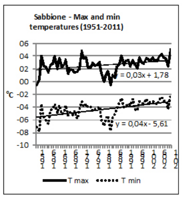
High altitude areas in the Alps are characterized by the presence of glacial and periglacial environments, which are currently susceptible to significant transformations. The climatic conditions are the main cause of the reduction of glaciers and the modification of alpine environment with remodelling processes on rock masses and debris deposits. These changes lead to a gradual evolution of geosphere and cryosphere with implications also on human activities. The object of this work is the study of the relationships between glacial and periglacial environments in the Hohsand basin (Formazza Valley, Lepontine Alps, Italy), where a storage pond of 1.23 km^2 (about 26 million m^3) is located gathering the ablation waters of the glaciers (the main are the Northern and the Southern Sabbione Glaciers, about 3.8 km^2 of total covered area in the 2007).

Literature data review and historical maps have been used to reconstruct the glaciers evolution since the end of the Little Ice Age (LIA). This analysis shows that the ice coverage of the basin has suffered of important reduction since the second half of the 19th century. Southern Hohsand Glacier retreated by 1,600 m in the period 1885÷1987 (average frontal retirement approx. 16 m/year). This rate increased in the period 1991÷2004 (approx. 23 m/year). The Northern Hohsand Glacier suffered of significant volumetric shrinkage (period 1885÷1991), estimated more than 50% (approx. 150 million m^3), and areal reduction, 40% (approx. 1.2 km^2).

The data extracted from meteorological stations located in the basin have been analyzed in order to characterize the climate of the study area, to verify the existence of climatic conditions for the development of cryotic processes and to investigate the morpho-climatic evolution of the basin. The data quality control and the statistical analysis of climatic data have been performed using RClimDex and AnClim softwares. Numerical values have been aggregated on monthly and annual basis and trends have been calculated for the main climatic parameters using the non-parametric test of Mann-Kendall to verify the statistical significance. The climatic trends of Sabbione are the following (period 1951÷2011): Maximum air temperature, significant increase of 0.03±0.01°C/year (FIG. 1); Minimum air temperature, significant increase of 0.04±0.01°C/year (FIG. 1); Liquid precipitation, non-significant increase of 1.15±1.9 mm/year; Fresh snow (Hn), significant decrease of -3.17±1.35 cm/year; Snow depth (Hs), significant decrease of -0.82±0.27 cm/year; Snowy days, non-significant decrease of -0.06±0.09 days/year; Snow cover absence, non-significant increase of 0.08±0.1 days/year.



The geomorphological analysis has been conducted in order to describe the geomorhological characteristics of the basin and to understand the evolution of the recently deglaciated areas. The data, derived from photographic interpretation (aerial images, 1955÷2001 and digital orthoimages, 1988÷2010) and field surveys, have been digitized in a GIS environment, using QuantumGIS and GRASS softwares. Through these data, detailed geomorphological maps and a map of glacial deposits of the basin have been realized.

A large amount of glacial deposits (3.2 km^2) has outcropped after the glaciers retirement and disappearance. The geomorphological analyses show the presence of periglacial landforms within these deposits. An active debris rock glacier has been identified in deglaciated site by the 50s of 20th century, in which a gradual emphasizing of its morphological expression has been observed since the 80s. Its evolution derived from the degradation of a LIA moraine, due to partial melting of the ice core. In the Hohsand basin there is also an active talus rock glacier. Moreover, periglacial landforms resulting from frost sorting and frost heaving processes, such as non-sorted circles and frost boils, have been found within glacial deposits. Non-sorted stripes have been also identified in till, which origin is related to the combination of cryotic and gravitative processes (frost sorting, frost heaving, frost creep and gelifluction).

To determine the potential distribution of permafrost the model PERMACLIM has been implemented in QuantumGIS, using the SEXTANTE platform and the Python programming language. Four IT calculation modules have been created in order to perform the data processing: “Distribution of snow based on slope”, which corrects the snow height according to the effects of the slope; “Ground surface Temperature”, that calculates surface temperatures for each cell of the DTM; “Mean band based on indexes” and “Monthly Mean”, which perform mathematical and statistical analyses on model results. The PERMACLIM is a process-oriented model which uses as input data a Digital Terrain Model (DTM) and climate data. The IT application calculates the Mean Annual Ground Surface Temperature for each point of the DTM including the snow buffering effect according to the heat conduction theory, which uses climate data and snow thermal characteristics. The needed input data are: DTM, Snow cover thickness, Air temperature, Thermal conductivity of snow and Sensible heat flux. To apply the PERMACLIM in the study area, snow thickness/distribution and air temperature have been derived from a distributed hydrological model developed by Arpa Piemonte. A DTM 50m of Piedmont has been also used. The thermal conductivity of snow has been calculated starting from density values extracted from stations of military service “Meteomont” (period 2000÷2010), integrated by data derived from 220 stratigraphic snowpack profiles of interregional institution for snow and avalanches - AINEVA (period 1996÷2010). The sensible heat flux has been derived from literature data. Air temperature and snow thickness of hydrological model have been compared with climatic data measured by meteorological station Formazza (period 2001÷2009). An additional analysis has been conducted using Landsat satellite images to verify the quality of the modelled snow distribution, comparing with remote sensing data, by using ENVI, ArcGIS and SAGA softwares. Finally, other permafrost models already available for the studied area (PERMAROCK mod., APMOD and Swiss Permafrost Map 1:50000) have been compared; the model results have been integrated by BTS measurements (Bottom temperatures of snow cover) performed by Arpa Piemonte in the late winter 2011.

The active rock glaciers, which are considered as indicators of permafrost presence, are located in sectors with permafrost probable. BTS measurements confirm a high probability of permafrost presence in the talus rock glacier; temperatures (Ts)<-3°C, likely permafrost indicator, have been recorded in these soils. Instead, according to the models, a part of the identified cryotic forms is located in sectors with less likely permafrost presence. These forms are probably the result of high frequency/intensity seasonal freeze-thaw cycles in areas with sporadic or absent permafrost.

The climatic evolution of the investigated area since the end of the LIA has caused a substantial decrease in glacial masses. In particular, the climatic trends of the past sixty years are the main cause of the pronounced glacial decline which is originated by ablation augmentation, due to the thermic increase in air temperatures, and by alimentation reduction caused by decrease in solid precipitation. The regression of glacial bodies has allowed the outcropping of large amounts of till. The geomorphological analysis shows that in these glacial deposits the climatic conditions has led to the development of cryotic processes and conditions for permafrost aggradation.

Most landforms resulting from cryotic processes on deposits have been observed in deglaciated areas before 50s/60s of the 20th century; therefore, it is evident that some decades are necessary for a sizeable development of cryotic processes, because the temperate glaciers interfere significantly with the thermal conditions of the substrate (thermal inertia). In addition, favourable climatic and geomorphological conditions (altitude, distribution and thickness of snow cover, etc.) and a coarse grain size of the clasts are also needed.

The transition from glacial to paraglacial/periglacial environments is also reflected on the morpho-dynamic evolution of the study area and it cannot be exclusively formulated as a report of presence/absence, but represents an example of space/time overlap, that influences and defines the structure of the recently deglaciated areas (eg. frost boil originated by processes of frost heaving on buried glacial ice).

Considering the debris rock glacier, the relationship between glacial and periglacial processes appears even more evident. Indeed, this form, deriving from moraine degradation, represents the most evident demonstration of the transition from a glacial environment to an environment characterized by cryotic processes. The recent rapid development of this form could be related to the modification and/or to the partial melting of the ice core, due to the rising air temperatures showed in the climate analyses. In addition, the permafrost models simulate a high probability of permafrost presence in the surrounding areas of glaciers. Therefore, if the glacial masses continue their regression according to the current trend and rate, the new deglaciated areas and deposits will be affected by cryotic processes. At the same time there will be a gradual stabilization of the areas where the frost action will not be present because of the increase in air temperatures.

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