electrical conductivity and T.D.S. as compared to graphite electrodes in downstream pumping wells for constant voltage and spacing between electrodes. Graphite is a carbon electrode which gives large voltage drop in later stages of electrolysis. This large voltage drop in case of graphite causes inefficient electro-osmosis and less control on ion flow giving high values of electrical conductivity and T.D.S. as compared to stainless steel.
4. It is confirmed from the figures of electrical conductivity that EKR-2 gives 68.53% reduction in the values of electrical conductivity as compared to control test. Similarly, EKR-3 gives 47.02% reduction and EKR-1 gives 42.25% reduction in electrical conductivity values. This can be directly related to the salinity of water, and we can say that EKR-2 with 10 cm center to center spacing of stainless steel electrodes the saltwater intrusion can be minimized up to 68.53% as that of control test which is optimum finding of the experiment.

Further research needs to be focused in order to analyze effect of voltage, salt concentration of source saltwater wells, grain size of soil, and other material of electrodes like copper, aluminum, etc. Experiments may be planned to lasts for more than 24 h duration for obtaining better results of electrolysis reaction in order to find out effect of varying parameters on pH of water in downstream wells.

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