Hydrogeological issues in geological hazard assessment

Paola Gattinoni

Research area: Transport Infrastructure and Geosciences
Main research topics ➞ Engineering Geology

GEOLOGICAL HAZARDS

- Groundwater resources depletion
- Landslides and river dynamic
- Civil constructions (i.e. tunnels, roads)

HYDROGEOLOGICAL CONCEPTUAL MODEL
Which issues are involved in the reconstruction of the hydrogeological conceptual model?

1. Type of aquifer $\leftrightarrow$ geomaterials
2. Hydraulic conductivity
3. Groundwater level
4. Hydrogeological balance
Which issues are involved in the reconstruction of the hydrogeological model?

1. Type of aquifer
2. Hydraulic conductivity
3. Groundwater level
4. Hydrogeological balance

The development of the hydrogeological conceptual model in a rock mass requires the knowledge of the orientation and geometry of the rock joints.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Flow equation</th>
<th>Unitary flow rate (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>$\lambda = \frac{96}{Re}$</td>
<td>$q_i = \frac{g\varepsilon^3}{12\nu} J_i$</td>
</tr>
<tr>
<td>Turbulent (smooth joints)</td>
<td>$\lambda = 0.316 Re^{-1/4}$</td>
<td>$q_i = \left[ \frac{g}{0.079} \left( \frac{2}{v} \right)^{1/4} \varepsilon^3 \cdot J_i \right]^{4/7}$</td>
</tr>
<tr>
<td>Turbulent (rough joints)</td>
<td>$\frac{1}{\sqrt{\lambda}} = -2 \log \left( \frac{\varepsilon}{D_h} \right)$</td>
<td>$q_i = 4\sqrt{g} \left[ \log \left( \frac{3.7}{\varepsilon^3} \right) \varepsilon^{1.5} \sqrt{J_i} \right]$</td>
</tr>
<tr>
<td>Inertial</td>
<td>$\lambda = \frac{96}{Re} \left[ 1 + 8.8 \left( \frac{\varepsilon}{D_h} \right)^{1.5} \right]$</td>
<td>$q_i = \frac{g\varepsilon^3}{12\nu \left[ 1 + 8.8 \left( \frac{\varepsilon}{D_h} \right)^{1.5} \right]} J_i$</td>
</tr>
<tr>
<td>Turbulent</td>
<td>$\frac{1}{\sqrt{\lambda}} = -2 \log \left( \frac{\varepsilon}{D_h} \right)$</td>
<td>$q_i = 4\sqrt{g} \left[ \log \left( \frac{1.9}{\varepsilon^3} \right) \varepsilon^{1.5} \sqrt{J_i} \right]$</td>
</tr>
</tbody>
</table>

Which issues are involved in the reconstruction of the hydrogeological model?

1. Type of aquifer

2. Hydraulic conductivity

- **Isotropic alluvial aquifer**
- **Anisotropic alluvial aquifer**
- **Anisotropic fractured aquifer**

Quite unusual

Typically the vertical permeability is lower than the horizontal one (anisotropy ratio $\cong 10$), because of soil deposition cycles.

In rocky aquifers the anisotropy is ruled by the orientation of fractures.

Which issues are involved in the reconstruction of the hydrogeological model?

1. Type of aquifer
2. Hydraulic conductivity
3. Groundwater level
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flow path, and then the recharge and discharge areas of the aquifer

groundwater boundaries (i.e., divides, …) and interactions with surface waters

Which issues are involved in the reconstruction of the hydrogeological model?

1. Type of aquifer
2. Hydraulic conductivity
3. Groundwater level
4. Hydrogeological balance

- Flow path, and then the recharge and discharge areas of the aquifer
- Groundwater boundaries (i.e., divides, ...) and interactions with surface waters
- Water table changes in time

Which issues are involved in the reconstruction of the hydrogeological model?

1. Type of aquifer
2. Hydraulic conductivity
3. Groundwater level
4. Hydrogeological balance

\[
\frac{\Delta V_s}{\Delta t} = i - q_{s-d}
\]

\[
\frac{\Delta V_d}{\Delta t} = q_{up} - q_{down} - q_{tun} + q_{s-d}
\]
How can we use the hydrogeological conceptual model for geological hazard assessment?

1) In slope dynamic
   Large scale hydrogeological susceptibility to landslide

2) In tunnel design
   Tunnel inflow assessment (design phase)

3) In underground infrastructures management
   Hydrogeological hazard in underground infrastructures (operational phase)
A lesson we learned

Structural and lithological setting

Hydrogeological setting

Hydrometric level of the lake which could trigger the landslide even without rainfall.

Rainfall which could trigger the landslide even without the lake.

Collapse

Factors controlling the slope dynamic

Predisposing factors

- Morphological setting (i.e., slope angle)
- Lithological (geomaterials) and structural setting (faults)
- Hydrogeological setting (permeability contrasts, supply conditions,...)
- Land use (vegetation, etc.)

Triggering factors

- Active tectonic (rock uplift, earthquakes,...)
- Intense and/or prolonged rainfall
- Groundwater and pore pressure changes
- Glacial processes (i.e. snow/ice/permafrost melt)
- Loading/excavation (both natural and anthropic)

After gravity, water is the main cause of landslides!

What hydrogeological conditions favor landslides?

- High permeability in the recharge zone of the aquifer
- Heterogeneities and permeability contrasts

Sensitivity of a landslide to triggering factors (rainfall, groundwater changes, …)

High fracturing degree of the rock mass (or karsism)

Convergence of the groundwater flow towards the landslide body

Low permeability layer

**Slope scale analysis**

1. Hydrogeological conceptual model (flow path, springs, levels, discharges)

2. Study of the hydrogeological causes that may predispose or trigger the collapse

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**Graphical Elements**:
- **Flow path**
- **Spring**
- **Groundwater flow models**
- **Stability analyses (stress-strain models)**

**Equation**: $y = -0.0267x + 1$

**$R^2$ Value**: 0.8122

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**Table**:

<table>
<thead>
<tr>
<th>Recharge [m/s]</th>
<th>$kC = 5e^{-6}/s$</th>
<th>$kC = 6e^{-6}/s$</th>
<th>$kC = 7e^{-6}/s$</th>
<th>$kC = 4e^{-6}/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta h$</td>
<td>$\Delta F_s/F_s \approx 5%$</td>
<td>$\Delta h=5\div6$ m $\Rightarrow \Delta F_s/F_s \approx 20%$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Graph**:
- **Legend**
- **Axes**

---

**References**:

Large scale analysis

Results can be extended on a wide domain considering the hydrogeological processes mainly controlling the slope stability.

HYDROGEOLOGICAL SUSCEPTIBILITY DEPENDING ON THE TYPES OF MOVEMENT:
- soil slip or debris flows triggered by infiltration;
- roto-translational slides, triggered by deep groundwater concentration.

The example of the large landslide in Maierato (Cz, 2010)

The landslide, a roto-translational slide ($V = 10 \, \text{Mm}^3$) evolved in flow (groundwater!), caused the evacuation of nearly 2,300 inhabitants and the destruction of one of the two main road infrastructures of the area.

Before

After

Long period of slope deformation
From in situ surveys and lab tests...
…to the landslide conceptual model…


- **Evaporitic limestone**
  - Drillings ⇒ geological weakness of the geomaterials
  - Weak rocks for lithology (very high primary porosity, behavior from plastic to quasi-liquid depending on the water content)

- **Sandstone**
  - Weak rocks for weathering (almost no cement)

- **Claystone**
...to the landslide concept


Evaporitic limestone
Sandstone

Extensional displacements, with a progressive lowering of the stratigraphic series,

...to the landslide conceptual model...

...to the landslide conceptual model...

Max monthly rainfall of the last 60 years (ARPACAL, 2010).

Rainfall in the last 20 days before the collapse: 100-years return period

Simulations were carried out by changing the groundwater level in order to point out the critical conditions, corresponding to an increase of the water table of about 15 m.
Similar geological and hydrogeological conditions in the whole urban area!

Is there a residual risk?

What’s the hazard in the urban area?
3D groundwater flow model

From model calibration…

Calibration in post-failure condition (after the landslide of February 2010).

Simulation of:
- Hydrogeological conditions, which triggered the landslide of February 2010 (pre-failure condition);
- Critical recharge in post-failure condition, which may trigger new landslides.

...to the hydrogeological susceptibility assessment

Groundwater flow rates

Water table drawdowns

Zones interested by groundwater flow concentration

How can we use the hydrogeological conceptual model for geological hazard assessment?

1) In slope dynamic

Large scale hydrogeological susceptibility to landslide

2) In tunnel design

Tunnel inflow assessment (design phase)

3) In underground infrastructures management

Hydrogeological hazard in underground infrastructures (operational phase)
## Geological hazards in tunneling

<table>
<thead>
<tr>
<th>Hazards for the tunnel</th>
<th>Hazards for the environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Tunnel and face instability or deformation</td>
<td>- Water resources pollution</td>
</tr>
<tr>
<td>- Water inflow</td>
<td>- Drying up or changes in spring regime</td>
</tr>
<tr>
<td>- Gas and aggressive waters</td>
<td>- Water table drawdown</td>
</tr>
<tr>
<td></td>
<td>- Surface settlements</td>
</tr>
<tr>
<td></td>
<td>- Landslides</td>
</tr>
</tbody>
</table>

**Hydrogeological issues are involved in both the points of view...**

![Diagram showing water management and delivery system](image)

Initial water table
Final water table

Zone with springs influenced by water table drawdown

Water management and delivery system

Hydrogeological conditions which could lead to significant water inflow in tunnel:

- High permeability geomaterials (i.e., granular soils, karst phenomena, porous or fractured rocks)

- Morphological setting (i.e. shallow tunnel, portals)

- Permeability contrast, buried river beds

- Faults or overthrusts having significant water supply, synclinal folds

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Type</th>
<th>L. (km)</th>
<th>$Q_{\text{max}}$ (m³/s)</th>
<th>$Q_{\text{min}}$ (m³/s)</th>
<th>Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sempione (ITA - CH)</td>
<td>Railway</td>
<td>19.8</td>
<td>1.700</td>
<td>0.864</td>
<td>Limestone</td>
</tr>
<tr>
<td>Vaglia (BO - FI)</td>
<td>Railway</td>
<td>18.6</td>
<td>0.080</td>
<td>-</td>
<td>Limestone, calcarenite, sandstone</td>
</tr>
<tr>
<td>Direttissima (BO - FI)</td>
<td>Railway</td>
<td>18.5</td>
<td>1.200</td>
<td>0.060</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Pavoncelli bis (AV)</td>
<td>Hydraulic</td>
<td>15.5</td>
<td>0.800</td>
<td>0.070</td>
<td>Limestone, Clay</td>
</tr>
<tr>
<td>Firenzuola (BO - FI)</td>
<td>Railway</td>
<td>15.1</td>
<td>0.277</td>
<td>0.070</td>
<td>Sandstone and marl</td>
</tr>
<tr>
<td>Frejus (T4)</td>
<td>Highway</td>
<td>12.9</td>
<td>0.007</td>
<td>0.001</td>
<td>Several</td>
</tr>
<tr>
<td>M. Bianco (Ti)</td>
<td>Highway</td>
<td>11.6</td>
<td>0.800</td>
<td>0.440</td>
<td>Granite</td>
</tr>
<tr>
<td>Raticosa (BO - FI)</td>
<td>Railway</td>
<td>10.4</td>
<td>0.037</td>
<td>-</td>
<td>Sandstone, marl and clay</td>
</tr>
<tr>
<td>Gran Sacco (A24)</td>
<td>Highway</td>
<td>10.2</td>
<td>3.000</td>
<td>0.600</td>
<td>Limestone</td>
</tr>
<tr>
<td>S. Lucia (NA - SA)</td>
<td>Railway</td>
<td>10.2</td>
<td>1.000</td>
<td>0.250</td>
<td>Limestone</td>
</tr>
<tr>
<td>Putifigari (SS)</td>
<td>Road</td>
<td>9.8</td>
<td>0.070</td>
<td>0.050</td>
<td>Vulcanites</td>
</tr>
<tr>
<td>Zuc del Bor (UD - AUT)</td>
<td>Railway</td>
<td>9.3</td>
<td>0.700</td>
<td>0.650</td>
<td>Limestone</td>
</tr>
<tr>
<td>S. Stefano (GE - F)</td>
<td>Railway</td>
<td>7.9</td>
<td>-</td>
<td>alta</td>
<td>Marly limestone, sandstone</td>
</tr>
<tr>
<td>M. Olimpino 2 (MI - CO)</td>
<td>Railway</td>
<td>7.2</td>
<td>elevata</td>
<td>-</td>
<td>Limestone, sands</td>
</tr>
<tr>
<td>Serena (PR - SP)</td>
<td>Railway</td>
<td>6.9</td>
<td>media</td>
<td>-</td>
<td>Calcarenites, breccia, flysch</td>
</tr>
<tr>
<td>M. La Mula</td>
<td>Hydraulic</td>
<td>6.3</td>
<td>0.200</td>
<td>0.800</td>
<td>Limestone, dolomite</td>
</tr>
<tr>
<td>Turchino (GE - AT)</td>
<td>Railway</td>
<td>6.4</td>
<td>0.110</td>
<td>0.075</td>
<td>Calceschists</td>
</tr>
<tr>
<td>Satriano (1° salto)</td>
<td>Hydraulic</td>
<td>6.4</td>
<td>elevata</td>
<td>-</td>
<td>Milonitic Granite</td>
</tr>
<tr>
<td>Gran S. Bernardo (T2)</td>
<td>Highway</td>
<td>5.9</td>
<td>scarsa bassa</td>
<td>-</td>
<td>Gneiss, schyst</td>
</tr>
<tr>
<td>S. Leopoldo (UD - AUT)</td>
<td>Railway</td>
<td>5.7</td>
<td>3.600</td>
<td>alta</td>
<td>Limestone</td>
</tr>
<tr>
<td>Gravere (TO - FRA)</td>
<td>Railway</td>
<td>5.6</td>
<td>elevata</td>
<td>0.013</td>
<td>Calceschists</td>
</tr>
<tr>
<td>Vado Ligure (ITA - FRA)</td>
<td>Railway</td>
<td>4.9</td>
<td>0.200</td>
<td>0.050</td>
<td>Dolomite</td>
</tr>
<tr>
<td>Colle Croce (ITA - FRA)</td>
<td>Road</td>
<td>4.1</td>
<td>scarsa bassa</td>
<td>0.000</td>
<td>Calceschists</td>
</tr>
<tr>
<td>Col di Tenda (ITA - FRA)</td>
<td>Railway</td>
<td>3.2</td>
<td>0.600</td>
<td>0.200</td>
<td>Limestone</td>
</tr>
<tr>
<td>Bypass Spriana</td>
<td>Hydraulic</td>
<td>3.2</td>
<td>0.300</td>
<td>0.040</td>
<td>Gneiss, limestone, dolomite</td>
</tr>
<tr>
<td>Villeneuve (A5)</td>
<td>Highway</td>
<td>3.2</td>
<td>0.200</td>
<td>0.001</td>
<td>Calceschists</td>
</tr>
<tr>
<td>Prè Saint Didier (A5)</td>
<td>Highway</td>
<td>2.8</td>
<td>0.100</td>
<td>0.080</td>
<td>Calceschists, sandstone</td>
</tr>
<tr>
<td>Moro (AN - BA)</td>
<td>Railway</td>
<td>1.9</td>
<td>0.080</td>
<td>-</td>
<td>Gravels and sands</td>
</tr>
<tr>
<td>Colle della Scala</td>
<td>Railway</td>
<td>-</td>
<td>elevata</td>
<td>alta</td>
<td>Limestone</td>
</tr>
<tr>
<td>Croccetta (Paola - CS)</td>
<td>Road</td>
<td>1.5</td>
<td>0.022</td>
<td>0.028</td>
<td>Tectonised schists</td>
</tr>
</tbody>
</table>

Examples of water inflow in different types of tunnel and for different types of aquifer.
The Gran Sasso massif bears a wide aquifer system of about 800 km². It’s made up mainly of limestone, in which karsism is locally well developed, and it is bounded by clastic low permeability units (mainly marls). Springs are located all along the basin boundaries. The motorway tunnel is located in the northern zone.

The main recharge zone of the aquifer is located in the Campo Imperatore basin, having an elevation about 2000 m a.s.l. Here the aquifer recharge reaches its highest value, higher than 1000 mm/y. Then, the groundwater flows towards the borders of the domain, bringing about several groups of springs.

The motorway tunnel is located at the bottom of the aquifer and nowadays it drains about 1.5 m³/s, which corresponds to less than 10% of the whole aquifer discharge.

Expensive geognostic surveys (geophysical surveys, drillings, in bore-hole tests)

Hydrogeological conceptual model

Limit in data acquisition

Best solution

Risk

Cost of the geognostic surveys

Hydrogeological data acquisition (%)

Cost of the geognostic surveys

Expensive geognostic surveys (geophysical surveys, drillings, in bore-hole tests)

Hydrogeological conceptual model

Limit in data acquisition

Best solution

Risk

Cost of the geognostic surveys

Hydrogeological data acquisition (%)

Excavation and tunnel support system that minimise tunnel inflow and its interferences with springs and wells

Analytic equations for tunnel inflow, with the related validity range

These equations have been developed for isotropic porous aquifers, but they are commonly used for discontinuous fractured aquifers, too.

All the above cited formulas are based on the hypothesis of homogeneous and isotropic aquifer, horizontal water table and $r << H/K$ hydraulic conductivity. $L$, length of the tunnel; $H$, depth of the tunnel centre from the water table; $h$, hydraulic head into the tunnel, $S$, specific storage coefficient, $r$, tunnel radius (with lining; $r_e$ is the external radius and $r_i$ is the internal radius), $R$, radius of influence, $K_i$, tunnel lining hydraulic conductivity, $D$, hydraulic load above land surface, $t$, time; $x$, spatial coordinate along the tunnel axis with the origin at the entry of the permeable zone, $v$, drilling speed, $\theta(L-x)$ Heaviside step function (also named unit step function, when $(L-x) < 0$, $\theta(L-x) = 0$ and when $(L-x) > 0$, $\theta(L-x) = 1$)

Can analytic equation be suitable for discontinuous rock masses?

Groundwater flow modelling through a discrete approach

Lithostatic load

Hydrostatic load

Coupled modelling of both hydraulic and mechanical processes in a jointed rock mass

Symmetry axis

Water table drawdown

Tunnel inflows along joints

Simulations for different joint set:
• dip and dip direction;
• spacing (1 – 12 m);
• surface aperture (1.29e-6 – 2.04e-6 m);
• connectivity (50 – 100%);
• tunnel depth (15 – 260 m);
• water table (15 – 135 m).

Joints spacing and aperture

Tunnel inflow linearly increases with joints frequency.

Tunnel inflow increases with joint aperture with a power law.

Tunnel depth

Joints aperture exponentially decreases with tunnel depth.

Tunnel inflow exponentially decreases with tunnel depth.

Joints dip

For the same value of equivalent permeability, tunnel inflow depends on joint dip.

- Orientation of the permeability tensor

- 550 joints intersections
- 213 joints intersections

Comparison between analytic formula and numerical results for different joint networks

The comparison points out that the analytic formulas overestimate the tunnel inflows and that the overestimation is bigger for geostructural setting having discontinuities with higher dips.

Based on the comparison between the numerical results and the tunnel inflows calculated with the Goodman equation, the following empirical relation was pointed out:

\[ Q = aQ_G^b \]

- \( Q \) (m\(^3\)/s) = tunnel inflow in discontinuous rock mass,
- \( Q_G \) (m\(^3\)/s) = tunnel inflow by Goodman’s equation,
- \( a \) and \( b \) are empirical dimensionless coefficients depending on:
  - dip of discontinuities,
  - hydraulic conductivity anisotropy ratio,
  - orientation of hydraulic conductivity tensor.

\[ b = \ln 3.463 F^{0.0342} \]
\[ a = \begin{cases} 
3.448 F^{0.8834} & \text{for } F < 1 \\
3.2411 F^{0.6805} & \text{for } F \geq 1 
\end{cases} \]

Where:
- \( n \) is the number of discontinuity sets,
- \( \alpha_i \) is the dip of \( i \)th discontinuity set,
- \( K_{\min} \) and \( K_{\max} \) are the minimum and maximum components of the hydraulic conductivity tensor,
- \( \theta_{\min} \) is the angle between \( K_{\min} \) direction and the horizontal plane,
- \( \varphi = \begin{cases} 
-1 & \text{if } \theta_{\min} > 45^\circ \\
1 & \text{if } \theta_{\min} \leq 45^\circ 
\end{cases} \)

Example: The “Monte Giglio” Tunnel

The medium-depth tunnel interests sedimentary rocks of the Lombardy Series. It is located below the water table for a length of 5.5 km, with no waterproofing.

The tunnel was divided into hydrogeological homogeneous stretches. For each one, the hydraulic conductivity tensor and the corresponding equivalent hydraulic conductivity were calculated based on the structural surveys and on depth pumping tests, that allowed to consider the decreasing of permeability with depth.

In some cases, the hydraulic conductivity ellipses (in the vertical plane orthogonal to the tunnel) show a great anisotropy, with the main hydraulic conductivity parallel to the vertical direction, such as for stretches 2, 4 and 6. As a consequence, for these cases the Goodman equation gives the highest overestimation, whereas the empirical relation allows an estimation of the tunnel inflow that better reproduces the observed values.

How can we use the hydrogeological conceptual model for geological hazard assessment?

1) In slope dynamic
   Large scale hydrogeological susceptibility to landslide

2) In tunnel design
   Tunnel inflow assessment (design phase)

3) In underground infrastructures management
   Hydrogeological hazard in underground infrastructures (operational phase)
The rise of the groundwater table has been about 8-10 m in the northern area, 4-5 m in the central zone of Milan and 2 m in the southern one. This rising trend interferes with the structures and infrastructures, bringing about both management troubles for the railway urban system and safety issues for the structures.
Examples of interference between groundwater and underground structures and infrastructures

The metro line green, which was designed to function in dry conditions, now lies below the water table, involving important waterproofing works.

If the groundwater trend will go on with the same rate, in the next ten years static problems will be triggered, even in presence of waterproofing lining.
The model domain covers an area with high density of hydrogeological data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Bottom surface Aquifer A</th>
<th>Upper surface Aquifer B</th>
<th>Bottom surface Aquifer B</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARG</td>
<td>1020</td>
<td>731</td>
<td>361</td>
<td>2112</td>
</tr>
</tbody>
</table>

Quite good accuracy in the reconstruction of the aquifer geometry:

Shallow aquifer
Aquitard
Semi-confined aquifer

Grid composed by cells (2.5 m x 2.5 m)

8 layers to represent Aquifer A* (Layer 1-6), aquitard (Layer 7) and Aquifer B* (Layer 8)

* ENI-Regione Lombardia aquifer definition

In order to simulate the metro tunnels (shown in black), the shallow layer was further divided in 6 sub-layers.

Gattinoni et al. (2014) “A 3D model of the aquifer of Milan (Northern Italy)”, SGEM, 2: 3-10.
1) Boundary and internal conditions

- Wells
  - No flow elements
  - $Q_{well} \approx 11 \text{ m}^3/\text{s}$
- SPECIFIED HEAD
- SPECIFIED FLOW
- FLOW DEPENDENT HEAD

- Constant head - piezometric survey in March 2014
- No flow element representing the tunnels, metro stations and foundations
- River (Lambro, Seveso, Olona)

2) Input equivalent hydraulic conductivity interpolation

- 45 cm/y
- 5 cm/y
- 80 cm/y

- Shallow aquifer
- Semi-confined aquifer
- Aquitard

**STEADY STATE CALIBRATION (March 2014)**

1) Local water table drawdown due to the impermeable infrastructures

2) Velocity vectors and velocity values in a cross-section nearby the Garibaldi station

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**Absolute residual mean:** 14 cm

**Scaled absolute residual mean:** 0.2%

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Probability distributions of:
(a) the recharge multiplying factor
(b) the withdrawal decreasing
Average groundwater rise simulated with the stochastic approach

Water table changes (in m) in some metro stations: $\Delta H_{50\%}$, $\Delta H_{75\%}$ and $\Delta H_{95\%}$ are respectively the 50%, 75% and 95% percentiles of the simulated values.

<table>
<thead>
<tr>
<th>Metro station</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta H_{50%}$</td>
</tr>
<tr>
<td>Garibaldi$^1$</td>
<td>3.12</td>
</tr>
<tr>
<td>Repubbl.$^2$</td>
<td>2.93</td>
</tr>
<tr>
<td>P.Venezia$^1$</td>
<td>2.71</td>
</tr>
<tr>
<td>Domodos.$^2$</td>
<td>3.08</td>
</tr>
<tr>
<td>Centrale$^1$</td>
<td>2.99</td>
</tr>
<tr>
<td>Lotto$^1$</td>
<td>3.20</td>
</tr>
<tr>
<td>Cadorna$^1$</td>
<td>2.81</td>
</tr>
<tr>
<td>Duomo$^3$</td>
<td>2.60</td>
</tr>
<tr>
<td>Loreto$^2$</td>
<td>2.76</td>
</tr>
<tr>
<td>Piola$^2$</td>
<td>2.56</td>
</tr>
<tr>
<td>Zara$^2$</td>
<td>3.03</td>
</tr>
<tr>
<td>Lambrate$^2$</td>
<td>2.51</td>
</tr>
</tbody>
</table>

Probability occurrences of water table in some metro stations, compared to their bottom and top altitudes.

Flooding hazard map of the metro tunnels

Probability that the water table exceeds the bottom altitude, for each metro line.

MITIGATION SOLUTIONS

RECHARGE MODIFICATION:
- Decreasing of infiltration rate in the domain (parasite water reduction, better management of irrigation channels, etc.)
- Restoration of the original hydraulic connection of the surface network

PUMPING MODIFICATION:
- Increasing pumping rate in aquifer A (10%-30%)

DRAINAGE TUNNEL:
- floodway-diverter of the Seveso River

### MITIGATION SOLUTIONS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Hypotesis</th>
<th>$\Delta h$ (m)</th>
<th>Area of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>Recharge reduction 25% in the whole domain</td>
<td>-0.7</td>
<td>Highest values equal to -1m in the western zone of Milan</td>
</tr>
<tr>
<td>I2</td>
<td>Draining tunnel (total discharge $\approx 2 \text{ m}^3/\text{s}$)</td>
<td>-2.5</td>
<td>Highest values equal to -5 m nearby the tunnel</td>
</tr>
<tr>
<td>I3_10</td>
<td>Pumping rate increase of 10% in aquifer A</td>
<td>-0.3</td>
<td>Located in the central area of Milan</td>
</tr>
<tr>
<td>I3_30</td>
<td>Pumping rate increase of 30% in aquifer A</td>
<td>-1.0</td>
<td>Located in the central area of Milan</td>
</tr>
<tr>
<td>I1+I2</td>
<td>Superimposition of scenarios I1 and I2</td>
<td>-3.0</td>
<td>Similar to scenario I2 but with a larger extension of the drawdown</td>
</tr>
<tr>
<td>I1+I3_30</td>
<td>Superimposition of scenarios I1 and I3_30</td>
<td>-1.5</td>
<td>Generalized over the whole domain, with max values in the central area</td>
</tr>
</tbody>
</table>

Non-structural measures can easily manage the short term hazard, whereas in the long term an integration between structural and non-structural measures will be necessary.

A drainage system located at the bottom of the metro tunnels would have kept the water table below the infrastructures, avoiding this kind of hazard.

Hydrogeological model is a key factor in geological hazard assessment and prevention!

Learn from yesterday,
Live for today,
Hope for tomorrow.

The important thing is not to stop questioning

*Albert Einstein*