Evaluation of groundwater-surface water interaction through groundwater modelling: simulation of the effects of removal of a dam along a river at a contaminated site in Northern France.

Valutazione dell'interazione tra acque sotterranee e acque superficiali attraverso la modellazione di flusso: simulazione degli effetti di rimozione di una diga lungo un fiume adiacente ad un sito contaminato nella Francia del Nord.

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Riassunto: Un modello di flusso numerico è stato sviluppato per un sito contaminato nella Francia del Nord. Lo scopo del lavoro era l'ottimizzazione di una barriera idraulica esistente per la messa in sicurezza del sito e la previsione dei possibili effetti sulla circolazione idrica sotterranea dovuti alla rimozione di una diga lungo un fiume adiacente al sito.

Il modello è stato sviluppato col codice alle differenze finite MODFLOW 2005 e rappresenta un'area con estensione di circa 800 x 500 m. E' stato calibrato utilizzando i dati piezometrici misurati in condizioni statiche e verificato 1) utilizzando dati piezometrici rappresentativi di condizioni dinamiche, 2) simulando delle prove di pompaggio mediante simulazioni in regime transitorio e 3) confrontando il deflusso di base medio del fiume con il deflusso idrico medio dalla falda al fiume simulato.

Il modello indica che la barriera idraulica nelle condizioni attuali di esercizio è parzialmente efficace e necessita di un'ottimizzazione. Ciò è confermato dai dati di qualità chimica delle acque del fiume, che mostrano l'esistenza di un apporto di contaminanti localizzato proveniente dal sito. Un primo scenario previsionale è stato sviluppato per l'ottimizzazione della barriera e ha indicato la necessità di attivare il pompaggio da tre nuovi pozzi con una portata di 0,5 m³/h ciascuno, in aggiunta ai pompaggi già attivi presso il sito.

Un secondo scenario previsionale ha simulato l'esercizio della

barriera nello scenario ottimizzato nelle condizioni in cui la diga, attualmente presente lungo il fiume presso il sito, venga rimossa. In queste condizioni, il modello indica che il drenaggio esercitato dal fiume verrà incrementato e che per garantire la tenuta idrochimica del sito sarà necessario un ulteriore aumento nelle portate da estrarre dalla barriera.

Con questo articolo si intende presentare un caso di studio che illustri quello che gli autori considerano un corretto approccio professionale, per cui è stato sviluppato il più semplice modello di flusso possibile con riferimento alla complessità del modello concettuale idrogeologico, all'abbondanza di dati e agli obiettivi della modellazione, ma dove sono state ricercate conferme multiple della correttezza dei risultati conseguiti.

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Abstract: *A numerical groundwater flow model has been developed for an industrial site bounded by a river in in Basse Normandie, Northern France. The scope of the work was the optimisation of the existing groundwater pump and treat system and the prediction of possible effects on groundwater circulation after the future removal of a dam located along the river.*

The model has been implemented with the finite difference code MODFLOW 2005 and represents an area with an extension of approximately 800 x 500 m. It has been calibrated using static conditions groundwater head data (wells deactivated) and verified with 1) abstracting conditions (wells abstracting) head data, 2) simulating pumping tests with transient simulations and 3) comparing measured average river baseflow with modelled river drainage.

The model indicates that the hydraulic barrier in the present abstraction scenario has some problematic areas and needs some improvements, as confirmed by the hydrochemical data of the river water.

A first predictive scenario has been developed to optimise the barrier, indicating that a flow rate of 0.5 m³/h each at three new barrier wells, in addition to the present abstraction scenario, should ensure the hydraulic containment of the site.

A second predictive scenario simulates the optimised groundwater abstractions without the presence of the dam along the neighbouring river. In these conditions, the river will increase the drainage effect on the aquifer, requiring a further increase in the rate of abstraction from the existing and new wells to ensure the hydraulic containment. With this paper we would like to present an example of what we think is a correct professional approach, with the design of the simplest model as possible depending on the hydrogeological conceptual model complexity, the abundance of data and the model objectives, and where multiple confirmations of the correctness of groundwater model results have been searched for.

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Introduction

Recent studies of the United States Environmental Protection Agency (U.S. EPA) and the Navy (Naval Facilities Engineering Command of United States) indicate that the majority of existing pump and treat systems have not been optimised since installation (Becker at al. 2006). Also as a consequence of the inadequacy of hydraulic barrier optimisation, the remediation progress in the sites where a pump and treat system is active is usually slower than expected, after the early operational phases (Hadley and Newell, 2012).

A groundwater model, if well designed and calibrated, is the best tool available to make predictions on the behaviour of complex aquifer systems (Anderson and Woessner, 1992). Particularly for contaminated sites, groundwater modelling is generally considered the most cost-effective way to predict the extent of groundwater contamination and design remedial solutions (Batu, 2005).

The increasing power of computers over recent years has simplified the realisation of more and more complex groundwater models, often without taking into account that an increase of model complexity, seen here as the number of input parameters, if generally corresponding to better fit to calibration targets, does not necessarily produce an increase in predictive performance. A trade-off exists between fitting and predictive model accuracy, because the improved fit is sometimes achieved by matching the observation errors (Hill, 2006).

This paper presents a groundwater flow model realised in the context of a professional consultancy, designed in a way to optimise the model complexity considering the relative scarcity of data and the simple hydrogeological conceptual model, increasing work efficiency and reducing the developing costs, in full accordance with the principle of parsimony. In addition, the model is designed to allow multiple independent confirmations of predictive performance and reliability.

Site description and available data

The site is an active industrial plant located in Basse Normandie (Northern France) subject to historical soil and groundwater contamination, primarily due to the use of chlorinated solvents.

It is underlain by Holocene alluvial deposits with a total thickness of 1 to 4 m. This material consists of silt with scattered gravels and is characterised by low to medium hydraulic conductivity. The underlying formations are fractured flysh and shales with unknown thickness (expected to be thousands of meters), that represent low conductivity hydrogeological units hydraulically connected to the overlying alluvial deposits. Although no regional groundwater contour maps are available to demonstrate the flow pattern, the regional groundwater flow direction is likely from West to East, parallel to the river valley.

In the central sector of the site, the presence of a former riverbed has been identified by the boring logs analysis (Figure 1). At the site, the depth of groundwater ranges from approximately 1.5 to 5 m below ground level (b.g.l.), corre-
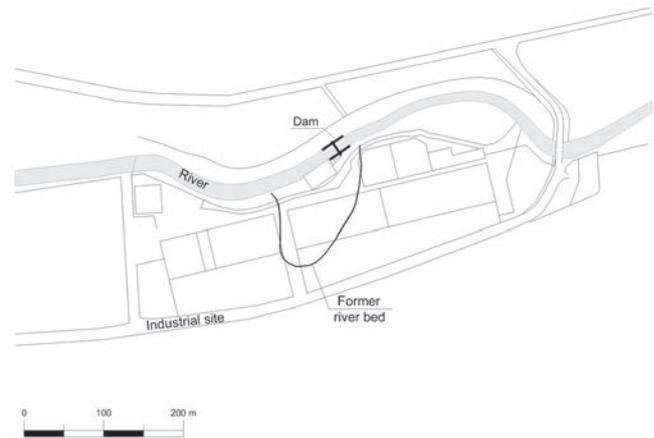

Fig. 1 - Site base map.

Fig. 1 - Mappa del sito.

sponding to an absolute groundwater elevation between 76 and 73 m above the average sea level; the water table is mainly located in the superficial layer of alluvial deposits.

The groundwater at the site is contaminated by Trichloroethene (TCE), cis1,2 Dichloroethene (cis-DCE), Vinyl Chloride and Total Petroleum Hydrocarbons (TPH). A pump and treat remediation system was installed in 1995.

Local groundwater contour maps corresponding to April 2010 and May 2010 are available. The April 2010 contour map is representative of the condition with all wells inactive (static conditions) and indicates that the river exerts a strong draining effect. The general flow direction is South-West to North-East and the average hydraulic gradient is about 0.6%, whereas in the Northern-Eastern sector of the site, immediately downstream from a sheet pile installed along the riverbed, the gradient rises to 1.5% (Figure 2A). The May 2010 groundwater contour map has been realised under abstracting conditions at the wells A, B, E, G, H, K and N. Abstractions create two areas of groundwater drawdown, which reverse flow and induceflow from the river to the aquifer (Figure 2B).

Transmissivity, hydraulic conductivity and storativity of the alluvial deposits have been determined with two constant rate pumping tests carried out by pumping water from wells E and N and measuring drawdown at neighbouring monitoring wells. The analysis of these pumping tests has been carried out with Neuman's curve-fitting method (Neuman, 1972). General transmissivity of the alluvial aquifer is 1.4×10^{-4} m^2/s (corresponding to a hydraulic conductivity of 1.44×10^{-4} m/s), whereas the evaluated transmissivity of the former river bed is 2.89×10^{-4} m^2/s (k=4.67×10^{-5} m/s). The *Infoterre database (http://infoterre.brgm.fr/) reports a transmissivity value for the shale unit of about $T=1 \times 10^{-3}$* m^2/s.

The hydrographs of the adjoining river and some tributaries have been provided by the Direction Regionale de l'Aménagement de l'Environnement et du Logement (DREAL) de Basse – Normandie for a number of gauging stations close to the industrial site, from 1975 to present. A baseflow contribution is evident in all the available hydrographs, indicating that there is a groundwater contribution to the river flow.
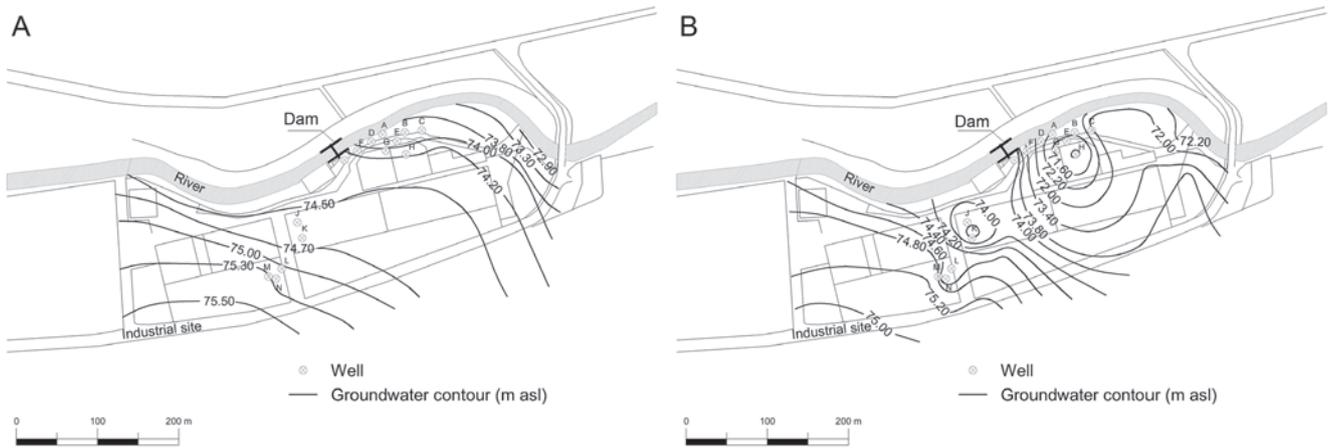
Fig. 2A, B - Groundwater contour maps under static and abstraction conditions.

Fig. 2A, B - Piezometrie in condizioni statiche e dinamiche.

Baseflow separation has been done with a method similar to the local minimum method reported in Healey, 2010 in order to estimate aquifer drainage (Figure 3). The method identifies a local minimum in the river hydrograph when daily flow rate is the lowest within a given period of time and assigns the average flow rate value within that period elsewhere. The resulting curve is considered representative of the river baseflow. With the available data, baseflow usually ranges from 0.5 m³/s, in summer, to 8 m³/s in winter, with an average value of 3.14 m³/s. The selected period length is 30 days. As the catchment basin extension is about 512 km², the unit baseflow ranges from 0.001 m³/s/km² to 0.015 m³/s/km², with an average value of 0.006 m³/s/km².

Recharge calculation

Aquifer recharge has been calculated using different approaches, in order to compare the results and get a reliable estimation (Healy, 2010).

At first, a simplified mass balance (Thornthwaite and Mather, 1955) has been calculated with daily cumulative precipitation and average air temperature data for a meteorological station located about 60 km North of the site, with data ranging from January 2004 to May 2011. Annual cumulative

rainfall in the selected period ranged between 698 to 1,117 mm, with an average value of 811 mm; annual average temperature varied between 10.5 to 11.7°C. Potential evapotranspiration has been calculated with the Thornthwaite method (Thornthwaite, 1948) and runoff coefficients of 0.5 for the urbanised areas and 0.3 for the draining areas have been assumed (Fetter, 2001). Calculated recharge with this method is 0.0005 m/day for urbanised areas and 0.00067 m/day for the draining areas.

A second approach applied is the "instantaneous recharge" method of Rorabaugh (Rorabaugh, 1964). For its application, the method requires the validity of some assumptions: the aquifer (the alluvial sediments and the underlying weathered bedrock) is thick relative to the change in water level caused by recharge, the stream fully penetrates the aquifer, the aquifer is isotropic, homogeneous and has uniform thickness, the aquifer is underlain by impermeable material, other factors do not affect water level and the recharge is instantaneous and uniformly distributed throughout the watershed (Mau and Winter, 1997). All the above mentioned criteria are reasonably met for the site, considering that 1) the river presents a significant drainage effect that could be considered the prevalent groundwater discharge term of the aquifer mass balance, 2) the riverbed intercepts the entire thickness of the alluvial deposits and of the weathered bedrock and 3) the underlying fractured rocks present a very low hydraulic conductivity. The Rorabaugh method has been implemented with the RORA program (Ruthledge, 1992 and 2007), downloadable from the United States Geological Service (USGS) web-site, using the 2010 hydraulic data of the river bounding the site, obtaining a recharge value of 0.0006 m/day, comparable to the value obtained with the simplified water mass balance method.

A third method for the recharge calculation consists in the baseflow separation analysis: the baseflow component of streamflow is assumed to be equivalent to groundwater recharge when the aquifer discharge is only into the river (Mau and Winter, 1997; Healy, 2000). This condition is substantially met for the site, where the only other groundwater discharge is from pumping wells, with negligible abstraction
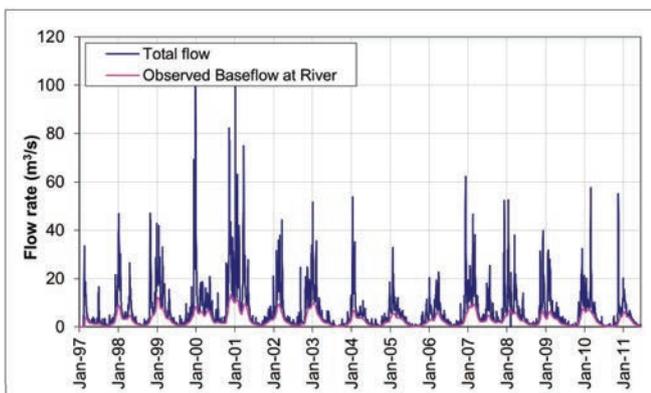

Fig. 3 - Streamflow hydrograph analysis with baseflow separation.

Fig. 3 - Analisi dell'idrogramma fluviale con separazione del deflusso di base.

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rates. Considering the abovementioned average baseflow of 3.14 m³/s and the catchment basin extension, average recharge is estimated as 0.00053 m/s, slightly lower than the value calculated with the Rorabaugh method and within the range of values obtained with the water mass balance calculations.

Groundwater flow model

The groundwater flow model has been realised with the finite-difference code MODFLOW 2005 (Harbaugh and McDonald, 1996; Harbaugh, 2005), with the graphical interface Groundwater Vistas 6 (Environmental Simulations, Inc. 2011).

The finite difference grid presents about 13,000 active cells, each with a planar extension of 5 x 8 m. The grid presents 2 layers, representing the alluvial sediments (Layer 1) and the fractured aquifer (Layer 2) (Figure 4).

Active cells are delimited at North with an alignment of "River" cells, representing a third type (Cauchy) boundary condition (Anderson and Woessner, 1992). Water depth at the river has been considered equal to 1.5 m upstream to the dam and 0.5 m downstream it, based on the field survey results. The Southern, Western and Eastern boundaries of the model are modelled as first type (Dirichlet) boundary conditions, defined with "Constant Head" (CH) cells based on the groundwater contour map of April 2010. These CH cells are far enough from the pumping wells to not influence the results of the calibration or predictive simulations (Figure 4).

Layer 1 geometry has been defined interpolating the ground elevations and the alluvial base elevation data derived by the soil boring logs. No data regarding the shale thickness were available, so a conventional thickness of 20 m has been considered.

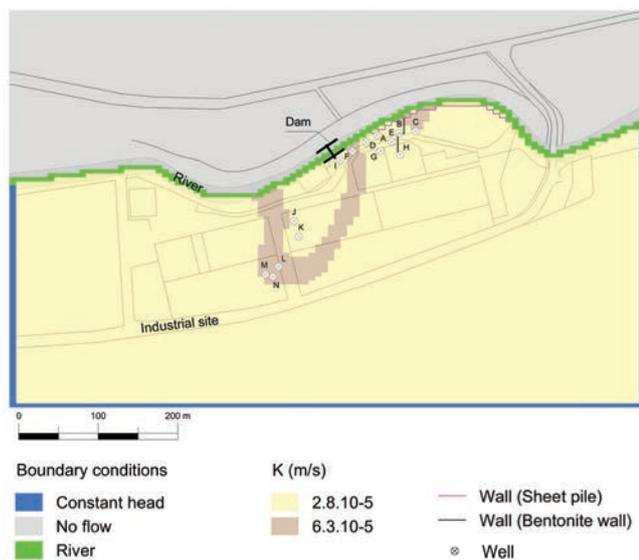The initial hydraulic conductivities of the alluvial material in Layer 1 have been quantified using the values obtained with the pumping test interpretation, namely 1.44×10^{-4} m/s at the PW3 area and 4.67×10^{-5} for the area around well N. The well N area value has been applied to a zone defined along the former riverbed (Figure 4). The hydraulic conductivity of the shale aquifer has been calculated dividing the aquifer transmissivity by a conventional thickness of 20 m, obtaining a value of K= 6×10^{-5} m/s. In this way, the transmissivity of the shale aquifer is correctly represented in the numeric model.

Initial values of recharge have been set to 0.0005 m/day for the urbanised areas and 0.0007 m/day for the draining areas.

Model calibration and verification

The model has been calibrated under the static conditions of April 2010 by means of a manual parameter optimisation after several rounds of sensitivity analysis. A total of 29 groundwater head measurements were available.

The calibration graph presents a satisfactory alignment along a 45° straight line (Figure 5). The calibration statistics (Table 1) indicate that the absolute residual mean is lower than the 10% of the simulated difference in heads, which is nor-
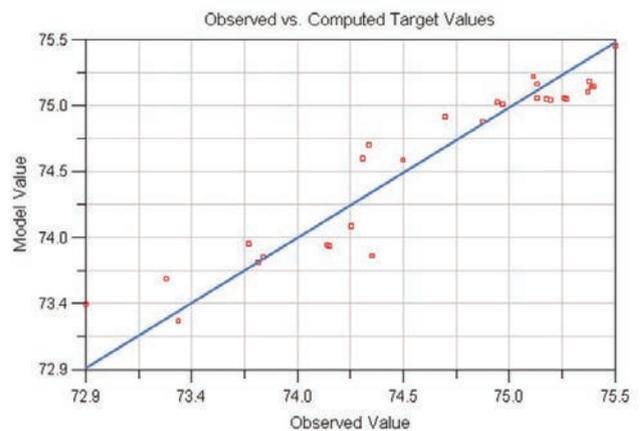

Fig. 5 - Calibration graphs under static conditions.
Fig. 5 - Grafico di calibrazione della simulazione in condizioni statiche.

Tab 1 - Calibration statistics of the static condition simulation.
Tab. 1 - Statistiche di calibrazione della simulazione in consizioni statiche.

Parameter	Value (resting cond.)	Value (abstracting cond.)
Residual Mean	0.02	0.02
Res. Std. Dev.	0.23	0.48
Res. Sum of Squares	1.53	6.57
Abs. Res. Mean	0.19	0.33
Min. Residual	-0.52	-1.51
Max. Residual	0.51	0.98
Range in Target Values	2.61	4.34
Abs. Res. Mean / Range	0.073	0.076

Fig. 4 - Model finite-difference grid, boundary conditions and hydraulic conductivity zones of Layer 1.
Fig. 4 - Griglia alle differenze finite, condizioni al contorno e zone di conducibilità idraulica del modello.

mally considered a target value for the acceptance of a model calibration (Anderson and Woessner, 1992). The groundwater flow directions in the modelled level contour map (Figure 6) are very similar to those represented in the groundwater level contour map of Figure 2.

The model has been verified under the abstracting conditions of May 2010. The calibration statistics are reported in Table 1: the residual mean is 0.02 m and the absolute residual mean is, again, lower than the 10% of the observed range in head. The modelled groundwater head contours of May 2010, reported in Figure 2, are quite similar to the interpolated contours (Figure 6). Close to wells F and E the extension of the area affected by drawdown in the simulation appears to be smaller than in the interpolated map, which is likely to be due to the distribution of the monitoring wells. The simulation should be considered more realistic than the interpolated level contour map in the vicinity of the abstraction wells.

To complete the model verification, the pumping tests executed at wells E and N have been modelled with two transient simulations. The computed time-drawdown curves at the monitoring wells were compared to the measured data, with satisfactory results (Figure 7).

Finally, the model under the static condition scenario has been used to calculate the unit flow rate drained by the river in the modelled area. When comparing this result with the calculated unit baseflow data, the model indicates a unit drainage of 0.0055 m^3/day/km^2, which is quite similar to the measured value of 0.0061 m^3/day/km^2.

During the calibration and verification process, the initial values of hydraulic conductivity were optimised as follows: alluvial aquifer: 2.6×10^{-5} m/s; alluvial aquifer (former riverbed): 6.3×10^{-5} m/s; fractured aquifer: 2.6×10^{-5} m/s. Recharge values for the calibrated model are 0.0004 m/day for urbanised areas and 0.0005 m/day for draining areas.
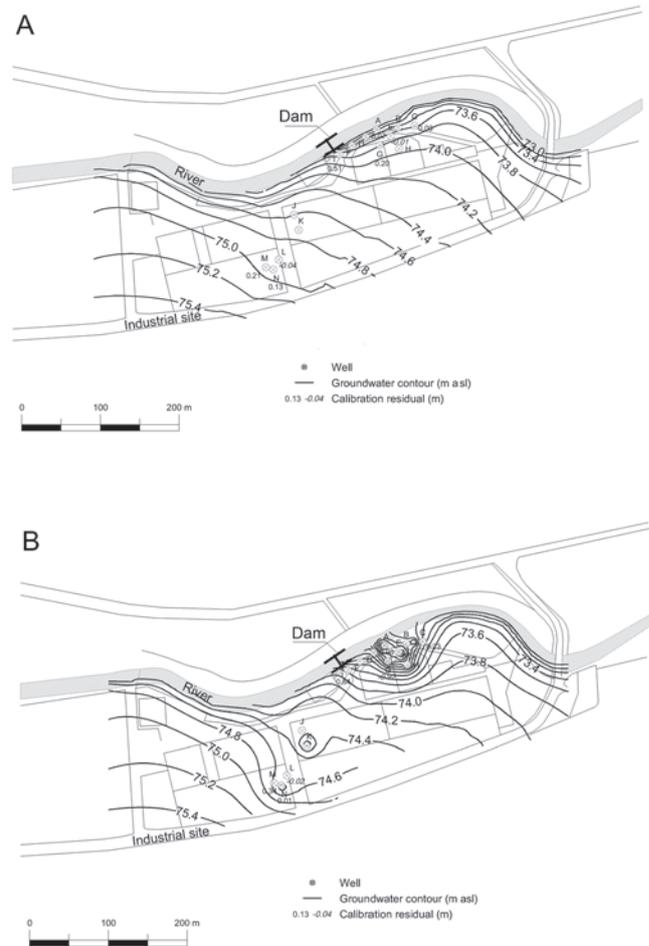

Fig. 6 - *Modelled groundwater contours under static and abstraction conditions.*
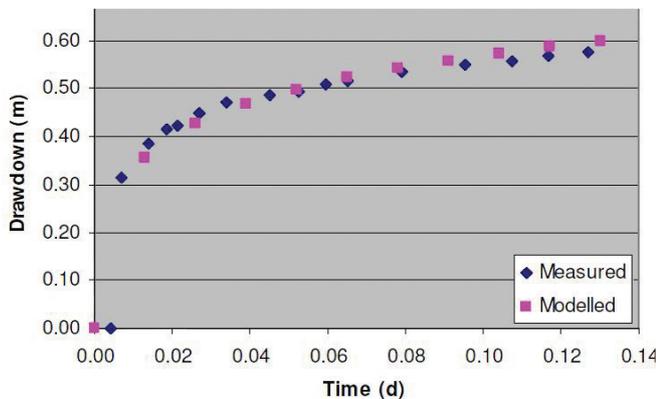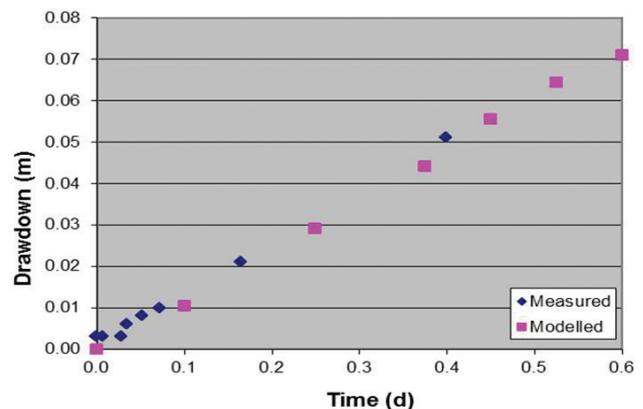Fig. 6 - Piezometrie simulate in condizioni statiche e dinamiche.

Fig. 7 - *Model verification: simulation of well N pumping test.*
Fig. 7 - Verifica del modello: simulazione della prova di pompaggio eseguita presso il pozzo N.
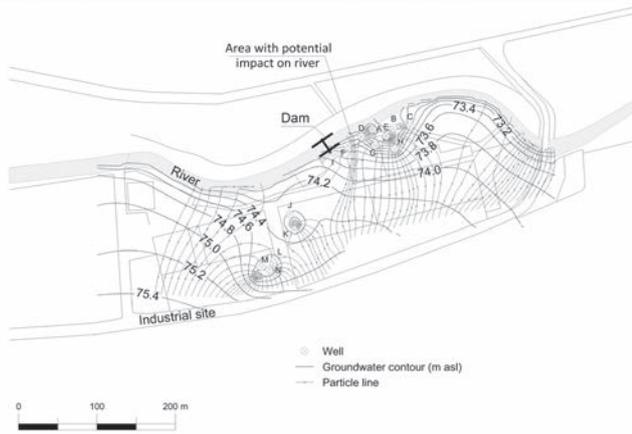
Fig. 8 - *Simulation of current conditions.*
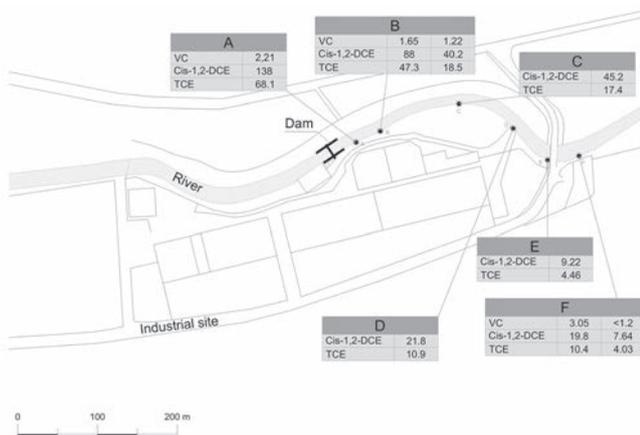Fig. 8 - Simulazione dello scenario attuale.

Fig. 9 - *Hydrochemical data along the river.*
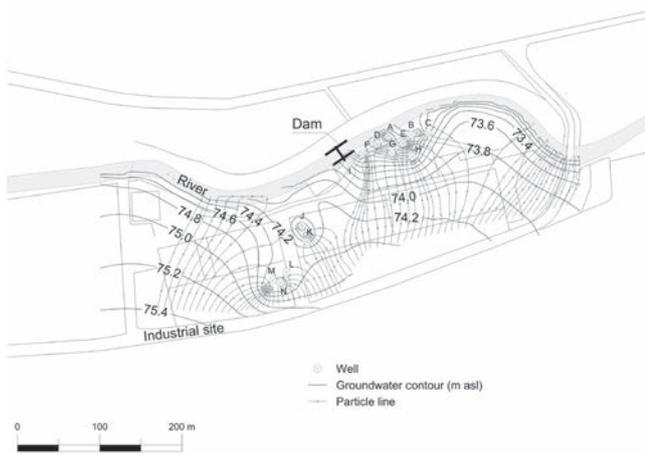Fig. 9 - Dati idrochimici delle acque del fiume.

Fig. 10 - *Optimised abstractions scenario simulation.*
Fig. 10 - Simulazione dello scenario di messa in sicurezza ottimizzato.

Simulation of current conditions

The calibrated model was used to simulate the present groundwater abstraction scenario in order to verify the effectiveness of the groundwater containment. Figure 8 represents the modelled groundwater contour map and the particle traces, calculated with the finite difference code MODPATH. It is possible to see that the majority of the particle lines are captured by wells, whereas in the area between monitoring wells I and A, some particle lines are captured by the river.

The model prediction is fully confirmed by hydrochemical data measured in July and August 2010, showing the maximum concentrations of chlorinated solvents in river water between wells I and A, with a general decrease of concentration downstream (Figure 9). The high degree of correspondence between simulated results and hydrochemical evidence in the river water confirms the reliability of this groundwater model to predict aquifer behaviour.

Optimised abstractions simulation

A future scenario has been developed to simulate groundwater abstraction at well J (close to well K) and at wells F and D (between wells I and A). This scenario considers the presence of the dam along the river. Pumping rates for wells J, F and D have been considered to be 0.50 m^3/h, based on the actual pumping rates of adjacent wells. The model results indicate that, under these conditions, all the particle lines are captured by wells and no more particle lines are captured by the river (Figure 10).

Some sectors of the facility, represented in yellow in the figure, still appear to be drained by the river, but the available records of groundwater analysis indicate that contaminant concentrations are acceptable.

Optimised abstractions and dam removal simulation

A second future scenario has been developed to simulate the removal of the dam along the river and the contemporary activation of pumping wells at optimised abstraction rates.

Conservatively, river water thicknesses have been set up to a constant value of 0.1 m in the whole model domain, which represents a draught scenario. In such a case, without the presence of the dam, the river will increase its drainage effect, with a rise of the hydraulic gradient in the North-Western sector of the facility.

Under this scenario (Figure 11), the model indicates an enlargement of the aquifer sector being drained by the river and that a slight increase in the flow rate at well F (from 0.5 to 0.6 m^3/h) would be required to capture all the particle lines. The sectors of the aquifer drained by the river are characterised, again, by low contaminant concentrations.
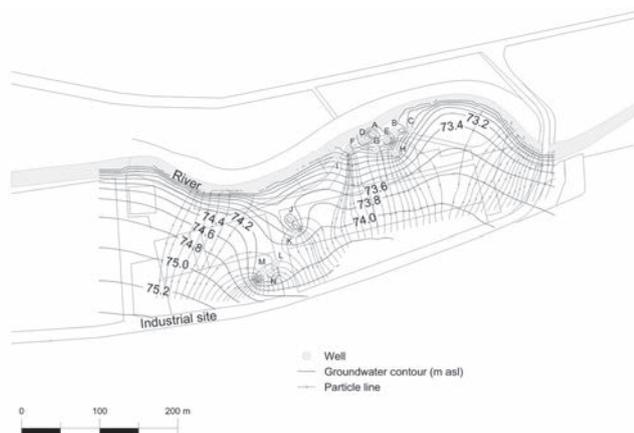
Fig. 11 - Optimised abstractions and dam removal scenario simulation.

Fig. 11 - Simulazione dello scenario di messa in sicurezza ottimizzato e rimozione della diga.

Conclusions

The model presented in this paper has been implemented after a complete data analysis, using a wide hydrogeological data-base and knowledge developed during the site characterisation, over several years. Particularly, the presence of long term meteorological data and a complete data-series of hydrometric levels for a river draining the aquifer close to the site, allowed a comprehensive recharge calculation, with multiple criteria that converged to similar solutions.

The model has been calibrated and validated in several independent ways: within static and pumping conditions, simulating a pumping test with a transient simulation, verifying the accordance between average river baseflow and modelled river drainage and comparing model solutions to the measured river hydrochemical data.

The calibrated model has been used to optimise the barrier well abstraction rate and locations and to predict the future hydrogeological scenario after the removal of a dam along the adjoining river, which would be difficult without a numerical model.

The robustness of the adopted model design and calibration procedure ensures high reliability of the model results and, at the same time, high computational velocity and work efficiency.

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