DOI: 10.4408/IJEGE.2006-01.S-17

# THE IMPORTANCE OF THE GEOLOGICAL MODEL TO UNDERSTAND AND PREDICT THE LIFE SPAN OF ROCKSLIDE DAMS: THE SCANNO LAKE CASE STUDY, CENTRAL ITALY

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## INTRODUCTION

The Scanno rockslide-avalanche dammed the Tasso river and caused the impoundment of the Scanno Lake which is one of the most famous example of naturally dammed lake in Central Apennines; it has an area of approximately 1 km$^2$, a perimeter of about 5 km and a maximum depth of 33 m (Riccardi, 1929). Far more significant is the presumed age of the lake. In fact, according to reports and documents by Roman historians the event could date back to 217 B.C. (Nicoletti *et alii*, 1993). Further, radiocarbon dating of a paleosoil sample collected in the accumulation area just below the rockslide debris yielded an age of about 12800 yr, thus giving a lower bound for the time of occurrence. These data, together with considerations on the rockslide debris aspect and upstream morphology, would suggest an age between 12000 and 2300 yr. It comes out that the life span of the dam is remarkable, since there is no record of catastrophic breaching during the past 2300 yr. As regards dimensions and morphology of the rockslide dam, the estimated volume of the debris accumulation is about 96×10$^6$ m$^3$, that presently covers an area of 2.6 km$^2$ with a maximum width of accumulation (W) about 2 km (Figure 1). The dam shows a considerable bulk and a relatively flat form. Such features, added to the presence of a pronounced frontal ridge as well as to a peculiar T shape, allow to ascribe it to the type III of the classification by Costa & Schuster (1988).

To explain such a long life span of the rockslide-avalanche dam and to get indications about its future stability conditions, it is fundamental to build a representative geological model especially aimed at defining:

geometry of the boundary surface between the rockslide debris and the bedrock;

geotechnical characteristics of the debris with special reference to hydraulic behavior (grain size, porosity, bulk permeability);

flownet within the rockslide deposit taking into account the complex geological and hydraulic boundary conditions imposed by the palaeovalley morphology and by the numerous springs downstream of the dam which are fed by different aquifers.

According to the mentioned objectives, a multidisciplinary research project has been purposely planned and is presently in progress. It is based on both site and laboratory investigations encompassing geological and geomorphological survey, hydrogeological measurements, chemical and isotope analyses, borehole drilling, pumping tests and electrical tomography. In the following sections, after an outline of the geological and hydrogeological setting of the Scanno area, are discussed the research methodology and the preliminary results so far acquired.

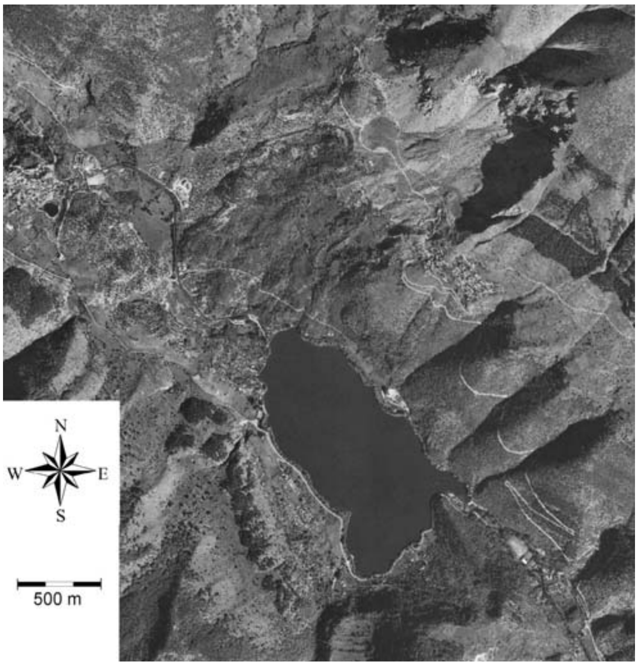


*Figure 1 - Aereal view of the rockslide dammed Scanno Lake*

## GEOLOGICAL SETTING

The Scanno Lake is located in the central part of the Apennines, a northeast-verging imbricate fold-thrust belt (Figure 2). The exposed thrust sheets consist of Triassic-Middle Miocene carbonate platform, ramp, and intraplatform facies (Cavinato *et alii*, 1995). High-angle, generally W-dipping normal faults across the southwestern slope of the range and extensional basins of generally post-Messinian age are widespread in the Central Apennines (CAVINATO & DE CELLES, 1999). The morphostructural setting is characterized by a pattern of blocks bounded by normal faults on the western side and by NW-SE to NNW-SSE thrust fronts on the eastern one. Regional uplift up to 1000-1500 meters affected the area since Early Pleistocene (DRAMIS, 1992) favouring the activity of normal faults on the Tyrrhenian side, where a number of tectonic steps were formed. Extensional tectonics has continued its activity up to Present, as testified by the displacement of the Holocene deposits and by the focal mechanisms of recent earthquakes.

## THE SCANNO ROCKSLIDE-AVALANCHE

A huge clastic deposit, interpreted as a morainic one until the early 1940's (e.g. the old official geological cartography by CASSETTI & CREMA, 1928; NICOLETTI *et alii*, 1993), has been investigated within the Sagittario valley (Figure 3). The main structural feature of the rockslide area is a wrench fault along the western flank of Mt. Genzana, dipping from 70° to 90° towards SW. Late Miocene mudstone and sandstone outcrop along the south-western side of the Genzana fault. At the north-eastern side (footwall) of the fault, rocks belonging to transition zone crop out, and consist of limestone and marly-limestone with chert nodules. These rocks are fairly jointed, and cataclastic zones are also present. The Scanno rockslide (detachment volume $\cong 82\times10^6$ $m^3$) involved all the above mentioned formations as well as open work breccias of Pleistocene age. It shows typical features such as frontal ridge, inverse sorting, spill out along the left flank and splash area in the surrounding zone. After the collapse onto the valley bottom the debris dammed the Palaeo-Tasso River and formed the Scanno Lake. The rockslide came off Mt. Rava, a shoulder of Mt. Genzana (Figure 3); the scar is markedly concave within the limestone and the rupture surface along the slope has a chair shape. The S-shaped geometry of the rupture surface is clearly connected to the geological-structural setting, and in particular to the bedding attitude, which favoured a sliding mechanism in the early stage of failure.

## HYDROGEOLOGICAL SETTING

The Tasso-Sagittario basin consists of mesozoic carbonate aquifers, with very complicated structural setting. The aquifers belonging to carbonate shelf domain have an effective infiltration of about 900 mm/year; the aquifers belonging to the transitional domain have an effective infiltration which has been estimated about 600 mm/year. Effective infiltration recharges large karst aquifers which feed huge springs with discharges in the order of some $m^3$. In addition, some "linear springs" (natural discharge of groundwater emerging directly into the streambed) have been detected in the area (Figure 4) (PIANELLI & BONI, 1995).

The head of the Sagittario River is located at elevations of about 1300 m asl, where it is called Tasso River. This river flows into the Scanno Lake (922 m a.s.l.) with a minimum discharge of 0.4 $m^3/s$ (base flow), including La Marca Spring (0.1 $m^3/s$) flowing directly into the Scanno Lake (SALVATI, 2002). The Scanno Lake has no effluent during dry periods (summer and autumn) and frequently during the entire year, with a steady water level. Only during intense pre-

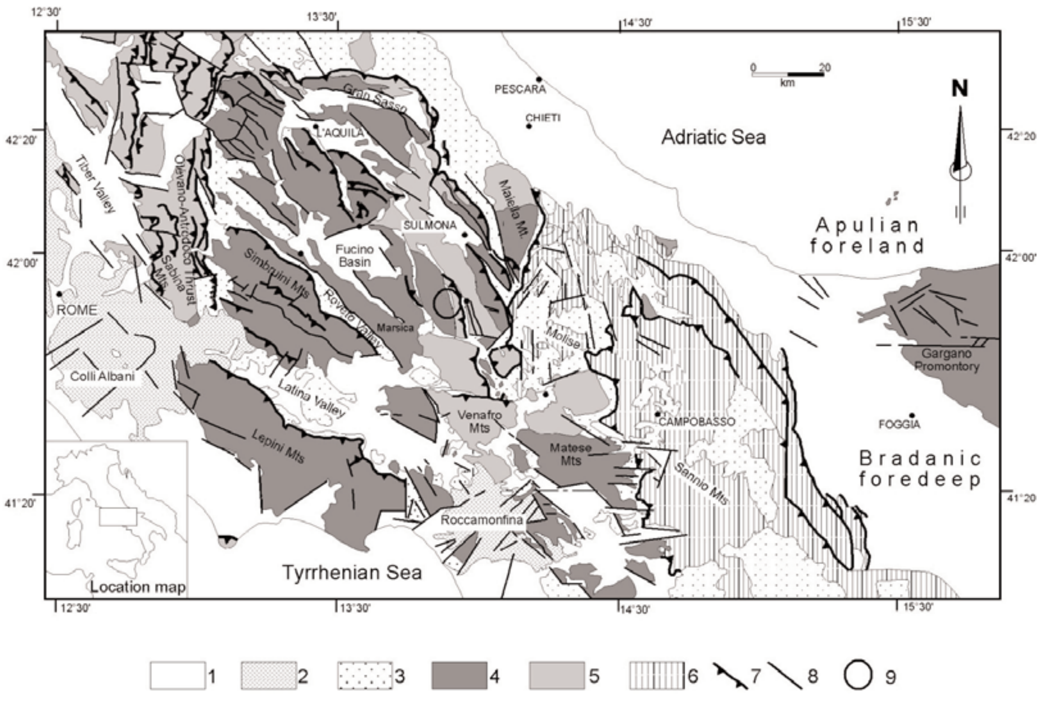


*Figure 2 - Simplified geological and structural map of the central Apennines. Key to legend: 1) marine and continental clastic deposits (Pliocene-Quaternary); 2) volcanic deposits (Pleistocene); 3) synorogenic hemipelagic and turbiditic sequences (Tortonian-Pliocene); 4) carbonate platform deposits (Triassic-Miocene); 5) slope and by-pass margin deposits (Liassic-Miocene); 6) Molise-Sannio pelagic deposits (Cretaceous-Miocene); 7) thrust; 8) normal and strike-slip fault; 9) location of the studied area*

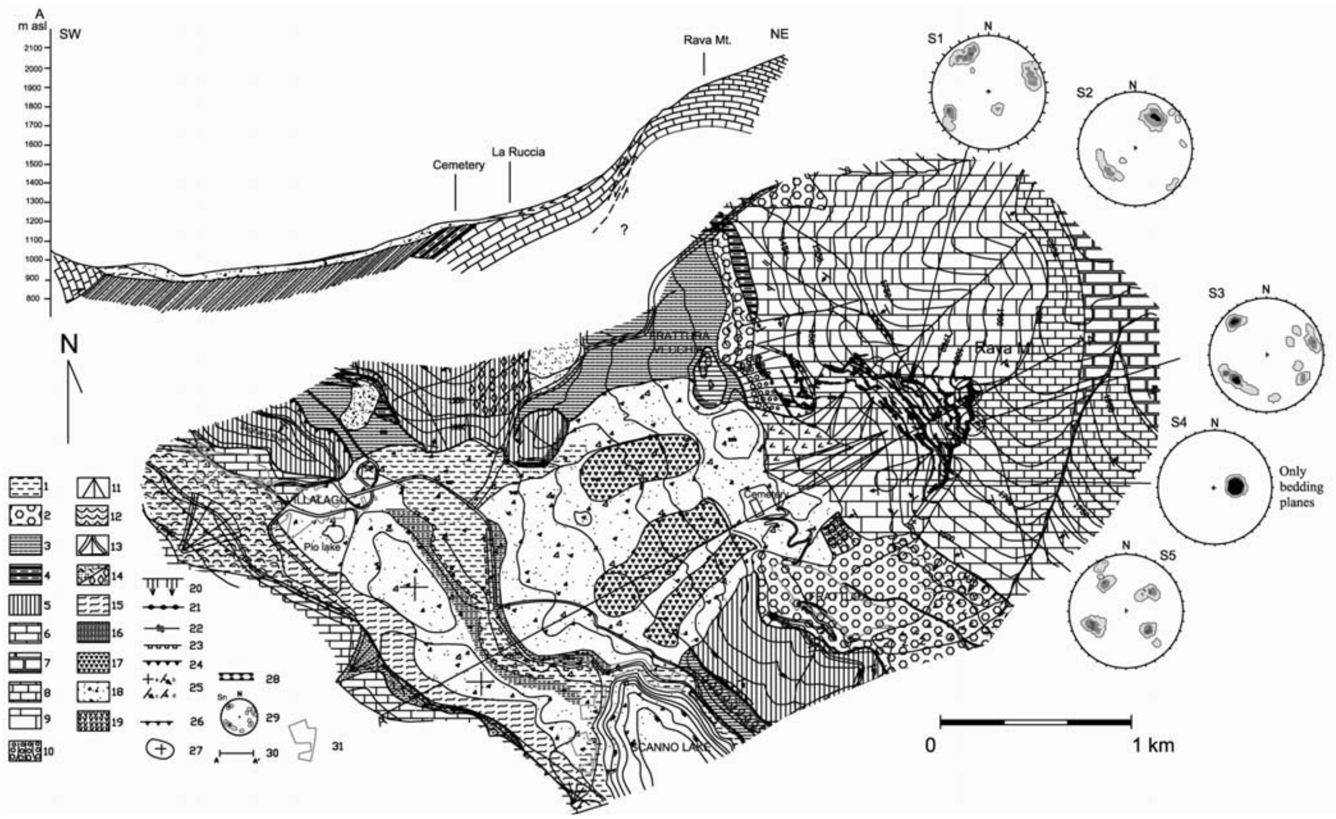


*Figure 3 - 1-Fluvial and fluvio-lacustrine deposits, alluvial fan, eluvio-colluvial deposits (Holocene); 2-Cemented breccias (Pleistocene-Holocene); 3-Turbiditic clay and sandstone (upper Miocene-Lower Pliocene); 4-Thinly bedded marly calcarenites (Middle-Upper Miocene); 5-Detritic limestones interlayered with calcareous breccias and micritic levels (Lower Cretaceous-Paleocene); 6-Detritic limestones with fossils (Middle Jurassic-Lower Cretaceous); 7-Detritic limestones with chert nodules (Upper Cretaceous); 8-Micritic marly limestones (Lower-Upper Cretaceous); 9-Detritic limestones (Lower Cretaceous); 10-Talus fan; 11-Debris fan; 12-Colluvial deposits; 13-Alluvial fan; 14-Talus slope; 15- Bulldozed flysch; 16-Fluvial deposits; 17-Rock fall debris; 18-Rock avalanche deposit; 19-Rock slide debris; 20-Fault; 21-Fold axis; 22-Wrench fault; 23-Terrace edges; 24-Overthrust; 25-Bedding attitude; 26-Rock fall scar; 27-Frontal ridges; 28-Gravitational trenches; 29-Schmidt net (lower hemisphere); 30-Geological section; 31-Town boundary*

cipitation periods the waters flows into the effluent inducing the formation of an ephemeral lake at Prato site with concentrate infiltration into the rockslide dam deposit (Figure 5, 6).

When discharge is not observed at the effluent, the inflow is assumed to be lost by evaporation and/or by infiltration into the rockslide dam deposits. Taking into account the climatic conditions, a preliminary water budget shows high infiltration values into the rockslide deposits (CASALE, 1995). Downstream the Sagittario River valley dam there are many springs (PERRONE, 1900) with a total discharge around 1 m$^3$/s (Villalago Springs), partially fed by karst aquifer outcropping on the left side of the valley. The contribution from the rockslide debris was up today unknown, because detailed

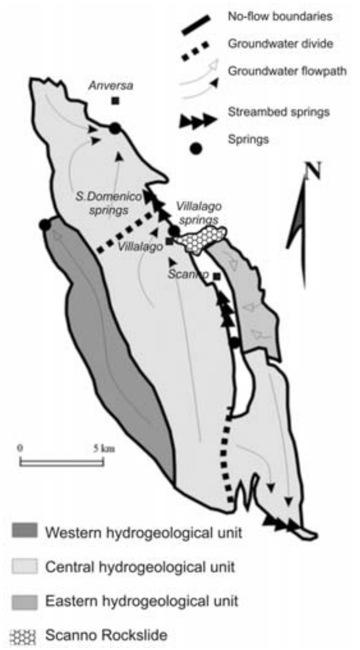


*Figure 4 - Hydrogeological setting of the Scanno area (modified from SALVATI, 2002)*

hydrogeological and hydrochemical studies about the origin of these groundwater have not ever been performed. Downstream the Sagittario valley, there are further springs and streambed springs (Sega and S. Domenico), with a total discharge of 1.8 $m^3/s$, which further complicate the hydrogeological setting.

## METHODOLOGY

The core goal of this research is to understand the factors bearing on the long lifespan of the Scanno rockslide dam and to assess its overall stability conditions, in relation to the geometry and technical characters of rockslide debris and in particular to the groundwater circulation.

The geometry and the geotechnical characters of the debris are function of the pre-rockslide Sagittario River valley morphology, of the mechanism of rockslide debris emplacement and of the parent rock mass outcropping on the western slope of Mt. Genzana.

Boreholes drilled in the morphological depressed areas of the rockslide deposit, lab investigation on debris samples taken from both outcrop and drilled cores, geophysical prospecting based on electrical tomography and hydrogeological measurements were all planned to obtain information on such topics.

The groundwater transfer role played by the rockslide debris is framed within the above described hydrogeological setting, which can be outlined as follows: a) the lake reservoir receiving waters from both watershed and hydrogeological basin (inflow); b) the rockslide debris transferring groundwater from the lake to the Villalago Springs (transfer); c) the Villalago Springs group, receiving contribution from both rockslide debris aquifer and regional carbonate aquifers (outflow).

Based on such scheme, hydrogeological investigations are in progress to obtain the following results:

- water budget of the Scanno Lake, with the evaluation of the infiltration losses into the rockslide deposits; the analysis is undertaken over a long-term period (climatic conditions in 50 years), over a monthly basis and during the 2003-04 hydrologic year;
- evaluation of the contribution from the rockslide deposits to the Villalago Springs, recording outflow and springs discharge values and their variations in different seasons of the 2003-04 period;
- evaluation of the permeability of the rockslide deposit, acquiring data on the hydraulic gradient based on lake water table and springs elevations as well as through pumping and injection tests in appositely drilled wells into the rockslide deposit;
- separation of the contribution from carbonate aquifers and from rockslide deposit to the Villalago Springs, by hydrochemical coupled sampling from the inlet, from the lake and from different springs, in different periods during the year;
- groundwater flowpaths modeling by stable isotope investigations, to distinguish actual flowpaths into the carbonate aquifers and into the rockslide deposits, to obtain information about the age of rock mass interacting with groundwater ($^{87}Sr/^{86}Sr$) (Banner *et alii*, 1989; Naftz *et alii*, 1997) and about recharge area elevations ($^{18}O/^{16}O$) (Clark & Fritz, 1997; Craig, 1961).

In this peculiar context, it is necessary to describe the complete water flowpath as the groundwater seeping through the rockslide debris is marked by peculiar isotope and chemical characteristics due to its origin. The lake waters coming from runoff and base flow of the Tasso River show peculiar values of stable isotopes ($^{18}O/^{16}O$ ratio as an expression of the mean altitude of precipitations and of mean recharge aquifer altitude; $^{87}Sr/^{86}Sr$ ratio as a function of age of the

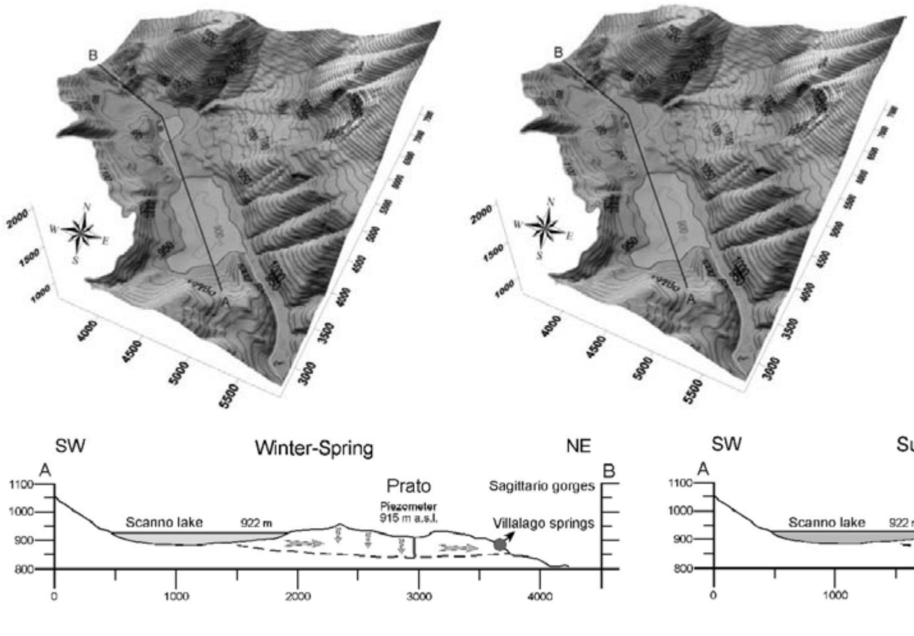


*Figure 5 - Digital elevation model and section along the Sagittario Valley (distances and elevations are in meters)*

*Figure 6 - Prato site during the winter period*

rocks constituting the aquifer). The different seasonal contribution of runoff and base flow waters to the lake determines different composition of the groundwater seepage through the rockslide debris aquifer along the year. As a consequence, the chemical composition of the Villalago Springs waters, which are fed by the rockslide debris aquifer, changes over time: during the dry season the contribution to the Villalago Springs comes from the carbonate aquifer and, for a lower amount, from the seepage into the rockslide debris. The electrical conductivity of these springwaters is relatively high, feeding the karst aquifer. At the same time, the isotope and chemical composition is related to the groundwater carbonate aquifers. Otherwise, during the rainy season, the contribution from the inflow water into the Scanno Lake, and of course into the rockslide deposit aquifer, is directly influenced by runoff waters. As a consequence, the electrical conductivity of the Villalago Springs shows lower values, caused by the dilution effect. In addition, ion content is lower and the isotope ratios are modified too.

In conclusion, hydrogeological and hydrogeochemical monitoring over time of the salinity, chemical and isotope concentration of the inlet, lake waters, rockslide deposit aquifer groundwater and Villalago springs could offer a refinement of the geological model in the Scanno Lake zone, better defining the groundwater circulation and the transfer role of the rockslide deposit.

## PRELIMINARY RESULTS AND REMARKS

As regards the geometry of the rockslide debris, the borehole at Prato site (Figure 6) shows the thickness of 65 m in correspondence with the assumed Palaeo-Tasso thalweg. Electrical tomography investigations, presently in progress, will give a more complete reconstruction of the bedrock top-surface.

With reference to the flownet geometry and the hdyrogeological budget, assuming the evaporation from the lake surface equal to the precipitation amount over the same surface, it comes out from the lake waters budget that the inflow amount and the infiltration into the rockslide debris are equal.

The measured discharges show an inflow between 0.45 (January 2004) and 0.9 $m^3/s$ (March 2004). In the same period, the outflow from the Scanno Lake ranges from 0 (no flow at the effluent) to 0.9 $m^3/s$, exactly corresponding to the inflow. At the Villalago Springs, the discharge increases from 0.7 (January) to 1.5 $m^3/s$ (March), evidencing a significant connection between the rockslide debris groundwater and the Villalago Springs themselves. However, the analysis of the discharge data in the dry period points out the feedback of the lake inflow to a variable percentage of Villalago Springs discharge.

As a matter of fact, the chemical analyses show the similarity of the inflow waters with these ones of the highest Villalago Springs. According to the electric conductivity data, it is possible to observe a general decreasing trend of the Villalago Springs salinity over time, due to the significant increase of the amount of runoff waters infiltrating into the rockslide debris as a result of the Lake outflow. A preliminary assessment of the hydraulic conductivity of the rockslide deposit aquifer shows a value of $10^{-3}$ m/s inferred from the groundwater flowrate (1-1.5 $m^3/s$), the section of the flownet (30000 $m^2$) and the hydraulic gradient (20‰).

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