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Using a stochastic approach to reduce risks in groundwater resources development: a case study in Sur, Oman

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INTRODUCTION

With increasing pressure on water resources in coastal regions, desalinization is often considered as a viable option. To this end, large amounts of seawater are needed. We present a case study for a desalination plant in Sur, Sultanate of Oman. Here the aquifer is strongly heterogeneous and is made of early Palaeocene-Eocene carbonates in sub-horizontal layers. This sediment deposition makes groundwater development particularly risky. Fresh water was not found in the area and the aquifer suffers from seawater intrusion. According to few existing seawater production boreholes at the site (for an existing desalination plant), there are no doubts that the seawater invades the aquifer system, certainly due to a very small hydraulic pressure gradient of freshwater. Thus, fresh groundwater is almost non-existent in the area and water supply at Sur city relies exclusively on seawater desalination.

The desalinization project involved the design, construction and 22-year operation of a new 80,200 m^3/day capacity Seawater Reverse Osmosis (SWRO) desalination plant at a given site close to the city. The plant requires up to 9,200 m^3/h of seawater, theoretically extracted either from the sea through an open intake or through beach wells along the coastline. If the first option is generally more costly than the second, the second is riskier, given that the availability of such a huge yield in a limited space and heterogeneous aquifer is hard to prove before well drilling and testing. This paper presents an analysis of the uncertainty of groundwater availability that was carried out using a stochastic approach and presented to the project founder to assist them in deciding which option to choose.

AVAILABILITY OF THE WATER RESOURCE

The objective of the first stage of the project was to identify the flow range of seawater that could reasonably be extracted from the site using on-shore boreholes or radial wells hereafter called “beachwells”.

An initial recognition survey was defined to appreciate the type of aquifer and the possible availability of the sea-water resource. This survey was conducted in three steps: an initial overview of the existing literature about geology and hydrogeology in the study area, 14 profiles of electrical resistance tomography for a total of 7000 m, and the drilling of four recognition boreholes to clarify the geological and hydrogeological contexts. The materials making up the first 50 meters of the aquifer were recognised as generally consolidated or cemented, except for a persistent clay layer typically found at depths between 27–35 meters. The dominant materials were generally light colored limestone, from off-white to pink, with coral and other sea fossils, suggesting a reef environment. In some places, the limestone was fragmented and coarse (breccia), and these deposits were usually hard especially in zones where the chert content was high. The geological deposits found at greater depths were quite different from those above. The average depth of the formation change was positioned at approximately 49–61 m b.g.l. These strata were darker, usually grey or grey-green in color, and were identified as calcarenites, quartz sands, and marls, and sometimes as siliceous limestone or calcareous sandstone. These consolidated rocks were interlayered with materials which had a lesser degree of induration, i.e. layers of soft clay or fairly friable sandstones, or a mixture of clay, sand and gravel. The aquifer conditions could be described as a fractured system, with large solution cavities (karst features) predominant at the top portions of the aquifer. The top of the aquifer typically appeared at the contact of the top layer of alluvium/conglomerate and a hard pinkish coloured limestone. The water strike was associated with a recrystallised zone of dolomitic limestone and chert, and often showed evidence of fractures. The karstic limestone was characterized by cavities and conduits, with sediments filling or partially filling these voids. Below the static water level (here the sea level) and up to 40 m deep, electrical resistivity of the terrains was low to very low with resistivity less than 20 Ω.m and mostly less than 1 Ω.m, due to seawater intrusion. If the existence of high sea-water production sites was not certified with this survey, it demonstrated that an important production could be expected from the first karstic levels when filled by sand and the lower levels from the underlying terrains. Production should be done through standard borehole equipped with screened casing and gravel-pack (in opposition to the radial wells initially planned).

A second recognition phase was defined in order to conduct the first quantitative evaluation of the karstic aquifer. The aquifer parameters were estimated by pumping tests over twenty new drilled test boreholes and by the previous geophysical investigations. From December 2006 to January 2007, 20 boreholes were drilled on the site and tested and for 19 of them, the pump test interpretation was possible. It gave an aquifer transmissivity ranging from 2E-1 m^2/s to 5E-3 m^2/s. The aquifer transmissivity was compared with the geological geometry, approached with the electrical resistivity of the terrain obtained from the geophysical campaign. The geophysical data (data on series of vertical profiles) was migrated in a single plane (vertical averaging) then analysed with geostatistical methods. The modelling of the experimental variogram with a theoretical variogram allowed the generation of a great number of equiprobable simulations, using the turning bands method, each of which respected the existing measured points and the spatial structure provided by the variogram (texture, size of heterogeneities), and the histogram of the resistivity values. The electrical resistivity maps were then converted in transmissivity. The main difficulty here consisted in finding a correct correlation between electrical resistivity and transmissivity, as this correlation is not linear. Geological interpretations of the area have shown that different possible transmissivities could correspond to a single resistivity value: a low resistivity could indicate the presence of clay, but it could also be interpreted as karstic conduits filled with sea-water. In this case, the relation had a crescent shape, confirmed by experimental data. The interpolation of transmissivity on the whole domain was carried out using the collocated cosimulation method. This method allowed us to create conditional simulations of transmissivity T (conditioned by the 19 measured values) using a background information (the maps of resistivity ρ), approximating the crescent-shaped relationship with a linear correlation. A hundred out of the infinity of descriptions of the spatial distribution of the aquifer transmissivity were generated in this way, each time using a different ρ -field for the background information. This enabled to propagate the uncertainty from the ρ -field to the T-field. The next stage involved classic groundwater flow computation (mathematical modelling), repeated for the hundred transmissivity maps (T-field). The flow calculation was done for three theoretical sets of wells, selected for the large variety of results obtained: 21 wells well dispersed on the productive zones, 78 wells located along a single line 100 m from the seaside and 140 wells along the seaside 50 m from the sea plus additional wells inshore. The drawdown in the wells was simulated with constant head conditions at the well location and the total discharge was extracted from the flow model balance. A statistical analysis was then conducted from these hundred total discharge estimates. The result of this stochastic modelling was a histogram of simulated maximum yields as shown in Fig. 1. It showed that sufficient sea-water resources were available to supply the desalination plant beneath the site. The boreholes number and position should then be optimised in order to reach an industrial operational well field.

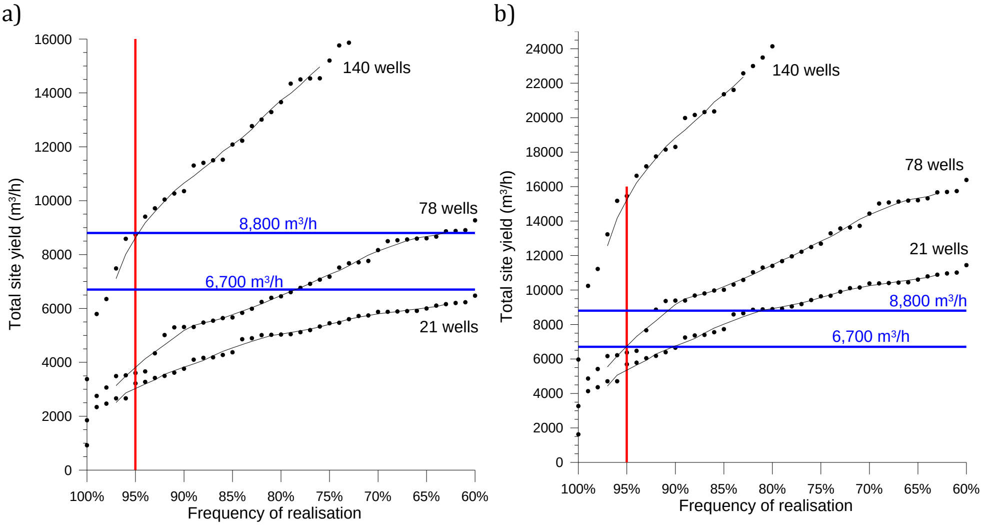

Figure 1. Maximum yield extracted from the site with a drawdown of 7.5 m. The black curve shows the cumulated histogram; the black dots show each of the simulated maximum yields. As the aquifer thickness may locally be about 30 to 35 m in the plant area, a value of 30 m is set for a series of conservative runs (a) and a value of 35 m for the aquifer thickness is set for a series of optimistic runs (b).

OPTIMISATION OF BOREHOLE NUMBER AND POSITION

The groundwater flow characterisation methodology included data filtering, well testing and stochastic inversion (Alcolea et al., 2009). In a first step, 200 simulations of transmissivity and storage coefficient fields were generated, conditioned to transmissivity and storage coefficient from pumping tests, using the regularized pilot points' method. Four head variation data sets (i.e. response to tidal fluctuation and to three long term pumping tests) were considered, and the models were calibrated simultaneously to the four data sets. In a second step, for the sake of comparison, we also obtained a "single best" solution by conditional estimation to the aforementioned data sets. Outcomes of these two sets are compared in terms of physical plausibility and fit to head variation data. We obtained 200 equally likely simulations of the transmissivity and storage coefficient fields that are plausible and fit well to the indirect head variation measurements. 100 out of the aforementioned 200 calibrated transmissivity fields were then used to design an optimum well field layout (Fig. 2).

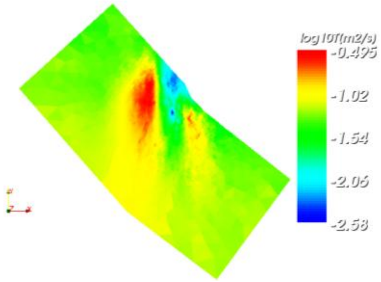

Figure 2. One of the hundred estimated transmissivity field obtained using optimum statistical parameters, conditioned to all available data.

The simulated transmissivity fields were first used to evaluate whether a global abstraction of 9,200 m^3/h was possible with a reasonable number of wells. These first simulations show that, with about 30 wells and a prescribed fixed uniform drawdown of a reasonable value of 8 m in all realizations (which involve having different discharges in each realisation and in each wells), such total discharge could be reached. Based on that result, the question was to define an optimal pumping configuration that was technically and economically feasible. The optimisation was carried using a genetic algorithm (Popov, Filipova, 2004; Popov, 2005) that minimized a cost function accounting for: (1) drilling, operational and maintenance costs, (2) target discharge and minimum drawdown (i.e., minimum aquifer vulnerability) and (3) technical feasibility of the solution. The pump types were limited to two for maintenance considerations. Potential well locations matched mesh nodes and the total number of potential well locations was restricted to 126, due to computing time considerations. These potential locations were placed on the entire model, but preferably in areas that seemed adequate *a priori*: close to the seaside and in zones of high transmissivity. An important constraint was that wells could only be drilled in a relatively limited portion of land owned by the project. The maximum acceptable drawdown in the aquifer was set to 15 m, since a larger drawdown would lead to insufficient saturated thickness and possible failures of the pumps. The optimum well field layout included 33 beachwells (including 8 ancient wells) producing either 100 or 70 l/s each. The position of 3 spare wells was obtained by increasing the water demand by 10%, allowing 3 new wells. The expected drawdown in the optimised wells (before head losses) was expected to range from 6 to 12 m (Fig. 3).

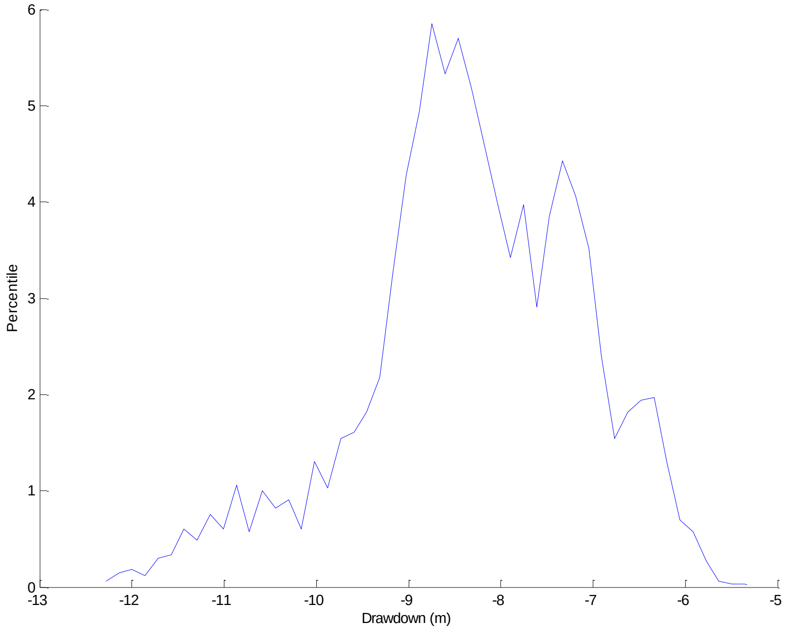

Figure 3. PDF of the drawdown at all optimized wells considering all realisations.

CONSTRUCTION PHASE

The results of the investigations described above were presented to the project founders and led to the project team deciding to implement the 100% beach well option at the construction stage. Based on the optimisation analysis, it was decided to drill 7 wells producing 70 l/s, lined with 14 inch casing, while 18 wells would produce 100 l/ s, lined with 16 inch casing. Additional 3 spare wells producing 100 l/s were also drilled, as well as 4 new wells (100 l/s) to replace inefficient existing wells (initially used for the existing plant). Boreholes were drilled to a depth from 75 to 90 m in order to obtain yields of 70 to 100 l/s and constructed in a manner that minimized the drawdown associated with these discharges. The drilling method employed was an air/foam system. Drilling bits were tri-cone roller-rock bits, 12¾ inch for the pilot hole, and 23½ inch for the reamed hole. After the hole was reamed, an air-lift system was put in place to clean out the fractures and estimate the yield of wells. After having performed open hole development, the holes were equipped with a minimum of 30 m of screen. Slot size was 3 mm to allow the placement of large size gravel (5–10 mm), with open areas of 9% and 7.5% for the 14 inch and 16 inch casings respectively.

All 32 beachwells were not drilled at the modelled location due to various technical constraints. Nevertheless, individual well performances were found to be as expected: a production from 65 to 125 l/s for drawdown limited to 1 to 10 m. The well field was then tested by sector and then globally, up to a production of some 9,200 m^3/h. The water quality was found as expected: EC ranged from 47,000 to 54,000 µS/cm. An estimate of suspended solids was done with Imhoff cones which consistently indicated a concentration of less than 5 mg /l. Silt Density Index (SDI) ranged from 4.9 to 5.8 and turbidity was less than 1.2 NTU. Such water needs little filtration before being used for reverse osmosis system. The new wells have all been equipped with submersible pumps and ancillary equipments. This includes a flowmeter and a pressure level transducer link to telemetry for each individual well in order to monitor their performance.

DISCUSSION AND CONCLUSIONS

Industrial operators are generally reluctant to drill water production wells when other options are feasible. Most often, the main argument is the uncertainty in the yield of the projected wells (David et al., 2009.). For the Sur project, a stochastic characterization of hydraulic parameters from tidal fluctuation and pumping test data was efficiently used to quantify the risks and help decision makers and later to design an optimum pumping network of brackish groundwater. This is therefore a promising methodology for designing well fields in highly heterogeneous aquifers.

The model was built in a conservative way to compensate for the different assumptions made such as discretisation, boundary conditions, pumping considered as continuous, etc. For example, the drawdowns calculated by the models can be underestimated in the pumping wells: they would have been different if another discretisation had been used. The bias caused by discretisation affects all the potential locations in the same way. However, this means that the actual values of the forecasted drawdowns in the pumping wells (before head losses) are slightly higher than these estimates. Nevertheless, the total 9,200 m^3/h required for the new plant facility can now be withdrawn from 32 “beachwells” with an average drawdown of about 12 m including head loses in the wells. Although such “beachwells” have already been in operation for many years in several countries around the world (e.g. Malta, Spain, Canary Islands, Greece, Israel, Saudi Arabia, US, etc.), they have usually been restricted to smaller scale plants (Schwarz et al., 2000; Wang et al., 2007). This project makes Sur the largest SWRO desalination plant in the world fed only by “beachwells”.

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