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Hydrogeological Aspects of Washing Waste Reuse in Quarry Lakes Rehabilitation

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***Abstract*—**According to the European laws, there is the possibility of reusing the washing wastes for the environmental requalification of quarry lakes. The paper deals with the hydrogeological aspects involved in this possibility, as the introduction of finest wastes in the quarry lakes can generate alterations of the hydrogeological setting of the area, and problems for the future accessibility of the zone. To evaluate the hydrogeological compatibility of the washing wastes reuse in quarry lakes a groundwater numerical model was carried out, pointing out both the hydrogeological feasibility of this intervention and some guide lines for its optimization, in terms of inflow point with regard the groundwater flow direction and loss of volume in the quarry lake.

***Keywords*—**Groundwater numerical modeling, hydrogeological alteration, quarry lake, silty-clay wastes.

I. Introduction

When gravels and sands are quarried, they have to be washed to remove the fine components (silt and clay with particle-size < 0.06 mm). The obtained semi-liquid product includes a solid percentage in between 15% and 60% and represents a quarrying waste, even if it is an inert material with potential reusing alternative.

The considerable volumes involved (on the average, a gravel-sand quarry can produce a fine component equal to 15% of its annual production) make the problem very interesting, both from the socio-economic and the technical-applicative point of view.

These products can be disposed using the filter press system to separate water from solid part or they can be temporarily stored in settling tanks, with all connected risks [1].

Anyway, the solid part has to be disposed or reused as raw material [2] to realize embankments and sub grades [3].

For an environmental rehabilitation, the Italian law 117/08 introduces the possibility to put the quarrying waste, inclusive the washing silt, into lakes (if the quarries are under the water table) or into the spaces resulting from quarry activity.

This solution would allow to reuse directly the material where it is produced and to reshape the basin in a natural way. It is also evident that the silt introduction into quarry lakes depends on the evaluation of some specific problems, such as:

– the chemical-physical characteristics of the silt: these characteristics don't have to affect the groundwater quality;
– the hydrogeological alterations caused by the deposition of the materials with low permeability; the above mentioned alterations depend on: the inflows, the sediments geometry and particle-size, the hydrogeological characteristics of the area and the washing waste chemistry;
– the silting stability, especially as regard the possible subsidence phenomena along the banks and in expectation of the future reuse of the area.

After having characterized the examined material, the above-named problems were analyzed both in theory and through the study of a real case. In this way it was possible to define some guide-lines for a correct introduction of the washing waste in the lakes without producing hydrogeological alterations in the surrounding areas.

II. The Reclamation of the Quarry Lakes

The deposition of fine-graded material within the quarry lakes begins already during the extraction of the inert material, when finer fractions are lost from the diggers and they gradually form a layer of loose unconsolidated material, characterized by low permeability, on the bottom of the lake.

The above-described settling process adds to the sedimentation of washing waste, when they are placed in the lake in a localized way. In this case, the main difference concerns the shape and the homogeneity of the deposit being formed. Indeed, the washing waste put in the lake shows a quite wide range of particle size and it is constituted by silt and clay, or sand (Fig. 1); so its deposition takes place prior to the coarser fractions.

This means that a predominantly sandy deposit is formed in the sections immediately downstream of the intake point, whereas in the more advanced sections the deposit becomes predominantly silty, as it was experimentally observed even in traditional settling tanks [1].

The shape and the size of the deposit obviously depend on the input mode of sludge (with or without settling tanks, with free expansion or in presence of containment barriers) as well as the position of the intake point as to the groundwater flow direction.

Finally, as regards the hydraulic characterization of the materials, some experimental tests performed on saturated silt in the settling tanks (therefore on the consolidated material) have shown permeability values of approximately $6 \cdot 10^{-8}$ m/s and rather poor mechanical properties ($c' \cong 2$ kPa, $\phi' \cong 30°$). But infiltrometer tests performed on site in unconsolidated

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material have provided considerably higher permeability values, ranging between 10^{-4} and $5\cdot10^{-6}$ m/s, varying according to thickness of the deposit.

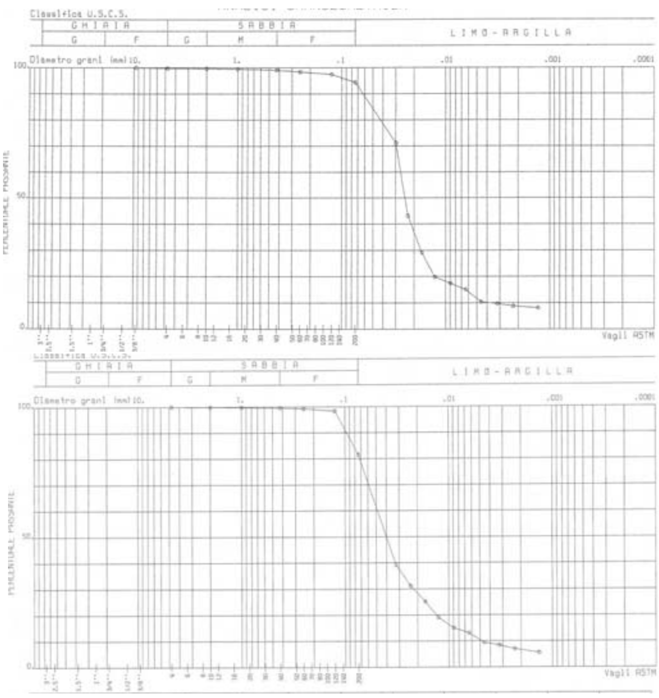

Fig. 1: Grain size distributions of the fine wastes of a quarry. (a): 11% of sand, 80% of silt, 8% of clay; (b): 29% of sand, 64% of silt, 7% of clay

III. Parametrical Modeling

Generally, the opening of quarries causes sensible deformations of the water table, that occurs in lowering and lifting respectively upstream and downstream of the quarry [4] [5]. The deposition of silt in the lake tends to mitigate these effects (Fig. 2). The hydrogeological study of some quarry lakes placed in the plain surrounding Milan, experimentally showed a decrease in the average permeability (theoretically infinite) and this trend is most pronounced for older quarries and for those characterized by greater production of silt (less valuable deposits).

A quantitative assessment of the effects produced by quarrying on the groundwater balance can be carried out both with traditional methods and with a modeling approach. The latter allows to analyze the aquifer system in a three-dimensional field, considering the actual complexity of the hydrogeological structure.

This type of analysis becomes essential to study and predict the effects on the hydrological balance, arising from the silt intake.

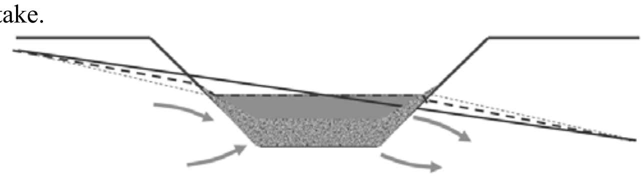

Fig. 2: Scheme of the water table deformations around quarry lakes. The continue line represents the undisturbed water table, the light dotted line represents the effects of the lake excavation and, finally, the darker dotted line shows the effects of both the lake excavation and the fine wastes deposition

A. Parametrical model implementation

In order to quantify the change of the water table resulting from the silt deposition in quarry lakes, a modelling approach was used, adopting the Modflow three-dimensional numerical model [6]. To this purpose a rectangular domain with an extension of 2 km^2, discretized by a grid of 200x100 meshes (square cells having 10 m side) was considered.

The simulations took into account different hydrological structures, characterized by two superimposed layered aquifers, a shallow one directly affected by quarrying, and a deeper one, separated by an aquitard (having transmissivity T = 10^{-6} m^2/s) or by an aquiclude (T = 10^{-8} m^2/s), considering a depth of excavation equal to or lower than the thickness of the first aquifer (Fig. 3).

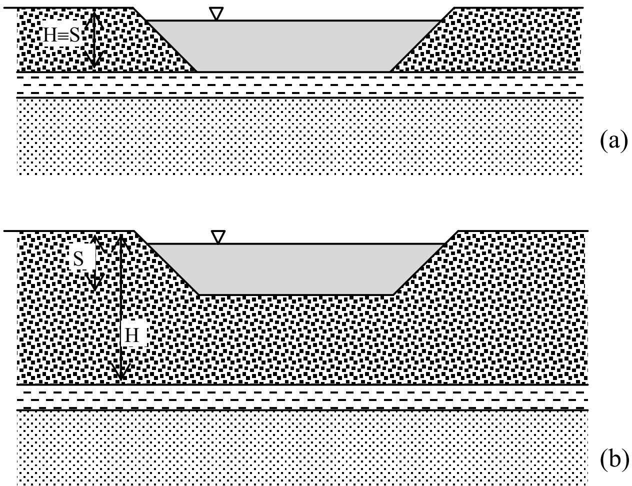

Fig. 3: Hydrogeological scheme used for modeling: (a) the excavation depth S is equal to the thickness of the first aquifer H; (b) S is lower than H

In addition, for each of these cases, different transmissivity values (ranging from $2\cdot10^{-1}$ and $2\cdot10^{-4}$ m^2/s) of the first level and different geometries of the silty deposit were considered; for the latter a permeability equal to 10^{-6} m/s was considered.

In particular, limited thicknesses, ranging from 2 to 10 m, and different depositional processes were considered for the silty deposit. In particular silty deposits were considered only at the bottom of the lake (Fig. 4a), at the bottom of the lake and on the banks (Fig. 4b), forming a cone, having dip less than (< 4°), localized near the sludge intake (Figs. 4c and 4d).

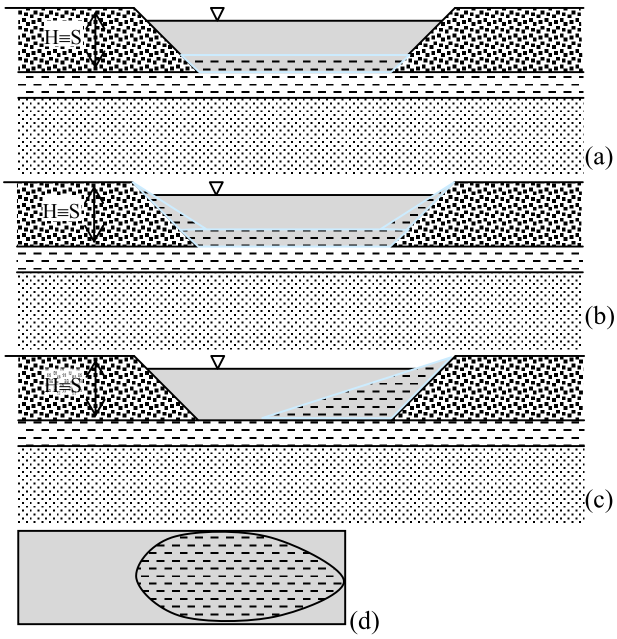

Fig. 4: Geometrical scheme of the silt deposition: by natural deposition only on the bottom (a) and both on the bottom and on the bank (b), by localized introduction both in section (c) and in plain view (d)

In order to reconstruct with sufficient detail the above described hydrogeological structures, it was necessary to divide the studied domain into 11 layers: one corresponding to deep aquifer, to which was assigned a permeability of 10^{-4} m/s, one to the aquitard/aquiclude and the other 9 for the detailed representation of the quarry lake.

Regarding the boundary conditions, a constant head upstream and downstream was imposed, corresponding to an average piezometric gradient of 0.5%.

Then, a quarry lake having size and shape variables was inserted within the domain; this lake was assimilated as a high permeability area.

The simulations were carried out parametrically, by analyzing the piezometric changes to the varying magnitudes involved.

B. Results discussion

The numerical modeling helped to quantify the phenomena of water table lowering and lifting that occur upstream and downstream the quarry lake when the geological structure changes, with or without silt.

Without silt, the recall of water from upstream and from the deeper aquifer toward the surface aquifer are confirmed. As a consequence, there is a release of water downstream (Fig. 5), whose size depends on the size of the lake.

The silt deposit on the bottom of the quarry lake, following the sedimentation of fine components during the excavation, causes a local reduction in the aquifer thickness (also evident in Fig. 4a); which means that, being aquifer discharge equal, the pressure gradient must increase. Indeed, the modeling has shown a rise of the hydraulic head upstream the quarry (equal to a maximum of about 20cm in the presence of 10 m of silt on the bottom) and an equivalent drawdown downstream; locally the gradient increases (equivalent to a maximum of 0.08% in presence of a 10m thick silty deposit).

If silt is present even on slopes, the groundwater transition within the stratum having a low permeability determines a strong localized loss of the load, as great as greater is the thickness of the deposit and the higher is the permeability contrast between the aquifer and the silt.

The simulations allowed to observe what follows:

– compared to the simulated water table with the silt-free quarry lake, a general increase in the piezometric level upstream the quarry and a drawdown downstream much more marked than that obtained with silt only on the bottom (Fig. 6);
– for a thickness of 10 m, the piezometric variations are in the range of ±1.5 m (corresponding to an increase of the hydraulic gradient equal to 0.3%). These piezometric variations induced by the presence of the silty deposit both on the bottom of the lake and on the slopes, tend to offset the hydrogeological imbalance caused by the quarry itself in the aquifer (lowering of the upstream piezometric level and elevation downstream the excavation).

As it is possible to observe in the trend of the equipotential lines (Fig. 6), the loss of the load induced by the presence of silt is mainly concentrated at the downstream side of the lake.

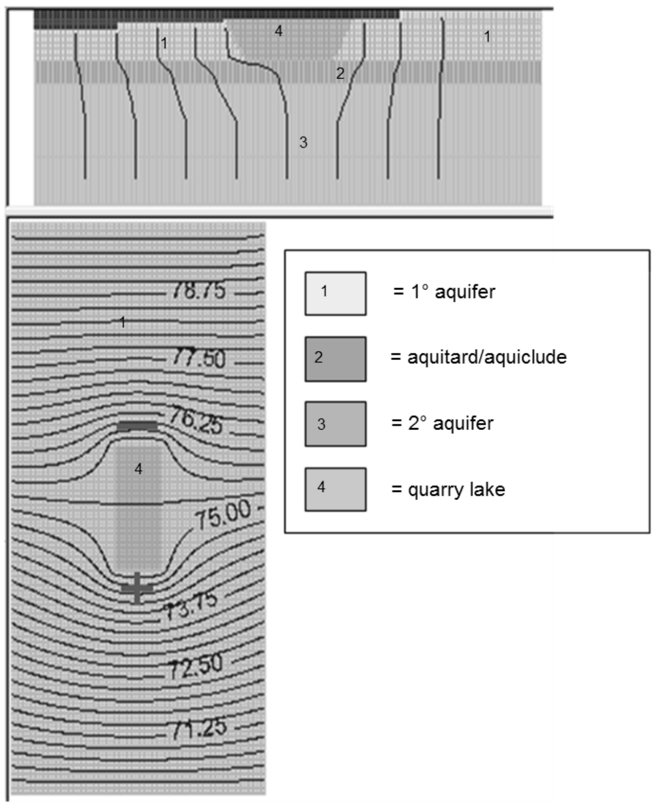

Fig. 5: Numerical modeling of the water table deformations around a quarry lake. The "+" symbol means an increase of the water table with reference to the undisturbed conditions, whereas the "-"

means a drawdown

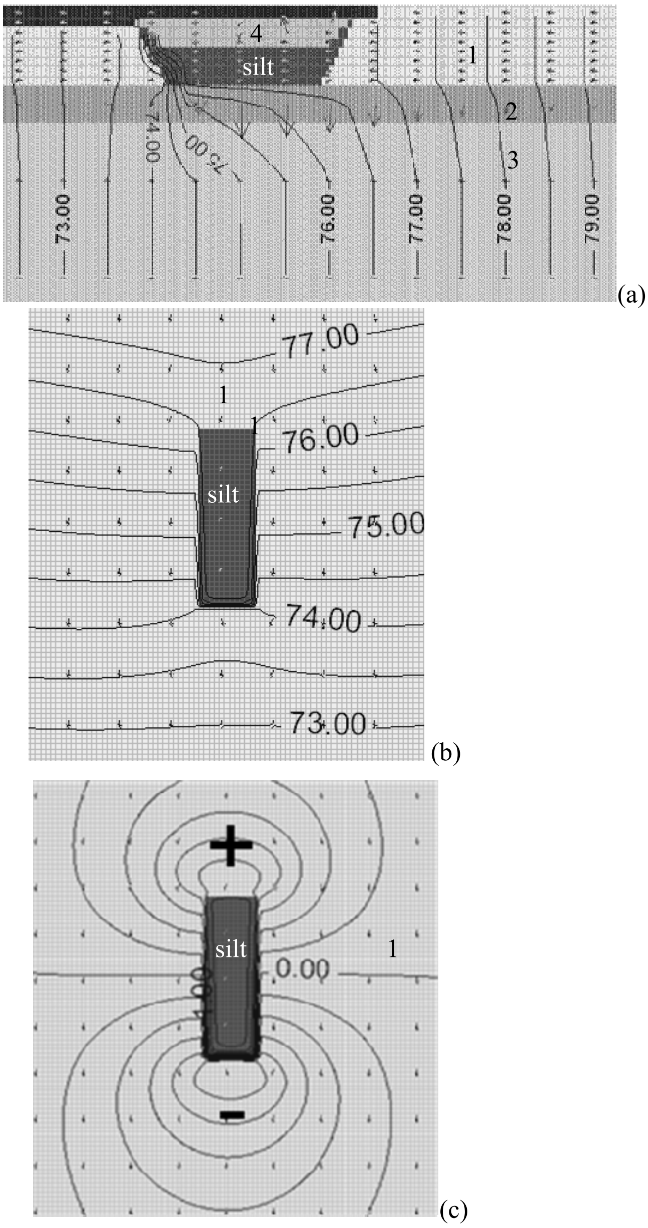

Fig. 6: Numerical modeling of the water table deformations in a quarry lake in presence of silt deposition both on the bottom and along the banks: equipotential lines (a) in section and (b) in pain view; (c) deformation with reference to the water table with the quarry lake (without silt). The “+” symbol means an increase of the water table with reference to the undisturbed conditions, whereas the “-“ means a drawdown

Moreover, the numerical modeling allowed to observe that the presence of silt on the slopes causes an inversion of the aquifer leakage conditions; without silt, the lake draws water from the aquitard below and then releases it respectively upstream and downstream the lake.

The presence of silt on the slopes, however, reverses the leakage upstream the lake ("dam effect"), so that the water filtration occurs from the aquitard to the deep aquifer (Fig. 6a).

This phenomenon is evident if one analyzes the components of the hydrological balance of the aquitard below the quarry lake with regard to different simulation scenarios (Fig. 7).

Moreover, it was observed that the piezometric variations are minimal in the presence of shallower excavations compared to the thickness of the first aquifer, so that the natural reclaim can also lead to the complete readjustment of the hydrogeological conditions (Figures 8 and 9).

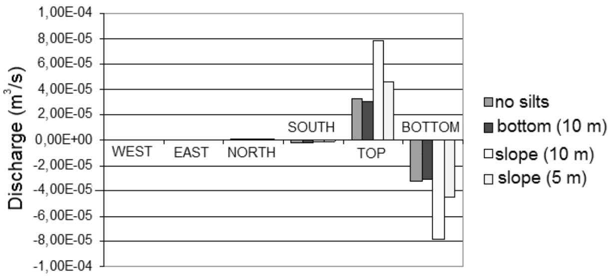

Fig. 7: Hydrogeological balance of the aquitard for different silty deposit scenarios

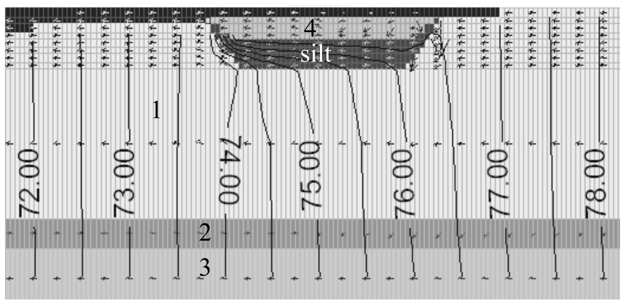

Fig. 8: Numerical modeling of the water table deformations in a quarry lake in presence of silt deposition both on the bottom and along the scarps for excavation depth very less than the first aquifer thickness

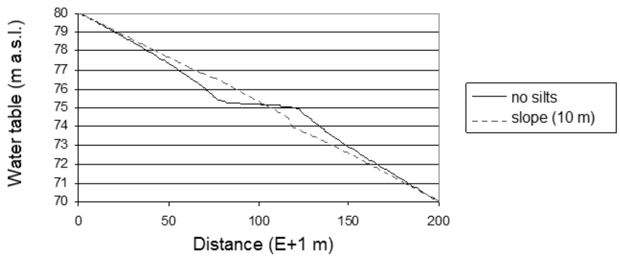

Fig. 9: Comparison between the water table deformations with and without silt for excavation depth very lesser than the first aquifer thickness

When the silty inflow is localized (Figs. 4c and 4d), the numerical modeling shows that the water table deformation is small (order of 10 cm for a filling of the lake amounting to 20% of the volume excavated), and localized.

As it can be seen in Figure 10, when the silt inflow makes upstream (in relation to the groundwater flow direction) in the silty filling, a filtration process triggers having a direction from the bottom upwards, and conversely, if the silty deposit is located downstream, the filtration takes direction from the top downwards, but if the silty inflow occurs laterally to the groundwater flow direction, no sensitive piezometric deformations are observed (Fig. 11).

According to the results obtained, it can be concluded that the piezometric variations induced by the deposition of silt in the quarry lake tend to offset the hydrogeological imbalance caused by the opening of a quarry within the same aquifer.

Even assuming a filling of the lake equal to 15-20% of the dig out material, the piezometric changes are very localized and small, especially if the inflow is orthogonal to the groundwater flow direction. However, it is clear that the scenarios identified through the numerical modeling are dependent on: the size of the quarrying areas, the geological and hydrogeological structure and the permeability of silt.

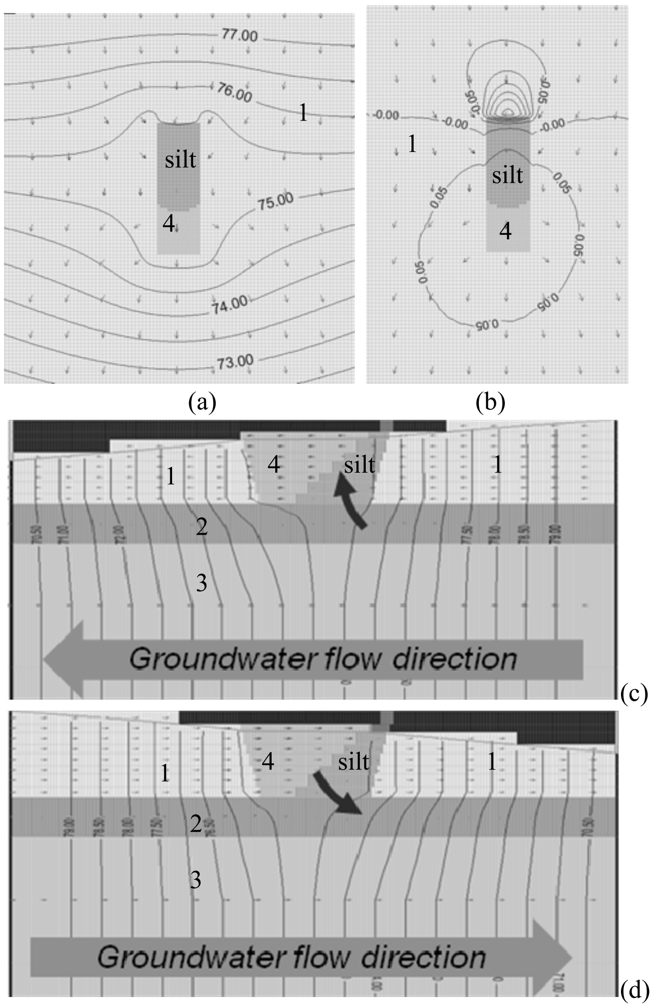

Fig. 10: Numerical modeling of the water table deformations around a quarry lake in presence of localized silt deposition: (a) pain view of the equipotential lines for above silt introduction; (b) corresponding equipotential lines deformations with reference to the case without silt; (c) section view of the flow path for above silt introduction; (d) section view of the flow path for below silt introduction

IV. Real Case Study

In order to verify the results previously explained on a real case, a quarrying area located in the central plains of Lombardy has been analyzed, trying to assess, by numerical modeling, the effects of a localized silty inflow on the water table and on the hydraulic balance of the bordering resurgences.

A. Geological and hydrogeological setting

From the geological point of view, quaternary fluvioglacial sediments predominate in the study area, sometimes interrupted by alluvial deposits of rivers. The stratigraphic correlations (Fig. 11) show that here the underground may be divided, by similarity and homogeneity of hydrogeological characteristics, in three lithozones that, from the top downward, are constituted by:

– sandy-gravelly deposits, up to about 30 m depth;
– sand and gravel deposits alternate with intercalated lenses of clay, up to about 110-120 m depth;
– predominantly clayey and sandy deposits, over 110-120 m depth.

The structural order of the aquifers assumes considerable importance, because its definition allows a correct discretization of the horizontal and vertical flow model.

For purposes of this study, the hydrological system has been simplified by identifying a phreatic aquifer , which is present in the gravelly-sandy lithozone (average permeability of about 10^{-2} m/s), and an underlying semi-confined aquifer that is present up to 110-120 m depth and characterized by an average permeability of 10^{-4} m/s. These two aquifers are separated by a discontinuous silty-clay layer, with an average transmissivity of about 10^{-7} m^2/s.

Analyzing the stratigraphic data, the pattern of groundwater aquifers was characterized, in particular with regard to the gradient of the base surface and the thickness of the unconfined aquifer, which is directly affected by quarrying and from which the resurgences present in the area derive.

This characterization showed that the base of the phreatic aquifer tends to widen to the south with an inclination approximately equal to 0.2%.

The water table within the studied domain (Fig. 12) has a prevailing NW-SE flow direction, with the contours of the groundwater elevations varying from a maximum of 120 m a.s.l. to a minimum of 102 m a.s.l. and an average gradient of 0.2%.

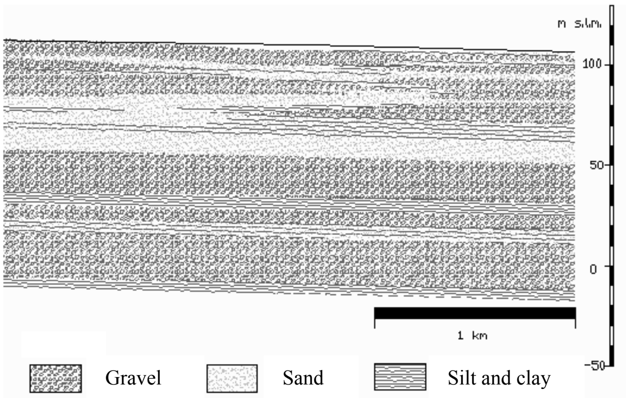

Fig. 11: Hydrogeological section of the studied area

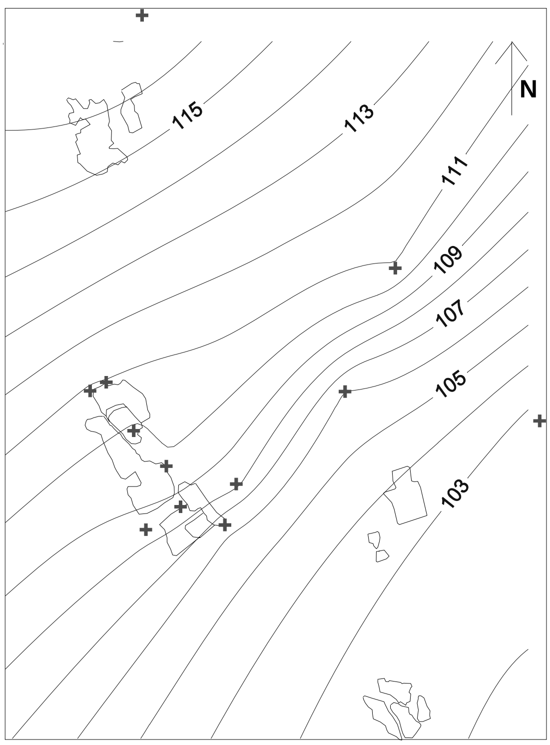

Fig. 12: Water table map (in m a.s.l.) in the studied area in minimum conditions (March-April 2005). The crosses show the localization of the piezometers used for the flow model calibration

B. Model implementation

The modeled area is rectangular, the larger side has NW-SE orientation (in the main groundwater flow direction) and a length of 10 km, the shorter side is 6 km long and oriented NE-SW (Fig. 11a).

In designing the model the conceptual model above-described has been used, considering three main layers (Fig. 11b), corresponding to the two aquifers identified and to the aquitard that separates them. Actually, the first aquifer was further discretized into 10 layers, to allow the modeling of silty deposit. The study domain was also discretized in a grid composed of 300 columns and 500 rows, with square mesh of constant size equal to 20 m side. Boundary conditions of the model are as follows (Fig. 13a):

– constant head (Dirichelet condition) at the boundary of the domain (both upstream and downstream and along both sides having NW-SE direction, Fig. 13a);
– head depending on flow where the resurgences indicated in Figure 13a are located (Cauchy condition); location, geometry and resurgences flow were derived from existing studies [7];
– constant flow at the wells (Fig. 13a); in particular, only the wells located near the quarry lakes have been considered, for a total extracted flow of 450 l/s;
– recharge to the top layer equal to 62 mm/year.

The model calibration was conducted in a steady-state condition referring to the period of March-April 2005 (maximum underlie of the water table) (Fig. 12).

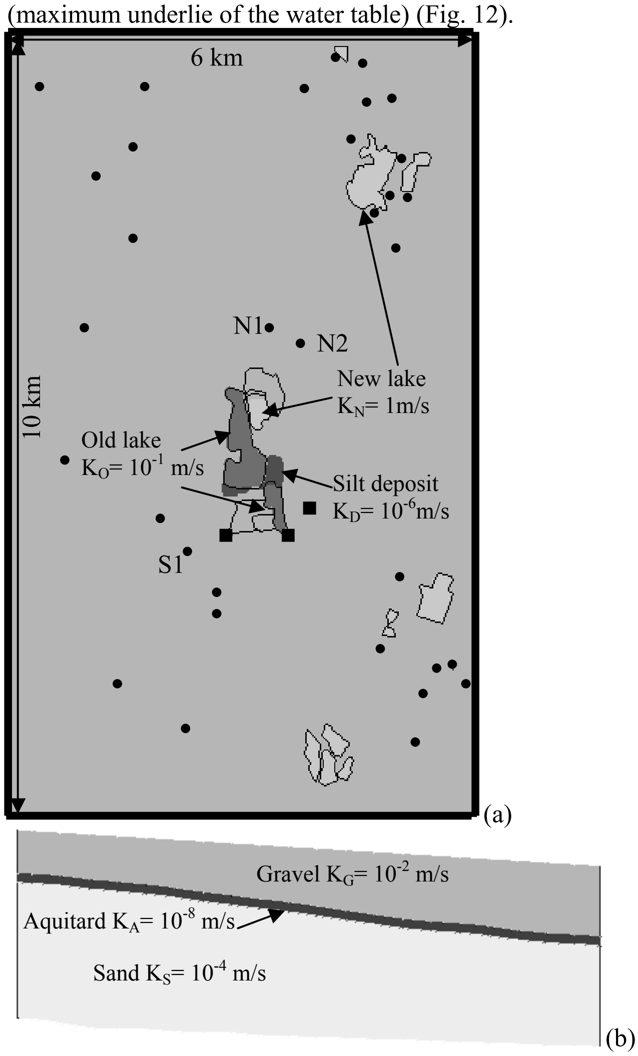

Fig. 13: (a) Modeling domain with the hydraulic conductivity distribution of the first layer and the model boundary conditions: constant head along the border domain, constant flow with squares and flow dependent head with circles (N1, N2 and N3 are the springs for which the modeling results will be shown in the following); (b) N-S section of the domain

The calibration interested the permeability value attributed to the quarry lakes and to the resurgences. The so calibrated model was then used to simulate the effects of silty inflow in relation to the future expansion of the considered quarrying.

C. Simulation results

During the application of the model the piezometric variations induced by a further expansion of quarrying activity in the aquifer and the simultaneous, localized inflow of the silt were simulated. In particular, it is assumed that the inflowing silt into several positions along the lake (Fig. 14) and inflowing volumes are respectively equal to 5%, 10% and 20% of the volume excavated. The results of simulations (Table 1 and Fig. 15) demonstrated what follows:

1) piezometric level changes:
   - without silt, the water table drawdown reaches 50 cm upstream whereas the water table increases downstream are around 25 cm;
   - in presence of localized silt, the water table drawdow is gradually decreasing with increasing volume (Fig. 15) till it reaches the limit of 30 cm for a volume of 20%, while downstream the elevations remain mainly unchanged;
2) changes of the resurgences flow (Table 1):
   - without silt, the expansion of the quarry lake involves a reduction of the resurgences flow closest to the quarry (Fig. 13a) in between 20 and 35%;
   - in the presence of silt, the flow reduction is attenuated, reaching values in between 5 and 15% when the volumes introduced (upstream or downstream) are equal to 20% of the dredged material.

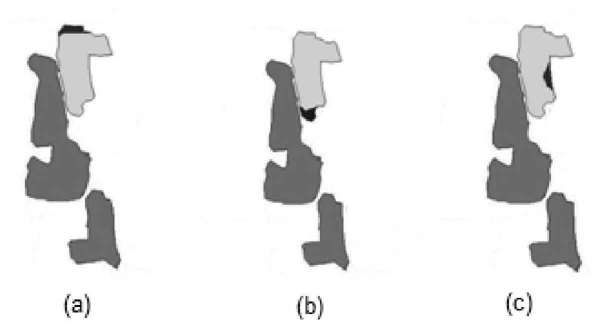

Fig. 14: Location of the silt (in dark) input point considered for the modeling: (a) upstream, (b) downstream and (c) laterally the quarry lake, with reference to the groundwater flow direction. In light gray is shown the active quarry lake with the dimensions provided for its expansion, whereas in deeper gray are shown the quarry lakes not directly interested by the intervention

The results obtained (Fig. 15 and Tab. 1) show that the presence of silt does not involve significant hydrological alteration; indeed, the effect is to partially rebalance, the imbalance produced by the opening and the expansion of the quarry itself. From this point of view, the best solution, as regards the resurgences hydrological balance, consists in inflowing the 20% of the silt amount upstream. It is clear, however, that this solution presents a number of drawbacks:

- stability problems of the deposit, because of the filtration motion that would be established locally (going from upstream to downstream and from the bottom upward);
- practical problems related to the production management; in the specific case being considered, in relation both to the location of facilities (which are located downstream) and to the quarrying activity.

Consequently, it is believed that the best solution is to introduce the silt downstream. As regard the volume of silt introduced, it is possible to observe that already limited volumes of silt (10%) are able to compensate hydrological alterations rather well.

TABLEI
PERCENT VARIATIONS OF THE SPRINGS DISCHARGE (FIG. 13A) FOR SEVERAL SIMULATION SCENARIOS, WITH RESPECT TO THE PRESENT DAY CONDITIONS

Scenario	Δdischarge N1 [%]	Δdischarge N2 [%]	Δdischarge S1 [%]
No silts	-25.38%	-37.05%	19.69%
Silts downstream 5%	-17.50%	-24.66%	9.14%
Silts downstream 10%	-10.55%	-14.13%	3.92%
Silts downstream 20%	-9.66%	-12.13%	3.71%
Silts upstream 5%	-21.78%	-22.20%	11.06%
Silts upstream 10%	-20.23%	-16.85%	9.56%
Silts upstream 20%	-13.69%	-3.51%	5.56%
Silts laretally 5%	-16.00%	-25.34%	10.28%
Silts laretally 10%	-14.26%	-23.02%	9.68%
Silts laretally 20%	-14.56%	-22.67%	10.06%

V. CONCLUSIONS

The numerical modeling and analysis of a real case show that, from a geological point of view, the silt deposition within the quarry lakes determines following effects:

3) piezometric variations that tend to offset the imbalance caused by the opening of the same quarry within the aquifer;
4) reversing of the aquifer leakage conditions, with minimal risk of contamination of the aquifer as a result of quarrying activities;
5) localized increase of hydraulic gradient in the downstream side of the lake, without substantial alteration of stability conditions.

As regards the stability of the banks, the main problem is connected to the bearing capacity of the silty material taken down, which limits the future usability of the area. Nevertheless, it is believed that the use of silt with localized inflows into the quarry lakes can be very useful for environmental restoration, providing for those areas a particular use to flora and fauna (e.g. wetlands, bed of reeds).
In light of the above, it nevertheless emphasizes the need for careful monitoring both of the various phenomena related to the placing of silt in the quarry lakes, and of the qualitative and quantitative characteristics of the silt.

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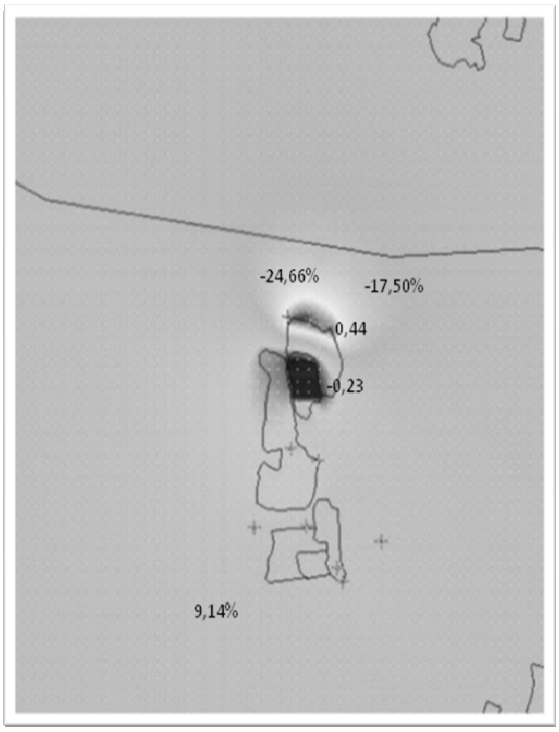

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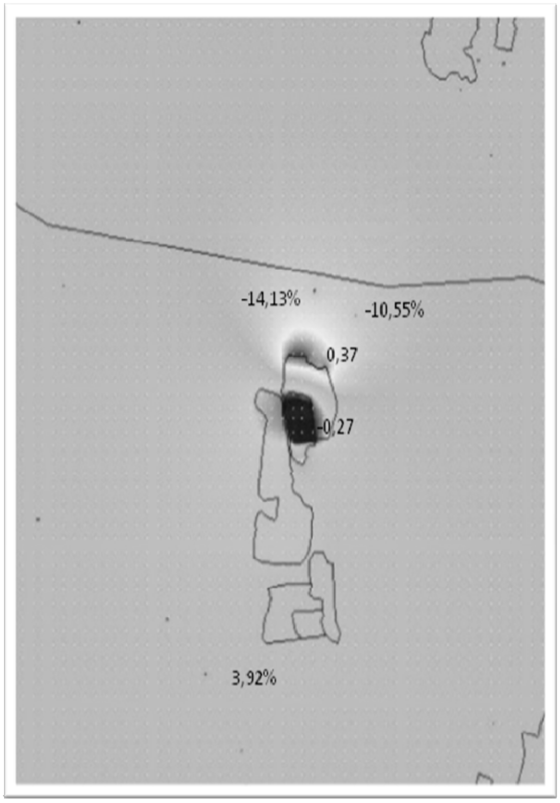

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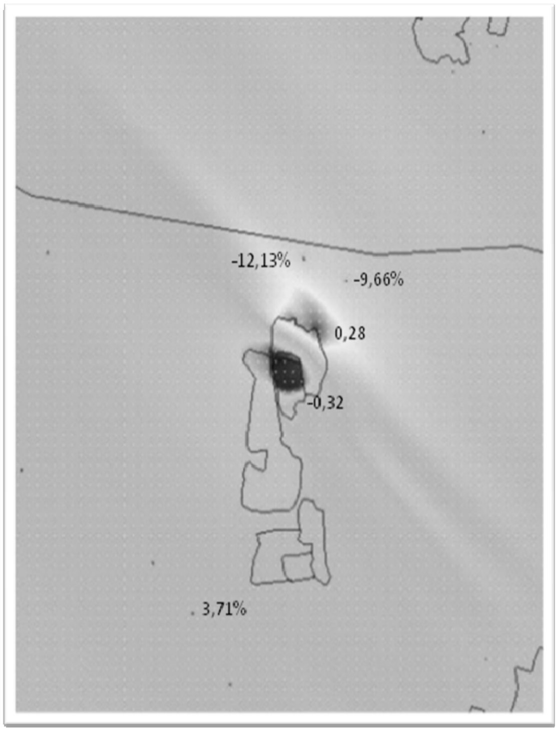

(c)

Fig. 15: Piezometrical drawdown arising from the quarry lake expansion, considering the concurrent silt deposition localized above the quarry lake with a volume equal to: (a) 5%, (b) 10% and (c) 20% of the excavated volume. The percent changes in springs discharge are also shown

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