Mitigating salt water advance using horizontal wells: risk based comparison of different approaches.

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Abstract Many coastal regions in the world experience an intensive salt water intrusion in aquifers due to natural and anthropogenic causes. Seawater intrusion is highly dependent on coastal geology (depositional channels, presence of fractures, etc…). A good geological characterization must therefore be undertaken to better understand the specific intrusion phenomenon and then select the best approach for remediation.

A number of techniques, such as fresh water injection or salt water extraction, can be used to prevent or retard the salinization process. With either technique, drilling horizontal wells can bring significant benefits as compared to vertical wells. They can be drilled with smaller surface footprints, and can allow extracting or injecting of significantly larger volumes of water as compared to conventional vertical wells. The first part of the study consists of simulating the performance of a horizontal well compared to a row of vertical wells as a barrier for a homogeneous aquifer.

The type of remediation technique to be used and the barrier design to be adopted will vary according to the aquifer characteristics that are, unfortunately, partly unknown. In the last part of this paper we show how, using a methodology based on the Monte Carlo approach, risk analysis can be used to reduce this uncertainty and select the best approach. The basic steps are: first, a geostatistical model is used to simulate a number of heterogeneous hydraulic conductivity fields consistent with the geostatistical model; second, the seawater intrusion steady state is solved for each heterogeneous field; third, transient simulations of the effect of fresh water injection and salt water extraction using vertical or horizontal wells are performed for each heterogeneous field. Lastly, the set of simulations produced for each remediation technique and barrier design is analyzed and the associated risks are compared.

In summary, with proper aquifer characterization, modeling and monitoring, during the barrier design, installation and exploitation phases, choices about the remediation measures can be made. In all cases, it appears that horizontal wells can contribute to the remediation process with increased efficiency and reduced costs.

Index Terms Horizontal well, remediation, risk analysis, seawater intrusion.

I. INTRODUCTION

The sustainable management of scarce water resources is an important issue in coastal and insular zones. All over the world the coastal areas of continents are currently experiencing a fast population growth due to a migration from inland areas. It is, for instance, frequently reported that about half of the world population already lives within 60 km of the shorelines. This rapid land use change with the combination of urban expansion and concurrent development of agriculture, industry, and tourism has often led to an overexploitation of groundwater resources. A similar pressure, and an even greater threat, exists in islands, mainly due to the development of tourism. In such areas it takes time before the salinization of aquifers due to the negative effects of human activities (e.g. lowering of the piezometric heads due to excessive overpumping) or a relative sea level rise is actually observed. The main reason is that, in the salinization process, enormous volumes of fresh groundwater have to be replaced by saline groundwater. As such, countermeasures to compensate the salinization process should be taken in time, since the time lag is considerable (from several decades to centuries) before these measures result in effective changes in the salinity distribution of the aquifer [1].

II. PRESENTATION OF THE CASE-STUDY USED TO COMPARE THE DIFFERENT REMEDIATION APPROACHES

Several alternate solutions can be used to prevent or retard the salinization process: fresh (e.g. treated) water injection vs. salt water extraction, horizontal wells vs. vertical wells. To compare these different mitigation approaches to salt water intrusion and assess their pros and cons, simulations were made with ECLIPSE®, a simulation code that was originally developed for oil and gas fields but that has recently been adapted to handle hydrogeological problems.

This simulation code can handle the density-driven flow conditions that are encountered in coastal aquifers. It has also inherited from its origin the capability of handling deviated or horizontal well trajectories that are commonly used by the oil industry but are also starting to be used in a groundwater context (e.g. for the remediation of polluted aquifers).

The modeled area is a 5410 m long, 11680 m wide and 100 m thick, confined aquifer. For the homogeneous case examined in part 3 and 4 hereafter, horizontal hydraulic conductivity has a constant value of $8.56.10^{-5}$ m/s, vertical hydraulic conductivity is $8.56.10^{-6}$ m/s and porosity is 20 %.

Manuscript received September, 2006
Schlumberger Water Services

A variable-size mesh discretization scheme has been adopted and the zone of interest is refined with cells of 5 m in all directions. For the boundary conditions, the sea is represented by a constant head boundary and a constant flux boundary is applied upstream for representing the inland aquifer. For each simulation run, corresponding to a different mitigation approach, the model has been initialized with the virgin aquifer conditions (i.e. the steady state condition without any human interference).

III. BASELINE CASE WITHOUT MITIGATION: IMPORTANCE OF FULL OR PARTIAL COMPLETION FOR FRESH WATER EXTRACTION

The impact on saltwater intrusion of the location and completion of the fresh water extraction wells, before the aquifer undergoes any type of remediation measures, has first been investigated. For that we placed 3 vertical fresh groundwater (FG) extraction wells 240 m upstream from the seawater wedge bottom limit. Those 3 FG wells are 95 m spaced and aligned parallel to the shore, and they are pumping 900m^3/d of fresh water each (fig.1).

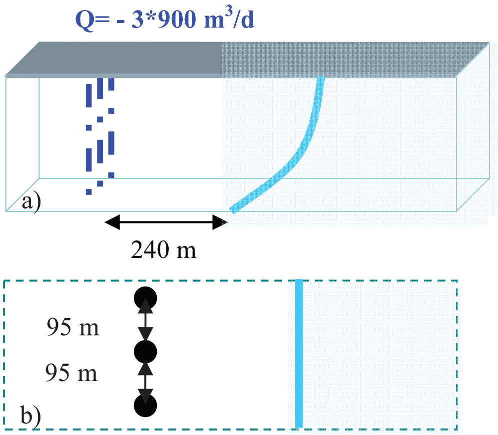


Fig.1 - Design of the fresh water extraction wells: a) side view, b) top view.

Since well completion (e.g. depth and length of the well screens) is known to be important when extracting fresh water from a coastal aquifer, we compared the behavior of 3 FG wells fully completed through the whole aquifer thickness (i.e. over 100 m long) and 3 FG wells with partial completion (i.e. over 50 m long, corresponding to the top half thickness).

Depending on completion length, the arrival time for seawater contamination was found to be quite different. For this model and the same 900 m^3/d well rates, having a partial completion delays the contamination (TDS >1500 mg/l) of 22 years: the contamination arrives 10 years later with full completion while with the partial completion it arrives 32 years later (fig.2). In both cases, the middle well of the 3 vertical wells extracting fresh groundwater is the one contaminated first.

In both cases, the seawater wedge first penetrates further inland but, for the wells that are fully completed, the contamination is quite fast as the wedge is arriving directly to the screens whereas, for the wells that are only partially completed, the up-coning phenomenon has to take place so that the saltwater reaches the screens, and the contamination is thereby delayed.

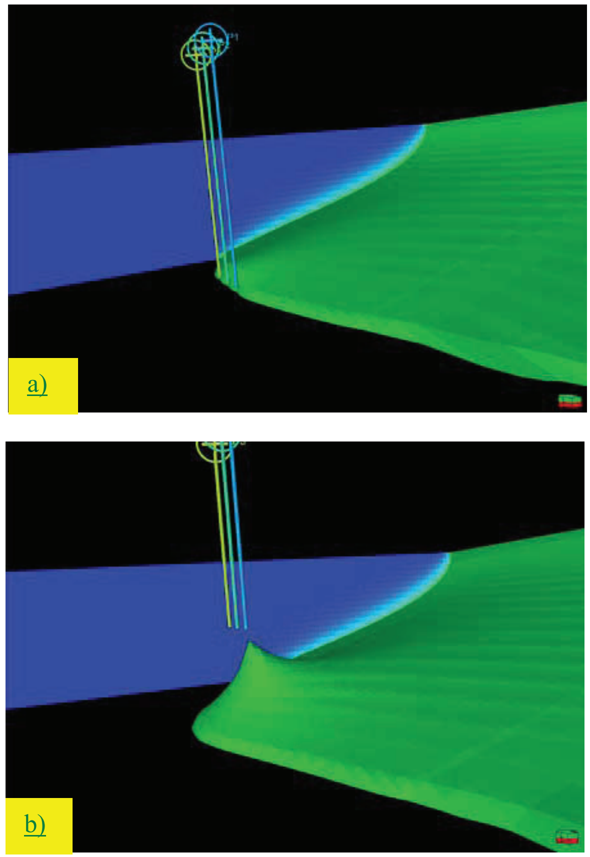


Fig.2 - Isosurfaces of 17500 mg/l in salt concentration, with: a) FG wells fully completed, b) FG wells partially completed.

IV. HORIZONTAL WELL VERSUS VERTICAL WELLS FOR INTRUSION BARRIERS

The measures that can be used to mitigate the progression of a saltwater wedge and to prevent the contamination of the FG wells can be subdivided into two types: preventive and curative measures. Preventive measures should, in principle, be preferred, but this may not be always possible any longer [2]. Curative measures, such as a reduction of the rates of FG abstraction in order not to exceed the sustainable yield, or a relocation of the FG abstraction wells in order to slightly increase this sustainable yield (by reducing the outflow of fresh groundwater into the sea), can sometimes be taken to achieve these goals.

However, most of the time, two kinds of curative measures are considered: either an artificial recharge aiming at increasing the sustainable yield and creating a pressure barrier to stop the advance of the saltwater wedge, or an abstraction of saline groundwater from the saltwater front zone. Although the way it works is less obvious than for the former, the latter measure actually results in reducing the losses of fresh groundwater by outflow into the sea. The abstracted saline groundwater can, under certain conditions, be used as a source for desalination [3].

Artificial recharge and saltwater abstraction measures are presently implemented by drilling barriers of vertical wells, aligned along the shoreline. The following paragraphs will present how, for both types of measures, those vertical well barriers could be substituted by drilling a single horizontal well, parallel to the shoreline.

A. Horizontal well technology for intrusion barriers

Horizontal drilling is not, so far, common practice for groundwater wells but, in the oil and gas industry, significant progress has been seen during the past decades in directional drilling, logging, and completions, taking horizontal wells from an experimental technique in the 1980s to a standard tool in the 1990s, with horizontal wellbore lengths up to several kilometers. Many types of specific completion equipment, e.g. with slotted liners and gravel packs, have been developed to hold the horizontal hole sections open and enhance fluid flow. The prime advantages of using horizontal wells compared to using vertical wells are: 1/ reduced footprint at ground surface and 2/ increased well productivity/injectivity, due to maximizing borehole exposure to the formation and to connecting heterogeneities such as fractures or higher permeability zones.

The two above-mentioned advantages may be decisive for the economical feasibility and technical performance of intrusion barriers, provided certain precautions are taken. A thorough geological survey is, for instance, required to determine the optimum wellbore trajectory and to specify the horizontal well characteristics for maximum barrier efficiency. In the case of a barrier using the water injection approach, geochemical compatibility tests between the fresh (or treated) injected water and the formation water also need to be run, so as to ensure that the two waters do no react to form precipitates that may clog the receiving formation [4].

We will now review what the horizontal well technology can bring, for both mitigation techniques: freshwater injection and saltwater extraction, in turn.

B. Injection of fresh water (artificial recharge)

Freshwater injection has been now used for some time to prevent saltwater intrusion in coastal aquifers. Since 1975 the Orange County Water Department (OCWD) in California has, for instance, operated a pressure barrier to prevent the ocean water from contaminating its groundwater supplies. This barrier is composed of a row of vertical wells injecting treated waste water and fresh water. A simulation exercise will now help us to understand what would happen if such a row of vertical wells is replaced by a horizontal well.

Let's consider the same aquifer as for the baseline case without mitigation, with the same three FG wells aligned parallel to the shore. But let's now assume that, this time, they are producing 960 m^3/d each and that, between the FG wells and the shore, three other, 50 m deep, vertical wells, located 25 m downstream of each FG well, screened over the 20m bottom interval, and injecting 60 m^3/d of freshwater each, are acting as an artificial recharge barrier (fig.3a). One can notice that the net total production of freshwater is kept the same as for the baseline case (i.e. 2700 m^3/d) and that only 1/15 of that amount is extracted in excess to be re-injected into the barrier.

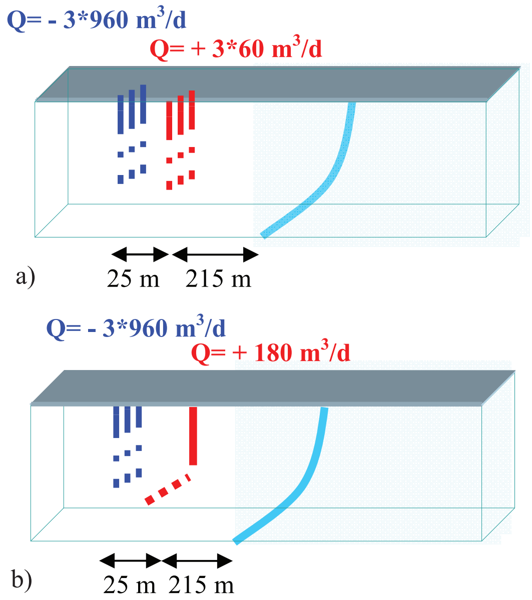


Fig.3 - Well locations and rates: a) 3 vertical wells injecting 180 m^3/d (total) of fresh water, b) 1 horizontal well injecting 180 m^3/d of fresh water.

To assess the impact of the horizontal well technology, let's also consider that, instead of the three vertical wells acting as a barrier, a single horizontal well, exactly at the same location (fig.3b), is injecting the same quantity as the three vertical wells, i.e. 180 m^3/d. Let's also consider two different horizontal well lengths: 100 m and 190 m (figure 4a and b).

The simulation results (see tab.1, fig.5 and 6) are the following: when no remediation is undergone (fig.5a), the middle FG well is contaminated after 32 years; when injecting freshwater into a barrier consisting of 3 vertical wells (fig.5b), the contamination arrives 5 years later; when injecting freshwater into a barrier consisting of a long or short horizontal well (fig.5c and d), the salt concentration at the FG wells never reaches the 1500 mg/l threshold.

Sensitivity tests indicate that, for this type of remediation using freshwater injection, the best results are obtained when the injection takes place where the upconing phenomenon stems from.

TAB.1 - CONTAMINATION ARRIVAL TIMES

INJECTION	No remediation	Vert. wells	Short horiz. well	Long horiz. well
Contamination time arrival	32	37	No	No

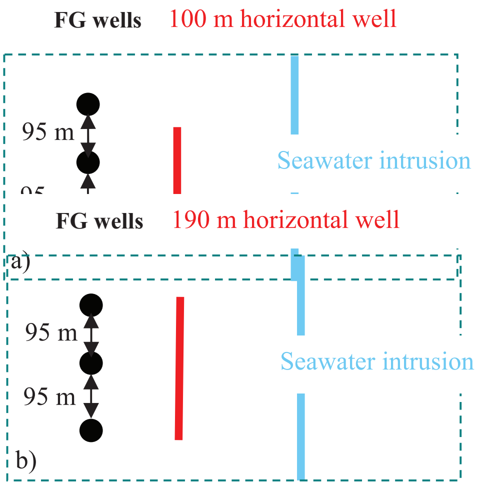
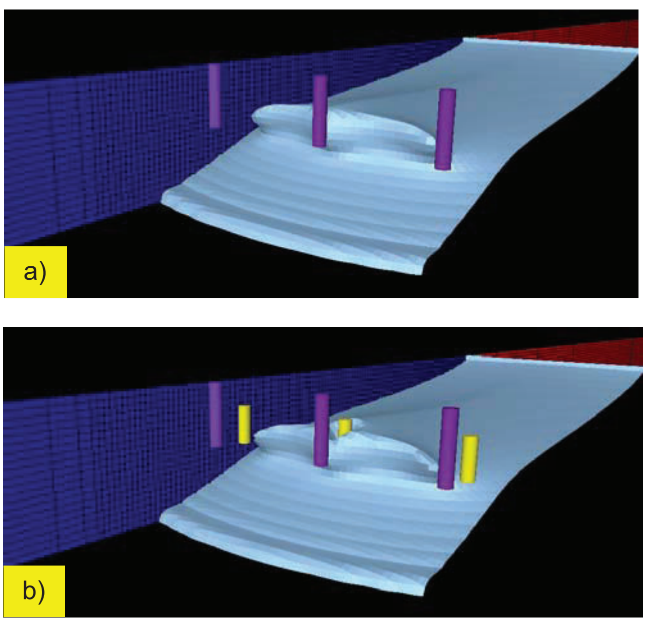


Fig.4 Top view from of both horizontal well designs:
a) short horizontal well, b) long horizontal well.

Fig.5 shows how vertical wells counter the seawater intrusion only very locally, resulting in a poor barrier effectiveness, while a horizontal well does not let seawater go further inland toward the FG screens over its entire length.

Comparing the two horizontal well designs, however, we can observe (fig.6) that, strangely enough, the long horizontal well is less efficient than the short horizontal well. But one must remember that, with both short and long wells injecting the same rate, the short horizontal well has a better injectivity and thereby a better effectiveness as a barrier.



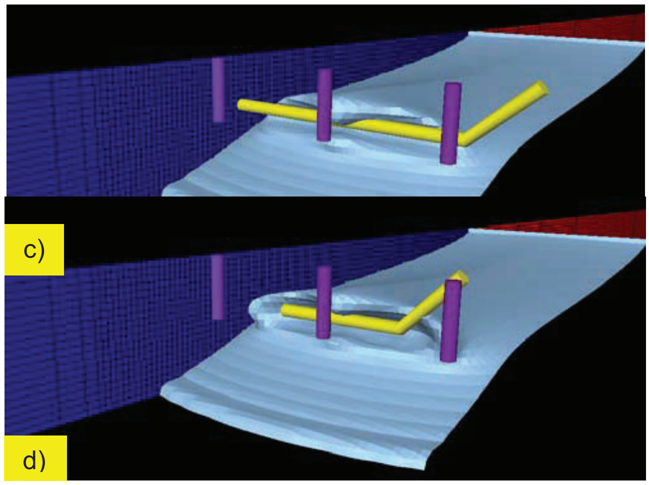


Fig.5 - Isosurfaces of 5000 mg/l after 60 years of simulation: a) FG wells without remediation, b) FG wells with vertical wells injecting fresh water, c) FG wells with one long horizontal well injecting fresh water, d) FG wells with one short horizontal well injecting fresh water.

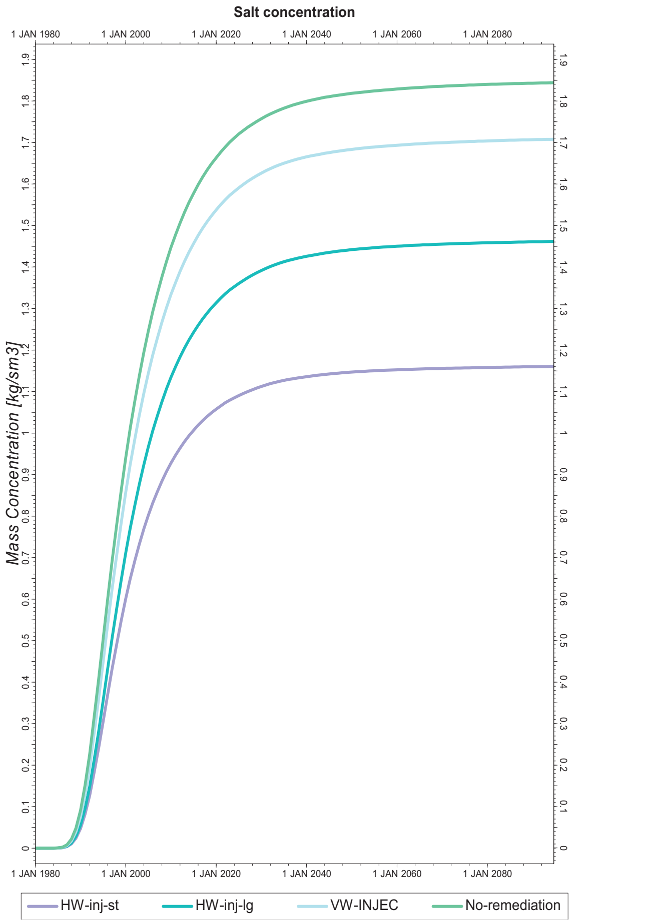


Fig.6 - Salt concentration at the middle FG well, for the different artificial recharge solutions: HW-inj-st short horizontal well, HW-inj-lg long horizontal well, VW-INJEC vertical wells.

C. Abstraction of saline or brackish groundwater

Abstraction of saline groundwater to control seawater intrusion in coastal aquifers is a far less common practice than freshwater injection for two reasons [1]: first, it may result in undesirably lowering the piezometric head in the aquifer if the abstracted rate is too high; second, the disposal of the extracted saline groundwater could be a problem. However, it should be noted that, not only simulation shows that this mitigation approach is very effective, but also the extracted water, especially when it is brackish due to underground mixing in the salt wedge vicinity, could be a cost-effective intake solution for a desalination plant.

As in the previous simulation exercise but, this time, for saline groundwater abstraction as a countermeasure to control seawater intrusion, we are going to examine the advantage of substituting a barrier consisting of vertical wells by a horizontal well. The configuration for the 3 FG wells and the vertical wells (or the horizontal well) extracting salt water will be the same one as for the artificial recharge barriers. The only parameters that will change are the rates, the distance between the FG wells and the barrier, and the depth of the horizontal well (fig.7).

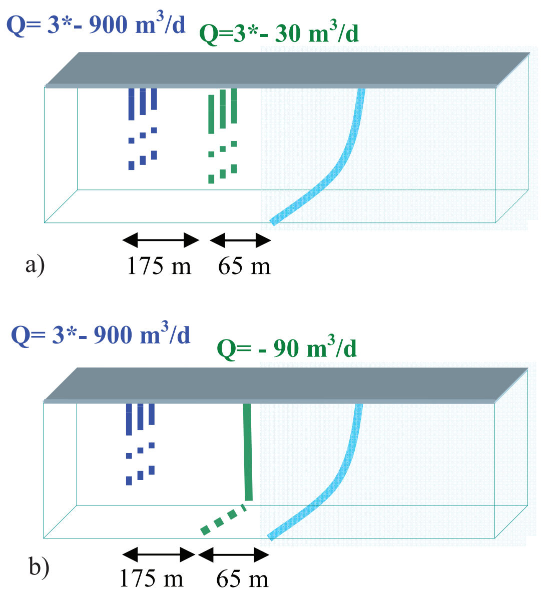


Fig.7 - Well location and rates: a) 3 vertical wells pumping 90 m^3/d (total) of salt water, b) one horizontal well pumping 90 m^3/d of salt water.

Let's assume that the FG wells are still extracting 2700 m^3/d in total of fresh water, but the 3 barrier vertical wells, or the horizontal well, are now extracting 90 m^3/d in total of saline or brackish water. One can notice that the amount of saltwater extracted only represents 1/30 of the produced freshwater, which is again a small quantity. The barrier will now be located a bit closer to the salt wedge, i.e. 175 m downstream of the FG wells, and the screened intervals of the barrier vertical or horizontal well(s) will now be located closer to the aquifer bottom. However, for this type of countermeasure, if the barrier well(s) must be positioned near the wedge, the exact location must not be as accurately optimized, compared to the case of a countermeasure using fresh water injection.

The simulation results (fig.8) also show that, at least in that case of a homogeneous aquifer, when using saltwater extraction as a countermeasure, whatever the design adopted for the barrier (vertical or horizontal wells), the FG wells are not contaminated by seawater i.e., the salt concentration stays permanently below the 1500 mg/l threshold. Using a horizontal well for the barrier is still better than using a row of vertical wells though: the salt concentration at the middle FG well is lower with a horizontal well than with 3 vertical wells. The length of the horizontal well is not so important in that case, since the salt concentration curves for the middle FG well are almost identical for short and long horizontal wells.

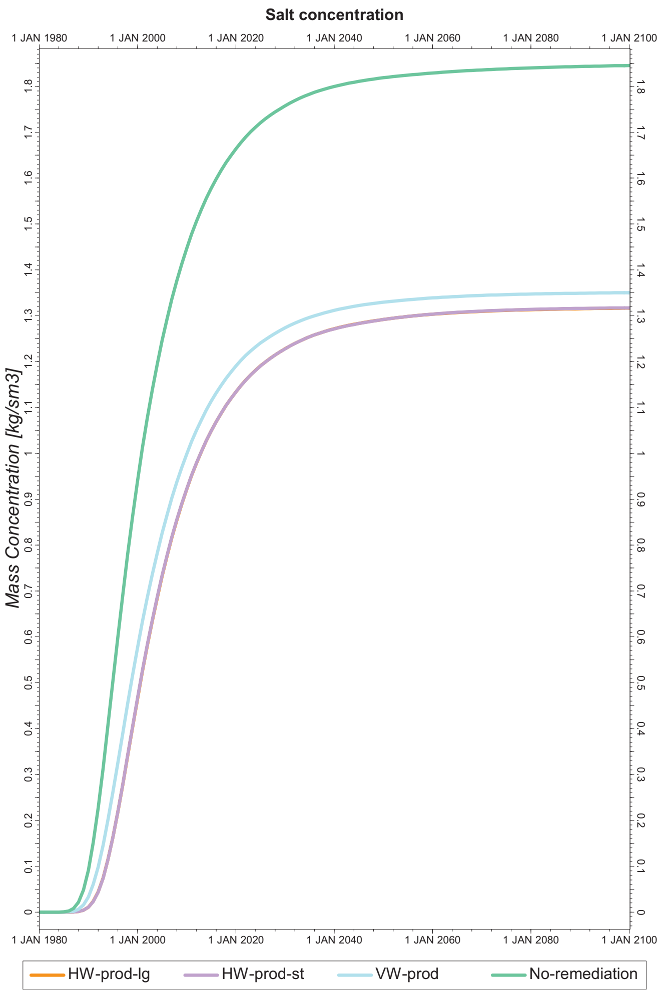


Fig.8 - Salt concentration at the middle FG well, for the different saline water abstraction solutions: HW-prod-lg long horizontal well, HW-prod-st short horizontal well, VW-prod vertical wells.

To summarize, the simulation exercices indicate that for both curative measures, artificial recharge and saline abstraction, a horizontal well seems to be more effective than vertical wells, at least in the case of a homogeneous aquifer. We will now briefly present a risk analysis study that was undertaken to verify whether the conclusions stay the same for a heterogeneous aquifer or not.

V. Risk Analysis for a Heterogeneous Aquifer

So far we have considered the coastal aquifer as homogeneous in our simulation exercises but seawater intrusion is known to be highly dependent on coastal geology (existence of depositional channels, presence of fractures, etc…). Even if a good geological characterization is undertaken for a real-world heterogeneous aquifer, uncertainty will always remain about the spatial distribution of hydraulic conductivities and a risk analysis study may be needed to support the choice of a given type of countermeasure and of a particular barrier design. To see if a horizontal well is statistically more effective than vertical wells for a seawater intrusion barrier, a geostatistical Monte-Carlo approach has been adopted to complement the simulation exercise conducted on a homogeneous aquifer problem. The case-study has been kept the same as previously; only the spatial distribution of hydraulic conductivity changes. Several heterogeneous cases, having the same variogram and same distribution characteristics for hydraulic conductivities (tab.2), were generated using Petrel®, a geological modeling tool. The choice of an anisotropic variogram (tab.3) allows the creation of a sizeable (i.e. statistically representative) number of different heterogeneous cases, all showing high and low conductivity "corridors" perpendicular to the shoreline (e.g. see fig.9). For each heterogeneous case, the seawater intrusion steady state condition was first obtained with ECLIPSE® (fig.10) and used as initial state for evaluating the effect of the different remediation measures.

Tab.2 Hydraulic conductivity distribution characteristics

	Absolute minimum	Absolute maximum	Mean	Std dev. (in Ln)
Hydraulic conductivity	$8.56.10^{-13}$ m/s	$8.56.10^{-2}$ m/s	$8.56.10^{-5}$ m/s	1

Tab.3 Gaussian variogram characteristics

	Major direction	Minor direction	Vertical
Range	3000 m	1000 m	10 m
Azimuth	90°	Dip	0°

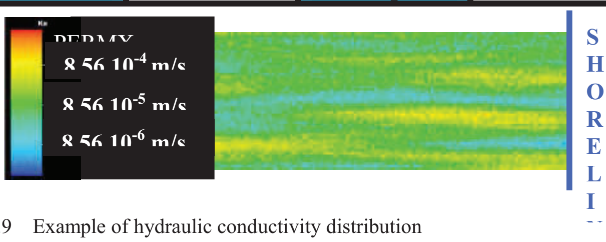


Fig.9 Example of hydraulic conductivity distribution

Then, for each heterogeneous hydraulic conductivity model, simulations were run for the different measures, i.e. the FG wells without any remediation, the FG wells with vertical or horizontal wells injecting freshwater, and the FG wells with vertical or horizontal wells extracting saltwater, all with the same rates as for the homogeneous case.

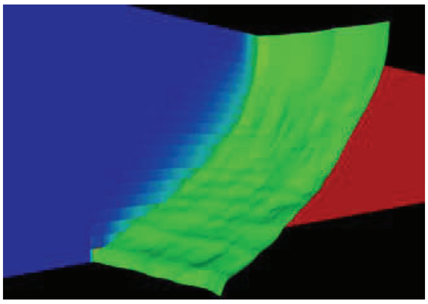


Fig.10 Isosurfaces of 17500 mg/l in salt concentration representing the seawater intrusion steady state for the heterogeous case.

The simulation results (fig.11 and fig.12) indicate that the effectiveness of the different remediation measures have the same ranking as in the homogeneous case: a horizontal well is still better than a row of vertical wells for both types of countermeasures, and a short horizontal well is still better than a long horizontal well for freshwater injection, and has an almost identical effect in the case of a saline water extraction.

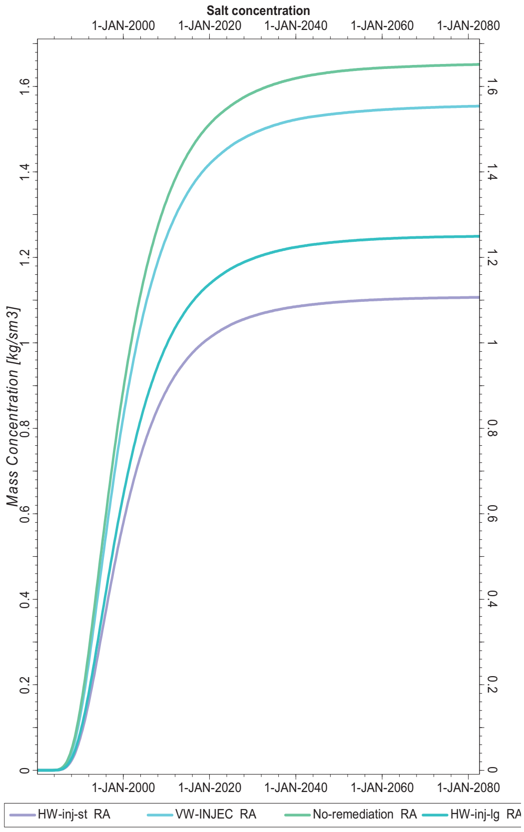


fig.11 - Salt concentration at the middle FG well, for the different artificial recharge solutions (heterogeneous aquifer case): HW-inj-st_RA short horiz.well, HW-inj-lg_RA long horiz. well, VW-INJEC_RA vertical wells.

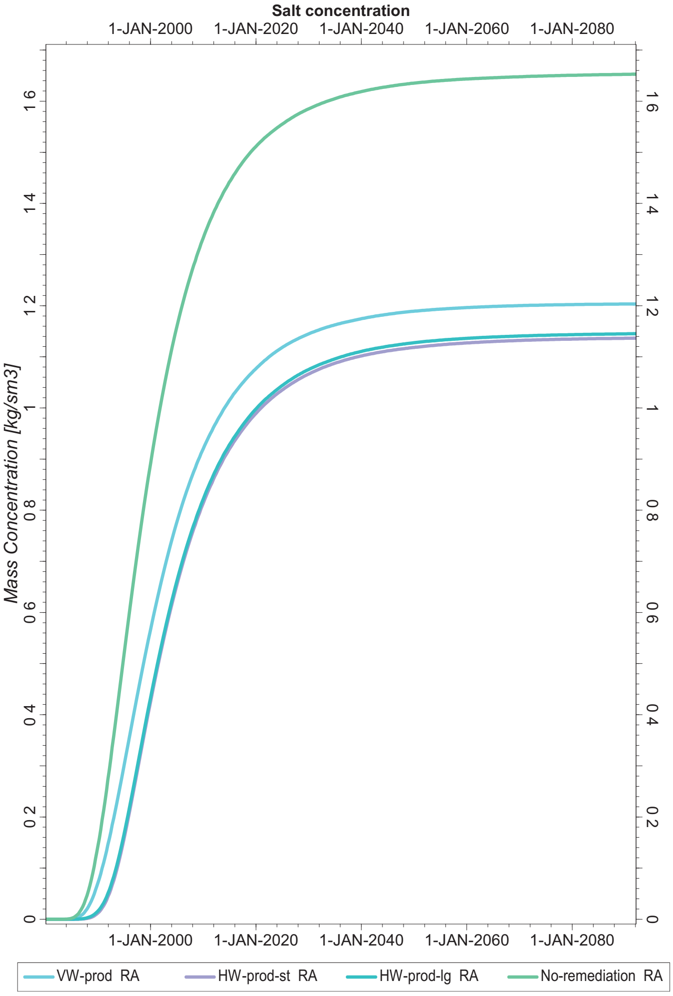


Fig.12 - Salt concentration at the middle FG well, for the different saline water abstraction solutions (heterogeneous aquifer case): HW-prod-lg_RA long horizontal well, HW-prod-st_RA short horizontal well, VW-prod_RA vertical wells.

VI. CONCLUSIONS

In summary, with proper aquifer characterization, modeling and monitoring during the barrier design, installation, and exploitation phases, horizontal wells can contribute to the remediation process with increased efficiency and reduced cost. The choice between the different possible types of remediation measures can be made, based on a risk analysis study. Freshwater injection and saltwater extraction with horizontal wells could even be combined, using a dual barrier: for instance, saline or brackish water could be extracted and desalinated so as to better meet the freshwater demand, while treated waste water is re-injected.

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