High alpine ponds shift upwards as average temperatures increase: A case study of the Ortles–Cevedale mountain group (Southern Alps, Italy) over the last 50 years

Franco Salerno [a,b,*], Sara Gambelli [a], Gaetano Viviano [a], Sudeep Thakuri [a,b,c], Nicolas Guyennon [a], Carlo D'Agata [c], Guglielmina Diolaiuti [b,c], Claudio Smiraglia [b,c], Fabrizio Stefani [a], Daniele Bocchiola [b,d], Gianni Tartari [a,b]

[a] *Water Research Institute, National Research Council (IRSA-CNR), Via del Mulino 19, Brugherio, MB 20861, Italy*
[b] *Ev-K2-CNR Committee, Via San Bernardino 145, Bergamo 24126, Italy*
[c] *Department of Earth Sciences "A. Desio", Università degli Studi di Milano, Via Mangiagalli 34, 20133 Milano, Italy*
[d] *DICA, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano 20138, Italy*

Received 21 January 2014
Received in revised form 9 June 2014
Accepted 10 June 2014
Available online 18 June 2014

1. Introduction

A substantial body of research demonstrates the sensitivity of lakes and ponds to climate and shows that physical, chemical, and biological lake properties respond rapidly to climate-related changes (Carpenter et al., 2007; Rosenzweig, 2007; Pham et al., 2008; Williamson et al., 2008; Adrian et al., 2009; Lami et al., 2010). Some climate-related signals are highly visible and easily measurable in lakes. For example, climate-driven fluctuations in lake surface area have been observed in many remote sites. In this context, Smol and Douglas (2007) reported the gradual, decadal-scale drying of high Arctic ponds between 1983 and 2006 due to changes in the ratio of precipitation to evaporation, and Yoshikawa and Hinzman (2003), Smith et al. (2005), and Morgenstern et al. (2011) found that lakes in areas of discontinuous permafrost in Alaska and Siberia were disappearing.

Previous research has examined the risks of glacier outburst floods caused by the sudden drainage of bodies of water located at the margins of glaciers. Glacier outburst floods (GLOFs) are well documented in the Hindu Kush Karakorum Himalaya. For example, Gardelle et al. (2010) provide a regional description, and Salerno et al. (2012) focus on the formation conditions of the glacial lakes. This phenomenon is also present in other parts of the world, including the European Alps, as described by Huggel et al. (2002) for the Swiss Alps and by Haeberli et al. (2002) for the Italian Alps.

However, in the Alps, only some special cases considering the potential risk of GLOFs were analyzed, while an extensive study of climate-driven fluctuations in the surface areas of a wider population of high elevation lakes and ponds is completely lacking. Catalan et al. (2009) defined these lakes as water bodies located above the tree line with a number of common features. They are relatively small, situated in sparsely vegetated catchments and exposed to extreme climates. Most of them are of glacial origin. These lakes are also unproductive

* Corresponding author at: Water Research Institute, National Research Council (IRSA-CNR), Via del Mulino 19, Brugherio, MB 20861, Italy. Tel.: +39 039 21694221; fax: +39 039 2004692.
E-mail address: salerno@irsa.cnr.it (F. Salerno).

due to their sparse soil development and small catchments (relative to lake volume). They tend to be in headwaters, far from populated areas, and experience minimal or no direct human activities in their catchments. While the difference between large ponds and small lakes is often debated, Hamerlík et al. (2014) report an interesting ecological threshold separating alpine pond and lake systems, where, at a surface area of $2 \cdot 10^4$ m^2, the species–area pattern changes significantly. In general, ponds are especially susceptible to the effects of climatic changes because of their relatively low water volumes and high surface area to depth ratios (Buraschi et al., 2005; Beniston, 2006). Therefore, these ponds act as early indicators of the impacts of climate change (Beniston, 2006; Williamson et al., 2009).

In this context, we selected a high-elevation area of the Italian Alps that (1) has a large number of ponds (Stelvio National Park, Lombardy Alps), (2) is well studied in regard to the recent glacier shrinkage processes (Diolaiuti and Smiraglia, 2010; D'Agata et al., 2013), (3) has a relative abundance of high-quality aerial photos from the last 50 years (D'Agata et al., 2013) and (4) represents one of the largest sectors of the glacierized areas in Lombardy. In this study, we inventory all ponds in the area with a minimum surface area of 800 m^2 (Supplementary material 1), and we examine their recent (i.e., last 50 years) surface area changes. In addition, we investigate climate variations within this area and their effect upon pond surface area fluctuations. We then discuss the possible links to the observed changes in glacial surfaces in this area (D'Agata et al., 2013).

2. Study area

The case study area covers the Lombardy sector of Stelvio National Park (SNP), one of the main protected areas of the Italian Alps (600 km^2) (Fig. 1). According to the Köppen–Geiger climate classification (Peel et al., 2007), this area features a temperate/cool continental-type climate with seasonal continuous snow cover above 1000 m a.s.l. Annual precipitation is approximately 750 mm y^{-1}, with the precipitation maximum during the end of the summer and onset of the fall, and the precipitation minimum during the winter (Diolaiuti et al., 2012).

The SNP is characterized by the Ortles–Cevedale mountain group, one of the most important glacierized sectors of Italy. The elevation ranges from 950 to 3905 m a.s.l., with an average value of 2425 m a.s.l. The highest peaks are Ortles (3905 m a.s.l.) and Cevedale (3769 m a.s.l.). The First Italian Glacier Inventory (CNR and CGI, 1961) classified 42 glaciers belonging to this group in the Lombardy Region. Among these glaciers are the Forni Glacier, the largest Italian valley glacier (approximately 11.4 km^2 area). It has experienced a marked decrease in length and area: from 17.8 km^2 at the end of the Little Ice Age (1860) to 11.4 km^2 in 2007 (−36.2%). In the same time frame, its tongue has retreated by approximately 2 km (Diolaiuti and Smiraglia, 2010).

Nangeroni (1983) compiled the first inventory of the Italian Alpine lakes. From this milestone of Italian limnology, it was determined that the selected study area has one of the largest numbers of high-elevation lakes of the entire Italian Alpine chain. However, no other study has defined the characteristics of these lakes in detail.

3. Data and methods

3.1. Data sources

Climate variations at the local level were investigated through the analysis of the monthly temperature and precipitation series of the Automatic Weather Station (AWS) located at Bormio (1225 m a.s.l., 46°28′13″ N, 10°22′21″ E) (Fig. 1), for the periods 1924–2007 and 1926–2003, respectively. The meteorological data were provided by ARPA Lombardia (Lombardy Agency for the Environment).

Three pond surface area records, from 1954, 1981, and 2007, are available for the study area. The same data sources and techniques used in this study were recently applied by D'Agata et al. (2013) in tracking the evolution of the surface areas of glaciers in this area. The 2007 area records were produced by combining pond limits that were manually digitized on registered color orthophotos (Volo Italia, 2007). This data source was used as the base layer for delimiting the pond boundaries. The orthophotos have a planimetric resolution of 0.5 m (nominal scale 1:10,000) and were spatially referenced to the local Transverse Mercator Coordinate System (Datum: D_Monte Mario).

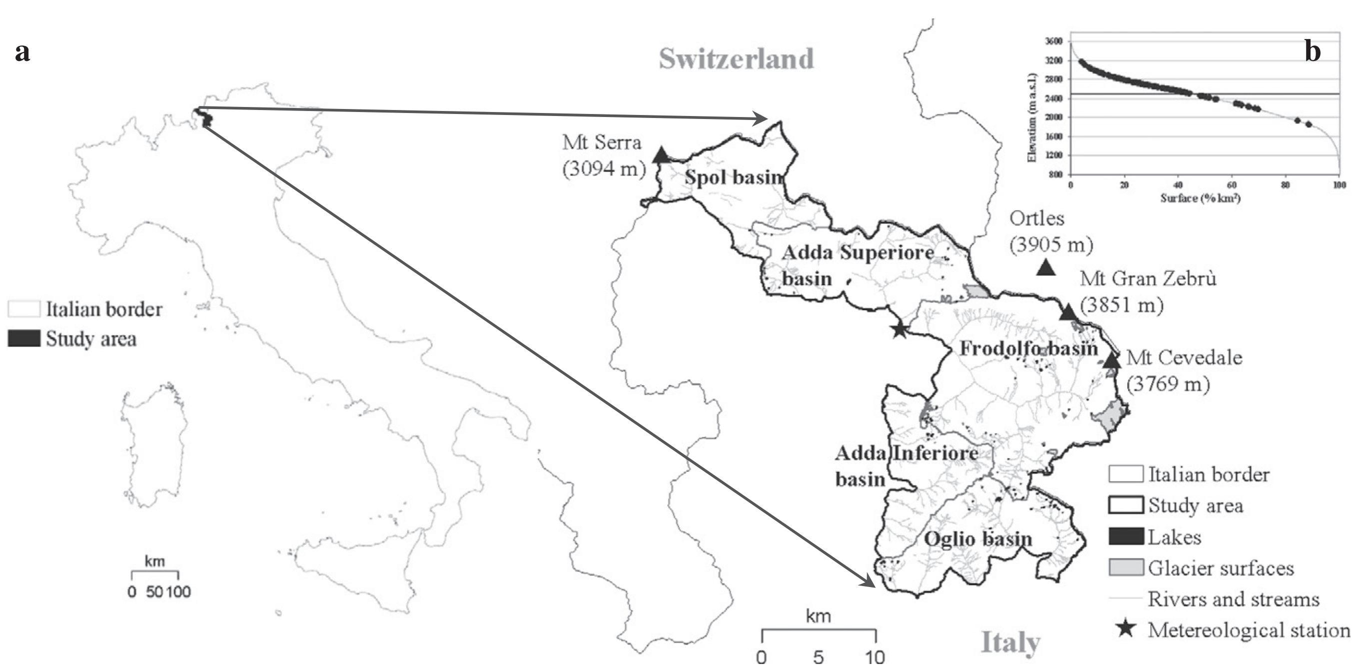

Fig. 1. a) Study area and location of the park. Ponds, rivers, glacierized areas and main sub-basins are also reported with the reference weather station. Supplementary material S1a–e shows detailed maps of the ponds for each sub-basin. b) Hypsometric curve and pond distribution.

The 1954 and 1981 area records were obtained by analyzing aerial photos (at a scale of approximately 1:20,000) with an optical stereoscopic system to obtain a 3D view. Then, the pond limits observed on the photos were reported as polygons in a GIS (Geographical Information System) environment. The 1:10,000 scale Technical Regional Map (CTR) of Lombardy Region was used as a raster base. The topographic data reported in the CTR were referenced to the beginning of the 1980s, thus allowing the evaluation of the accuracy of our findings from the 1981 aerial photos (Salerno and Tartari, 2009). All imagery was taken during the same months (between August and September), permitting a homogeneous interannual comparison and avoiding seasonal pond level fluctuations (Tartari et al., 2008). The use of aerial photos for detecting changes in a lake population characterized by small surface areas is suitable if we consider the uncertainty associated with satellite sensors. Salerno et al. (2012) illustrates the relationship between lake size and the respective uncertainties of measurement from satellite sensors that differ by the degree of resolution. By using a generic high-resolution sensor (1 m) for a lake with a median size of $0.25 \cdot 10^4$ m^2, as in this case, the sensor is able to determine the lake surface with an uncertainty of less than 10%. However, if a sensor resolution one class higher (5 m) was used, then the error would exceed 30%. Because high-resolution sensor data are available only for the most recent years (shown below), the aerial photos are the most suitable data source for minimizing the uncertainty in this type of multi-temporal study.

The Digital Elevation Model (DEM) used in this study is part of the new DEM available for entire Italian territory, named TINITALY/01, with a spatial resolution of 10 m, as discussed in Tarquini et al. (2007) and Tarquini et al. (2012). The vertical accuracy was evaluated through numerous land control points and estimated to be less than 3.5 m.

3.2. Pond inventory and uncertainty of measurements

Supplementary material 1 describes the criteria for pond identification and cataloging, while Figs. S1 to S5 show detailed maps of the ponds for each sub-basin.

Before analyzing the uncertainty of the measurements, we must first consider the interpretation problem of the pond boundaries in the photos. We observed that ponds situated in shaded areas might not be readily distinguished using both orthophotos and aerial photogrammetric sources, leading to a possible source of error. This source of error needs to be carefully considered to ensure that any differences observed between different sources actually reflect real changes occurring in nature. To ensure that the presence or absence of a pond is real for the ponds digitalized on the orthophotos of 2007, we selected the doubtful cases (possible shadows) from the real water bodies. Subsequently, we clustered them in dimensional classes and calculated the percentage of doubt (i.e., possibly misclassified ponds) for each. In this manner, we were able to determine a threshold of 800 m^2, above which the percentage of doubtful cases is lower than 5%. Consequently, we considered and inventoried only ponds with an area greater than this threshold in all of the source data.

Concerning the accuracy of the measurements, we refer mainly to the work of Salerno et al. (2008), Tartari et al. (2008), and Salerno et al. (2012), which address in detail the problem of uncertainty in the topographical measurements related to glaciers and ponds obtained from remote sensing imagery, maps and photos. The uncertainty in the measurement of a shape's dimension (Aerial Error, AE) is dependent both upon the Linear Error (LE) and its perimeter (l). In particular for ponds (as discussed also by McMillan et al. (2007), Fujita et al. (2009), and Gardelle et al. (2010) in the calculation of LE), only the Linear Resolution Error (LRE) needs to be considered as the co-registration error does not play a key role. For instance, the ponds considered here are small, and comparisons are made at the entity level and not at the pixel level. The LRE is limited by the resolution of the source data. In the specific study of temporal variations of ponds, Fujita et al. (2009) and Salerno et al. (2012) assumed an error of ± 0.5 pixels. In this study, the LRE is 0.25 m for the orthophotos of 2007 and 0.5 m for the aerial photographs of 1954 and 1981.

3.3. Statistical analysis

3.3.1. Analysis of climatic trends

The Mann–Kendall test (MK) (Mann, 1945; Kendall, 1975) is widely used to assess significant trends in hydro-meteorological time series (e.g., Zhang et al., 2000; Yue and Wang, 2002; Carraro et al., 2012a, 2012b; Guyennon et al., 2013). This test is non-parametric and is therefore less sensitive to extreme sample values. Additionally, MK is independent from the hypothesis about the nature of the trend (linear or not). The MK verifies the assumption of stationarity of the investigated series by ensuring that the associated normalized Kendall's tau coefficient, $\mu(\tau)$, is included within the confidence interval for a given significance level (for $\alpha = 5\%$, the $\mu(\tau)$ is below -1.96 and over 1.96). In the sequential form (seqMK) (Gerstengarbe and Werner, 1999), $\mu(\tau)$ is calculated for each element of the sample. The procedure is applied forward starting from the oldest values (progressive) and backward by starting from the most recent values (retrograde). If no trend is present, then the patterns of progressive and retrograde $\mu(\tau)$ versus time (i.e., years) present several crossing points, while a unique crossing period allows the approximate location of the starting point of the trend (Tonkaz et al., 2007; Bocchiola and Diolaiuti, 2010). In this study, the seqMK is applied to monthly vectors. Monitoring the seasonal non-stationarity, the monthly progressive $\mu(\tau)$ is reported with a pseudo color code, where the warm colors represent the positive slopes and cold colors the negative ones. Color codes associated with values outside of the range (-1.96 to 1.96) possess darker tones to highlight the trend significance. Moreover, to monitor the overall non-stationarity of the time series, both the progressive and retrograde $\mu(\tau)$ at the annual scale are reported. We used the Sen's slope (Sen, 1986) as a robust linear regression allowing the quantification of the potential trends revealed by the seqMK (i.e., Bocchiola and Diolaiuti, 2010).

3.3.2. Analysis of pond morphology changes

The significant differences between pond features were investigated with the use of ANOVA (the analysis of variance) at $p < 0.05$ followed by post hoc testing (Tukey's honestly significant difference, Tukey HSD) at $p < 0.05$ to examine specific differences among more than two groups (Hays, 1988). The normality of the residuals of the compared datasets was tested through the Shapiro–Wilk test (Royston, 1982a, b).

Moreover, we conducted a Principal Component Analysis (PCA) of pond features to obtain information on relationships among the data and to look for reasons that could justify possible changes observed in the surface areas of ponds. This projection method is obtained by linear combinations of variables along orthogonal axes, called principal components (Settle et al., 2007). We performed this multivariate data analysis method using the “princomp” and the “biplot” function in the R Project (Venables and Ripley, 2002). Table 1 shows the list and description of the morphological features of ponds considered in this study.

Table 1
List and description of morphological features of ponds considered in this study.

Pond features	Description
Δ area 54–81	Pond surface area difference in the 1954–1981 period
Δ area 81–07	Pond surface area difference in the 1981–2007 period
Slope	Sub-basin slope
Sub-basin	Sub-basin surface area
Basin	Basin surface area
Aspect	Sub-basin aspect
Glaciers 81	Surface area of glaciers in the sub-basin in 1981
Glaciers 07	Surface area of glaciers in the sub-basin in 2007
Δ glacier 54–81	Glacier surface area difference in the 1954–1981 period
Δ glacier 81–07	Glacier surface area difference in the 1981–2007 period

4. Results

4.1. Pond features

Table 2 provides a general summary of the morphological features and changes that occurred between 1954 and 2007, and all data presented and discussed in this paper are reported in Supplementary material 2. The total number of ponds detected in 2007 is 116, corresponding to an overall surface of 59.0 (±2%) · 10^4 m^2 and a median size of 0.20 (±3%) · 10^4 m^2. The median area of the direct drainage sub-basins in 2007 is 15.7 · 10^4 m^2, and when the surfaces of basins belonging to ponds of lower order are included, the median area becomes 23.4 · 10^4 m^2. The mean slope of the sub-basins is 24.3% and their mean aspect is 167°; in other words, they are, on average, oriented toward the south-southeast.

In 1954, 34% of the ponds were positioned in a basin that also contained at least one glacier, for a total area of 11.6 km^2. Fig. 2a complements the information provided by Table 2 by showing the frequency distribution of ponds relative to their elevation. These ponds are located at a mean altitude of 2676 m a.s.l. in 2007, and within an elevation zone ranging from 2200 to 3100 m a.s.l. The pond population has a normal distribution versus the elevation (Fig. 2a). Therefore, ponds are more abundant at intermediate altitudes (2600–2700 m a.s.l.) as a result of lower slopes at these altitudes (Fig. 2c). In fact, the hypsographic curve of the SNP (Fig. 1b) has a certain maturity of erosion, also called an equilibrium phase (Scheidegger, 1987), which features steeper slopes at the “head” and the “toe” of the curve (Willgoose and Hancock, 1998). Ponds are more numerous and therefore more stable in basins with a lower slope because a more structured surface hydrography can develop. In this regard, we observed higher correlation at these elevations (2600–2900 m a.s.l.) between pond and basin size (Fig. 2d). Therefore, at the margins of the distribution of Fig. 2a (i.e., under 2500 m and above 2900 m a.s.l.), the boundary conditions of ponds are less favorable to ensure their stability, and less abundant. However, we can observe in Fig. 2b that at these elevations they are larger. These sizes signify that at these elevations, there are characteristics (i.e., large basins at low altitudes (Fig. 2e) and numerous glaciers at high altitudes (Fig. 2f)) that favor pond development, although their stability is not guaranteed, as suggested by their reduced number. These considerations will be useful in the Discussion section of this work.

4.2. Changes in pond population

Fig. 3 shows the main differences in the pond population since 1954 (see also Table 2). We observed that from 1954 to 1981, the total area of the ponds is essentially unchanged (62.8 (±3%) · 10^4 m^2 in 1954 and 63.1 (±3%) · 10^4 m^2 in 1981, corresponding to a variation of +0.5% (±4%)), while in 2007 there is a slight decrease that results in a difference of −5.9% (±3%) between 1954 and 2007 (Fig. 3a). In contrast, Fig. 3b displays the variation in the total number of ponds. A peak is noted in 1981 (131 ponds), but the total number of ponds in 1954 and 2007 is the same (116 ponds). This trend is similar to that observed for the difference in surface areas. Therefore, in the recent fifty years, it appears that there have been no significant changes in the size and number of ponds. However, in contrast, we observe in Fig. 3c that since 1981, there has been a substantial increase in the mean elevation of the entire pond population that reaches +55 (±3.5) m. In the previous period, only a slight increase in elevation is observed.

What are the reasons that caused the increase in the elevation of ponds?

Table 2
General summary of the morphometric features of ponds from 1954 to 2007.

Year		1954	1981	2007
Number of lakes (N)	Total	116	130	116
Elevation (m) a.s.l.	Mean	2618	2623	2676
	Max	2995	3046	3177
	Min	1860	1860	1860
Perimeter (10^4 m)	Median	0.02	0.02	0.02
Lake surface (10^4 m^2)	Median	0.25 (±5%)	0.21 (±5%)	0.20 (±3%)
	Total	62.8 (±3%)	63.1 (±3%)	59.0 (±2%)
Sub-basins surface (10^4 m^2)	Median	14.4	15.0	15.7
Basin surface (10^4 m^2)	Median	20.5	21.7	23.4
Glacier surface in lake basins (10^4 km^2)	Total	11.6	10.0	7.4
Sub-basins slope (%)	Mean	23.2	23.7	24.3
	Max	38.0	38.0	38.0
	Min	6.9	6.9	8.6
Sub-basins aspect (°)	Mean	156	162	167
	Max	328	328	328
	Min	51	51	51

4.3. Change in ponds surface area versus elevation

To understand the causes of this phenomenon, the plots in Fig. 4a and b (for the periods 1954–1981 and 1981–2007, respectively) show the frequency distribution versus elevation of disappearing ponds, new ponds (appearing ponds), and those ponds present in both periods (common ponds). Similarly, Fig. 4d and e show the sum of surface area lost or gained by all ponds belonging to each elevation class over the same time periods.

One of our primary observations is that during the 1981–2007 period, new ponds appeared at higher elevations (2927 m a.s.l. on average) than the previous period. We tested this statement with the Tukey HSD test, which shows a high significance for the difference between the median elevation of these ponds compared to that of all other groups ($p < 0.001$). The same test shows no significant differences between the elevations of the other groups. Furthermore, we observe that the lowest quartile (25th percentile) of the disappearing ponds in the 1981–2007 period is much lower (2398 m a.s.l.) than the other groups and, in particular, is much lower than the disappearing ponds in the previous period (2571 m a.s.l.). The disappearance of ponds at lower elevations and the appearance of new ponds closer to the mountain ridges, compared to the 1954–1981 period, explain an upward shift of 55 m by the pond population. A clear overall picture of the phenomenon is provided by Fig. 4c, which shows the net balance of appearances and disappearances over the entire study period (1954–2007). Fig. 4f, considering the differences in surface area, confirms what was observed when we analyzed the number of ponds: an overall decrease at the lowest elevations (≤2600 m a.s.l.) and an increase at the highest elevations (≤2900 m a.s.l.).

Another interesting aspect of the 1981–2007 period is that both the disappearance of ponds and the surface area reductions have bimodal trends with relevant peaks at 2400 m and 2800 m a.s.l. (Fig. 4b and e). This dual trend does not seem to be present in the previous period, which features a single peak at the 2600 m intermediate elevation (Fig. 4a and d). When considering the appearances of new water bodies and the consequent increase of surface area, in the second period the phenomenon in both cases is concentrated at 2900 m a.s.l. (Fig. 4b and c), while in the first period the situation is more chaotic. However, the highest increases in area were at 2800 m a.s.l. (Fig. 4d), which corresponds to a peak of new ponds between 2700 and 2800 m a.s.l. (Fig. 4a).

To explore the reasons that could have determined this pattern of change, we conducted the PCAs among the observed differences in terms of surface area and certain pond morphological features. We subdivided the analysis by separately considering the appearing and disappearing ponds and the two periods. Moreover, we separated the ponds into more elevation groups where the elevation frequency distribution presented a bimodal or unclear unimodal behavior (Fig. 4), as mentioned above. The six selected cases are presented from Figs. 5a to 7f.

First, the surface area increases are well correlated with the differences observed in the surface areas of the glaciers included in the basins of the new ponds over 2650 m a.s.l. during the 1954–1981 period

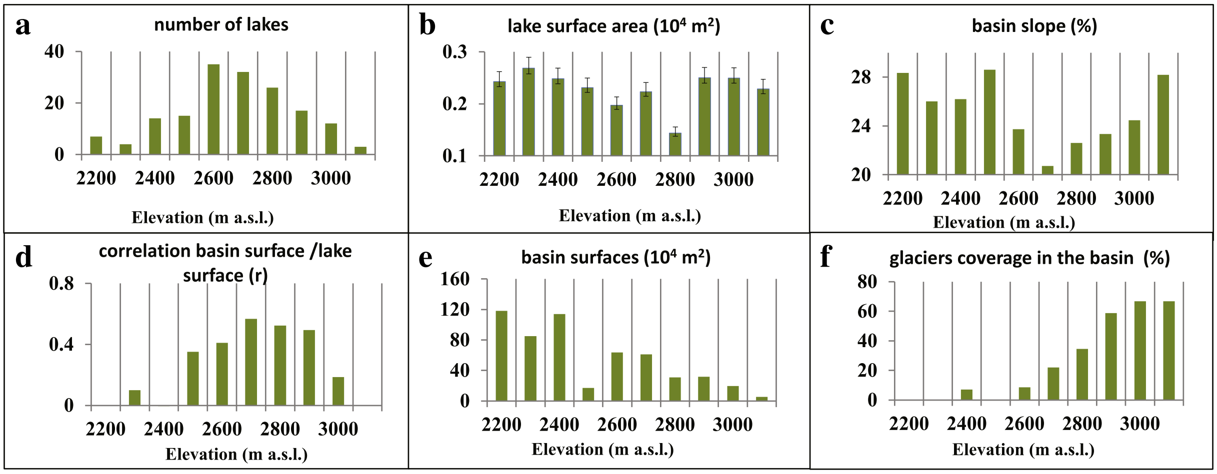

Fig. 2. Frequency distribution of pond features versus pond elevation: a) Number of ponds, b) Median pond surface area, c) Mean basin slope, d) Correlation coefficient between basin and pond surface area, e) Basin area, and f) Glacier coverage in the basin.

(Fig. 5b) and for all appearing ponds during the 1981–2007 period (Fig. 5c) (the variables are as follows: Δ *area 54–81* vs. Δ *glacier 54–81*, $r = 0.62$, $p < 0.001$; Δ *area 81–07* vs. Δ *glacier 81–07*, $r = 0.63$, $p < 0.001$). In Fig. 5b, the increases in surface area are also highly correlated with the basin *slope*, but this effect is due to the autocorrelation between the basin *slope* and the decreases in glacier area surfaces. On the contrary, the new ponds below 2650 m a.s.l. do not show any clear relationship with the other variables (Fig. 5a).

In the analysis of the disappearance of ponds, between 1981 and 2007, the ponds below 2500 m a.s.l. (Fig. 5e), which mainly correspond to the lowest peak of the disappearing ponds in the pond frequency distribution of Fig. 4b, decreased in correlation with the mean *aspect* of their basin ($r = 0.64$, $p < 0.001$). In other words, the southward-facing basins favored a reduction in the surface area of the ponds. Similarly, steep *slopes* also favored surface area reductions ($r = 0.55$, $p < 0.001$). However, above 2500 m a.s.l. (Fig. 5f), which mainly corresponds to the upper peak of disappearing ponds in the pond frequency distribution of Fig. 4b, those ponds which appeared or increased in size during the previous period (1954–1981) disappeared during the same time period. This result indicates that the ponds that increased or appeared in the 1954–1981 period began to empty after a few decades and finally disappeared ($r = 0.93$, $p < 0.001$). Unfortunately, testing this relationship for the disappearing ponds in the 1954–1981 period is not possible because we do not know the evolution of the ponds before 1954. Thus, Fig. 5d shows a direct relationship between surface loss and basin size, but this is mainly due to the strict relationship between pond surface areas and basin areas, which does not provide useful information regarding the reasons for the disappearances.

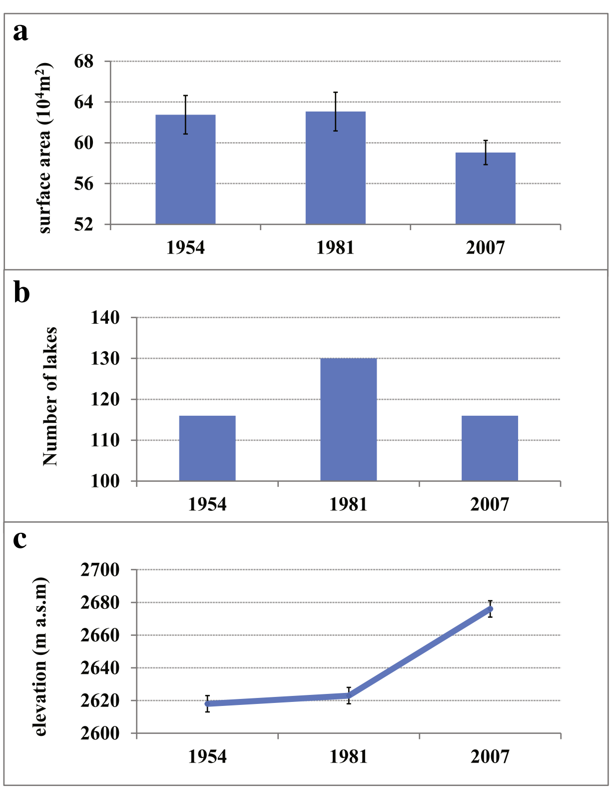

Fig. 3. Changes that have occurred since 1954 in the pond population: a) Total surface area of ponds — the vertical bars represent the uncertainty associated with the measurement, b) Total number of ponds, and c) Mean elevation of the entire pond population.

4.4. Change examples

Fig. 6 provides two examples of the changes that occurred in the pond population during the 1981–2007 period. This is the period in which we observed the greatest evidence of change that caused the increase in the elevation of the ponds. In the first case, Fig. 6a shows five ponds located in the Adda Superiore basin between 2600 and 3100 m a.s.l. We note the recent appearance of two new water bodies (ADD-S_26 and ADD-S_27) located over 2800 m a.s.l. In particular, the pond ADD-S_26 is a proglacial pond. Furthermore, we observe at a lower altitude, the concomitant disappearance of the pond ADD-S_25. This pond was formed during the 1954–1981 period due to the retreat of the glacier, as shown in the historical glacier outlines. Analogously, we observe the disappearance of the pond ADD-S_24; however, in this case, it has not been substituted with another at higher altitude, most likely due to the stationarity of the glacial front. Finally, the ADD-S_26 pond belongs to the category of those few ponds that appeared in 1981 and that have continued to exist until 2007. In this case, the local geomorphology must have favored the durability of the pond (you can notice the presence of a flat topography) and the lack of pond development at higher altitudes even though the glacier has retreated considerably (e.g., due to steep slopes). The second case (Fig. 6b) refers instead to the Oglio basin: we observe that seven ponds (mean elevation 2488 m a.s.l.) that were mainly south–north oriented disappeared, but four other ponds located at higher altitude (mean elevation 2695 m a.s.l.) did not.

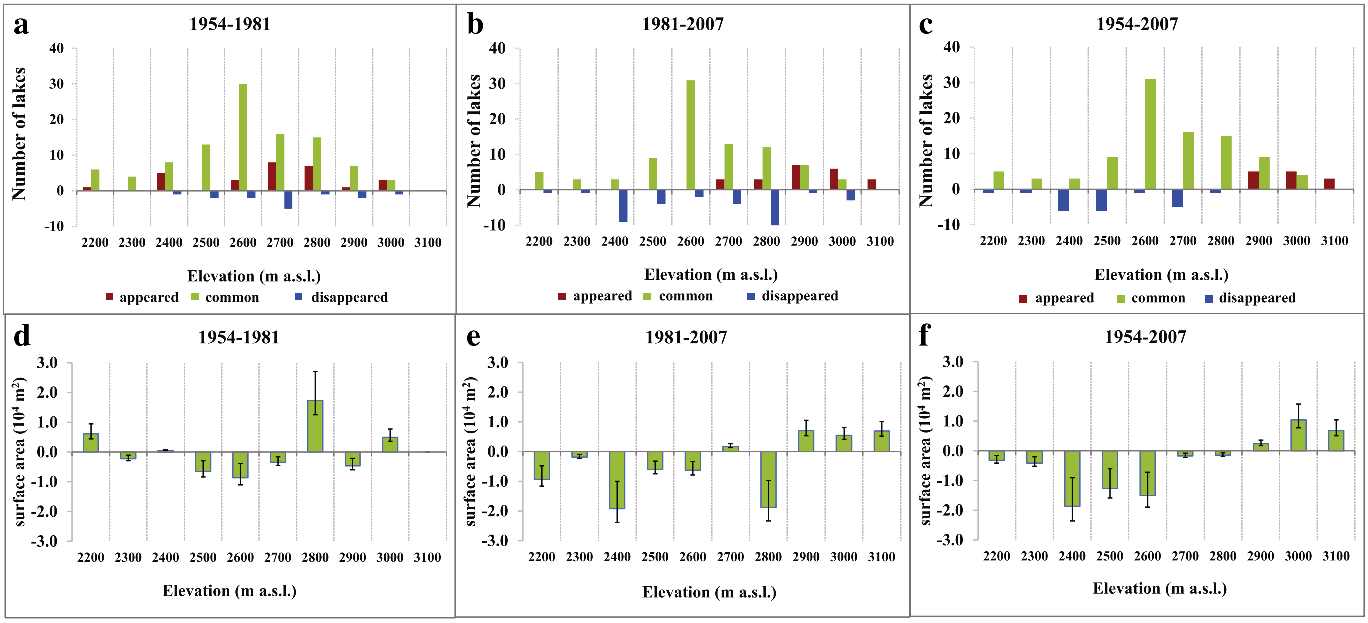

Fig. 4. Frequency distribution versus elevation of appeared, disappeared, and common ponds for 1954–1981 (a) and 1981–2007 (b). Net balance of appearing and disappearing ponds in the overall analyzed period (1954–2007) (c). Sum of surface area lost or gained by all ponds belonging to each elevation class for the 1954–1981, 1981–2007, and 1954–2007 periods as (d), (e), and (f), respectively.

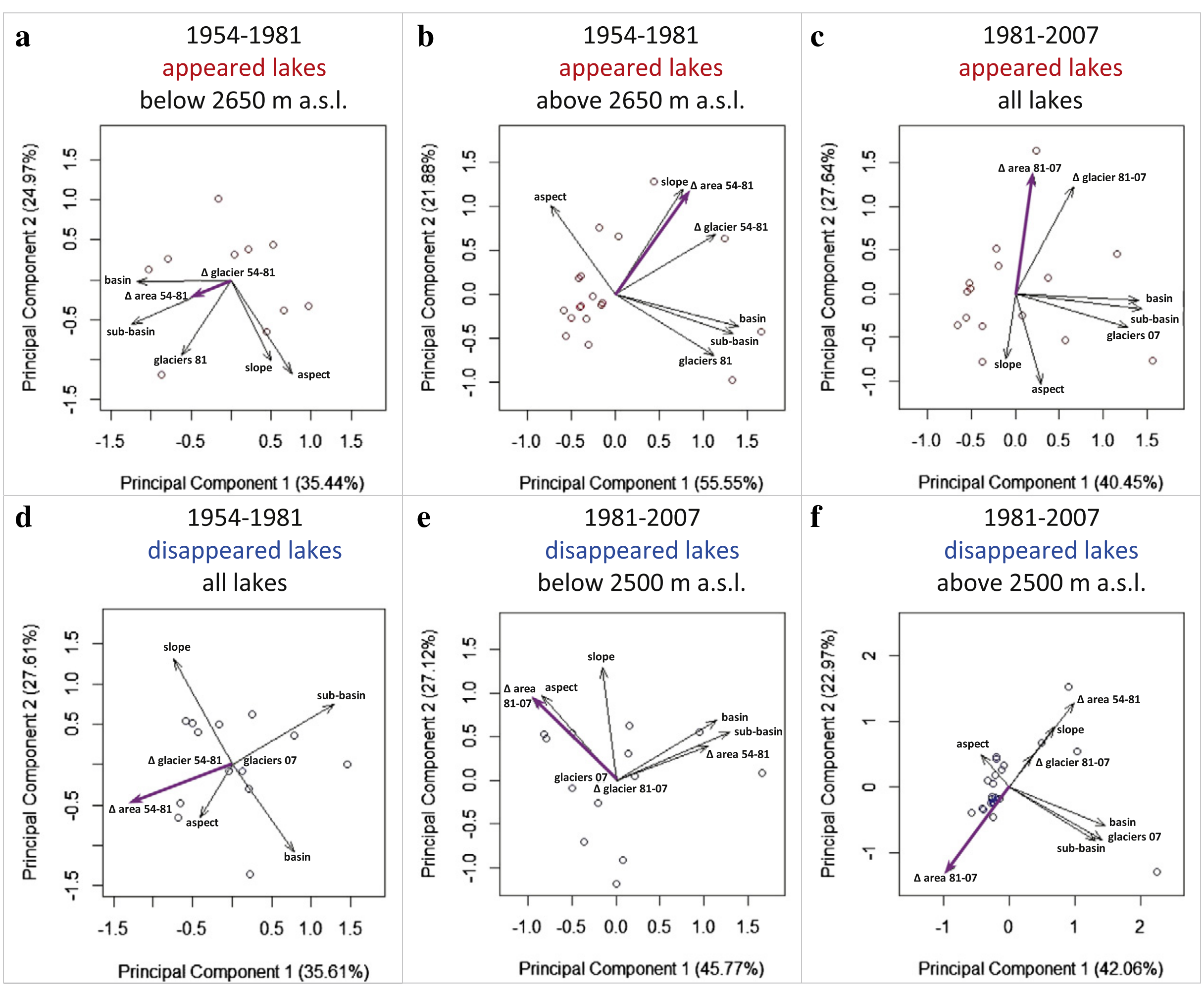

Fig. 5. Principal Component Analyses (PCAs) among the observed differences in terms of surface area and morphological features of ponds. From a) to f) the selected cases are presented (refer to the text). A list and description of morphological features of the ponds are reported in Table 1.

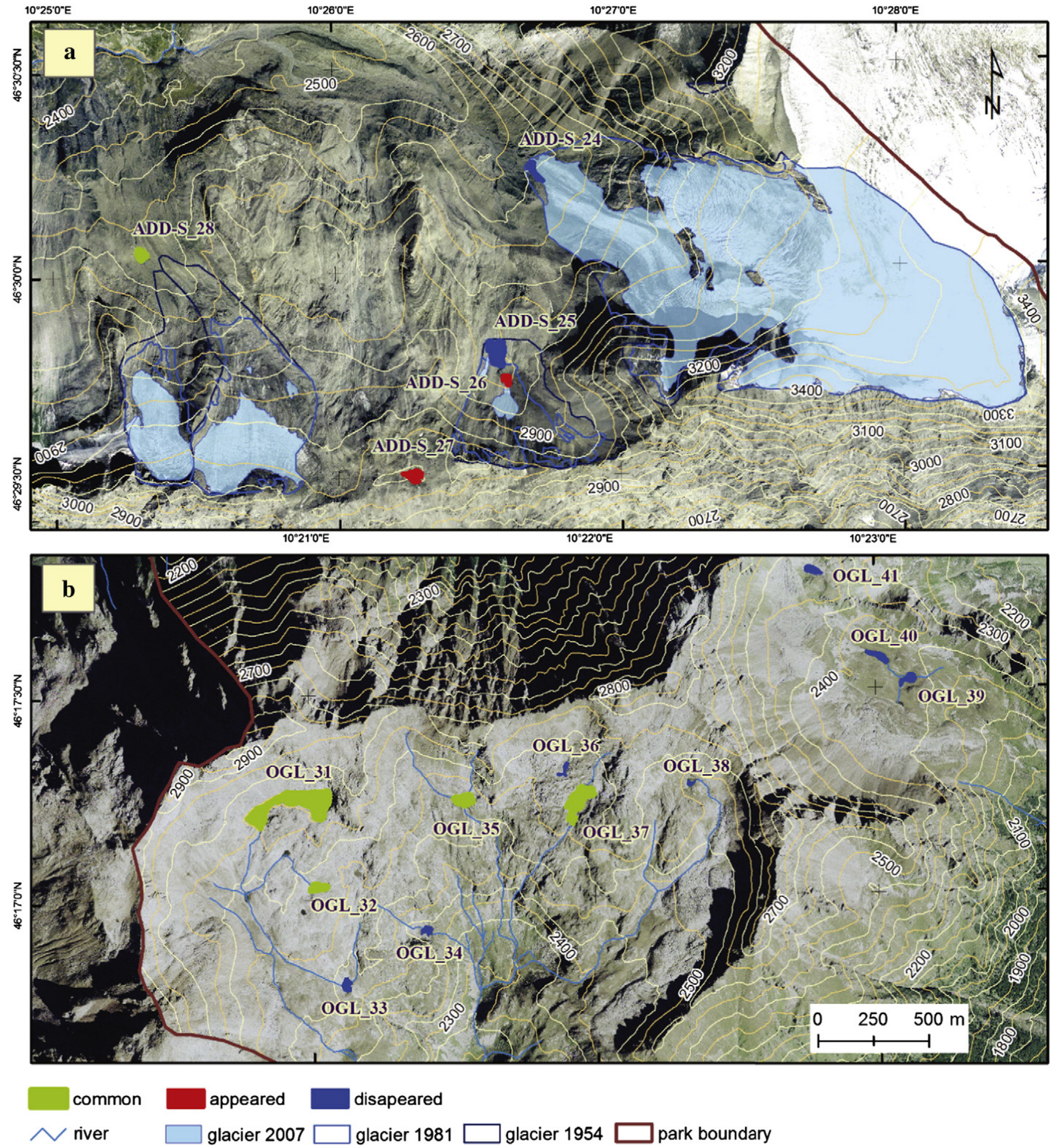

Fig. 6. Examples of some appeared, disappeared, and common ponds for the 1981–2007 period. The background image is the color orthophoto of 2007 (resolution 0.5 m). a) Changes occurred at higher elevations. b) Disappearance of ponds at lower elevations. Refer to the text for further details.

4.5. Climate trend

Although the numbers and sizes of the ponds appear to be constant (as previously reported), the appearance and disappearance of water bodies suggest that there must be processes occurring that have dramatically changed the distribution of the ponds. To discover these processes, we first analyzed the climatic trend of the case study area.

Fig. 7 shows the temperature trend from 1924 to 2007. The top graph (Fig. 7a) shows the trend of annual temperature means. The central grid (Fig. 7b), through a gradation of colors from blue to red, represents the temperature trend expressed for each month using the seqMK. The colors in cool tones indicate those months that recorded a decreasing trend in temperature. The transition between azure and blue shows that this trend is significant. In contrast, warm tones indicate

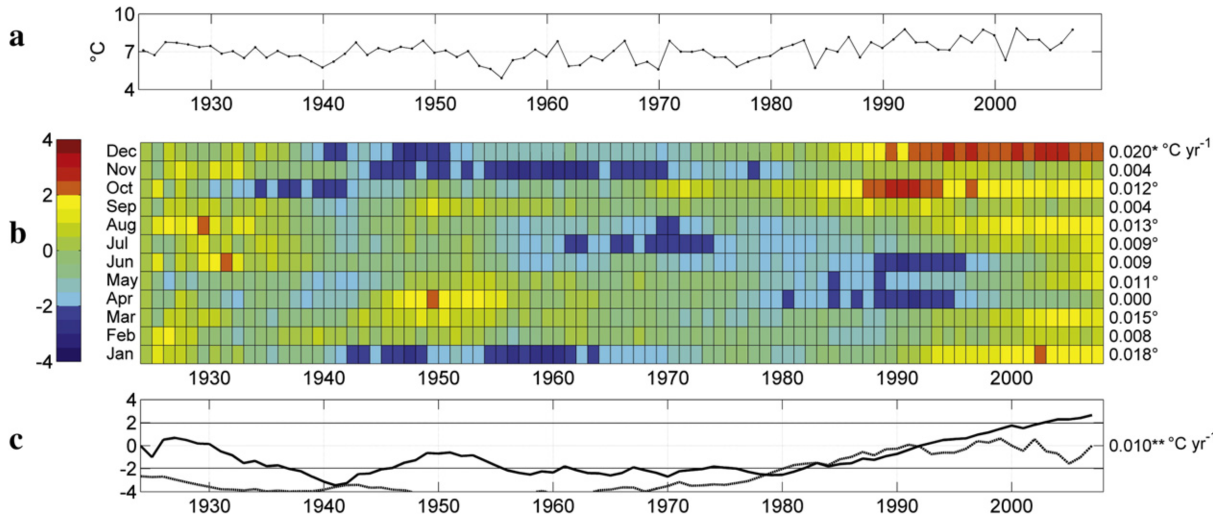

Fig. 7. a) Annual mean temperature trend. b) Sequential Mann–Kendall test applied at the monthly level. On the left, the color bar represents the normalized Kendall's tau coefficient μ(τ). The color tones below −1.96 and over 1.96 are significant (α = 5%). On the right, the Sen's slopes and the relevant significant levels are shown for each month (*p-value = 0.05 and **p-value = 0.01). c) Progressive (black line) and retrograde (dotted line) μ(τ) applied at annual scale. On the right, the annual Sen's slope.

a rising trend. Furthermore, the transition between yellow and orange highlights that this trend is significant. From 1930 to 1990, we see different azure/blue cells, which means in those years, and for many months of the year, there was a negative trend that was sometimes significant (especially in the winter months). On the contrary, in the spring months of the 1950s, there was a slight increase in temperature. However, the real increase in temperature was recorded in the early 1990s. During that time, the cells became more yellow and orange in all months of the year, though the phenomenon was more pronounced during the winter months (October, December and January are significant when considering the whole period). Fig. 7c shows that the most recent changing point occurred in the middle 1940s. After 40 years of a significant decreasing trend (until the mid-1950s), a positive trend began in the early 1990s and became significant after 2000.

Overall, between 1924 and 2007, the increase in temperature was 0.012 °C y^{-1} (Fig. 7c). From 1954 to 1981, the first period analyzed in this study, the trend was always significantly negative, which means that we experienced lower temperatures (on average) than in the 1930s. However because the inflection point was prior to 1954, the increasing trend that is present today was already in place by this period, with a slope equal to 0.014 °C y^{-1}. In the following period (1981–2007), the annual temperature increase tripled (0.038 °C y^{-1}).

The analysis of the precipitation is conducted with the same representation used for the temperature. Fig. 8a shows the annual precipitation means for the period 1926–2007. Even in this case, the central grid (Fig. 8b) represents, through a gradation of colors from blue to red, the precipitation trend for each month. The cells of the years from the 1930s to the 1960s are mainly azure/blue, which means that in those years, and for many months of the year, there was a significant negative trend (Fig. 8c). However, for the last 40 years, the precipitation trend has been constant for all months (+0.67 mm y^{-1}), with the exception of January (a significant increase during the 1980s). Currently, no month presents a significant trend. Fig. 7c shows that the most recent changing points are located in the middle 1970s, which definitely ends the negative trend period and transitions into the constant positive trend.

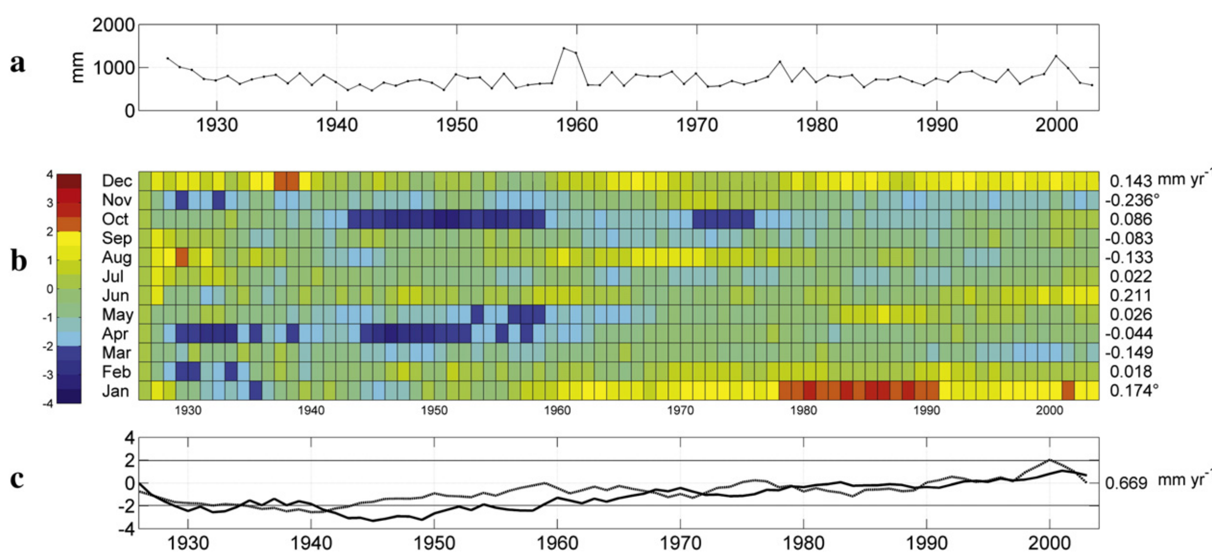

Fig. 8. a) Annual mean precipitation trend. b) Sequential Mann–Kendall test applied at monthly level. See Fig. 7b for details. c) Progressive (black line) and retrograde (dotted line) μ(τ) applied at annual scale. On the right, the annual Sen's slope.

5. Discussion

5.1. Climate-driven fluctuation of pond surface areas at high elevation

The mean temperature trends showed an increase of 0.012 °C y^{-1} (Fig. 7c) from 1924 to 2007 which was the same rate observed as a century average for the Alpine region (1.2 °C) (Auer et al., 2007). As shown by other authors (i.e., Brunetti et al., 2004; Ciccarelli et al., 2008), the phenomenon is more pronounced during the winter months, while, as observed by Jones and Moberg (2003) for all of Europe, the first peak in temperature recorded worldwide is in our case only slightly notable.

The real increase in temperature is distinct from the early 1990s. In the 1981–2007 period, the temperature rises considerably, with an acceleration trend three times higher than in the previous period (1954–1981). With regard to the precipitation trend, studies on the greater Alpine region highlighted differences in Total Precipitation (TP) trends in different zones of the Alps. Whereas stations located north of the ridge present some increases in TP, decreases prevail in the south (Brunetti et al., 2006a, 2009; Auer et al., 2007). However, low-resolution analysis revealed no significant trends for TP in the northeastern-most area of Italy during the last century (Brunetti et al., 2001, 2004, 2006b). Furthermore, Brugnara et al. (2012) performed a high-resolution analysis of precipitation trends in the central Alps over the last century (1922–2009) and found a weak (non-significant) decrease in TP. This study notes that the TP does not seem to substantially change in our case study. Therefore, the observed impacts on pond surfaces can only be due to the average air temperature increase.

We found that in both periods (from 1954 to the present), ponds increased in size and new ponds appeared at higher elevations due to glacial shrinkage and retreat. Since 1981, the phenomenon is concentrated above 2900 m a.s.l. (Fig. 6a), and this is supposedly due to the acceleration of retreat of glacier termini, which was described for the SNP area by D'Agata et al. (2013). In support of this thesis, it was also noted that until 1981, none of these ponds were directly connected with glaciers, while in 2007, we observed 5 new ice-contact ponds (i.e., moraine-dammed ponds that are in contact with the glacier terminus). These 5 ponds are as follows: ADD-S_26, at the terminus of the Crapinellin Glacier; FROD_38, at the terminus of the Dosegù Glacier; FROD_41, at the terminus of the Vallombrina Glacier; FROD_44, at the terminus of the Sforzellina Glacier; and FROD_34, at the terminus of the Forni Glacier. Supplementary material S1a–e shows the relevant detailed maps. D'Agata et al. (2013) observed that in the last few decades (1981–2007) the glacial shrinkage ($-0.50 \pm 0.3\%\ y^{-1}$) was double than that of the previous period ($-0.24 \pm 0.1\%\ y^{-1}$). These results are consistent with glacial retreat observed in the Alps in the last decades (Paul et al., 2007; Knoll and Kerschner, 2009; Bocchiola and Diolaiuti, 2010). The same authors affirm that the recent retreat of glacier termini produced favorable settings for small ice-contact ponds behind moraine ridges. Due to the passing of a few years, or the accelerating retreat of the glacier snouts, a rapid evolution from ice-contact to distal proglacial ponds occurred.

5.2. Transition toward a paraglacial system

From a geodynamic point of view, the transition from a glacial system to a paraglacial system is now occurring (Ballantyne and Benn, 1996). For example, the areas where the main shaping and driving factors were recent glaciers are now subject to the action of melting water, slope evolution and dynamics. The subsequent step is the transition from a paraglacial environment to a periglacial environment, where cold and snow are dominant without glacial ice or melt water (D'Agata et al., 2013). We examined this evolution over time and across an elevation gradient. In fact, the emergence of new ponds in 1981 was accompanied by their substantial disappearance in 2007, and a concomitant appearance of new, intrinsically ephemeral environments at higher elevations (Fig. 6a). The existence of these ponds allows water to be stored at higher elevations, even if for only short and temporary periods, creating local ecosystems where yeasts and bacteria adapted to extreme environments are able to survive (Buzzini et al., 2005). To date, there is limited knowledge on how these extreme ecosystems respond to climate change; however, the research is rapidly growing and the understanding of the microbial diversity and biogeochemical processes is developing (Yde et al., 2011). These landforms host different forms of life that either originate from the subglacial communities or from later settlement by pioneering species (Buzzini et al., 2005). Hence, the periglacial landscape permits the study of how the microbial community changes from being dominated by subglacial structures to gradually adapt to periglacial environmental conditions.

The transition from subglacial to periglacial ecosystems in the Alps is of particular interest because it may involve significant changes in net greenhouse gas (GHG) sinks and sources (Bárcena et al., 2010). Furthermore, microorganisms play a major role in the cycling of macronutrients, such as carbon and nitrogen, through a variety of aerobic and anaerobic processes. These processes include respiration, methane oxidation and production, nitrification and denitrification, sulfur oxidation and reduction and are relevant in climatic terms because they directly affect GHG budgets on a global scale (refer to Yde et al., 2011).

5.3. Climate-driven fluctuation of pond surface areas at lower elevation

In contrast, we observed that the disappearance and the general reduction of pond surface areas at lower altitudes from 1981 are related to the basins' aspects (Fig. 6b). In general, the basins of these ponds are characterized by low glacier cover (absent in most cases) (Fig. 2f) and a weak correlation in basin/pond size (Fig. 2d). Both factors suggest the hypothesis that evaporation processes play a more important role in the water balance of ponds located at lower altitudes. In this regard, we observed that a more southward oriented aspect accompanied by steeper slopes favors reduction in pond surface areas (Fig. 5e). Coops et al. (2000) show that both of these conditions are subject to higher values of incident solar radiation, thus driving higher temperatures. Therefore, the observed increase in the mean air temperature that occurred in the last few decades could have increased the evaporative processes for those ponds located at lower altitudes, which are more southward oriented and have steeper basin slopes. In addition, Smol and Douglas (2007) report gradual, decadal-scale drying of high Arctic ponds between 1983 and 2006 due to changes in the ratio of precipitation and evaporation. This is confirmed in our case study. Indeed, when the Thornthwaite's formula is applied (Thornthwaite, 1948), this ratio (total annual evaporation divided by annual cumulate precipitation) changes from 0.41 in 1954, to 0.42 in 1981 and to 0.55 in 2007.

5.4. Ecological perspective

From an ecological perspective, the surface area reduction of these ponds, and in particular the disappearance of most of them, signifies the loss of unique mountain ecosystems and, consequently, negatively affects the local biodiversity. These shallow surface waters are hotspots both in terms of species composition and biological traits, and they provide significant ecosystem services (EPCN, 2008; Manfredi et al., 2010; Céréghino et al., 2014). While pond biologists have focused on the aquatic biota, it is noteworthy that the interactions at the aquatic–terrestrial interface are numerous, and the high productivity of ponds is profitable to the terrestrial biocenoses (e.g., emerging adult insects and amphibians are preyed on by many animals) (Céréghino et al., 2014). Furthermore, mountain ecosystems often host local endemic species because species isolation is enhanced at high elevations compared to lowland vegetated ecosystems, where climatic niches are spread over wider surface areas (Beniston, 2003).

6. Conclusions

The selected study area (the Ortles–Cevedale mountain group, Southern Alps, Italy) is one of the areas most characterized by high-altitude ponds of the entire Italian alpine chain (Nangeroni, 1983). This area is also well studied in terms of recent glacier shrinkages (D'Agata et al., 2013). In this study, we inventory all ponds in the area with a minimum threshold of 800 m^2 and study their surface area changes over the last 50 years. While investigating the climate variations, we found an increase in the mean annual temperature equal to the increase observed on average for the alpine region (Auer et al., 2007) and constant total annual precipitation conditions that differ minimally from the weak (non-significant) decrease observed by Brugnara et al. (2012) in the Central Alps over the last century (1922–2009).

Under the pressure of the increasing temperatures of the last few decades (1981–2007), a rate threefold stronger than the rate of the previous period (1954–1981), we described two distinct impacts on pond surface areas: i) since 1981, at lower altitudes, we found the disappearance and a general reduction in pond surface areas, which we have attributed to the increase in evaporative processes; and ii) at higher altitudes, we observed that in both periods (from 1954 to present), ponds increased their size and new ponds appeared as a consequence of glacial shrinkage and retreat. However, the new ponds are ephemeral. The appearance of new environments is accompanied by their disappearance and a concomitant appearance of new ones at higher altitudes, which is a clear sign of the transition from a glacial system to a paraglacial one. Under this pressure, the next transition could be to a periglacial scenario, where cold and snow will be dominant in the absence of glaciers and glacial melt water.

Surface area changes have been shown to be a highly visible and easily measurable signal of the impact of climate change on alpine environments, as already demonstrated in other remote areas of the world (Smith et al., 2005; Smol and Douglas, 2007; Tartari et al., 2008; Gardelle et al., 2010). There is a clear need to extend this analysis to other sites in the Alps to gain a regional understanding of the phenomenon. As a first step, these findings have made it possible to preliminarily interpret the variations that climate change has created in these environments, and effects on the environments' ecological roles and their value as ecosystem services (Céréghino et al., 2014).

Supplementary data to this article can be found online .

Acknowledgments

This work was performed under the framework of the SHARE STELVIO pilot project. This project, supported by the Lombardy Government through FLA (Fondazione Lombardia per l'Ambiente) and EvK2CNR Committee, is devoted to detecting and quantifying climate change effects and impacts in the area of the Stelvio National Park (Lombardy, Italy). The authors are grateful to the Lombardy Region for the research support. The aerial photos and the 2007 orthophotos were analyzed in cooperation with the Infrastructure for the Territory Information Unit of the Lombardy Region through an agreement between Lombardy Region and the University of Milan. Franco Salerno is grateful to Marianna Polidoro for the support during the entire research project.

References

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., van Donk, E., Weyhenmeyer, G.A., Winderl, M., 2009. Lakes as sentinels of climate change. Limnol. Oceanogr. 54, 2283–2297.

Auer, et al., 2007. HISTALP — historical instrumental climatological surface time series of the Greater Alpine Region. Int. J. Climatol. 27, 17–46.

Ballantyne, C.K., Benn, D.I., 1996. Paraglacial slope adjustment during recent deglaciation and its implications for slope evolution in formerly glaciated environments, In: Anderson, M.G., Brooks, S.M. (Eds.), Advances in Hillslope Processes, 2nd edn. Wiley, Chichester, pp. 1173–1195.

Bárcena, T.G., Yde, J.C., Finster, K.W., 2010. Methane flux and high-affinity methanotrophic diversity along the chronosequence of a receding glacier in Greenland. Ann. Glaciol. 51 (56), 23–31.

Beniston, M., 2003. Climatic change in mountain regions: a review of possible impacts. Clim. Chang. 59, 5–31.

Beniston, M., 2006. Mountain weather and climate: a general overview and a focus on climatic change in the Alps. Hydrobiologia 562, 3–16.

Bocchiola, D., Diolaiuti, G., 2010. Evidence of climate change within the Adamello Glacier of Italy. Theor. Appl. Climatol. 100, 351–369.

Brugnara, Y., Brunetti, M., Maugeri, M., Nanni, T., Simolo, C., 2012. High-resolution analysis of daily precipitation trends in the central Alps over the last century. Int. J. Climatol. 32, 1406–1422.

Brunetti, M., Maugeri, M., Nanni, T., 2001. Changes in total precipitation, rainy days and extreme events in northeastern Italy. Int. J. Climatol. 21, 861–871.

Brunetti, M., Maugeri, M., Monti, F., Nanni, T., 2004. Changes in daily precipitation frequency and distribution in Italy over the last 120 years. J. Geophys. Res. 109 (D5). http://dx.doi.org/10.1029/2003JD004296.

Brunetti, M., Maugeri, M., Monti, F., Nanni, T., 2006a. Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. Int. J. Climatol. 26, 345–381.

Brunetti, M., Maugeri, M., Nanni, T., Auer, I., Böhm, R., Schöner, W., 2006b. Precipitation variability and changes in the greater alpine region over the 1800–2003 period. J. Geophys. Res. 111 (D11). http://dx.doi.org/10.1029/2005JD006674.

Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Auer, I., B¨ohm, R., Sch¨oner, W., 2009. Climate variability and change in the Greater Alpine Region over the last two centuries based on multi-variable analysis. Int. J. Climatol. 29, 2197–2225.

Buraschi, E., Salerno, F., Monguzzi, C., Barbiero, G., Tartari, G., 2005. Characterization of the Italian lake-types and identification of their reference sites using anthropogenic pressure factors. J. Limnol. 64 (1), 75–84.

Buzzini, P., Turchetti, B., Diolaiuti, G., D'Agata, C., Martini, A., Smiraglia, C., 2005. Culturable yeasts in meltwaters draining from two glaciers in the Italian Alps. Ann. Glaciol. 40, 119–122.

Carpenter, et al., 2007. Understanding regional change: a comparison of two lake districts. Bioscience 57, 323–335.

Carraro, E., Guyennon, N., Hamilton, D., Valsecchi, L., Manfredi, E.C., Viviano, G., et al., 2012a. Coupling high-resolution measurements to a three-dimensional lake model to assess the spatial and temporal dynamics of the cyanobacterium *Planktothrix rubescens* in a medium-sized lake. Hydrobiologia 698, 77–95.

Carraro, E., Guyennon, N., Viviano, G., Manfredi, E.C., Valsecchi, L., Salerno, F., et al., 2012b. Impact of global and local pressures on the ecology of a medium-sized pre-alpine lake. In: Jordan, F., Jorgensen, S.E. (Eds.), Models of the Ecological Hierarchy: From Molecules to the Ecosphere. Elsevier, pp. 259–274.

Catalan, J., Curtis, C.J., Kernan, M., 2009. Remote European mountain lake ecosystems: regionalisation and ecological status. Freshw. Biol. 54, 2419–2432.

Céréghino, R., Boix, D., Cauchie, H.M., Koen Martens, K., Oertli, B., 2014. The ecological role of ponds in a changing world. Hydrobiologia 723, 1–6.

Ciccarelli, N., von Hardenberg, J., Provenzale, A., Ronchi, C., Vargiu, A., Pelosini, R., 2008. Climate variability in north-western Italy during the second half of the 20th century. Global Planet. Change 63 (2–3), 185–195.

Consiglio Nazionale delle Ricerche (CNR), Comitato Glaciologico Italiano (CGI), 1961. Catasto dei Ghiacciai Italiani. Volumes I, II and III, Torino, Italy. (At) http://www.glaciologia.it/pubblicazioni/.

Coops, N.C., Waring, R.H., Moncrieff, J.B., 2000. Estimating mean monthly incident solar radiation on horizontal and inclined slopes from mean monthly temperatures extremes. Int. J. Biometeorol. 44 (4), 204–211.

D'Agata, C., Bocchiola, D., Maragno, D., Smiraglia, C., Diolaiuti, G.A., 2013. Glacier shrinkage driven by climate change during half a century (1954–2007) in the Ortles–Cevedale group (Stelvio National Park, Lombardy, Italian Alps). Theor. Appl. Climatol. http://dx.doi.org/10.1007/s00704-013-0938-5.

Diolaiuti, G., Smiraglia, C., 2010. Changing glaciers in a changing climate: how vanishing geomorphosites have been driving deep changes on mountain landscape and environment. Géomorphol. Relief Process. Env. 2, 131–152.

Diolaiuti, G., Bocchiola, D., D'Agata, C., Smiraglia, C., 2012. Evidence of climate change impact upon glaciers' recession within the Italian Alps: the case of Lombardy glaciers. Theor. Appl. Climatol. 109, 429–445.

EPCN, 2008. The Pond Manifesto. (Available) http://campus.hesge.ch/epcn/projects.asp.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., Sharma, R., 2009. Recent changes in Imja Glacial lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. Environ. Res. Lett. 4, 1–7.

Gardelle, J., Arnaud, Y., Berthier, E., 2010. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. Global Planet. Change 75 (1–2), 47–55.

Gerstengarbe, F.W., Werner, P.C., 1999. Estimation of the beginning and end of recurrent events within a climate regime. Clim. Res. 11, 77–91.

Guyennon, N., Romano, E., Portoghese, I., Salerno, F., Calmanti, S., Petrangeli, A.B., Tartari, G., Copetti, D., 2013. Benefits from using combined dynamical–statistical downscaling approaches — lessons from a case study in the Mediterranean region. Hydrol. Earth Syst. Sci. 17, 705–720.

Haeberli, W., Kääb, A., Paul, F., Chiarle, M., Mortara, G., Mazza, A., Deline, P., Richardson, S., 2002. A surge-type movement at Ghiacciaio del Belvedere and a developing slope instability in the east face of Monte Rosa, Macugnaga, Italian Alps. Nor. Geogr. Tidsskr. 56, 104–111.

Hamerlík, L., Svitok, M., Novikmec, M., Očadlík, M., Bitušík, P., 2014. Local, among-site, and regional diversity patterns of benthic macroinvertebrates in high altitude waterbodies: do ponds differ from lakes? Hydrobiologia 723, 41–52.
Hays, W.L., 1988. Comparisons among means. Statistics. , 11. Rinehart and Wilson Inc., Orlando, Fla: Holt, pp. 418–421.
Huggel, C., Kääb, A., Haeberli, W., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can. Geotech. J. 39, 316–330.
Jones, P.D., Moberg, A., 2003. Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001. J. Clim. 16, 26–223.
Kendall, M.G., 1975. Rank Correlation Methods. Oxford University Press, New York,.
Knoll, C., Kerschner, H., 2009. A glacier inventory for South Tyrol, Italy, based on airborne laser scanner data. J. Glaciol. 50, 46–52.
Lami, A., Marchetto, A., Musazzi, S., Salerno, F., Tartari, G., Guilizzoni, P., Rogora, M., Tartari, G.A., 2010. Chemical and biological response of two small lakes in the Khumbu Valley, Himalayas (Nepal) to short-term variability and climatic change as detected by long-term monitoring and paleolimnological methods. Hydrobiologia 648, 189–205.
Manfredi, E.C., Flury, B., Viviano, G., Thakuri, S., Khanal, S.N., Jha, P.K., et al., 2010. Solid waste and water quality management models for Sagarmatha National Park and Buffer Zone, Nepal: implementation of a participatory modeling framework. Mt. Res. Dev. 30, 127–142.
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13, 245–259.
McMillan, M., Nienow, P., Shepherd, A., Benham, T., Sole, A., 2007. Seasonal evolution of supra-glacial lakes on the Greenland Ice Sheet. Earth Planet. Sci. Lett. 262, 484–492.
Morgenstern, A., Grosse, G., Günther, F., Fedorova, I., Schirrmeister, L., 2011. Spatial analyses of thermokarst lakes and basins in Yedoma landscapes of the Lena Delta. Cryosphere 5 (4), 849–867.
Nangeroni, G., 1983. Elenco-Catalogo dei laghi alpini del bacino Adda-Lariano. Atti Soc. ital. Sci. nat. Museo civ. Stor. nat. Milano. 124 (3 – 4), 193–223.
Paul, F., Kääb, A., Haeberli, W., 2007. Recent glacier changes in the Alps observed from satellite: consequences for future monitoring strategies. Global Planet. Change 56 (1/2), 111–122.
Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen–Geiger climate classification. Hydrol. Earth Syst. Sci. 11, 1633–1644.
Pham, S.V., Leavitt, P.R., McGowan, S., Peres-Nato, P., 2008. Spatial variability of climate and land-use effects on lakes of the northern Great Plains. Limnol. Oceanogr. 53, 728–742.
Rosenzweig, C., 2007. Assessment of observed changes and responses in natural and managed systems. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., et al. (Eds.), Climate Change 2007 — Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, UK, pp. 79–131.
Royston, J.P., 1982a. Algorithm AS181: the W test for normality. Appl. Stat. 31, 176–180.
Royston, J.P., 1982b. An extension of Shapiro and Wilk's W test for normality to large samples. Appl. Stat. 31, 115–124.
Salerno, F., Tartari, G., 2009. A coupled approach of surface hydrological modelling and Wavelet Analysis for understanding the baseflow components of river discharge in karst environments. J. Hydrol. 376, 295–306.
Salerno, F., Buraschi, E., Bruccoleri, G., Tartari, G., Smiraglia, C., 2008. Glacier surface-area changes in Sagarmatha National Park, Nepal, in the second half of the 20th century, by comparison of historical maps. J. Glaciol. 54 (187), 738–752.
Salerno, F., Thakuri, S., D'Agata, C., Smiraglia, C., Manfredi, E.C., Viviano, G., Tartari, G., 2012. Glacial lake distribution in the Mount Everest region: uncertainty of measurement and conditions of formation. Global Planet. Change 92–93, 30–39.
Scheidegger, A.E., 1987. Systematic Geomorphology. Springer-Veriag, New York, NY,.
Sen, P.K., 1986. Estimates of the regression coefficient based on Kendall's tau. Am. Stat. Assoc. J. 63, 1379–1389.
Settle, S., Goonetilleke, A., Ayoko, G.A., 2007. Determination of surrogate indicators for phosphorus and solids in urban storm water: application of multivariate data analysis techniques. Water Air Soil Pollut. 182, 149–161.
Smith, L.C., Sheng, Y., MacDonald, G.M., Hinzman, L.D., 2005. Disappearing Arctic lakes. Science 308 1429-1429.
Smol, J., Douglas, M., 2007. From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. Front. Ecol. Environ. 5, 466–474.
Tarquini, S., Isola, I., Favalli, M., Mazzarini, F., Bisson, M., Pareschi, M.T., Boschi, E., 2007. TINITALY/01: a new Triangular Irregular Network of Italy. Ann. Geophys. 50, 407–425.
Tarquini, S., Vinci, S., Favalli, M., Doumaz, F., Fornaciai, A., Nannipieri, L., 2012. Release of a 10-m-resolution DEM for the Italian territory: comparison with global-coverage DEMs and anaglyph-mode exploration via the web. Comput. Geosci. 38, 168–170.
Tartari, G., Salerno, F., Buraschi, E., Bruccoleri, G., Smiraglia, C., 2008. Lake surface area variations in the North-Eastern sector of Sagarmatha National Park (Nepal) at the end of the 20th Century by comparison of historical maps. J. Limnol. 67 (2), 139–154.
Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.
Tonkaz, Z., Cetin, M., Tulucu, K., 2007. The impact of water resources development projects on water vapour pressure trends in a semi-arid region, Turkey. Clim. Chang. 82, 195–209.
Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S-Plus, Fourth edition. Springer-Verlag, New York, p. 495.
Volo Italia, 2007. Program "it2000"® — TerraItaly® 98/99. (At) http://www.terraitaly.it/product.tpl.
Willgoose, G., Hancock, G., 1998. Revisiting the hypsometric curve as an indicator of form and process in transportation-limited catchment. Earth Surf. Process. 23, 611–623.
Williamson, C.E., Dodds, W., Kratz, T.K., Palmer, M., 2008. Lakes and streams as sentinels of environmental change in terrestrial and atmospheric processes. Front. Ecol. Environ. 6, 247–254.
Williamson, C.E., Saros, J.E., Schindler, D.W., 2009. Sentinels of change. Science 323 887-887.
Yde, J.C., Bárcena, G.T., Finster, K.W., 2011. Subglacial and Proglacial Ecosystem Responses to Climate Change. In: Blanco, J., Kheradmand, H. (Eds.), Climate Change – Geophysical Foundations and Ecological Effects. InTech, Rijeka, pp. 459–478.
Yoshikawa, K., Hinzman, L.D., 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost Periglac. 14, 151–160.
Yue, S., Wang, C.Y., 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann–Kendall test. Water Resour. Res. 38 (6), 1068. http://dx.doi.org/10.1029/2001WR000861.
Zhang, X., Vincent, L.A., Hogg, W.D., Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th century. Atmos. Ocean. 38 (3), 395–429.