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ORIGINAL ARTICLE

Installation of a vertical slurry wall around an Italian quarry lake: complications arising and simulation of the effects on groundwater flow

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Abstract Slurry walls are non-structural barriers that are constructed underground to impede groundwater flow or manage groundwater control problems. The study area is in the Piemonte plain (Italy), close to the River Po. Quarrying works carried out below the piezometric surface created two big quarry lakes. The local groundwater system is characterized by a lower semi-confined aquifer, which is overlain by a semi-permeable bed of clayey peat (aquitard) and an upper unconfined aquifer. Locally, the peat fades away and the granulometry of this horizon becomes silty sandy. A planned enlargement of the quarry will increase the size and depth of the quarry lakes. So the aquitard bed between the two aquifers will be damaged, creating a mixing rate of groundwater. Such a procedure would not be compatible with the presence of two municipal wells upstream from the quarries. Consequently, the installation of a vertical diaphragm (slurry wall) is recommended to separate the aquifers and to act as a filter for the groundwater flowing from the unconfined to the semi-confined aquifer. To predict the consequences caused by the installation of the vertical diaphragm separating the unconfined aquifer and the semi-confined one, a specifically adjusted finite-difference model was used. The model showed a maximum rising of the water table equal to 12 cm, just upstream of the diaphragm and for a distance of about 100 m, and a maximum lowering of 2 cm just downstream of the diaphragm. However, the slurry wall would not cause any change in the piezometric head in the area where there are municipal wells and, hence, will not have any negative effect on the functionality of the municipal wells. Moreover, the migration of water from the unconfined aquifer through the vertical diaphragm will stimulate a series of attenuation and auto-depuration processes of eventual contaminants. These processes are due to the higher crossing time that the groundwater flow takes to go through the vertical barrier ($t_a = 96.5$ days, whereas for the horizontal semi-permeable layer $t_a = 9.6$ days). So, the vertical diaphragm can be a resolutive element, representing a mediation and separation factor between the unconfined and the semi-confined aquifers along the border of the quarrying areas, and a protective barrier for the water quality of the quarry lake and the semi-confined aquifer.

Keywords Numerical modelling · Quarry lake · Groundwater flow · Finite differences · Slurry wall · Italy

Introduction

The study area is in the Piemonte plain that comprises the municipalities of La Loggia and Carignano (Province of Torino, Italy) (Fig. 1).

In this area, along the River Po, sand and gravel were extracted below the water table, which created two large quarry lakes.

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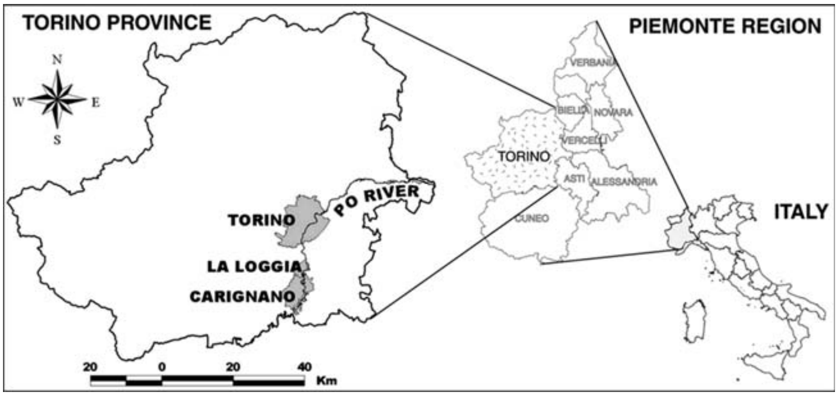


Fig. 1 Geographical location of the study area

A recent plan for the enlargement and deepening of the quarries provoked controversy because of three municipal wells in areas of a few hundred metres upstream.

These three well locations take groundwater from the semi-confined aquifer, which, after the deepening of the quarries, would become connected with an unconfined aquifer over a wide area near the lake, thus creating the risk of intercepting low-quality water from the unconfined aquifer.

The two aquifers are currently separated by a semi-permeable clayey peat bed (aquitard) layer, on average 1.5 m thick. Locally, the peat bed fades away and the granulometry of that horizon becomes silty sandy, which causes a local mixing water zone between both the unconfined and the semi-confined aquifer.

Data gathered from a detailed hydrogeological reconstruction of the site are the basis for the installation of a medium separating the two aquifers, which is directed to mediate and reduce the migration of water from the superficial to the lower aquifer, currently performed by the natural semi-permeable layer.

The medium suggested is a vertical low-permeability diaphragm, which has to be installed adjacent to the border of the quarry areas.

The vertical diaphragm can be bottomed on the aquitard, transverse compared to the groundwater flow; slurry wall thickness can be of 2 m and hydraulic conductivity equal to 1.6×10^{-7} m/s.

Study area

Regional geological and lithostratigraphic outline

The study area is in the southern part of the Piemonte plain, about 10 km south of Torino. It is on the west bank of the River Po, between the river itself and a 7–8 m terrace extended in a north–south direction of an average altitude of 227 m a.s.l.

Holocene fluvial deposits (flO), characterized by gravelly and gravelly sandy alluvia of the riverbed and by sandy clayey alluvia, outcrop on the eastern portion of the studied area (Fig. 2).

To the west of the studied area, the mid-Pleistocene (flR) of glacio-fluvial and fluvial outcrop.

Within the portion of the studied plain, it is possible to highlight three distinctive litho-stratigraphic complexes (Fig. 3), listed from top to bottom (Bortolami et al. 2002; Bove et al. 2005a):

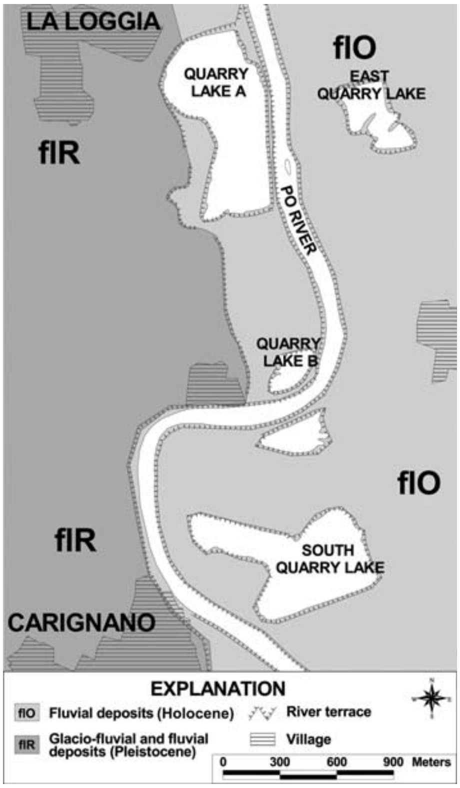


Fig. 2 Geology of the study area and location of Quarry Lake A, B and East

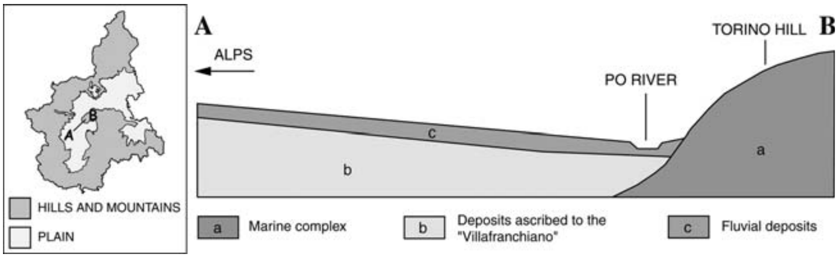


Fig. 3 Sketch of the stratigraphical complex (not in scale)

1. Fluvial deposits complex (late Pleistocene—mid-Holocene): deposits characterized by gravelly sandy texture, with subordinate silty clayey intercalations.
2. ‘Villafranchiano’ complex (late Pliocene—early Pleistocene): fluvial-lacustrine deposits characterized by alternations of silty clayey and gravelly sandy horizons. The ‘Villafranchiano’ complex is found at different levels beneath the southern Piemonte plain; this complex ends in the proximity of the study area. To the south of this area, the fluvial deposits of the Quaternary, which overlie the ‘Villafranchiano’ complex rest directly on an eroded surface of the late Pliocene deposits (Lucchesi 2001).
3. Marine complex (early Pliocene): marine sediments with fine texture that underlie the above sediments and represent the underground continuation of the Tertiary marine complex of the Torino Hill.

Local hydrogeological and litho-stratigraphical outline

A detailed lithostratigraphic and hydrogeological investigation was presented to describe the local lithostratigraphic outline. Three lithostratigraphic cross sections were produced by using data from stratigraphic reports of boreholes and soil samples (Figs. 4, 5).

Some lithostratigraphic levels were highlighted as follows from top to bottom:

1. The first level is characterized by medium to fine sandy deposits with some fine gravel; the thickness is about 10–12 m above the terrace and about 3–4 m just below the terrace; it represents the unconfined aquifer of modest permeability and low discharge.
2. The second level is the silty clayey aquitard bed with intercalations of peat and lignite, whose thickness is from 0.5 to 3 m and found at depths between 2.4 and 14.6 m. The thickness of this horizon decreases while proceeding from west to east and from south to north; it has a declination of very few degrees towards east–northeast. From a hydrological point of view, this layer represents the aquitard that partially confines to the lower aquifer. Locally, the peat fades away and the granulometry of this horizon becomes silty sandy, which causes a local mixing water zone between the unconfined aquifer and the semi-confined one.
3. A third layer about 60 m in depth, characterized by gravelly sandy deposits with rare intercalations of silty clayey sediments, represents the semi-confined aquifer with greater permeability compared with the unconfined aquifer above.
4. The bottommost layers consist of deposits mainly composed of clay, characterized by rare fossil.

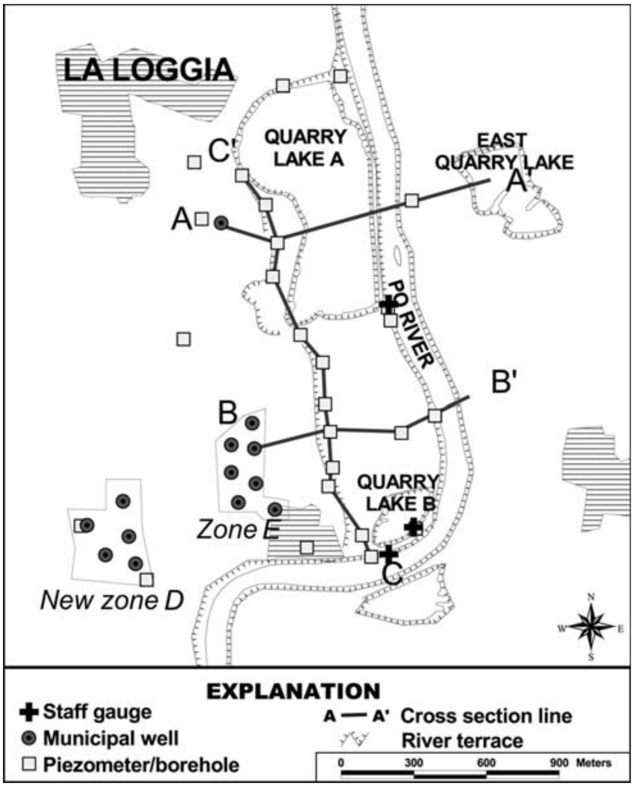
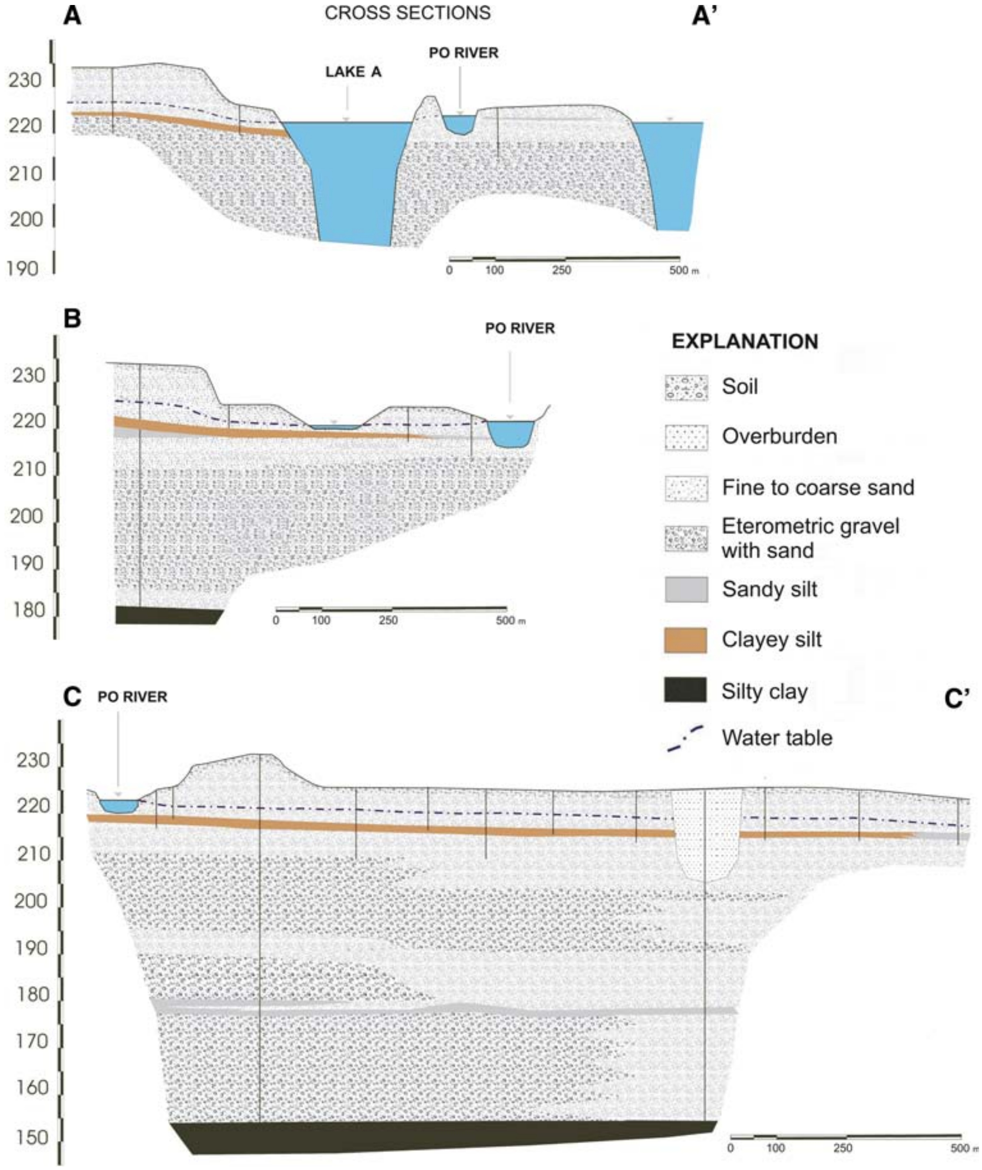


Fig. 4 Location of the study area, existing and newly made boreholes and cross-section lines

Fig. 5 Cross sections



The first three identified layers correspond to the fluvial deposit complex. On the contrary, the bottom clayey layer, identified as the impermeable substratum, coincides with the marine deposit and is characterized by an angular unconformity at the top.

On the basis of a palynologic study, the silty clayey layer of the aquitard bed found in the fluvial deposit can be connected to a cold climatic condition; a wood sample from the top of the peaty layer yielded a radiometric age of 30,660 + 1,290 years earlier than the present (Tropeano and Cerchio 1984; Charrier and Peretti 1975, 1977).

The clayey peaty layers are therefore connected, as far as their genesis is concerned, to a fluvial pattern, which is probably meander shaped with local formation of peat bogs during part of the Quaternary (Wurm).

Description of the proposed expansion due to the extraction works

The excavation of gravel and sand currently carried out in the study area has caused the development of two quarry lakes called Lake A (surface: 370,000 m^2; depth: 56 m) and Lake B (surface: 42,000 m^2; depth: 25 m). The planned expansion of the quarrying practice covers an area of about 178,000 m^2. The quarry lakes present in this area will be enlarged above the water table and subsequently deepened under the water table up to a maximum depth of about 57 m from the hydraulic head of the quarry lakes.

Following the planned excavation procedures, the area will be characterized by the presence of a single artificial basin stretching along the north–south direction and connecting the current Lakes A and B. This lake will be characterized by a maximum length of nearly 2 km and a maximum width of about 500 m (Fig. 6).

Two areas equipped with active municipal wells, called ‘Zone E’ and ‘New Zone D’, are upstream of the Quarry Lakes A and B (Fig. 4). At least four municipal wells in ‘Zone E’ will be relocated in ‘New Zone D’ to avoid any interference between the wells and the excavation procedures at the quarries.

The well screens are generally below the clayey peaty stratum (aquitard) and intercept the semi-confined aquifer. Their depth varies between 51 and 56 m.

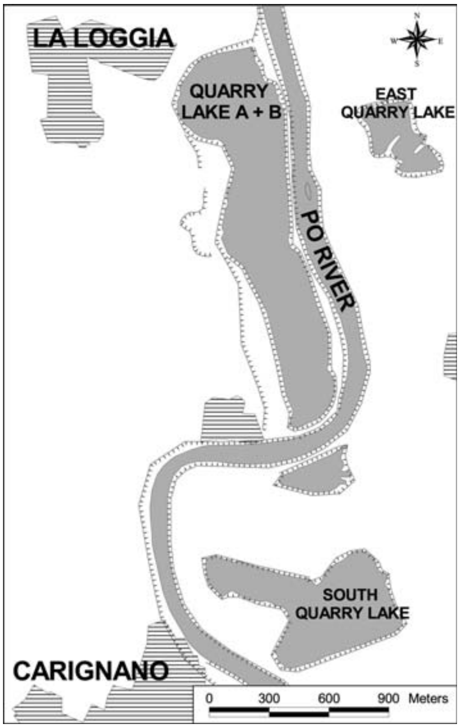


Fig. 6 Situation after the planned quarry enlargement: Lakes A and B will be combined into one single large lake (A + B)

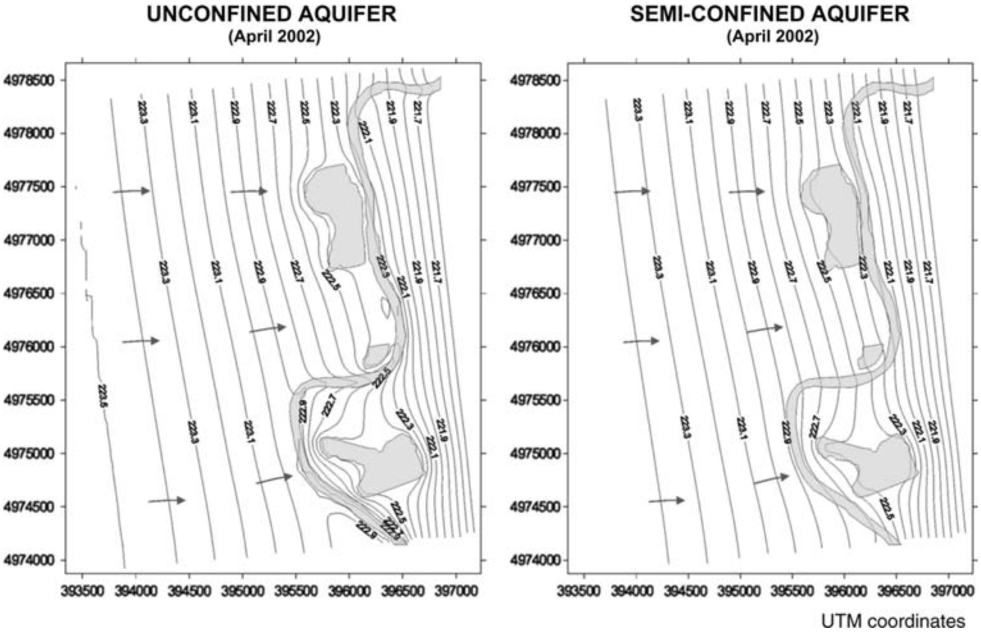
Materials and methods

Potentriometric surface reconstruction of the unconfined and semi-confined aquifer

The potentiometric surface in the unconfined and semi-confined aquifer has been reconstructed by interpolating the groundwater head data collected from wells and boreholes in the study area during the campaign in April 2002. The piezometric maps of April 2002 show a potentiometric surface in stationary conditions (Fig. 7). The potentiometric surface is in full agreement with the bibliographic data on a regional scale (Bortolami et al. 1990, 2000; Bove et al. 2005b): piezometric lines are placed parallel to the relief contour and converge in the plain towards the River Po, which represents the local base level.

On a local scale, the groundwater flow has a general direction from west–southwest towards east–northeast and is highly influenced by the presence of the River Po and the quarry lakes. Furthermore, the River Po acts as the supplier south of the study area and as drainage in the northern part of Lake A.

Fig. 7 Hydraulic heads (metres above sea level) and groundwater flow directions for unconfined and semi-confined aquifers



Moreover, the quarry lakes act as groundwater drainage upstream and as supply downstream.

A peculiar situation is highlighted with Lake A, which, being closer to the River Po, shows strong indications of the influence from the river. Likewise, the eastern bank of the lake is supplied by the River Po. Such an outcome is probably linked to the presence of a canal about 2 km to the north that creates an artificial rising effect upstream in the River Po.

The piezometric map of the semi-confined aquifer is very similar to the unconfined aquifer piezometric map, although the semi-confined aquifer is little or very little influenced by the presence of surface water bodies.

Nevertheless, the unconfined aquifer shows values of groundwater heads slightly greater than those of the semi-confined one. From this, it is possible to deduce that, generally, in natural conditions, the migration of water from the unconfined to the semi-confined aquifer may occur. Such migration is mediated by the semi-permeable layer (aquitard).

The seasonal groundwater level is strongly influenced by meteorological supplies, even promoting seasonal fluctuations of meteoric proportions, and by anthropic changes, such as the uptake for irrigation purposes. Additionally, as the River Po acts as drainage for groundwater, the oscillations of the water table are reflected in the river discharge.

The diagrams of piezometric and river level annual variations (Figs. 8, 9) highlight a maximum variation of piezometric level equal to 2.63 m, an oscillation of the River Po level of 3.17 m (year 1999) and a variation of lake level for Lake B equal to 2.35 m (year 1999). The maximum piezometric level occurs in April–May, whereas the River Po shows a maximum level in the spring and autumn months.

Description of the vertical slurry wall as a mitigation technique

On the basis of the hydrogeological features of the study area, an excavation deeper than the separation layer (aquitard bed) between the unconfined and the semi-confined aquifer would give rise to a possible increase of the mixing rate between the two aquifers (Fig. 10).

To minimize the effects that the excavation might cause, the plan is to construct a separation barrier between the two aquifers along the border of the existing and planned quarries. The horizontal natural layer would therefore mediate the migration of groundwater from the unconfined aquifer to the semi-confined aquifer. The infrastructure would be a vertical low-permeability slurry wall separating the unconfined and the semi-confined aquifer (Fig. 11). Essentially, the water transfer from the unconfined aquifer to the semi-confined one through the planned vertical diaphragm will promote the occurrence of some attenuation and purification processes of pollutants. Such processes can be compared with those that are already naturally occurring when groundwater transfers from

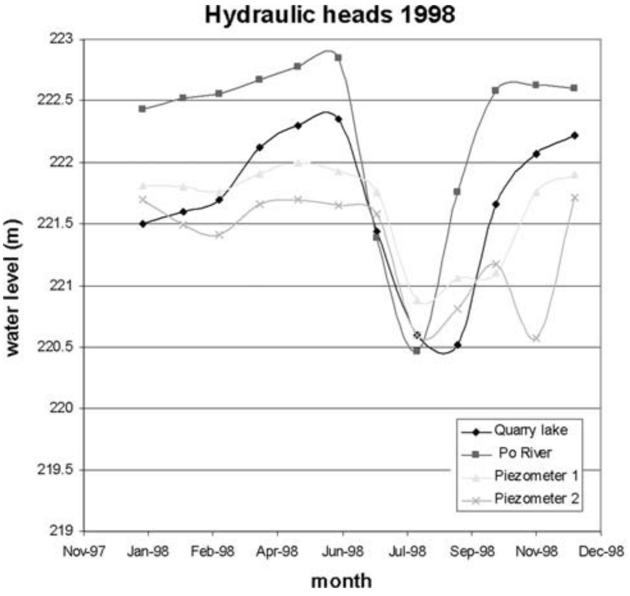


Fig. 8 Variations in 1998 for piezometric level (for two boreholes, 1 and 2) and river and lake levels (for two hydrometric rods near Quarry B, Quarry Lake and River Po)

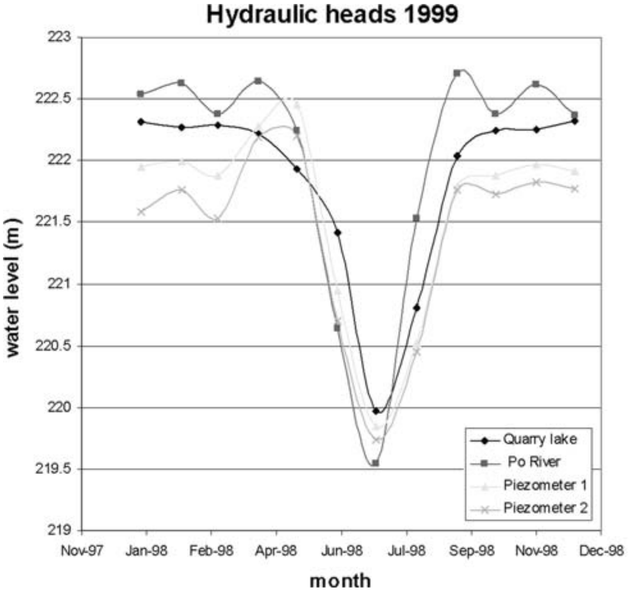


Fig. 9 Variations in 1999 for piezometric level (for two boreholes, 1 and 2) and river and lake levels (for two hydrometric rods near Quarry B, Quarry Lake and River Po)

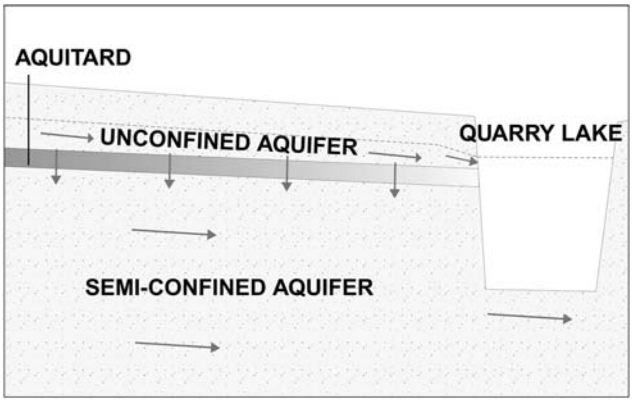


Fig. 10 Groundwater circulation diagram without the vertical slurry wall

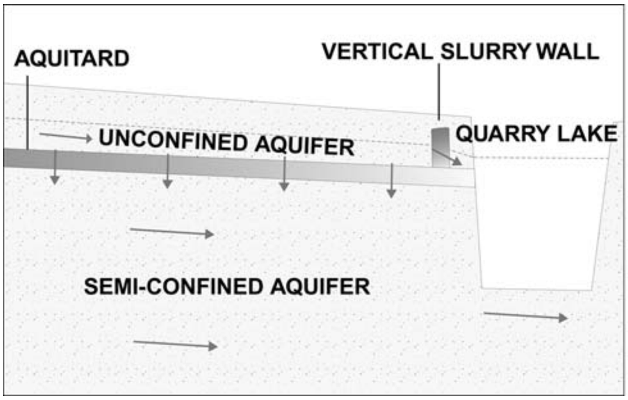


Fig. 11 Groundwater circulation diagram with the vertical slurry wall

the unconfined aquifer to the semi-confined one through the horizontal semi-permeable layer. Furthermore, the pumping that is currently occurring from the municipal wells (Azienda Acquedotto Municipale di Torino) to the west of Quarry Lake B creates a cone of depression that affects the semi-confined aquifer, causing the draw-down of the piezometric level. The natural transfer of water from the unconfined aquifer to the lower aquifer in stationary conditions, through the semi-permeable layer, will inevitably increase in dynamic conditions.

The vertical low-permeability diaphragm starting in the unsaturated zone will be bottomed on the existing semi-permeable layer (aquitard bed) and surround, in the north and west, the existing quarry lakes and the planned expansion area.

Mathematical simulation

The simulation was carried out in two phases:

Phase (a) Reconstruction of the groundwater flow in stationary conditions for the current situation.

Phase (b) Evaluation of the effects that the diaphragm and the enlargement of the quarry might have on groundwater flow.

The finite-difference model 'MODFLOW' (McDonald and Harbaugh 1988) was applied to achieve this target. Its application has allowed the examination and description of the possible consequences that the installation of the slurry wall perpendicular to the groundwater flow would cause on the unconfined and semi-confined aquifers. Moreover, investigations evidenced the possible effect that the vertical diaphragm might have on municipal wells upstream, by estimating the piezometric variations caused by its installation.

The first step in the implementation of the model was the elaboration of the hydrogeological conceptual model on the basis of the hydrogeological, stratigraphic and piezometric data already in possession or appositely measured.

The simulations carried out, therefore, were compared with the actual current situation to verify the appropriateness of the hydrogeologic interpretation. In this way, the final simulated scenario representative of April 2002 was achieved.

The implementation of the mathematical model consists of:

- discretization of the modelling area,
- definition of the limits of the system under investigation (boundary conditions),
- definition of the variables within the hydrogeologic system: cells hydraulic properties, features of river and quarry lakes,
- definition of the external stress to the system: drainage and recharge.

Discretization of the modelling area

The discretized domain includes three quarry lakes: Lake A to the north, Lake B to the south and Lake South to the right of the River Po and to the south of Lake B.

The investigated area has been discretized along the directions X, Y and Z (Fig. 12). The study domain has been outlined with a rectangle 3.5 km wide and 4.5 km long and subdivided into 90 rows and 70 columns that form 6,300 squared cells (50×50 m^2).

With regard to the vertical discretization, the need to achieve a sufficient precision rate led to the partition of the simulation domain into six layers: the first represented the unconfined aquifer, the second the aquitard and the third, forth, fifth and sixth represented the semi-confined aquifer.

The geometric shape of each layer was derived from stratigraphical data; such data were handled with geostatical methods to evidence the bed and the top of the layers (Fig. 12).

Boundary conditions and layer typology

Within the study area, there were no natural limits, which might be used as impermeable limits or as piezometric constant-head. Consequently, the model boundaries were defined by using cells with constant-head along the borders to the west and to the east of the simulation area. Such borders were perpendicular to the average flow direction of groundwater.

On the contrary, the northern and southern borders, which are aligned with the streamlines were simulated as impermeable limits.

The River Po was simulated via the ‘River’ function. The modelling of the River Po was found to be the most critical part of the model implementation.

The following hydrogeologic characteristics were attributed to the six layers modelled:

- Layer 1: unconfined (type 1: layer transmissivity may vary; it is calculated from the conductivity and thickness of the saturated zone; storage coefficient remains constant);
- Layer 2: confined/unconfined (type 2: layer transmissivity remains constant; storage coefficient varies from values typical of the confined stratum to those for the unconfined one);
- Layers 3–6: confined (type 0: both transmissivity and storage coefficient remain unchanged throughout the modelling exercise).

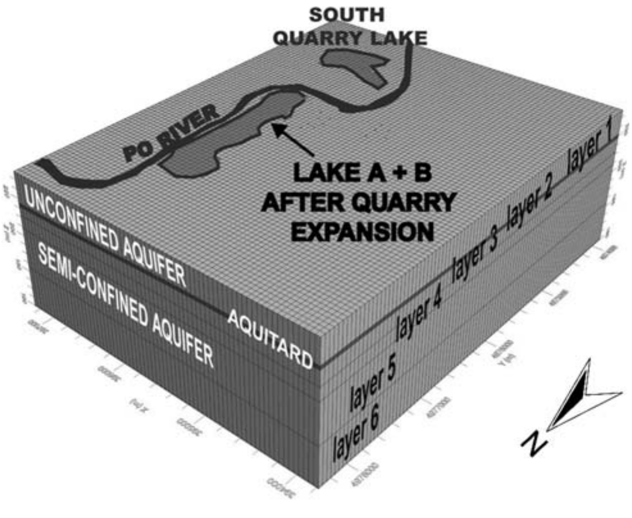


Fig. 12 Three-dimensional diagram of the discretized area

Input data

The cells not defined as inactive or as constant-head were detailed by a set of data derived from bibliographic literature (Geostudio, unpublished data, 1997; Gautero 1998; Di Molfetta, unpublished data, 2002). Particularly, hydrogeological parameters of the unconfined aquifer and of the aquitard were extrapolated from the results of pumping tests within the study area.

Table 1 summarizes the data, describing the aquifers and the aquitard used during the application of the model.

The quarry lakes were modelled by attributing, to the layers where water occurred, a high-hydraulic conductivity ($k_x = k_y = k_z = 1.0$ m/s) and an effective porosity of n_e equal to 1.

The unconfined aquifer recharge for the discretized area was evaluated on the basis of the rainfall and supply due to irrigation and adjusted during the model calibration phase.

The effective infiltration rate, homogeneously distributed over the study area, was valued as 250 mm/year. Furthermore, an evaporation rate of 1,320 mm/year was assigned to the cells coinciding with the lakes.

Calibration and model validation

The model calibration was carried out by using the piezometric data collected in April 2002 under stationary conditions.

The agreement between the calculated and observed potentiometric surface in 21 sampled points (Fig. 13) highlighted the high reliability of the simulations.

Additionally, the model indicates hydraulic heads of the lake more or less coinciding with the measurements carried out on the hydrometric rods.

Finally, the evaluation of the hydraulic balance for the study area, which estimated the extent of groundwater exchanges, showed a sum of flows in input equal to the flows in output with a percentile difference of

Table 1 Input data for the model

Parameter		Value
Unconfined aquifer (Layer 1)	$k_x = k_y$	3.5E-4 m/s
	K_z	1.75E-4 m/s
	n_e	0.10
Aquitard (Layer 2)	$k_x = k_y$	1.7E-6 m/s
	K_z	8.5E-7 m/s
	n_e	0.05
Semi-confined aquifer (Layer 3–6)	$k_x = k_y$	7.0E-4 m/s
	K_z	3.5E-4 m/s
	n_e	0.15

–0.08%. Such results present a substantial validity of the simulation.

Groundwater flow modelling

After checking the reliability of the model during the calibration phase, two likely scenarios were hypothesized. These referred to the status of the final plan after the creation of a single quarry lake that will connect the current Lakes A and B.

Hence, the modelling of the piezometric surface was carried out for the following two cases:

- presence of a single lake (A + B) and absence of the vertical diaphragm,
- presence of a single lake (A + B) and presence of the vertical diaphragm.

Morphology of the piezometric surface with the absence of the vertical diaphragm

In the case in which the slurry wall is absent, the flow direction is from west–southwest towards east–northeast (Fig. 14). The pattern of the piezometric surface in Layer 3 shows a trend similar to the water table, although it appears to be little influenced by the presence of superficial water bodies. Furthermore, no particular differences are found between the modelled and the actual piezometric surfaces. Nevertheless, the piezometric lines lay parallel to the border of the planned lake, which will connect the current Lakes A and B.

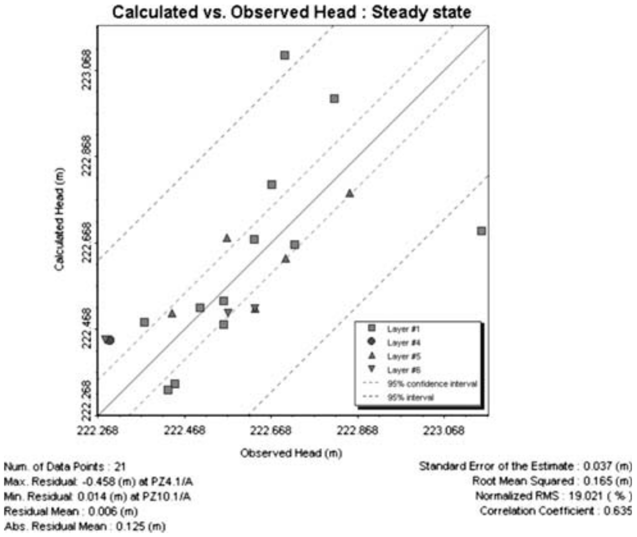


Fig. 13 Calibration of the groundwater model; relationship between simulated and observed hydraulic heads

Morphology of potentiometric surface with the presence of the vertical diaphragm

The previously developed model was applied by hypothesizing the presence of the slurry wall installed upstream from the only planned lake. Such a vertical diaphragm, bottomed on the silty clayey layer (Layer 2), is transverse compared to the groundwater flow and lengthens, from north to south, to the foot of the terrace escarpment. The slurry wall had a thickness of 2 m and hydraulic conductivity equal to 1.6×10^{-7} m/s.

Figure 15 shows the three-dimensional trend of the vertical diaphragm as modelled with the finite-difference model MODFLOW.

The simulation of the piezometric surface with the vertical diaphragm (Fig. 16) highlights a general pattern of the flow from west–southwest to east–northeast and a strong influence from the River Po and the quarry lakes compared with the outcome in the absence of the slurry wall.

Nonetheless, the presence of the vertical diaphragm generates a slight deflection of the potentiometric surface on the sides of the diaphragm itself. Additionally, a slight increase in the hydraulic gradient is reflected upstream and downstream from the slurry wall.

The potentiometric surface of Layer 3 displays the same trend and gradient as the unconfined aquifer, but is not significantly influenced by the presence of superficial water bodies and vertical diaphragm.

Effects of the vertical diaphragm on potentiometric surfaces

To evaluate the possible influences that the slurry wall might have on the hydraulic head, the potentiometric surfaces, obtained from the application of the model implemented in the presence and the absence of the vertical diaphragm, were compared.

Hydraulic head variations, for unconfined and semi-confined aquifers, caused by the installation of the vertical diaphragm, are shown in Fig. 17. In particular, the hydraulic head variations observed for Layers 1 and 3 are highlighted. The response of Layers 4–6 were, in actual fact, very similar to that of Layer 3.

The simulation, with the presence of the slurry wall, shows modest hydraulic head variations in Layer 1. Specifically, a zone parallel to the vertical diaphragm, in which the hydraulic head increase varies from 1 to 11 cm, is identifiable upstream of the diaphragm itself. Downstream, on the contrary, the hydraulic head shows a slight decrease of 1–2 cm.

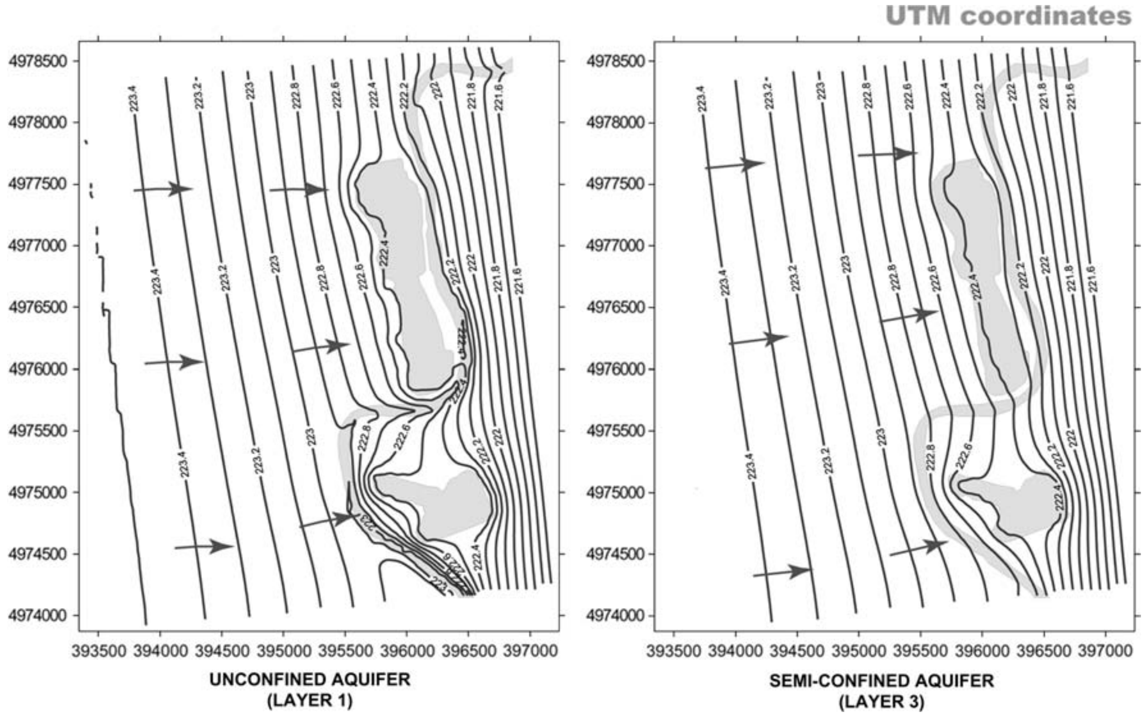


Fig. 14 Simulated water table and potentiometric surface maps (metres above the sea level) in the absence of the vertical diaphragm. Potentiometric surface in Layer 3 is identical to Layers 4–6

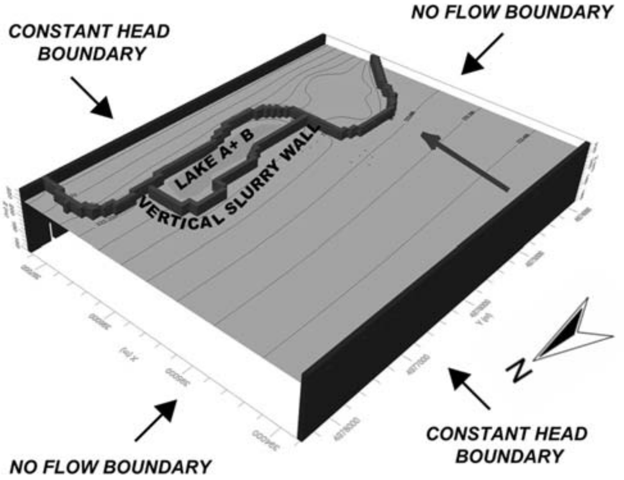


Fig. 15 Boundary conditions of the model, location of the vertical diaphragm, simulated water table and groundwater flow direction

Layer 3 shows a hydraulic head variation, caused by the construction of the vertical slurry wall, which is totally insignificant (1 cm).

Finally, the mathematical simulation indicates that hydraulic head variation caused by the installation of the vertical diaphragm has no influence on the functionality of the municipal wells in ‘Zone E’ and ‘New Zone D’. The pumping sites are found much further west of the area where the simulation showed piezometric variations. The maximum hydraulic head increase that the vertical diaphragm can cause is, according to the simulation, 1 cm for ‘Zone E’, which is also nearer to the diaphragm. Nevertheless, such a zone is planned to be moved to a new area adjacent to ‘New Zone D’.

Crossing time and possible attenuation processes of contaminants through the slurry wall

The aim of the vertical diaphragm is to mitigate possible contaminants within the unconfined aquifer as a result of its filtering ability.

The attenuation potential of the vertical diaphragm can be indirectly evaluated with the time that groundwater takes to cross the diaphragm, solely due to the process of advection.

Such deduction can be carried out by applying the following relationship:

$$v_{\mathrm{e}} = S/t_{\mathrm{a}} = Ki/n_{\mathrm{e}},$$

where v_{e} is the velocity, S the thickness of the diaphragm, t_{a} the diaphragm crossing time, K the hydraulic conductivity, i the hydraulic gradient and n_{e} is the effective porosity.

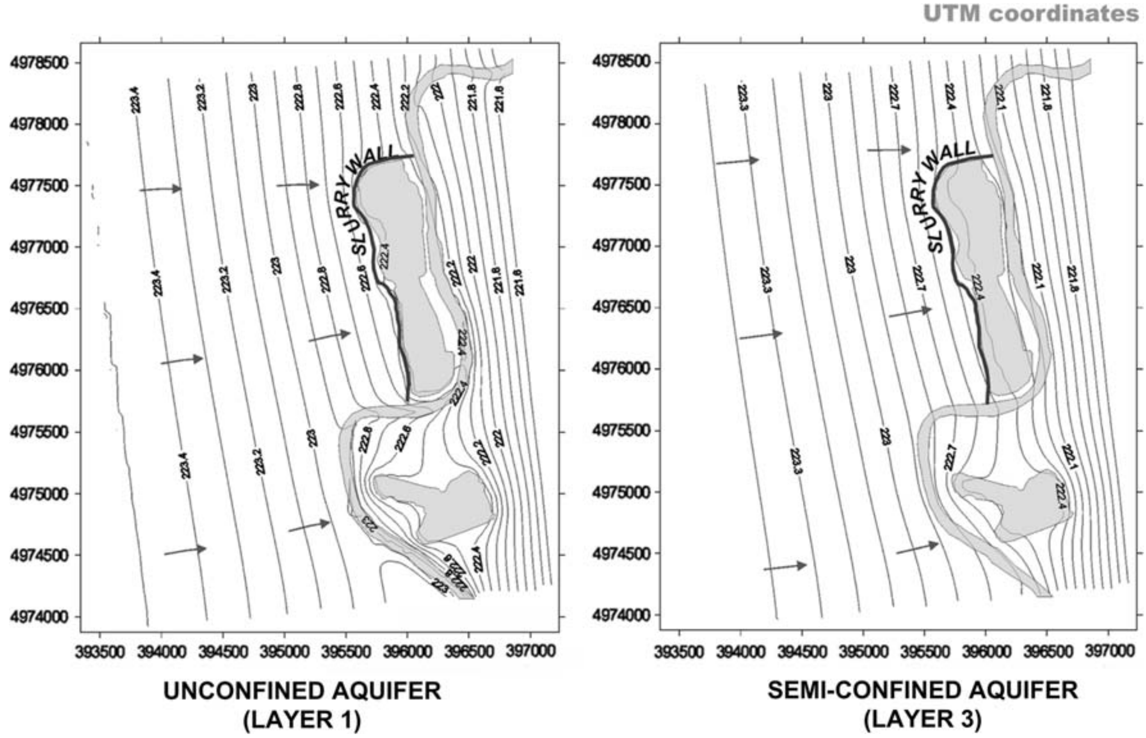


Fig. 16 Simulated water table and potentiometric surface maps (metres above the sea level) in the presence of the vertical diaphragm. Potentiometric surface in Layer 3 is identical to Layers 4–6

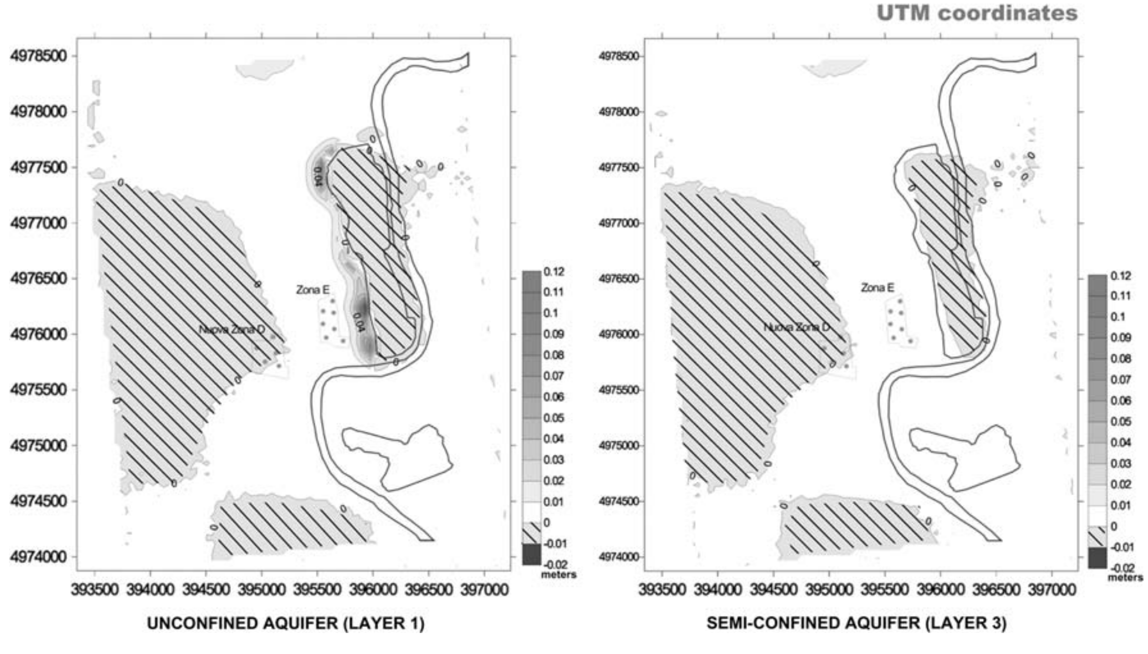


Fig. 17 Hydraulic head variations as a consequence of the installation of the slurry wall (m). The variations found in Layers 4–6 are identical to those in Layer 3

Since

$$i = \mathrm{d}h/S,$$

then

$$t_\mathrm{a} = S\,n_\mathrm{e}/(K\,\mathrm{d}h/S) = S^2 n_\mathrm{e}/K,$$

where dh is the difference between piezometric head upstream and downstream from the diaphragm.

As K is equal to 1.6×10^{-7} m/s, dh to 0.15 m, n_e to 0.05 and S to 2 m, the evaluated crossing time is 96.5 days.

Such time appears to be crucial for allowing biologic contamination abatement processes to take place; in fact, the average survival time for viruses and pathogen bacteria in groundwater does not exceed 60 days. Moreover, the high-contact time between contaminants and clayey minerals would ensure the establishment of a series of attenuation processes.

It is necessary to emphasize that, with the same hydrodynamic conditions, the crossing time for the horizontal semi-permeable layer results in an average of 9.6 days.

Results and discussion

This hydrogeological report evaluates the consequences and effectiveness of a low-permeability slurry wall that would separate the unconfined and semi-confined aquifers along the border of a quarry lake.

The enlargement of a quarrying site, along the River Po in the province of Torino, would involve the extension and deepening of the excavating area below the semi-permeable layer, which separates the unconfined and the semi-confined aquifers; it introduces the possibility of a greater mixing rate between the two aquifers in comparison with the current situation.

The planned infrastructure mitigates the consequences of digging below the semi-permeable layer and acts as a separator between the two aquifers along the border of the quarry basin. Furthermore, this slurry wall will reduce the possible water migration between the superficial aquifer and the lower semi-confined aquifer, in the same way as the natural semi-permeable layer.

An accurate reconstruction of the local hydrogeological structure was carried out by using borehole and in situ test data.

The local hydrogeology is characterized by a superficial aquifer and a semi-permeable layer that semi-confines a lower aquifer.

Lithostratigraphic and piezometric data clearly indicate that, even in natural conditions, a vertical migration of water occurs from the unconfined aquifer to a semi-confined one. Such movement is mitigated by a horizontal semi-permeable layer (aquitard) with a thickness varying from 0.5 to 3 m. This layer displays a reduction from west to east in the direction of the River Po. Locally, the granulometry becomes much coarser, i.e. silty sandy. To the east of the River Po, lithostratigraphic data reveal the absence of this layer, which re-emerges locally. This causes a local and direct mixing of superficial and deep waters enclosed by the semi-confined aquifer.

These data have, therefore, allowed the implementation of a hydrogeological model, by means of the finite-difference model (MODFLOW), to predict the consequences caused by the installation of the vertical diaphragm separating the unconfined aquifer and the semi-confined one.

As far as the consequences on the hydrogeologic conditions are concerned, the outcomes of the model compared with the actual condition showed a maximum rising of the water table equal to 12 cm, just upstream of the diaphragm and for a distance of about 100 m, and a maximum lowering of 2 cm just downstream of the diaphragm.

The construction of the slurry wall would not cause any change in the piezometric head in the area where there are municipal wells; hence, it will not have any negative effect on the functionality of the municipal wells.

Finally, as far as the quality of the groundwater is concerned, the migration of water from the unconfined aquifer through the vertical diaphragm will stimulate a series of attenuation and auto-depuration processes of eventual contaminants. Such processes can be compared with those that already naturally occur when groundwater migrates from the unconfined aquifer into the semi-confined aquifer through the horizontal semi-permeable layer. In addition, these processes will occur more effectively due to the higher crossing time that the groundwater flow would take to go through the vertical barrier (t_a = 96.5 days whereas for the horizontal semi-permeable layer t_a = 9.6 days).

In conclusion, the installation of the vertical diaphragm will positively represent a resolutive element, representing a mediation and separation factor between the unconfined and the semi-confined aquifers along the border of the quarrying areas, and therefore a protective barrier for the water quality of the quarry lake and consequently of the semi-confined aquifer.

References

Bortolami G, De Luca DA, Filippini G (1990) Caratteristiche geolitologiche e geoidrologiche della pianura torinese "Geological and hydrogeological features of Torino plain". In: Le acque sotterranee della pianura di Torino: aspetti e problemi. Provincia di Torino, Assessorato all'ecologia, M/S Lit.: 9–16

Bortolami G, De Luca DA, Masciocco L, Morelli di Popolo e Ticineto A (2000) La cartografia tematica nella pianificazione territoriale: la carta della vulnerabilità della falda idrica superficiale nel territorio della Provincia di Torino "Thematic cartography in territorial pianification: the vulnerability map of surface aquifer in Torino Province". Geologia dell'Ambiente 1:25–30

Bortolami G, De Luca DA, Masciocco L, Morelli di Popolo e Ticineto A (2002) Le acque sotterranee della pianura di Torino: carta della base dell'acquifero superficiale "Groundwater of Torino plain: map of surface aquifer bed". Assessorato Risorse idriche e atmosferiche, Prov. Torino, Lit. Savigliano, 32pp

Bove A, Casaccio D, Destefanis E, De Luca DA, Lasagna M, Masciocco L, Ossella L, Tonussi M (2005a) Assetto geoidrologico della Regione Piemonte "Hydrogeological sketch of Piemonte". Idrogeologia della pianura piemontese, Regione Piemonte, Mariogros Industrie Grafiche S.p.A., Torino, 17pp

Bove A, Casaccio D, Destefanis E, De Luca DA, Lasagna M, Masciocco L, Ossella L, Tonussi M (2005b) Piezometria della falda superficiale nel territorio di pianura della Regione Piemonte "Potentiometric surface map of Piemonte plain". Idrogeologia della pianura piemontese, Regione Piemonte, Mariogros Industrie Grafiche S.p.A., Torino, 10pp

Charrier G, Peretti L (1975) Analisi palinologica e datazione radiometrica ^{14}C di depositi torbosi intermorenici della regione alpina piemontese, applicate allo studio del clima e dell'ambiente durante il Quaternario superiore "Palynological analyses and radiometric ^{14}C dating of peat in morainic deposits of Piedmont Alpine region applied to the study of climate and natural environment during upper Quaternary". Boll Comit Glac It 23:51–56

Charrier G, Peretti L (1977) Ricerche sull'evoluzione del clima e dell'ambiente durante il quaternario nel settore delle Alpi Occidentali Italiane "Quaternary evolution of climate and environment in the Italian Western Alps". Boll Ist ed Orto Bot Univ Torino 22:157–192

Gautero L (1998) Simulazione mediante modello matematico delle operazioni di lagunaggio in Comune di La Loggia (TO) "Mathematical simulation of lagoonal in La Loggia Municipality (Torino)". GEAM marzo 1:61–67

Lucchesi S (2001) Sintesi preliminare dei dati di sottosuolo della pianura piemontese centrale "Preliminary summary of subsoil features in central Piemonte plain". GEAM 28(2–3):115–121

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference groundwater flow model. Scientific Software Group, Book 6, WA, USA

Tropeano D, Cerchio E (1984) L'orizzonte torboso wurmiano nel sottosuolo della pianura piemontese meridionale. Osservazioni preliminari "Wurmian level of peat in subsoil of southern Piemonte plain". Boll Associazione Mineraria Subalpina 3:199–221