CHEMICAL ENGINEERING TRANSACTIONS
VOL. 28, 2012
Guest Editor: Carlo Merli

ISBN 978-88-95608-19-8; ISSN 1974-9791

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1228042

Control and Dynamic Management of a Sixty-seven Wells Hydraulic Barrier

Daniele Arlotti*[a], Rossella Bozzini[a], Marco Petitta[b], Marcello Mancini[c], Marcello Pianu[c], Gino Alberto Blanco[d], Chiara Sbarbati[b], Raffaela Colombo[a],

[a]Foster Wheeler Italiana, via Caboto 1, 20094 Corsico (MI), Italy
[b]Università di Roma La Sapienza, Dipartimento di Scienze della Terra, Piazzale Aldo Moro 5, 00185 Roma, Italy
[c]Eni S.p.A. Divisione Refining & Marketing, Via Laurentina 449, 00142 Roma, Italy
[d]Raffineria di Gela S.p.A., Contrada Piana del Signore, 93012 Gela (CL), Italy
*daniele_arlotti@fwceu.com

The Gela Refinery's (Sicily Region, South Italy) hydraulic barrier consists of 67 wells, located along the refinery's seaside border, dedicated to groundwater pumping and free product recovery, and it is part of the remediation system approved by the Public Authorities. In order to manage the hydraulic barrier, water table measurement of about 350 piezometers and weekly dynamic levels of the pumping wells are collected and inserted into a relational database that allows a real-time management of the extensive information gathered.
Every well pumping rate has been defined by hydraulic simulation modelling. Given that the aquifer is a dynamic system, periodically all collected data are analyzed and if necessary, based on the results of the simulation modelling, the well pumping rates are updated: this flow rate is called the "optimized pumping rate". The check and control of the barrier proper operation is conducted through the daily acquisition via the distributed control system (DCS) of all the barrier operation data jointly with all the significant field information. Based on the data collected, routine and extraordinary maintenance activities are planned and implemented to guarantee optimal operation conditions of each component of the pumping system.
The acquisition of a large amount of data (freatimetric levels of all refinery piezometers, dynamic levels of wells, hydrochemical data of wells and piezometers) and their interpretation and processing using a relational database and numerical simulation modelling allows the reconstruction of the groundwater flow and of the barrier's effect on the groundwater table.
The dynamic management of the barrier, using the simulation modelling, proved to be an essential tool to modulate the pumping rate following seasonal variability and allows the system operator and Control Authorities to verify the performance and effectiveness of the barrier, in terms of maintaining the hydraulic containment of the aquifer and of hydraulic efficiency of the remediation system.

1. Introduction

The Gela Refinery's (Sicily Region, South Italy) hydraulic barrier consists of 67 wells, dedicated to groundwater pumping end free product recovery. The 67 wells are located along the Refinery seaside border, where there is also a two-part physical barrier, with an overall length of approximately 3700 m (Figure 1). The wells were activated progressively from 1998, and the current layout of the barrier has

Please cite this article as: Arlotti D., Bozzini R., Petitta M., Mancini M., Pianu M., Blanco A., Sbarbati C. and Colombo R., 2012, Control and dynamic management of a sixty-seven wells hydraulic barrier, Chemical Engineering Transactions, 28, 247-252
DOI: 10.3303/CET1228042

been operating since 2007, transferring pumped groundwater to a dedicated water treatment plant named TAF.

The barrier is part of the remediation system approved by Public Authorities, which provides a wider range of intervention for the safety and rehabilitation of the main aquifer, in order to:

- Recover the supernatant free product floating on groundwater;
- Provide the hydraulic containment of pollutants dissolved in groundwater, using groundwater depression induced by the barrier pumping wells;
- Treat the water pumped by the hydraulic barrier wells.

Water pumped by wells, at approximately 220 m^3/h, is sent through the interconnecting network consisting of two separate pipelines for high and low arsenic content water, to the groundwater treatment plant. The TAF plant was designed to receive a maximum capacity of 300 m^3/h, taking into account the contribution of other companies present in the industrial site. The supernatant product recovered is collected by a dedicated network and transferred to a refinery tank, to be reused in the production process.

The 67 barrier wells have a depth of between 15 m and 33 m and are designed for containment of the main aquifer. This aquifer consists of sands and sandy-loam, with a thickness between 25 and 30 m, thickest near the coastline. Low permeability layers are locally interbedded and generate local superficial perched aquifers. Below the main aquifer there is an aquitard, consisting of fairly thick "clayey silt" with an average power of 25 m. This low permeability level is the lower limit to the groundwater flow of the main phreatic aquifer.

The separate phase product is present in some wells of the barrier, where a selective recovery system is installed. For the dissolved phase contamination, monitoring has shown the widespread presence of:

- Sulfates and Boron, presumably related to the proximity of the site to the sea;
- Iron and Manganese, variously located throughout the plant and also in the nearby Gela plain;
- Benzene and TPH (Total Petroleum Hydrocarbons); these compounds were found to be localized in the central portion of the plant, where separate phase product is also present.

Monitoring also observed the occasional presence of some inorganic compounds (free Cyanides, Nitrogen compounds, Fluorides), Polycyclic Aromatic Hydrocarbons (PAH), metals (Aluminium, Antimony, Arsenic, Chromium, Nickel, Lead and Copper) and chlorinated compounds.

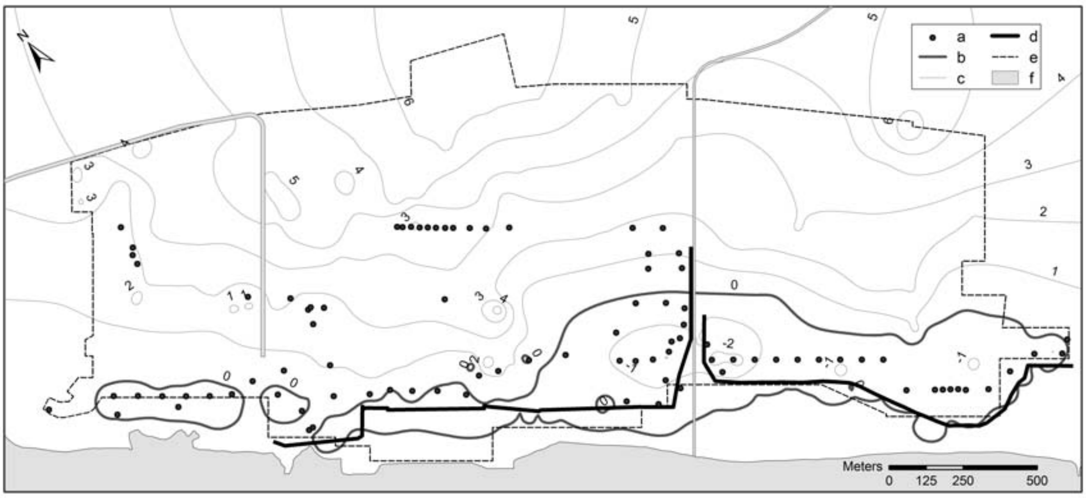

Figure 1: Piezometric map (equidistance 1 m) of the study area; a) pumping wells; b) piezometric line 0 m a.s.l.; c) piezometric lines; d) physical barrier; e) Refinery boundary; f) sea.

2. Collecting and processing data for the management of the barrier

In order to manage the hydraulic barrier, water table measurement of about 350 piezometers and weekly dynamic levels of the pumping wells are collected and processed on a monthly basis. All collected data, along with daily pumping rates and hydrogeological and hydrochemical data, are inserted into a relational database that allows real-time management of the extensive information gathered. The database in Microsoft Access offers the possibility to extract, analyze and compare different data, for evaluation of the efficiency of the remediation activities. A map of the groundwater flow in the Refinery is shown in Figure 1.

Periodically, pumping rates of single wells are considered and modified if necessary, with the following aims in order of priority: a) to ensure the hydraulic confinement of the contaminant plume; b) to limit the marine water intrusion by monitoring the electric conductivity of the extracted waters; c) to minimize the lowering of the dynamic water table in the pumping wells to avoid high hydraulic gradients; d) to recover the maximum mass of contaminant, taking into account the characteristics of the treatment plant; e) to force back to the wells polluted groundwater trapped between pumping wells and the physical barriers. In addition, data are processed at reduced time frequency, on a weekly or daily basis, to evaluate the effect of local and rapid changes in the groundwater hydrodynamics due to wells and pipeline maintenance, extreme rainfall events or other possible changes. In these cases, flow modelling helps to change the pumping rate of each well, to ensure swift hydraulic confinement of the site.

Yearly chemical analyses are considered in the hydraulic barrier management, verifying the efficacy of the remediation plan in the long term. Taking into account the spatial and temporal trend of the concentration of the main classes of contaminants, in each piezometer and along vertical transects, a dynamic management has been adopted, requiring hot-spot withdrawals and changes in pumping rates with respect to initial plans approved for the remediation. In the last two years, additional sampling by multilevel packer systems have been added to the normal sampling activities, to verify possible stratification of contaminants and to obtain a more realistic evaluation of the dissolved contaminant mass in groundwater.

3. Groundwater flow simulation by 3D mathematical model

Groundwater flow modelling was performed by means of the numerical code MODFLOW-2005, while SEAWAT-2000 has been chosen for density-dependent simulations, taking into account seawater intrusion (Harbaugh, 2005; Langevin et al., 2007). Parameter calibration of modelling results has been optimized by the PEST package. Input data are represented by the pumping rate of each well and a distribution of hydraulic conductivity, ranging from 10^{-4} to 10^{-8} m/s, which takes into account both geological vertical heterogeneity obtained by stratigraphies and hydrodynamic data derived from pumping and slug tests. This heterogeneity requires a dense discretization of the site, which includes 12 layers, 92 rows and 234 columns. Refined mesh has been adopted close to the hydraulic and to the physical barriers.

Constraints of the model are represented by a general head boundary along the inflow side, based on water table values measured close to the limit of the Refinery; lateral head-dependent boundaries are included along the Gela River on West side and the Valle Priolo Stream on East side; flow exchanges along these boundaries are close to zero, due to the groundwater flow direction which is coincident with the boundary. Along the shoreline, a constant-head condition has been created, to simulate the effect of the sea level, whose changes with time have been considered negligible. The existence of a marine water canal into the Refinery requires investigation into possible exchanges between surface and groundwater. The presence of a physical barrier has been simulated by a "wall" function having an hydraulic conductivity of 10^{-12} m/s, and of course by extraction rate from wells. Calibration of the flow model has been obtained by comparison with real water table data, collected since 2003. For the density-dependent model, calibration is based on chloride distribution in groundwater. For both parameters the adopted model is in good agreement with field data, both in steady-state and transient conditions.

Monthly simulations in steady-state conditions have been run from pumping well data, obtaining a positive calibration, with less than 40 cm of mean difference between simulated and measured piezometric data. For dynamic management, flow budget and particle tracking forward and backward resulting from the simulation are considered, verifying capture zones of the wells and hydraulic containment of the site (Figure 2). Density dependent simulations are compared with chemical-physical logs for monitoring wells, chemical analyses of pumping wells and also piezometers, including multilevel samplings (Bear et al., 1999).

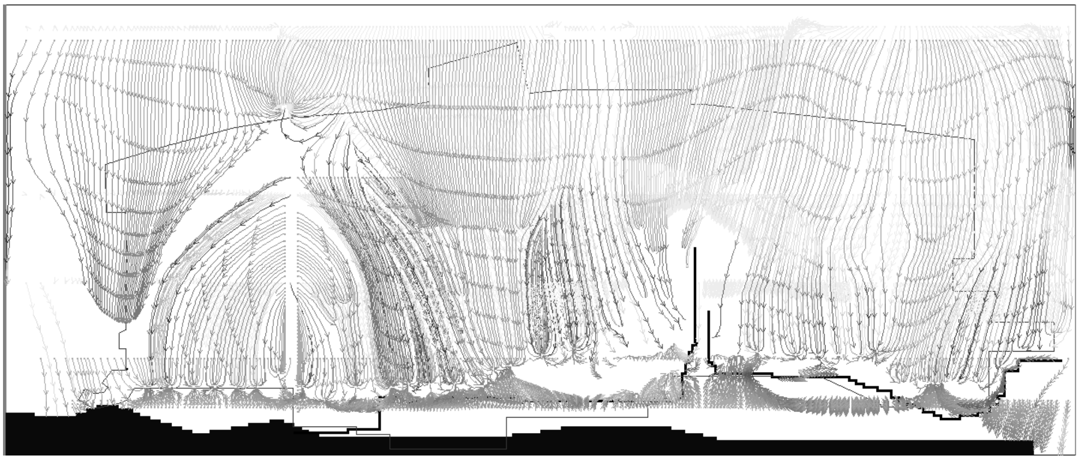

Figure 2 – Modelling simulation by particle tracking forward evidencing the hydraulic confinement.

In addition, short-term transient simulations have been implemented for evaluating changes in pumping rate when operational halts affect the hydraulic barrier. This implies the increase of adjacent pumping wells respective to the well affected by malfunctioning and/or the increase of pumping rate at the end of the halt. These simulations can be preventive, considering possible scenarios of reducing rates in different part of the site, or directly realized during specific situations requiring reducing rates of single or grouped wells.

The numerical model is used also for verifying the interaction between the hydraulic and the physical barriers, considering flow direction and hydrodynamic forced by the co-existence of the double remediation tools. Detailed modelling has indicated a "stagnation zone" located immediately downgradient of the physical barrier, where marine groundwater reclaimed by pumping wells under the physical barrier has created a no-flow zone excluded by the hydrodynamic of the aquifer (Figure 3).

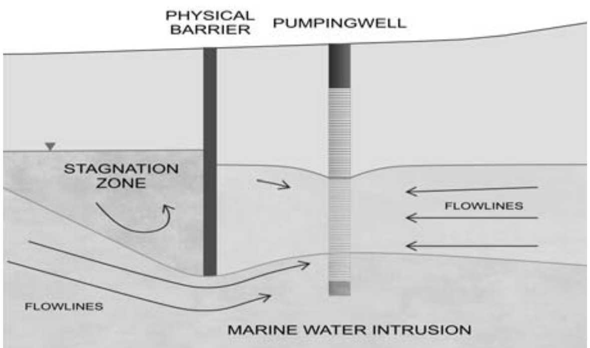

Figure 3 – Groundwater flow detail close to the hydraulic and physical barrier, evidencing a stagnation zone and the marine water intrusion.

In these areas previously allocated contaminants cannot be captured by the pumping wells and at the same time they cannot flow to the shoreline, due to the density contrast with the marine intruded groundwater.

4. Dynamic management of the barrier

Every well pumping rate has been defined by hydraulic simulation modelling. Given that the aquifer is a dynamic system, periodically all collected data are analyzed and if necessary, based on the results of the simulation modelling, the well pumping rates are updated: this flow rate is called "optimized pumping rate". This allows handling of specific situations, such as special weather events (heavy or low rainfall), hydrochemical evidence at the monitoring wells and pumping wells (as increasing trend in salinity nearby the barrier) and routine/extraordinary maintenance of some wells, assuring the barrier hydraulic containment.

With this tool, changes due to natural seasonal or longer oscillations can be solved by changes in recovery rates by single or groups of withdrawal wells. In fact, during 2007 and 2008 the water table suffered by a low-recharge rate and consequently the pumping rate was sufficient to reach the hydrometric zero along the entire shorefront of the hydraulic barrier. Conversely, in 2009 and 2010, a high recharge period caused the water table to rise, requiring an increase in pumping rates in the high-conductivity zones of the site, where the water table was reduced to values close to the hydrometric zero. In these cases, the hydraulic confinement has been guaranteed by the model, which demonstrated that the capture zones of the wells were efficient along the entire shoreline. During 2011, the natural water table gradually returned to previously recorded values, allowing the hydraulic barrier to reach the hydrometric zero in correspondence with the pumping wells.

Similarly, seasonal changes in water table can be suffered by dynamic management, changing flow rate of single wells and verifying that between the hydraulic and physical barrier, groundwater flow is reclaimed by the pumping wells or, in the worst case, that the low velocity of the flow allows the flow direction inversion at the end of the rainy season, ensuring hydraulic containment of the polluted site.

5. Barrier monitoring, maintenance and operation

The check and control of the barrier proper operation is conducted through the daily acquisition via DCS of all the barrier operation data jointly with all the significant field information. At the TAF plant control room, a DCS has been installed to register and control the operating data coming from the pumping wells, the water and product pumping units, the pre-treatment units and the product storage tank. In addition to data collected by the DCS, weekly field surveys are conducted in each well in order to verify the proper recording of data to DCS and to collect the data that are not acquired by the DCS.

Monitoring and verifying the correct operation of the groundwater containment system are designed and implemented to:

- Ensure the continuous operation of the hydraulic barrier wells, in compliance with the project parameters;
- Maintain system efficiency (hydraulic, structural, mechanical electrical and instrumental), minimizing wells service interruption during routine and extraordinary maintenance;
- Ensure that the flow rates of pumping wells are consistent with those established by the dynamic management system (see Chapter 4).

As a result of all activities and controls carried out, and based on the collected data, necessary routine maintenance (e.g. substitution of water pumps and product recovery pumps) and extraordinary maintenance (such as video inspection, stepped and / or long-term pumping tests, well rehabilitation activities), are designed to ensure optimal operation conditions.

The extraordinary maintenance of well rehabilitation is planned when a lowering of the well dynamic level is detected, indicating gradual clogging of the drain. These interventions consist of a sequence of activities: brushing, debris removal using airlift, preliminary video inspection, surging, jetting tools, second debris removal with airlift, final video inspection. Finally, a stepped pumping test is performed to verify if the efficiency of the well has been recovered. On average, 14 interventions per year of extraordinary maintenance are usually made.

6. Conclusions

All the companies present in the industrial site have submitted to Public Authorities an "Operative protocol for water quality monitoring" that currently is under approval. The monitoring protocol will be the instrument to monitor and verify, in a uniform, consistent and unique way, in the whole multi-company plant:

- The constant and correct operation of all groundwater remediation systems, according to the approved remediation project, in order to promptly operate in case of malfunction;
- The hydraulic efficiency of these systems;
- The groundwater quality evolution, upstream and downstream of the remediation systems (hydrochemical effectiveness);
- The treatment plant TAF performance.

The acquisition of a large amount of data (water table levels of all refinery piezometers, dynamic levels of wells, hydrochemical data of wells and piezometers) and their interpretation and processing using relational database and numerical simulation modelling, allows reconstruction of the groundwater flow and of the barrier's effect on the groundwater table. An overall picture of the system is obtained, both in terms of groundwater direction and extension of the barrier hydraulic capture front, depending on the applied wells pumping rates.
The dynamic management of the barrier, using the simulation modelling, proved to be an essential tool to modulate the pumping rate following seasonal variability and allows the system operator and Control Authorities to verify the performance and effectiveness of the barrier, in terms of maintaining the hydraulic containment of the aquifer and of hydraulic efficiency of the remediation system.

References

Bear J., Cheng A. H.-D., Sorek S., Ouazar D., Herrera I.,1999. Seawater Intrusion in Coastal Aquifers – Concepts, Methods and Practices. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Harbaugh A. W., 2005. MODFLOW-2005, the US Geological Survey modular ground-water model – the Ground-Water Flow Process. US Geological Survey Techniques and Methods 6-A16.

Langevin C. D., Thorne D. T. Jr., Dausman A. M., Sukop M. C., Guo Weixing, 2007. SEAWAT Version 4: A Computer Program for Simulation of Multi-Species Solute and Heat Transport. US Geological Survey Techniques and Methods Book 6, Chapter A22, 39 p.