Electrokinetic Fences against Sea Water Intrusion

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ABSTRACT:

One of the major concerns today in fresh water supply along coastal areas is seawater intrusion into fresh water aquifers mainly as a result of over pumping or salt-water intrusion from the sea. There are several more or less effective methods to overcome this problem, such as groundwater ridges, recharge basins, or barrier wells to pump out salt water and recharge a fresh water gradient towards the sea. Rising cost of water and maintenance and uncertainty of long-term potable water availability force authorities to find other ways to deal with this problem. An innovative solution is the creation of electrokinetic fences or electrokinetic barriers along the coast. Computer simulations, assuming different boundary conditions, indicate that electrokinetic fencing can be a viable and interesting alternative, especially when the electricity to activate the fence comes from sustainable energy sources such as wind energy and solar power.

INTRODUCTION

In many areas of the world groundwater is still a major source of fresh water. However, it becomes more and more difficult to meet the ever increasing demands of fresh water, especially in densely populated coastal areas. Almost two thirds of the world's population lives within 400 km of the ocean shoreline; just over half live within 200 km, an area taking up only 10% of the earth's surface *[1].*

One of the major concerns in this respect is sea-water intrusion into fresh water aquifers. Under natural conditions fresh water flows from inland aquifers and recharge areas to discharge areas to the sea: groundwater flows from areas with higher groundwater levels to areas with lower groundwater levels *[2].* This natural movement of fresh water towards the sea prevents intrusion of seawater into the coastal freshwater aquifers. This process can be reversed, because of natural factors such as tidal fluctuations, long term climate and sea level changes, changes in evaporation and recharge rates. Human activities however, such as pumping of fresh groundwater in coastal areas, have the greatest impact on sea water intrusion.

The problem can in general be addressed by maintaining the proper balance between water being pumped from the aquifer and the amount of water recharging it. Constant monitoring of the fresh-saline-water interface is necessary in determining the proper management technique. There are several methods to keep seawater intrusion at bay, but aging infrastructure, rising cost of water and maintenance and uncertainty of long-term potable water availability force water authorities to look for alternatives that are cheaper, last longer and are preferably sustainable. One of these alternatives is deployment of electrochemical technology in the form of an electrokinetic fence.

PROBLEM DESCRIPTION

Under natural conditions virtually all coastal aquifers around the world experience seawater intrusion to some degree due to the density differences between salt water and fresh water, which is caused by the higher mineral content of the seawater. It results in pressure differences leading to a natural flow of seawater inland into the fresh groundwater, when the groundwater levels of the inland aquifer are not high enough. This can have a natural cause, but is in most cases the result of human activities, such as over pumping. Fresh water is less dense than salt water, therefore it floats on top. The relationship between the fresh water and seawater pressures is described by the Ghyben-Herzberg principle (Figure 1), which indicates that for every meter of groundwater above sea level there are forty meters of fresh water below sea level. In reality the situation is, as so often, somewhat different and relates to the fact that the fresh-salt interface is not always a sharp, distinct boundary, but a transition or diffusion zone where fresh and salt water are mixed *[3].*

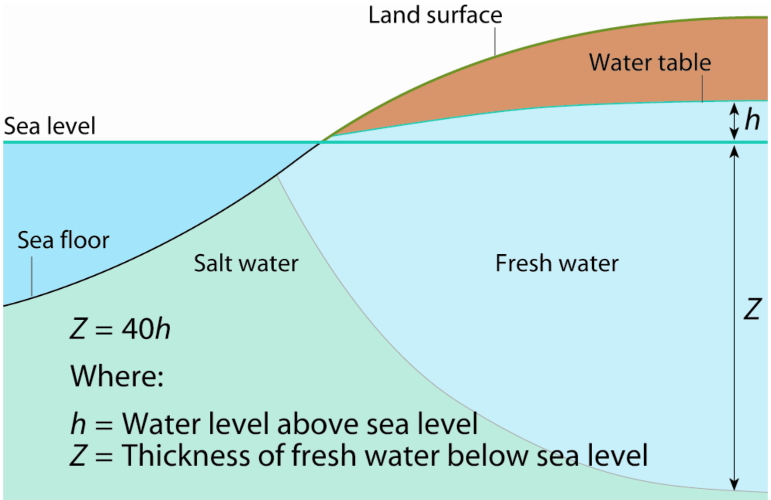

Figure 1 The Ghyben-Herzberg Relation

The thickness of this fresh-brackish-saline zone depends under natural conditions on the dispersivity of the hydrogeological units within the aquifer. Whatever the case, lowering of the groundwater level has an immediate effect on the position of the fresh-brackish-salt water interface. Unlimited groundwater extraction in coastal areas can result in the closure of some wells in a water-collection area or even closure and relocation of a complete well field. In other cases a switch to a costly desalinization plant is the only alternative.

The extent and velocity of sea water intrusion can best be illustrated by an example from China, where coastal aquifers have been studied for saltwater intrusion since the early 1960s. Studies conducted in the City of Laizou in 1971, and in the City of Longkou in 1979 *[4]* indicated that excessive pumping of the groundwater in these areas had caused serious saltwater intrusion. It concerns a transition zone of 1.5 to 6.0 km and an aquifer area of more than 580 km^2. In the beginning, the observations were taken from specific, isolated spots (0.5 km^2). Over time, the intrusion area spread as increases in water extraction for agricultural and industrial purposes continued. In 1979, the saltwater intrusion area covered 16 km^2, 39 km^2 in 1982, 71 km^2 in 1984, and 196 km^2 in 1987. By 1989, the saltwater intrusion area became a continuous zone covering an area of 238 km^2 in Laizhou. In the 1970s, the saltwater intrusion area in the southwestern part of the study area increased by 4 km^2 each year. In the early 1980s, this number increased to 11.1 km^2, and after the mid-1980s to 30 km^2.

Along other shorelines around the world, the situation may be better or worse, depending on site specific conditions, such as e.g. hydrogeology, climate (rainfall, evaporation), presence of rivers, population density, and land use.

CONTROL OF SALT-WATER INTRUSION

There are several methods to stop seawater intrusion. The most common are drilling of deep recharge wells to create groundwater ridges or barrier wells. There are also recharge or infiltration basins using river or runoff water. During the past years other methods have been investigated especially in the US, such as slurry walls, deep soil mixing, grout curtain, jet grouting and even in situ vitrification *[5].*

Recharge wells, recharge basins and barrier wells have proven to be very useful in maintaining the proper equilibrium between pumping and groundwater recharge. Effective control of saltwater intrusion can only be exercised by a combination of proper monitoring techniques, 2D or 3D seawater intrusion modeling *[6]* and deploying the proper methods described above. However, there are also situations where this is not possible or applicable e.g. because of lack of surface water and in such cases electrokinetic fences are an alternative.

ELECTROCHEMICAL TECHNOLOGY

Electrokinetic fencing is a derivative application of electrochemical remediation or electro-reclamation. This technology has been developed for practical application by Lageman & Pool since the late 1980s *[7,8]*. Electro-reclamation is applied to remove toxic inorganic, organic and/or polar species like ions or complexes of heavy metals, arsenic cyanide, fluoride, chloride etc. from soil and groundwater by inducing direct electrical current (DC) into the soil via arrays of anodes and cathodes. The electrodes are not in direct contact with the soil but are hanging in special, mutually connected vertical well screens (electrode housing) wherein a solution (electrolyte) is circulated. This electrolyte solution not only conditions important physico-chemical processes around the electrodes, but it also captures the contaminants: positive charged compounds are captured in the electrolyte of the cathode electrode housings, while negative charged compounds are captured in the electrolyte of the anode electrode housings. Anodes and cathodes have independent circulation systems, which are connected to a water (electrolyte) treatment facility above ground.

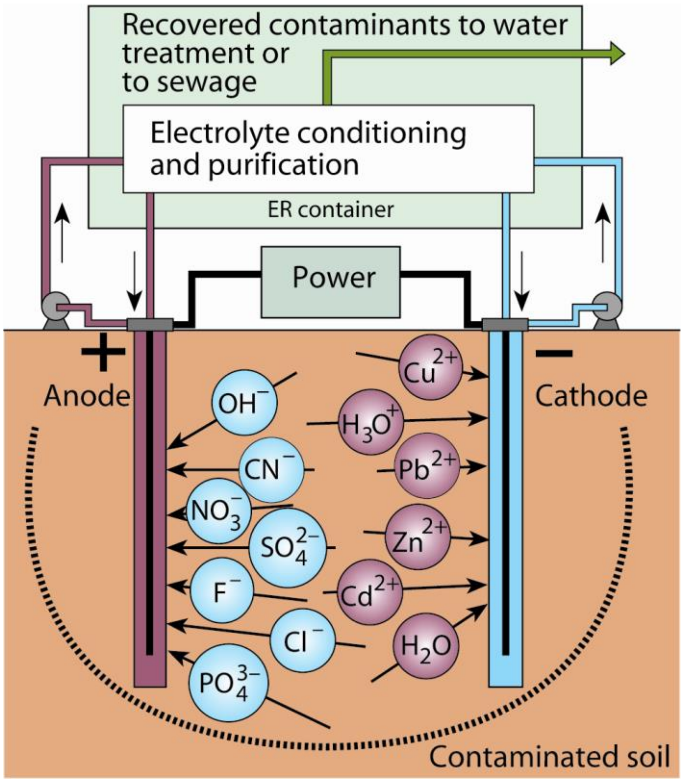

Figure 2. Schematic field setup of electro-reclamation

When applied in contaminated soil, the equilibrium between solid phase (e.g. metal salt, and/or metal adsorbed to clay particles) and liquid phase (groundwater, soil moisture) is disturbed by the electrical DC field. The metal salt dissolves and the adsorbed species (heavy metal, arsenic etc.) desorbs from the soil particles. Both go into solution and are transported to the electrode of opposite charge. This is not a simple continuous process, however. The extent of this electrokinetic transport depends amongst others on the cation (CEC) or anion (AEC) exchange capacity of the soil, the solubility product of the compound and the pH of the groundwater. Somewhere along the way, a particular ion will be adsorbed again and then desorbed and so on, until it is finally captured in one of the electrolytes.

An electrokinetic fence by contrast should be envisaged as an in-situ method to fence off, and contain contaminants in polluted groundwater plumes, or as an in-situ method to induce polar nutrient components into the groundwater plume to activate bioremediation *[9]*. The ionic contaminants are transported downstream by groundwater movement and once they are entering the zone of influence of the DC field, they have to be deflected towards the electrodes of opposite charge. To be captured into the electrode housings, the electrical potential between the electrodes has to be large enough for the ions to overcome the groundwater flow velocity. An electrokinetic fence only removes the contaminants but does not influence the groundwater flow regime, contrary to pumping, water injection through recharge wells, installation of slurry walls, deep soil mixing, grout curtains etc.

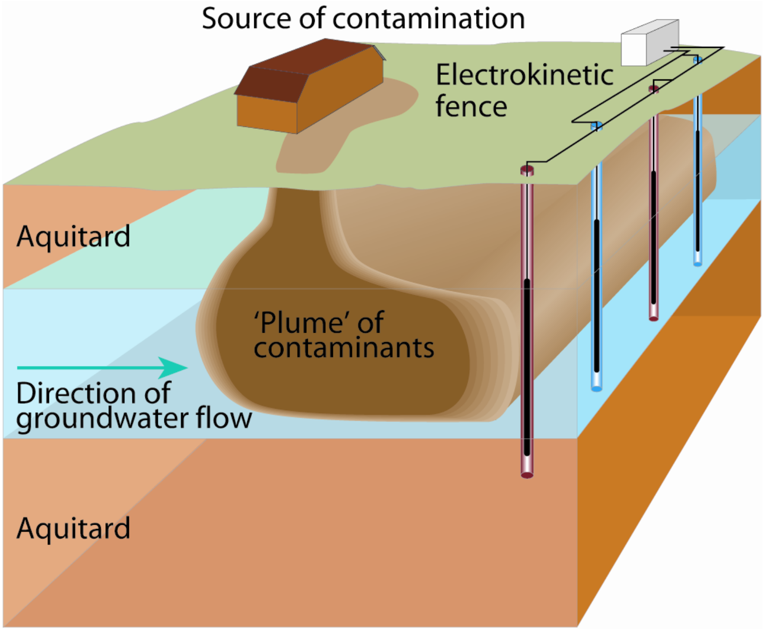

Figure 3. Artist impression of a vertical electrokinetic fence (© Lambda Consult, 2013)

Instead of heavy metals or other contaminants, it can also be deployed as a means to pick up dissolved components at the front of an advancing fresh-brackish-saline water interface, such as sodium (Na^+) and chloride (Cl^-) ions. Under the influence of the electrical DC field, Na^+, Cl^- and other ions and polar components are transported by the groundwater towards the fence where they are deflected towards the anode or cathode electrode screens and captured in the electrolyte solutions circulating inside the well screens.

When the concentration of e.g. chloride has reached a certain preset value, the chloride is removed from the electrode solutions above ground. The mass of chloride and/or sodium that is removed can simply be calculated according to Faraday's law:

$$m = \frac{I * t * M}{F * z}$$

wherein:

m = Mass of chloride and/or sodium (g)

I = Current (A)

T = Time (s)

M = Molar mass of chloride (35.5) and/or sodium (23) C/mol

F = Faraday's constant (96485)

Z = Valence of chloride and/or sodium (1)

However, it is not necessary to remove all chloride and sodium. Only so much has to be captured that the sodium and chloride concentration of the water that passes the electrokinetic fence fits the standards for potable water or irrigation water, or whatever the water is used for.

Electrokinetic fences can be installed both vertically as shown in figure 3 and horizontally as shown in the underlying figure 4.

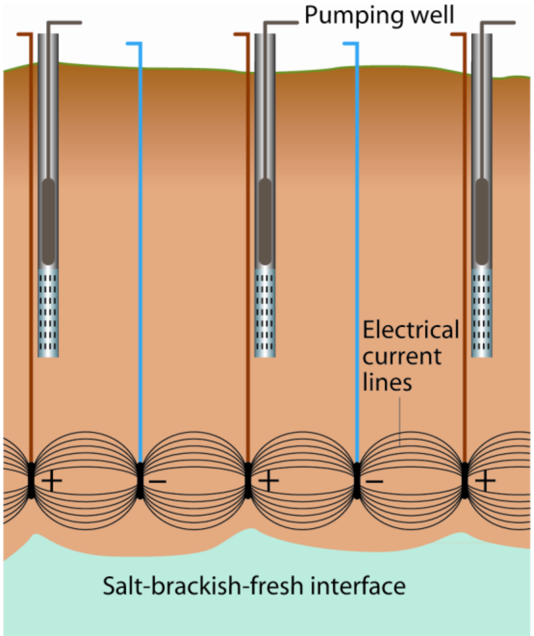

Figure 4. Horizontal electrokinetic fence underneath pumping wells (© Lambda Consult, 2013)

Thus, in a coastal zone, there might be situations as depicted in figures 5a and 5b.

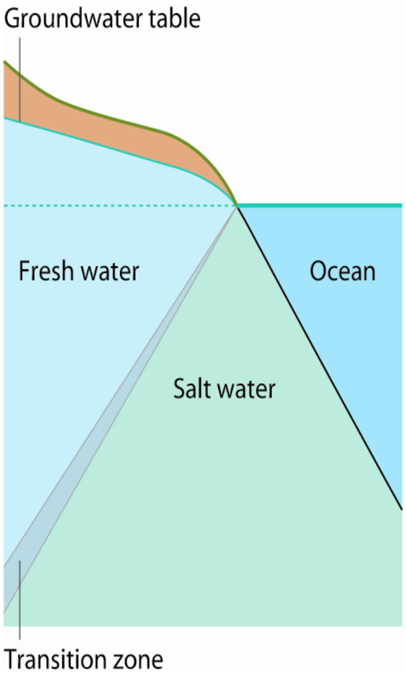

Figure 5a. Natural situation without well field (© Lambda Consult, 2013)

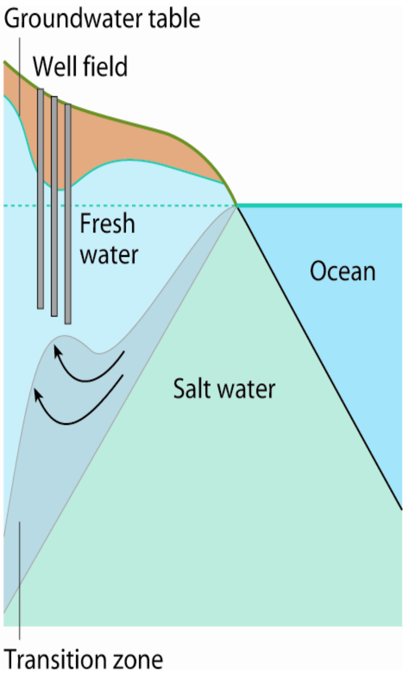

Figure 5b. Upconing of the transition zone as a result of groundwater pumping (© Lambda Consult, 2013)

The impending salinization of the well field as shown in figure 5b can be counteracted by installing either a horizontal or a vertical electrokinetic fence (see figures 6a and 6b respectively).

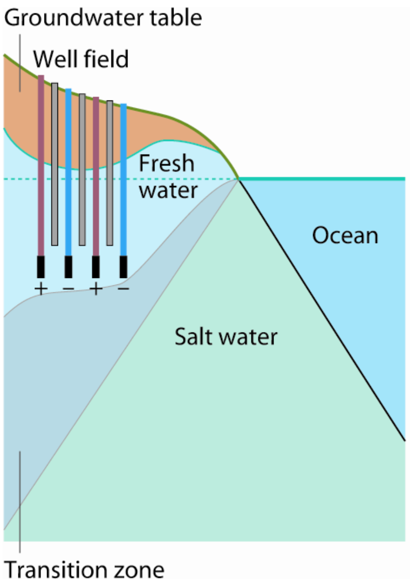

Figure 6a. Horizontal electrokinetic fence stops vertical sea water intrusion by capturing and removing chloride (© Lambda Consult, 2013)

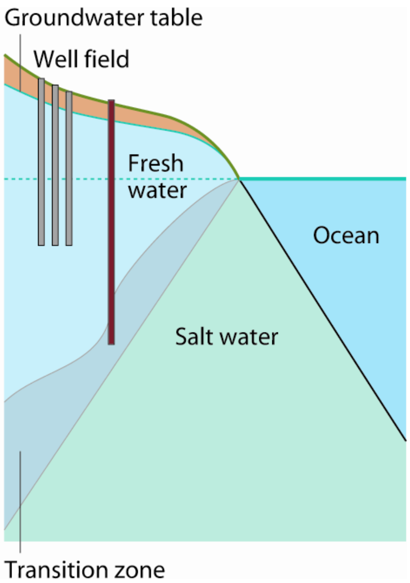

Figure 6b. Vertical electrokinetic fence stops lateral sea water intrusion by capturing and removing chloride (© Lambda Consult, 2013)

The efficacy of an electrokinetic fence can in general be defined as:

$$N_d = \frac{\text{number of charged particles captured by the fence}}{\text{number of charged particles entering the fence zone}} \quad \text{or} \quad N_d = \frac{C_b - C_e}{C_b} * 100,$$

wherein:

N_d = Efficacy (%)

C_b = Concentration of ions in front of the fence (µg/l)

C_e = Concentration of ions after the fence (µg/l)

Apart from the voltage other important parameters governing the efficacy and technical-economical aspects of an electrokinetic fence are:

V_{gw}	Groundwater velocity	m/year
K_{ek}	Electrokinetic mobility	m^2/Vs
φ	Electrical potential	V
K	Specific electrical conductivity of the soil	S/m
R_f	Resistivity of the soil (1/K)	Ohm.m
H	Length of the electrodes (depth of the fence)	m
L	Length of the fence	m
D	Distance between the electrodes	m
r	Radius of the electrodes	m

It will not be difficult to see that the groundwater velocity is one of the major factors in determining whether an electrokinetic fence is economically viable or even possible from the point of view of electrical power supply. The higher the groundwater velocity the higher the necessary voltage between the electrodes and the higher the necessary current per meter electrode and clearly the higher the annual operating cost. There is however, a limit to the current, which can be supplied by the electrodes. Too high currents will lead to excessive heat generation, even boiling electrolytes and a system getting out of control. The method to diminish the necessary electrical power is to decrease the distance between the electrodes: the smaller the distance the less electrical potential is needed to deflect and capture the ions at the electrode screens and the less electrical current has to be supplied by the electrodes. But smaller distances mean more electrodes and thus higher initial capital costs to build and install the fence. It is therefore necessary to optimize capital cost and annual operating cost.

Optimization is accomplished by first using a simple analytical formula to calculate preliminary values of the necessary voltage and current as a function of the distance between the electrodes, the soil and water resistivity, ion mobility and groundwater velocity. These values are then validated in a computer program, which calculates the flow path of the ion when entering the zone of the fence (see figure 7). On the basis of these results one can run several simulations to obtain the optimum values for installation and operating costs of the electrokinetic fence.

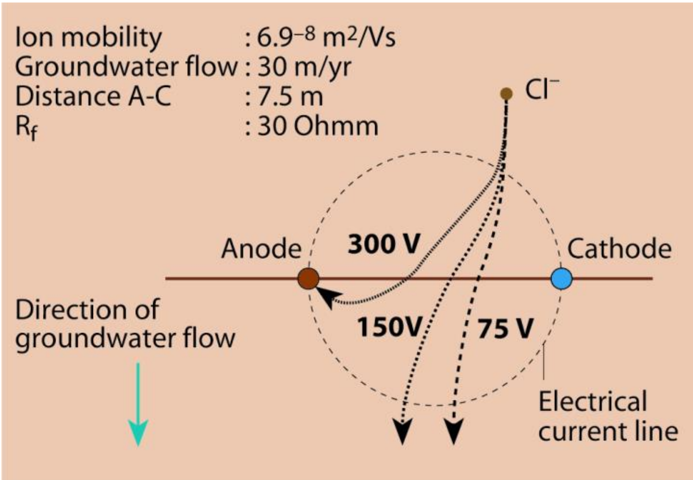

Figure 7. Computer simulation of chloride ion entering the fence zone (top view) (© Lambda Consult, 2013)

From figure 7 it can be observed that at a groundwater velocity of 30 m/year about ¼ of the chloride ions entering the fence area near the cathode is captured at an applied potential of 75 V between the electrodes. At 150 V about ½ of the chloride ions is captured and at 300 V all of the chloride ions are captured. The distance between the electrodes is 7.5 m and the electrical power is a function of the required voltage over the electrodes and the resistivity of the soil.

An electrokinetic fence has been in operation in Tokyo since 2005 at the site of an industrial area to prevent chromium migrating to the adjacent downstream site of a neighbouring company.
Another electrokinetic fence has been installed and tested in the Netherlands during the period 2001-2007 in the form of an electrokinetic biofence *[10]*. This fence has been installed near the building of a chemical laundry to disperse electrokinetically dissolved polar nutrients in the groundwater in order to enhance reductive dechlorinization of present perchloroethene (PCE), trichloroethene (TCE), Cis 1,2-dichloroethene (C-DCE) and vinylchloride (VC). The fence, powered by photovoltaic solar panels, acted as a temporary safety measure to avoid further migration of the contamination from the source area underneath the building to the plume area.

HYDRAULIC VS ELECTROKINETIC COSTS

A recent study of seawater barriers along the West Coast Basin in California concludes that injection wells have been successfully used to battle seawater intrusion in the over-drafted aquifers since the early 1950s *[11]*. With a total length of the barriers of 27.6 km and an average barrier depth of 130 m, the barrier surface area amounts to 3,588,000 m². Annual costs of water injection (37.8*10^6 m³) and maintenance amount to US$ 19 million. This leads to a cost of US$ 5.3 per m² of barrier surface area. Cost calculations of an electrokinetic fence assuming similar conditions arrive at about US$ 4 per m² of fence area, or a total of US$ 14,3 million, a difference of US$ 4.7million. It should also be noted that there is no need to inject almost 38 million m³ of fresh water, which can be used elsewhere. Moreover, in this particular case about 2/3 of the annual running costs pertain to depreciation cost of the electrokinetic fence over a period of 25 years, while the remaining1/3 are electricity and maintenance costs, assuming US$ 0.10 per kWh. Coastal areas in general, have good wind conditions and a large part of the annual energy demand could be obtained from wind energy. Together with solar energy, which more often than not is also abundantly available, energy could for a major part be generated by sustainable sources such as wind energy and solar power.

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