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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

Gianni TARTARI*, Franco SALERNO[1)], Elisa BURASCHI[1)], Gabriele BRUCCOLERI[1)] and Claudio SMIRAGLIA[2)]

[1)]Water Research Institute, Italian National Research Council (IRSA-CNR), Brugherio, Milan, Italy
[2)]Earth Sciences Department "Ardito Desio", University of Milan, Italy
*e-mail corresponding author: tartari@irsa.cnr.it

ABSTRACT

The purpose of the present work was to investigate variations in the surface areas of lakes in the north-east sector of Sagarmatha National Park (Nepal) at the end of the 20th century, through comparison of the Mount Everest maps based on a survey done in the early 1980s, and the official Map of Nepal based on a survey done at the beginning of the 1990s. The analysis of the changes occurring between the 1980s and the 1990s in the surface areas and distribution of lakes in the north-east sector of SNP reveals that lake areas substantially increased, by 15.4 (-5.5; +5.7)% (median 12.5%), within hydrographic basins that included a certain amount of glacial cover. In fact, 96% of the lakes whose surface area increased are located in glacial basins. Conversely, the majority of the lakes without glacial cover in their catchment showed a reduction in surface area, and in many cases disappeared (83% of the lakes that disappeared were situated in basins without glaciers). This different behaviour of these two types of lakes, though observed over a short time span, would appear to be consistent with the consequences of temperature increases recorded from the beginning of 1980s on a global and local scale. The digital tool produced (Limnological Information System, LIS) as part of this work is intended to provide a useful platform for extending the analysis to entire area of SNP, as well as for subsequent comparisons based on earlier maps or more recent satellite images.

Keywords: Sagarmatha National Park, lakes cadastre, Mount Everest, GIS

1. INTRODUCTION

The study of hydrographic environments calls for an integrated perspective on the variables responsible for the processes which determine their characteristics (Larson *et al*. 1994; Karlsson *et al*. 2005, Battarbee *et al*. 2005). Lakes of glacial origin, for example, exhibit a variability that is closely tied to the geomorphological, climate and hydrological factors typical of the latitude and altitude at which their hydrographic basins are located (Lami *et al*. 1998; Kamenik *et al*. 2001; Sommaruga & Psenner 2001).

Global climate changes have an impact on the aquatic and terrestrial ecosystems of mountain areas, and these impacts are magnified by their biotic and abiotic fragility (Brown *et al*. 2007; Karlsson *et al*. 2005). These are in fact highly sensitive and vulnerable ecosystems (Haeberli 1990; IPCC 2007), and for this reason universally considered ideal sites for the study of long term environmental changes (Batterbee *et al*. 2002; Baudo *et al*. 2007; www.ilternet.edu/index.html).

The Himalaya-Karakoram-Hindu-Kush chain contains some of the largest glacier masses found outside of polar regions. From a hydrological perspective, these glacial masses play a fundamental role in the environmental system of the entire Asian continent (Agrawala *et al*. 2003; Krishna 2005; Anthwal *et al*. 2006). In fact, they constitute a water resource which assures the survival of millions of people who inhabit the basins of the Indus, Ganges and Brahmaputra rivers (Sharma 2001), especially during the glacier melt season and in the upper portions of the basins. The retreat of these glaciers could reduce the availability of water, with dramatic effects on biodiversity, especially within protected habitats, as well as on the populations, their means of subsistence, irrigation and energy, with long-term repercussions upon food supply within the region. In many cases, the retreat and downwasting of glaciers is most visibly evinced by the rapid growth in the number and size of glacial lakes. Such changes can result in catastrophic glacier lake outburst floods (GLOFs), which in the region constitute the strongest manifestation of the deglaciation process and its attendant risks. Currently, in SNP, it is Lakes Imja Tsho and Dig Tsho which are at greatest risk of GLOF. The first (1.5 km long and 0.5 km across; Yamada & Sharma 1993) formed from the glacier of the same name beginning in the 1950s, while Lake Dig Tsho (length 0.6 km, and width of up to 0.2 km in 1974; ICIMOD/UNEP 2001) formed from Langmuche Glacier, and constitutes the most significant GLOF event recorded in Nepal, in terms of damage caused. In 1985 its outburst flood released a wave of water and debris 10-15 metres high: a hydroelectricity project, 14 bridges, 30 houses and farmland worth USD 4 million were destroyed (Joe & Rai 2005).

Tab. 1. Map features used for the lake cadastres.

Lake cadastres	LCN '80s	LCN '90s
Maps	Mount Everest	Official Nepali map
Scale	1:50,000	1:50,000
Edition	National Geographic Society, Washington D.C., 1988	Survey Department of His Majesty's Government of Nepal (HMGN) in cooperation with the Government of Finland, 1997
Projection	Spheroid: Bessel Trasverse Mercator Projection x Origin: 0° Ny Origin: 87° EScale factor: 1.000	Spheroid: Everest 1830 Modified UTM Projectionx Origin: 0° Ny Origin: 87° EScale factor: 0.999
Acquisition andinterpretation	Aerotriangulation using vertical photography from a camera aboard U.S. Space Shuttle Columbia (December 1983). Aerial photogrammetry and survey of 1984	Aerial photogrammetry of December 1992, terrestrial survey done in 1996
Isohypses	Equidistance of 40 m	Equidistance of 40 m
Territory covered by the map	Latitude: 3,080,000 – 3,116,500 Longitude 479,000 – 505,000	All Nepal
Sheets	One sheet	2786-04, 2787-01 and 2886-16

For these reasons, it is important to study the morphological variations of glaciers and lakes in remote mountain areas such as Sagarmatha National Park (SNP), Nepal, which is subject to extreme climate conditions.

It was therefore decided, at the end of 1980s, to initiate development of a Geographical Information System (GIS) for SNP that could serve as a tool for supporting a multidisciplinary approach to the limnological, paleolimnological, glaciological, meteorological, anthropic and other studies undertaken by the Ev-K2-CNR Project (www.evk2cnr.org). Given the difficulty of developing an information system with such a high degree of integration between different disciplinary areas, the work of creating the GIS was broken down into a number of steps. The first of these involved, within an area limited to the north-east sector of the Park (Antoninetti *et al*. 1998), acquiring only the morphometric characteristics of the lakes (Tartari *et al*. 1998a), along with the distribution of their geological types and a first determination of the glacial cover present in the hydrographic basins (Bortolami 1998; Tartari *et al*. 1998b). More recently, Salerno *et al*. (2008) have instead investigated the variations in the surface areas of glaciers for the whole of SNP during the second half of the 20th century, through comparison of a map of the late 1950s (Schneider 1967) with the Official Map of Nepal of the early 1990s (HMGN 1997). Subsequently, and taking advantage of the availability of the Official Map of Nepal updated to the early 1990s (Tab. 1), as part of a project promoted by Ev-K2-CNR Committee (Salerno *et al*. 2006) and through a collaboration between IRSA-CNR and the University of Milan Earth Sciences Department, the work was continued to create a specific GIS tool for limnological research called the Limnological Information System (LIS), designed to incorporate multiple layers for tracking over time the quantitative and qualitative evolution of the lakes in response to natural and anthropic pressure factors. The first phase in the creation of the LIS, described in this paper, has the aim of updating and completing the previous cadastre for the north-east sector of the Park (Tartari *et al*. 1998a), analysing the changes that have occurred, with a view to continuing the work in future to cover all of SNP, as well as extending the morphometric analysis back to the 1950s.

2. BACKGROUND

The first limnological studies of the Mount Everest area (Sagarmatha in Nepalese, Chomolangma in Tibetan, Qomolangma in Chinese) were carried out in the 1960s (Löffler 1969). This pioneering work indicated that the lakes in this region have a certain stability over time, as well as being of great interest from an ecological perspective. The Water Research Institute (IRSA-CNR) began studying the lake environments in SNP in 1989 (Gosso *et al*. 1993). This work was then continued in close collaboration with the Institute of Ecosystem Studies (ISE-CNR), within the framework of research activities coordinated by Ev-K2-CNR Committee (Tartari *et al*. 1998a), to examine the physical, climatological and the more strictly hydrobiological aspects. The research activities were initially focused on the hydro-geochemical characterisation of the lakes over a wide spatial radius, with a view to collecting as much information as possible on the hydrochemical characteristics in dissolved phase (Tartari *et al*. 1998c), to be put in relation with the morphological, geological and glaciological characteristics of the territory of SNP (Bortolami 1998; Smiraglia 1998), after which the analysis was extended to the limnological and paleolimnological characterisation (Lami & Giussani 1998). The initial limnological work (1989-1992) resulted in the chemical characterisation of the lakes, highlighting the significant role of atmospheric depositions (Gosso *et al*. 1993). In seven expeditions conducted between 1989 and 1997, a total of 31 lakes were sampled and 48 were visited (Tartari *et al*. 1998b), leading to the identification of many temporary water bodies not distinguishable as such on the maps. Between 1992 and 1997, the

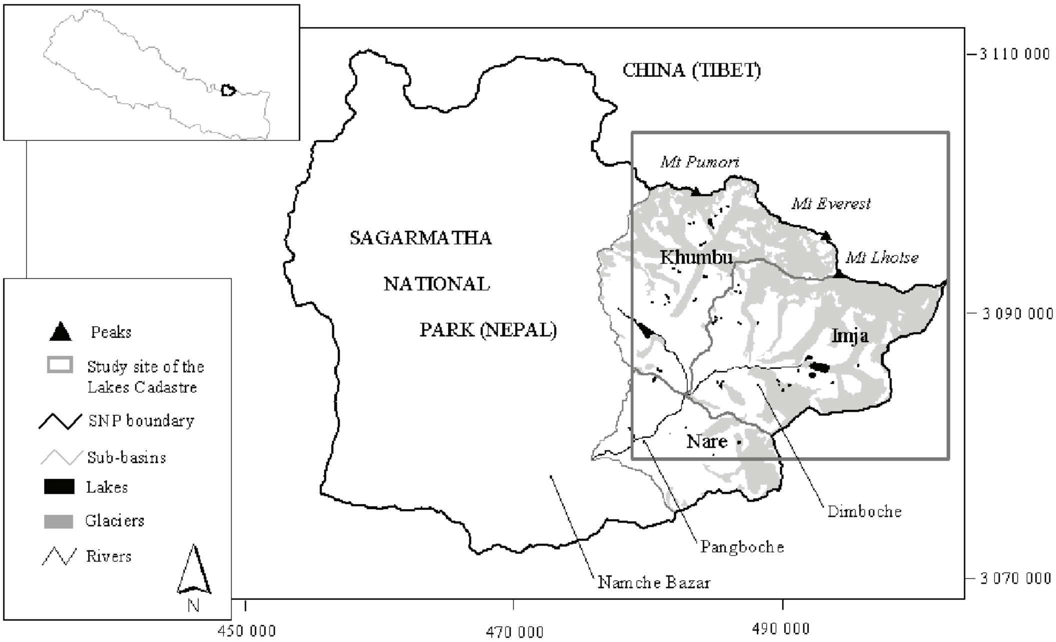

Fig. 1. Location of Sagarmatha National Park and of the study site of the Lakes Cadastre.

pelagic biocoenosis of 28 lakes was determined (Bertoni *et al*. 1998) and paleolimnological studies of 4 lakes were carried out (Lami *et al*. 1998), revealing a close relation between the biology of the lakes and the fluctuations in climate occurring over several hundred years (Lami *et al*. 2007).

In 1992, a first cartographic study was carried out to compile a lake cadastre. Because at that time an accurate geographical positioning system was not available, the field activities were based directly on the maps. For more details on the approach followed, the reader is referred to the original paper (Tartari *et al*. 1998a). Each water body was assigned a univocal sequential code (Lake Cadastre Number, LCN), hereinafter suffixed as pertaining to the map "of the eighties" (LCN '80s) to distinguish it from the succeeding cadastre produced using the later topographic map "of the nineties" (LCN '90s), which is described in the present work (Tab. 1).

This initial cadastre was subsequently integrated with new data from glaciological and morphological field surveys, whose results were published in a special issue (Vol. 57) of the journal "Memorie dell'Istituto Italiano di Idrobiologia" (Lami & Giussani 1998).

3. STUDY SITE

SNP is situated in Solu-Khumbu District, in the north-eastern region of Nepal (Fig. 1), and occupies the northernmost part of the Dudh Koshi River Basin, which is in its turn part of the Koshi River Basin (or Sapta Koshi Basin), one of the seven major hydrographic basins into which Nepal is subdivided. The northern boundary of the Park coincides with the water divide of the Himalayan mountain range, which runs along the international border between China and Nepal, while its southern boundary extends down to Monjo.

The first cadastre derived from the 1980s map was limited to the lakes in the north-east sector of the Park (Fig. 1), and therefore its updating based on the 1990s map was likewise circumscribed to the same area. Given that the Mount Everest map extends from 479,000 to 505,000 East and from 3,080,000 to 3,116,500 North, the territory covered by the two cadastres accounts for 28.0% (320 km^2) of the total area of SNP (1141 km^2). The studied area comprises elevations ranging from 3910 m (near Pangboche) to 8848 m (Mount Everest). This same group of mountains includes another peak above 8000 m (Lhotse), and another one higher than 7000 m (Pumori). All the lakes recorded in the LCN '80s were situated between 4460 m and 5645 m in altitude, with the maximum frequency of altitude distribution falling between 5100 m and 5300 m (Tartari *et al*. 1998a). The feeding of the lakes is attributable prevalently to perennial snows and glaciers, rather than runoff. However there are some lakes that do not have glacial masses in their hydrographic basin. These often prove to be temporary ponds, although in the case of lakes fed by glaciers and/or snowfields it is not infrequent to observe strong level variations during the inter-monsoon period (October-March).

Byers (2005) describes the climate features of SNP: geographically, SNP lies within the subtropical Asian monsoon zone that is characterised by pronounced summer rainfall maxima (Rao 1976; Mani 1981; Barry & Chorley 1992), with over 80 percent of the annual precipitation falling during an approximately four-month period between June and September (Ueno *et al*.

2008). Winters are normally dry, although occasional mid-latitude cyclones, driven by the subtropical jet stream that takes its winter position just south of the Himalayan ridge, can cause heavy snowfall events (Zimmermann *et al*. 1986). The prevailing axis of the monsoons is southern and south-western (Rao 1976; Müller 1980). Ageta (1976) observes that whereas monsoon activity from the southern foot of the Himalayas decreases moving toward the interior of the main range of the Himalayas, precipitation instead increases at some of the higher points in the interior of the range. For instance the average annual precipitation of Namche Bazaar (3450 m, 3,076,374 N, 471,819 E) is around 1000 mm y^{-1} and decreases with elevation gain (around 500 mm y^{-1} in Dingboche, 4355 m, 3,086,138 N, 483,780 E), while the total amount of precipitation around peaks and ridges can be 4 or 5 times greater than that around valley bottoms (Higuchi *et al*. 1982).

4. METHODS

4.1. Cartographic sources used

The topographic and thematic maps available for Nepal are reported in Gspurning *et al*. (2004) and well documented in Pradhananga (2002), which provides a complete account of all the existing (topographical, land resource, thematic, derived, etc.) maps of Nepal's Topographical Survey Branch. Of the available maps, the Official Map of Nepal published in 1997 is the most recent and covers the entire area of SNP.

The maps used for compiling the two cadastres, the ″Mount Everest″ map for the LCN '80s, and the Official Map of Nepal for the LCN '90s, are on the same scale (1: 50,000), and it is therefore possible to compare the level of detail of the information they contain.

The Mount Everest map clearly shows the date of the field survey: December 1984. The Official Map of Nepal is not so clear about this point, however the aerial photogrammetry was taken in December 1992 (Iwata *et al.* 2000). The above two maps shall hereinafter be referred to as the 1980s and the 1990s map, and allow us to analyse the changes occurring over a period of almost 10 years. Table 1 details the characteristics of these two maps.

The two maps were georeferenced according to the projection system of the Official map of Nepal. However this was not done by simply altering the projection system of the Mount Everest map. Rather, we proceeded to resample this map with the ArcView© tool, using around one hundred map control points (the mountain peaks) evenly distributed on the maps. The *a posteriori* check showed that the maximum horizontal deviation (along the X and Y axes) did not exceed 5 m (Georeferencing Error, GE).

4.2. Evaluation of the accuracy of the maps

Before analysing the errors arising from the process of cartographic representation and its subsequent conversion from analog to digital form, we must first of all consider the problem of the interpretation of lake features. This factor must be taken into account to ensure that any differences observed between the two maps effectively reflect real changes occurring in nature, and are not an artefact of different degrees of accuracy in the construction of the two maps. For the specific purposes of this work, this implies evaluating the comparability of the lake boundaries, and whether the presence or absence of the mapped water bodies on the two maps is real. With respect to comparability, there are no particular problems connected with the cartographer's interpretation; any potential uncertainty lies more with the degree of precision adopted in tracing the lake boundaries and the processing of the data. Both these aspects will be discussed in detail in the following section. One element which can, however, constitute a source of error for the lake boundaries is the time of year when the areal photogrammetry used for constructing the maps is carried out. In fact, considering the large different seasonal water input at these altitudes, lakes are subject to strong fluctuations in level, and hence in their surface areas, over the course of the year. In any case, this possible error is avoided considering that the two maps are based on data collected approximately in the same season of the year (December), thereby assuring comparability of the maps with respect to the hydrological regime.

Determining whether the population of lakes recorded on each of the two maps effectively reflects the true population of lakes present in nature is, instead, no simple matter. In general, it is reasonable to assume that if a lake has been mapped then it represents a truly extant water body, it being difficult to mistake other landscape features for lakes in aerial photogrammetry. On the other hand, a lake that is not mapped might either have been truly absent in nature, or omitted by mistake. Discriminating between these two possibilities would require retracing the process followed by the cartographers, considering a multiplicity of data sources: photographic material, photogrammetric images, direct observations, as well as the personal experience of the cartographer in interpreting the features on the terrain. Obviously, this is not a feasible alternative, and would entail considering any map unusable for the purposes of inventorying lakes. Even the use of remote sensing data cannot guarantee against any omission errors in the tracing of some lakes, although this source, which relies on the thermal response of the lakes, at least avoids the possibility that certain lakes may not be detected. For example lakes situated in shaded areas might not be readily distinguished using an aerial photogrammetric source, thus giving rise to a possible source of error.

Nevertheless, despite the difficulty of ascertaining the true presence or absence in nature of the lakes traced on the two maps (and also considering that some lakes could be frozen), it is important to determine whether the results of the comparison can be ascribed to real changes occurring in nature. Consequently, the error associated with area variations due to any omission errors in the tracing of some lakes on either of the maps (Omission Error, *OE*) was calculated simply as the difference between the change in area of all the lakes recorded on either of the maps and the area change computed by including only the lakes present on both maps.

4.3. The cartographic error

Verifying the quality of the data, from acquisition through to processing, is essential for assuring the plausibility of the results. In the present work, the data processing involved a conversion of topographic maps from analog to digital form, entailing a series of approximations with inevitable effects on data quality. It should be noted that a final cartographical representation is dependent on various factors, including the precision of the map, the Georeferencing Error (*GE*) and the precision of the operator which gives rise to the vectorization error. Assuming the vectorization error to be minimal, and having dealt with the *GE* of the maps as discussed previously (about 5 m along the X and Y axes), we can now further account for the precision of the data.

Every map has a well-defined metric precision which derives from the process by which it was constructed. The precision of the location of points and the level of detail of a topographic map, whether in digital or analog format, are determined by its scale factor. The precision of a derived cartographic representation is the degree of planimetric and altimetric tolerance between the coordinates of any given point on the source map and the coordinates of that same point on the derived map. Evaluating the precision of a derived map is therefore necessarily dependent on an evaluation of the precision of the source map. The graphical resolution limit of a map can be assigned an arbitrary value of around 0.2 mm, based on the threshold visible to the human eye. The level of approximation of a map is conventionally given by this limit of 0.2 mm multiplied by the scale factor. Therefore, for the source maps used in this work (scale 1:50,000), the approximation (Linear Resolution Error, *LRE*) corresponds to 0.2 mm *50,000, i.e. to a resolution of 10 m (Inghilleri 1974).

However, as discussed previously, there is also the georeferencing error (*GE*) to consider. Therefore, the overall error associated with the distance between two points (Linear Error, *LE*) must take into account the *GE* in addition to the *LRE*, and can be calculated as the quadratic sum of both errors (Bevington & Robinson 1992) according to equation (1). For the linear comparisons carried out in this paper the *LE* is around 11 m.

$$LE = \sqrt{(LRE)^2 + (GE)^2} \qquad (1$$

GIS based processing is often used for analysing variations in areas and volumes. It is therefore necessary to determine the deviation between the actual values and those computed based on the digitized data. Because the perimeter of an area is delineated by manual digitizing, the value of the planimetric vectorization error is often used to quantify the Area Resolution Error (*ARE*), which therefore represents the range of tolerance of the area measurements in question. The *ARE* is usually computed as the product of the perimeter of the area in question (*p*) and the Linear Resolution Error (*LRE*) (Inghilleri 1974). Considering that the *LE* is greater than the *LRE*, the error associated with an area (Area Error, *AE*) must therefore be computed as the product of the *LE* and the perimeter of the area (*p*) according to equation (2).

$$AE = LE \times p \qquad (2$$

When the *AE* is referred to the lake area variations between the 1980s and the 1990s, it is computed as the quadratic sum of the *AEs* associated with each of the 1980s and 1990s areas. In the same way, the total error (Total Error, *TOT_E*), arising from the omission error in tracing the lakes (*OE*) and the Area Error (*AE*), is computed as the quadratic sum of both errors (Bevington & Robinson 1992).

In this paper we considered an approximation limit to 0.001 km^2 (1 hectare) that corresponds to the magnitude of the lowest *AEs* calculated. Any lower threshold has been included in the analysis, therefore all mapped lakes have been included in the present study.

4.4. Statistical analysis

The statistical method used in this work is the Wilcoxon paired-sample test, also called Wilcoxon's-T test for one sample or for two dependent samples (Wilcoxon 1964). This test is suitable for use when the frequency distributions of the series are not based on Gaussian distributions. The observed differences between the two series of data are validated by a non-parametric inferential analysis based on the median, as this is a more representative index than the mean for non-symmetrical distributions. Through this test it is possible to evaluate the probability for discarding the null hypothesis (which in this work is often that the differences observed between the two cadastres not significant). A significance level (α) is generally chosen to define the rejection range of the null hypothesis as $\alpha = 0.05$ or $\alpha = 0.01$. The *p*-value thus gives a measure of the plausibility of the null hypothesis, defined as the minimum significance level α of the test for which the null hypothesis would be rejected. If $p < \alpha$ the null hypothesis is rejected and the differences are deemed significant. The significance was obtained using the table of critical values of Wilcoxon's-*T*, as a function of the number of observations *n* and the different significance levels (α) (Lehmann 1975). In the main analysis discussed below, the Wilcoxon's-*T* test is applied and discussed.

Tab. 2. Hydro-morphological features of the lake watersheds in the new LCN '90s cadastre.

Lake code		Order	River watershed	Link				Sub-basin surface	Watershed surface	Sub-basin perimeter	Glacier surface in sub-basin	Glacier surface in watershed	Influent	Effluent
LCN '90	LCN '80	N	Name	I	II	III	IV	km^2	km^2	km	km^2	km^2		
1	1	1	Khumbu					0.71	0.71	3.89	0.37	0.37	no	no
2	2	1	Khumbu					0.67	0.67	4.54	0.58	0.58	no	no
3	3	1	Khumbu					1.77	1.77	5.98	1.50	1.50	no	yes
4	4	2	Khumbu	3				0.05	1.81	1.95	0.02	1.52	yes	yes
5	5	1	Khumbu					0.34	0.34	3.00	0.17	0.17	no	no
6	6	1	Khumbu					0.33	0.33	2.47	0.12	0.12	no	no
8	8	1	Khumbu					0.54	0.54	3.79	0.00	0.00	no	no
9	9	1	Khumbu					0.73	0.73	3.39	0.10	0.10	no	yes
10	10	2	Khumbu	9	153			0.34	1.08	3.22	0.00	0.10	yes	yes
11	11	1	Khumbu					2.67	2.67	6.65	0.21	0.21	yes	yes
14	14	1	Khumbu					0.66	0.66	3.58	0.00	0.00	no	yes
15	15	1	Khumbu					0.29	0.29	2.44	0.00	0.00	no	yes
16	16	1	Khumbu					1.07	1.07	4.19	0.00	0.00	yes	yes
17	17	2	Imja	155				0.21	0.49	2.56	0.09	0.17	yes	yes
18	18	1	Imja					0.11	0.11	1.37	0.00	0.00	no	no
19	19	3	Imja	17	155			0.07	0.55	2.10	0.00	0.17	yes	yes
20	20	2	Imja	21	22			0.07	0.29	1.05	0.00	0.00	no	yes
21	21	2	Imja	22				0.22	0.26	2.32	0.00	0.00	no	no
24	24	2	Khumbu	15				23.37	23.66	29.49	3.23	3.23	no	yes
28	28	2	Khumbu	2627				0.03	1.13	1.40	0.00	0.35	no	no
29	29	1	Nare					0.45	0.45	3.22	0.00	0.00	no	no
30	30	1	Nare					0.34	0.34	3.17	0.00	0.00	no	yes
31	31	1	Imja					5.37	5.37	9.84	1.36	1.36	no	no
32	32	2	Imja	31				0.12	5.50	1.92	0.00	1.36	no	no
33	33	1	Nare					0.87	0.87	5.06	0.00	0.00	no	no
34	34	1	Nare					0.71	0.71	5.04	0.00	0.00	yes	yes
36	36	1	Imja					0.20	0.20	2.45	0.00	0.00	no	no
37	37	1	Imja					0.50	0.50	2.83	0.05	0.05	no	no
38	38	2	Imja	37				0.09	0.59	2.14	0.00	0.05	no	no
40	40	2	Imja	39				2.61	3.01	7.78	0.00	0.00	no	yes
41	41	1	Imja					0.57	0.57	3.55	0.00	0.00	no	no
42	42	3	Imja	159	43	44		0.22	4.20	2.71	0.18	3.85	no	no
43	43	1	Imja					1.04	1.04	6.40	0.87	0.87	no	no
44	44	1	Imja					2.36	2.36	6.25	2.39	2.39	no	no
46	46	1	Nare					0.94	0.94	4.42	0.43	0.43	no	no
51	51	1	Imja					1.05	1.05	4.33	0.26	0.26	yes	yes
53	53	1	Imja					0.40	0.40	2.62	0.00	0.00	yes	yes
54	54	1	Imja					1.14	1.14	4.45	0.10	0.10	no	yes
55	55	1	Imja					0.23	0.23	3.04	0.00	0.00	yes	yes
62	62	1	Imja					0.98	0.98	4.15	0.64	0.64	yes	yes
63	63	1	Imja					0.08	0.08	1.71	0.00	0.00	no	no
152	Absent	2	Khumbu	1213				0.14	1.12	2.14	0.00	0.00	yes	yes
153	Absent	1	Khumbu					0.01	0.01	0.57	0.00	0.00	no	no
154	Absent	1	Khumbu					0.18	0.18	2.14	0.00	0.00	no	no
155	Absent	1	Imja					0.28	0.28	2.04	0.08	0.08	yes	yes
159	Absent	2	Imja	43	44			0.56	3.95	3.98	0.41	3.67	yes	yes
160	Absent	2	Imja	51	52			2.88	4.15	9.06	0.40	0.74	yes	yes
161	161	2	Imja	56	55	62	63	47.21	48.69	51.67	35.03	35.04	no	yes
162	no	1	Khumbu					0.72	0.72	4.08	0.40	0.40	no	no
1213	12/13	1	Khumbu					0.98	0.98	4.03	0.00	0.00	yes	yes
2627	26/27	1	Khumbu					1.10	1.10	4.68	0.35	0.35	no	no
Absent	7	1	Khumbu					0.58	0.58	3.65	0.00	0.00	no	no
Absent	22	1	Imja					0.04	0.03	0.73	0.00	0.00	no	no
Absent	23	1	Imja					0.11	0.11	1.34	0.00	0.00	no	no
Absent	25	1	Imja					0.29	0.29	2.64	0.00	0.00	no	no
Absent	39	1	Imja					0.38	0.38	2.83	0.00	0.00	no	yes
Absent	45	1	Imja					0.17	0.17	2.44	0.00	0.00	no	no
Absent	47	1	Nare					0.60	0.60	0.80	0.60	0.60	no	no
Absent	48	1	Imja					0.44	0.44	3.15	0.00	0.00	no	no
Absent	49	1	Imja					0.06	0.06	1.78	0.00	0.00	no	no
Absent	50	1	Imja					0.05	0.05	1.55	0.00	0.00	no	no
Absent	52	1	Imja					0.22	0.22	4.19	0.08	0.08	no	no
Absent	56	1	Imja					0.18	0.18	1.68	0.01	0.01	no	no
Min								0.01	0.01	0.57	0.00	0.00		
Max								47.2	48.7	51.7	35.0	35.0		
Mean								1.77	2.13	4.57	0.79	0.97		
Median								0.40	0.59	3.15	0.00	0.05		

Tab. 3. Morphological features of lakes included in the LCN '80s and in the LCN '90s.

Lake code		Lake tipology		Elevation a.s.l.	Lake perimeter		Lake surface			Longitude	Latitude
LCN '90	LCN '80	LCN '90	LCN '80	m	LCN '90 km	LCN '80 km	LCN '90 km²	LCN '80 km²	Differences %	m	m
1	1		Pro	5385	0.58	0.54	0.022	0.020	10.0	484927	3098445
2	2	Pro	Pro	5430	0.34	0.39	0.007	0.007	0.0	484571	3098043
3	3	Supra	Pro	5318	1.52	1.46	0.122	0.114	7.0	484122	3097529
4	4	Pro		5280	0.50	0.44	0.016	0.011	45.5	484369	3097132
5	5			5400	0.44	0.41	0.013	0.012	8.3	482615	3097413
6	6			5440	0.35	0.23	0.008	0.003	166.7	482930	3097478
8	8			5180	1.17	0.91	0.029	0.028	3.6	483715	3095982
9	9			5213	0.38	0.29	0.009	0.006	50.0	481367	3094028
10	10			5067	0.52	0.57	0.017	0.017	0.0	481825	3093804
11	11			5048	0.73	0.61	0.026	0.018	44.4	483761	3093486
14	14			4890	0.23	0.28	0.004	0.005	-20.0	480755	3091382
15	15			5160	0.26	0.29	0.004	0.005	-20.0	479766	3091570
16	16			4939	0.70	0.86	0.014	0.028	-50.0	483064	3091778
17	17			5540	0.48	0.51	0.008	0.009	-11.1	484581	3090414
18	18			5509	0.30	0.29	0.006	0.005	20.0	484956	3090336
19	19			5420	0.26	0.34	0.003	0.006	-50.0	484595	3090227
20	20			5420	0.24	0.28	0.004	0.005	-20.0	484575	3090102
21	21			5480	0.68	0.47	0.033	0.015	120.0	484346	3089974
24	24			4532	3.63	3.74	0.536	0.556	-3.6	479356	3089383
28	28			5074	0.19	0.19	0.003	0.003	0.0	480478	3086369
29	29			5172	0.99	0.91	0.047	0.041	14.6	479977	3085765
30	30			5111	0.29	0.29	0.005	0.006	-16.7	479873	3085134
31	31			4680	1.48	1.89	0.057	0.074	-23.0	484926	3085353
32	32			4640	0.34	0.26	0.006	0.004	50.0	484671	3085540
33	33			4460	0.34	0.37	0.006	0.008	-25.0	482294	3082126
34	34			4960	0.26	0.20	0.005	0.003	66.7	484378	3080063
36	36			5560	0.34	0.28	0.007	0.006	16.7	486242	3092860
37	37			5436	0.39	0.32	0.010	0.006	66.7	486048	3092348
38	38			5436	0.52	0.43	0.014	0.009	55.6	486383	3092257
40	40			5180	0.75	0.84	0.020	0.023	-13.0	486338	3089978
41	41			5193	0.28	0.28	0.004	0.004	0.0	487703	3089957
42	42	Supra		4960	0.50	0.50	0.014	0.014	0.0	489198	3085668
43	43	Supra	Pro	5146	0.64	0.48	0.025	0.016	56.3	490081	3085330
44	44	Supra	Pro	5180	0.63	0.44	0.029	0.013	123.1	489623	3084941
46	46	Supra		5360	0.50	0.48	0.016	0.013	23.1	486281	3080999
51	51			5230	0.19	0.18	0.003	0.002	50.0	494662	3088134
53	53			5000	0.41	0.44	0.008	0.009	-11.1	490740	3086428
54	54			5002	1.32	1.34	0.131	0.135	-3.0	491775	3086085
55	55			5229	0.36	0.41	0.009	0.010	-10.0	493279	3085520
62	62			5200	0.19	0.46	0.002	0.010	-85.7	495671	3087634
63	63			5180	0.37	0.34	0.008	0.005	60.0	495213	3086795
152	Absent			4920	0.26		0.004			481041	3091548
153	Absent			5440	0.24		0.004			481593	3094430
154	Absent			5040	0.18		0.002			482882	3094063
155	Absent			5520	0.18		0.002			484419	3090666
159	Absent	Supra		4960	0.34		0.008			489261	3085371
160	Absent			5000	1.20		0.070			491523	3087408
161	161	Pro	Pro	5010	3.89	3.09	0.705	0.500	41.0	492303	3086670
162	Absent			5380	0.41		0.010			485457	3098742
1213	12/13			4960	0.79	0.65	0.027	0.013	107.7	480931	3091969
2627	26/27			5040	0.75	0.75	0.016	0.018	-11.1	480206	3086462
Absent	7			5315		0.52		0.008		482586	3096994
Absent	22			5458		0.28		0.003		484446	3089793
Absent	23			5511		0.22		0.003		484420	3089605
Absent	25			4983		0.25		0.003		483893	3087420
Absent	39			5381		0.44		0.013		485225	3091054
Absent	45			5072		0.31		0.005		488110	3083783
Absent	47	Supra		5320		0.24		0.004		487455	3080144
Absent	48			5271		0.26		0.004		490274	3090607
Absent	49			5305		0.17		0.002		490386	3090305
Absent	50			5239		0.18		0.002		490366	3089096
Absent	52			5093		0.27		0.004		492457	3087258
Absent	56			5427		0.30		0.004		492777	3084739
Min				4460	0.176	0.167	0.002	0.002			
Max				5560	3.889	3.741	0.705	0.556			
Mean				5185	0.643	0.574	0.042	0.033			
Median				5193	0.409	0.397	0.009	0.008			
Total							2.158	1.870	15.4		

5. RESULTS

The results presented in this work are aimed at updating, completing, and analysing any changes intervening since the first cadastre of the lakes compiled for the north-eastern portion of SNP (Tartari *et al*. 1998a). Tables 2 and 3 show all the morphometric data obtained from the LCN '90s classification, alongside those from the preceding LCN '80s. In the discussion, we will analyse the differences observed and asses their possible causes.

5.1. Criteria for identifying the lakes and hydrological basins

The first step in updating the lakes cadastre involved analysing the surface hydrographic network recorded on the 1990s map. This led to the identification of three sub-basins of the Imja Khola River, a left tributary of the Dudh Koshi River, which were by convention assigned the name of their largest associated glacier: the Nare glacier, Imja glacier and Khumbu glacier. The hydrographic basins of the lakes recorded on the 1980s map, as well as of the lakes present only on the later map, were both traced on the 1990s map. For the lakes that had disappeared in the newer map, the measurements were taken from the 1980s map.

To maintain consistency with the 1980s cadastre, the same nomenclature for identifying the lakes was retained, consisting of the acronym LCN (Lake Cadastre Number) followed by a number (Tab. 2). The resulting univocal code can be accompanied by one or more local names, or by a name assigned by researchers that has come into common usage (e.g., Pyramid Lake), even though there are only few such cases, with the majority of lakes remaining anonymous. However there remain some differences between the numbering adopted in the LCN '80s and LCN '90s cadastres, which are detailed below.

The attribution of the Lake Code to newly formed lakes was done proceeding from east to west. However we must consider that the LCN '80s included 6 lakes situated outside the boundaries of SNP (LCN: 57, 58, 59, 60, 61 and 64). These lakes were therefore excluded from the analysis of the two cadastres, and so their codes do not appear in the lists. In the case of lakes not included in one of the two maps, the description "Absent" is entered in the list. Many hydrographic basins incorporate sub-basins of lower order. For this reason, it was deemed useful to keep the data disaggregated, digitizing for each lake its direct drainage basin, and maintaining in the GIS the data pertaining to the connected basins of each lake, thereby avoiding the overlap of areas.

In the LCN '80s cadastre, Supraglacial lakes (Ageta 2000) had been excluded because they were not deemed limnologically relevant, in light of their rapid evolution and recent formation. In fact such water bodies can be better defined as ice-melt ponds rather than fully fledged lakes. Consequently, also in the LCN '90s cadastre, Supraglacial lakes have not been included, with the exception of those that were differently classified in the preceding cadastre and only subsequently became Supraglacial by effect of the glacier's advance.

In particular, we note that while Lake Imja Tsho was excluded from the LCN '80s cadastre because it was classified as Supraglacial, this same lake is instead included in the LCN '90s cadastre (LCN 161; Tab. 2), having been reclassified as Proglacial by virtue of being moraine-dammed. We therefore proceeded to also digitize this lake into the map of the 1980s. Finally, lakes 12/13 and 26/27, which in the 1980s map appeared as independent water bodies, appear instead united in the 1990s map. Therefore, they have been designated in the new cadastre as LCN 1213 and LCN 2627 (Tab. 2).

5.2. Identification of the lakes and hydrological basins

The lakes considered were situated in three watersheds: the Narebasin , 82.38 km^2 in size, the Imja basin (158.01 km^2), and the Khumbu basin (145.10 km^2) (Fig. 1). Table 2 details the morphometric characteristics of the hydrographic basins of the individual lakes in the LCN '90s cadastre. The link field shows the codes of their constituent lower-order basins, the sub-basin area field shows the area of the sub-basin draining directly into the lake, while the total watershed area of the basin in question, obtained by summing the areas of all its constituent sub-basins, is shown in the field Total Watershed Area. Table 2 also shows the extent of glacial cover present in each lake's direct drainage sub-basin (Total glacier area in the sub-basin) and the extent of glacial cover on the entire basin pertaining to the lake (Total glacier area in the watershed).

The average area of the direct drainage sub-basins of the lakes (Sub-basin Area) was found to be 1.77 km^2, while the average area of the lake basin (Watershed Area) was 2.13 km^2. The size of the basins ranged from 0.01 km^2 for lake LCN 153, to 48.69 km^2 for lake 161 (Imja Tsho). Finally, for each lake, the presence of any tributaries and/or effluents was identified on the map. Overall, out of 63 lakes examined, 16 had a tributary (25%) and 27 had an effluent (42%).

5.3. Comparison between the lakes in the LCN '80s and LCN '90s cadastres

Figure 2 (from a to c) shows the geographical location of the lakes in the LCN '90s cadastre, also indicating those that disappeared or were newly formed, relative to the LCN '80s cadastre.

Table 3 shows the list of the lakes and the morphometric measurements derived from the Mount Everest map and from the Official Map of Nepal: the area of the lake, its perimeter, the cartographic elevation, referred to the Mount Everest map for LCN '80s and to the Official Map of Nepal for those identified as newly formed, the plane coordinates of the lake centroid, and finally its type under the classification system set out below.

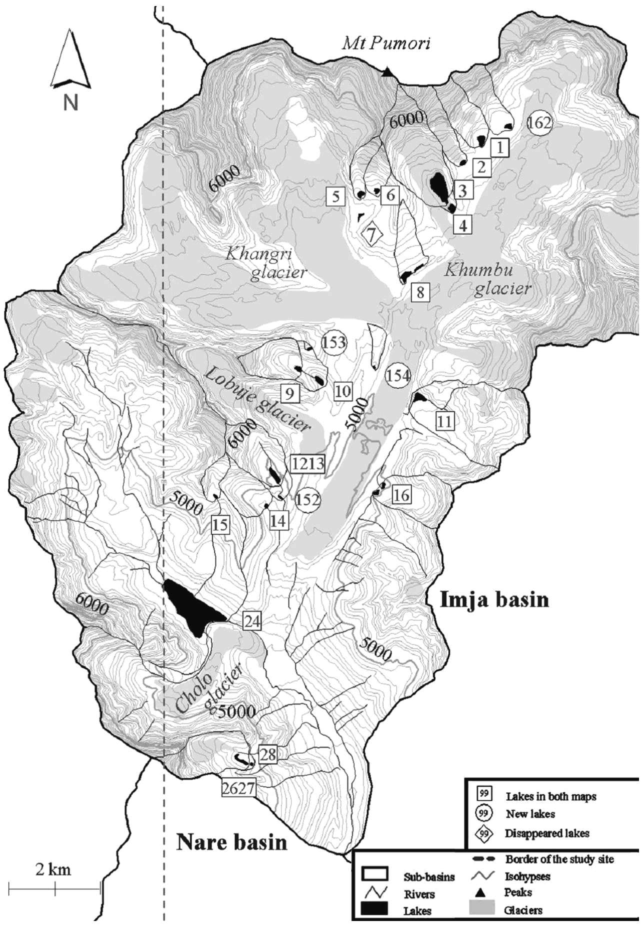

Fig. 2(a). Limnological Information System: map of the distribution of lakes in the Khumbu basin, Nepal. Topographic map: HMGN, 1997; lakes in both maps and new lakes: HMGN, 1997; disappeared lakes: Mount Everest map (see Tab. 1 for maps references).

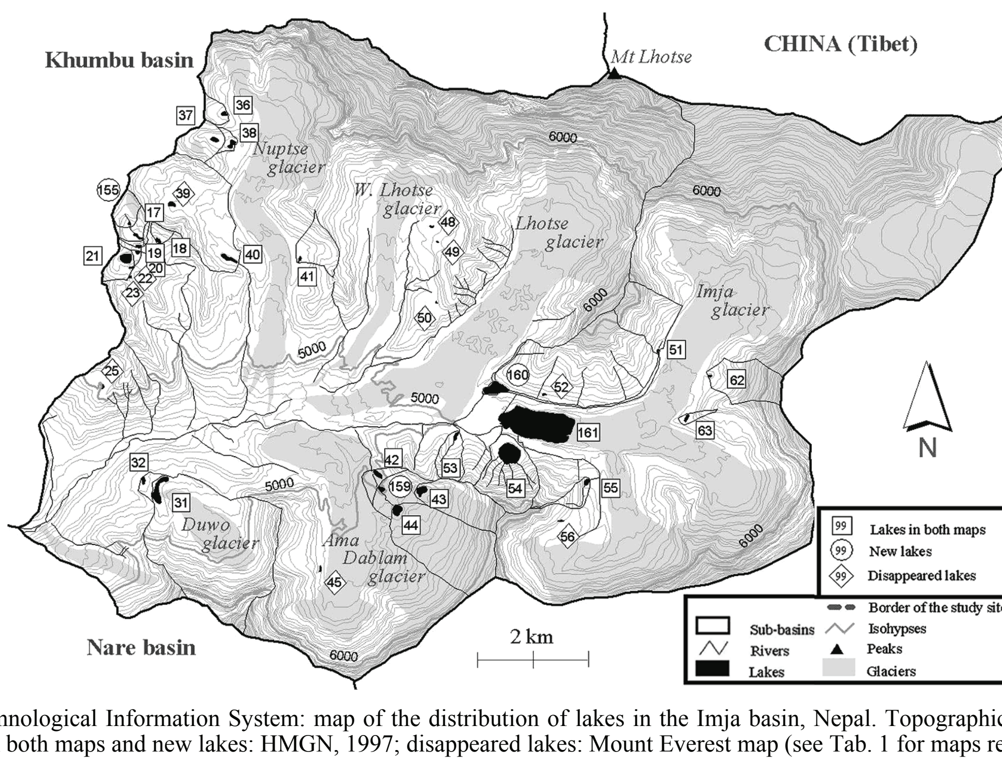

Fig. 2(b). Limnological Information System: map of the distribution of lakes in the Imja basin, Nepal. Topographic map: HMGN, 1997; lakes in both maps and new lakes: HMGN, 1997; disappeared lakes: Mount Everest map (see Tab. 1 for maps references).

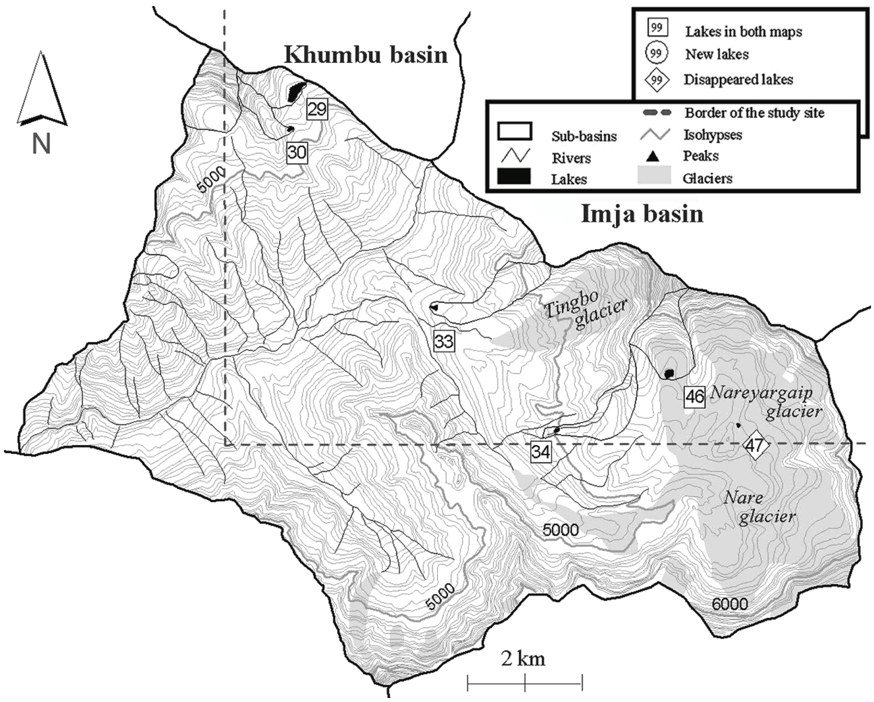

Fig. 2(c). Limnological Information System: map of the distribution of lakes in the Nare basin, Nepal. Topographic map: HMGN, 1997; lakes in both maps and new lakes: HMGN, 1997; disappeared lakes: Mount Everest map (see Tab. 1 for maps references).

The classification system for the lakes is based on that proposed in Ageta (2000), which subdivides lakes situated in high glaciation areas into:

1. Supraglacial ice-melt lakes (Supra): Located on top of the glacier. Usually, most of them are shallow and small in size, but they tend to connect to each other and grow into large contiguous lakes.
2. Proglacial lakes (Pro): Moraine-dammed and in contact with the glacier front. Some of them store large quantities of water and are susceptible to GLOFs.
3. Lakes not directly connected with glaciers or located in basin without glaciers (None): More stable over time than the other types.

The above approach was deemed more useful than the conventional classification of lakes according to Hutchinson (1957), Tonolli (1969) or Wetzel (2001), because it highlights the relationship between the lake and the glacier present in its hydrographic basin, and provides additional elements for understanding the mechanisms which regulate its chemical activity, as already discussed in Tartari *et al*. (1998c).

Overall, from the data of table 3 we can observe:

a) the LCN '80s cadastre counted a total of 56 lakes, with an average area of 0.033 km^2. The smallest lakes were LCN 49, 50 and 51 with an area of 0.002 km^2. LCN 161 (Imja Tsho) and LCN 24 were those with the largest areas (respectively 0.500 km^2 and 0.556 km^2), while the total sum of the lake areas in the 1980s was 1.870 km^2.
b) Within the same area, the LCN '90s records a total of 51 lakes, 5 less than the preceding cadastre, and with an average area of 0.042 km^2. The lakes LCN 62, 154, 155 are the smallest (0.002 km^2), while LCN 161 (Imja Tsho) and LCN 24 are the largest (respectively 0.705 km^2 and 0.536 km^2). The sum of the lake areas in the 1990s is 2.158 km^2, corresponding to an increase of 0. 288 km^2 compared with the LCN '80s.
c) In both the studied historical periods, the altitude distribution of the lakes ranged from 4460 m (LCN 33) to 5560 m (LCN 36).

The results in table 3 reveal a difference between the total lake areas recorded in the two cadastres, the causes of which are analysed in the discussion below. The total lake area showed an increase of 15.4%, with an uncertainty between -5.5% and +5.7% (median 12.5%), computed as described in the methods section. This increase is reduced to 6.1% if we do not consider lake LCN 161 (Imja Tsho), which during the period under study alone accounted for an area increase of 0.205 km^2 (corresponding to a difference of 41.0%). The application of Wilcoxon's-T test to each difference between total lake areas recorded in the two cadastres indicates that the observed differences are significant (p <0.05).

Set against this increase in the total area of the lakes, there is however a reduction in their number from 56 to 51 (-8.9%). From table 3 and figure 2 we also note that, during the time span under study, in reality a total of 12 lakes disappeared (LCN: 7, 22, 23, 25, 39, 45, 47, 48, 49, 50, 52, 56), prevalently situated in the Imja Glacier basin, while 7 new lakes appeared (LCN: 152, 153, 154, 155, 159, 160, 162), thus resulting in a net loss of 5 lakes.

In particular, we note the formation of lake LCN 160, in the proximity of the Imja Tsho lake, which is of large size (0.070 km^2) compared to the average area of the lakes under study. We can therefore reasonably rule out a possible error of omission in the tracing for this lake. However its history provides a significant indicator of the overall instability of the lakes in this high altitude region. Lake LCN 160, which is formed in a lateral moraine of Imja Tsho, is known to have a low stability and a discontinuous existence over the 20th century (Gspurning *et al*. 2004).

6. DISCUSSION

The scatter plot of figure 3 shows the areas of the lakes recorded in the LCN '80s cadastre, compared with those of the LCN '90s cadastre. This indicates, on the one hand, a good comparability of the data from the two cadastres, and on the other that the individual lakes, during the period intervening between the two maps, experienced both increases and reductions in area. This observation allows us to rule out any systematic error arising from the accuracy of tracing, the projection, the scale factor or the processing of the lake areas on the two maps, which would render meaningless any interpretation of the observed variations.

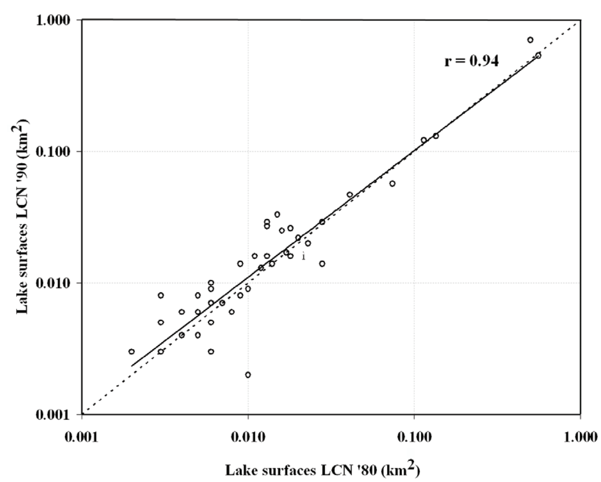

Fig. 3. Comparison between the lake areas measured on the Mount Everest Map (LCN '80s) and the lake areas derived from the Official Map of Nepal (LCN '90s). The dotted line represents the bisector, while the solid line represents the regression line.

In **table 4** a summary of the morphometric characteristics of the lake population (LCN '90s) is presented for the north-eastern sector of SNP, which for ease of comparison also includes some morphological elements obtained from the Mount Everest map for the LCN '80s glacier population.

Within the region under study (320 km^2), the LCN '90s cadastre records a total of 51 lakes, distributed with an average density of approx. 2 lakes per 10 km^2. The lakes are situated at a median elevation of 5180 m, with an interquartile range between 5001 and 5381 m. The median areas of the sub-basins and basins are respectively 0.54 and 0.72 km^2. This value differs greatly from the mean value (2.13 and 2.56 km^2, respectively), pointing to the dominance of small drainage areas. Likewise, the mean and median lake areas indicate a broad prevalence of small sized water bodies (Fig. 4a) with a asymmetric frequency distribution.

The mean areas of the lakes present on both the maps is 0.047 km^2 (LCN'90s). The mean area of the lakes that disappeared is about 1/10th of this value (0.005 km^2), whereas the mean area of the newly formed lakes is instead greater (0.014 km^2). Against a net loss of 5 lakes, the mean lake area (Fig. 4b) increased by about 1/3 (from 0.033 km^2 to 0.042 km^2).

The lakes present on both maps (Fig. 5a) have a mean elevation of 5143 m. The 12 lakes which disappeared instead had a mean elevation of 5283 m, that is to say 140 m higher, and corresponding to 13% of the altitude range of the lakes (1080 m), a non negligible difference if set against the mean elevation (p <0.01). The newly formed lakes, instead, are situated at an intermediate point between the two distributions (5171 m) with no statistically significant difference relative to the lakes present on both maps. Looking instead at the total set of lakes included on the two maps (Fig. 5b), we find a mean elevation of 5147 m (LCN '80s) compared with 5173 m (LCN '90s), that is to say a 26 m difference, which is negligible (2.4%) with respect to the altitude range of the population. Also in this case, no statistically significant difference was found between the two series.

Table 5 shows the differences occurring between the two historical periods, both in terms of the number of lakes and in terms of their area variations. The 7 newly formed lakes are evenly distributed in basins with and without glaciers, while the lakes that disappeared (12) were prevalently concentrated in basins without glaciers (10 out of 12, or 83%).

Each lake has an average of 0.79 km^2 of glacial cover within its own direct drainage basin, which increases to 0.97 km^2 if we also consider the glaciers present in the lower-order basins of the lakes, bringing the cover of the emerged basin to nearly half of its total area (46%).

The glacial cover is not, however, evenly distributed among the lake basins. Of the 63 lakes examined, nearly 60% (36 lakes) do not have glaciers in their direct drainage basin. One quarter of the lakes have glacial cover on 19% of their basin, while about 15% of the lakes have glacial cover on between 70 and 85% of their basin.

The general increase in the total lake area (average 15.4%;median 12.5%) is therefore unevenly distributed among the different types of lakes. The Proglacial lakes are those that showed the greatest area increase: 40.5%, with an uncertainty range from -15.6% and +15.6%.

Tab. 4. General summary of the morphometric features of lakes, sub-basins, watershed and glaciers in the LCN '90s cadastre.

	LCN Year	Unit	N	Min	Max	Mean	Median	10%ile	25%ile	75%ile	90%ile
Lakes	LCN '90		51								
	LCN '80		56								
Longitude	LCN '90	m		479356	495671						
Latitude	LCN '90	m		3080063	3098742						
Elevation	LCN '80-'90	m		4460	5560	5163	5180	4920	5001	5381	5440
Subbasin surface	LCN '90	km²		0.01	47.21	2.13	0.54	0.08	0.21	0.98	2.61
Watershed surface	LCN '90	km²		0.01	48.69	2.56	0.72	0.23	0.37	1.12	4.15
Subbasin perimeter	LCN '90	km		0.57	51.67	5.11	3.39	1.92	2.38	4.42	6.65
Lake perimeter	LCN '90	km		0.18	3.89	0.64	0.41	0.23	0.28	0.65	1.20
	LCN '80	km		0.17	3.74	0.57	0.40	0.22	0.28	0.51	0.91
Lake surface	LCN '90	km²		0.002	0.705	0.042	0.009	0.003	0.005	0.021	0.057
	LCN '80	km²		0.002	0.556	0.033	0.008	0.003	0.004	0.014	0.035
	Differences	%		-85.7	166.7	18.9	5.3	-22.1	-11.1	46.3	66.7
Glacier surface in sub-basin	LCN '90	km²		0.000	35.030	0.967	0.000	0.000	0.000	0.280	0.873
Glacier surface in watershed	LCN '90	km²		0.000	35.037	1.181	0.102	0.000	0.000	0.406	1.523

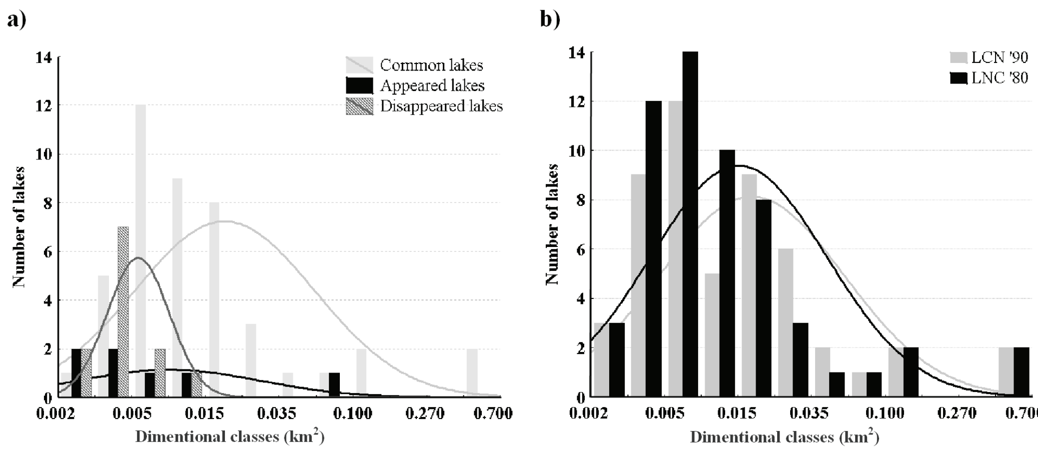

Fig. 4. Frequency distribution of the lakes relative to their areas. **a**) Comparison between the lakes present at both the historical times under study (areas obtained from the 1990s map), of the newly formed lakes, and of the lakes which disappeared. **b**) Frequency distribution of the lakes present on the two maps.

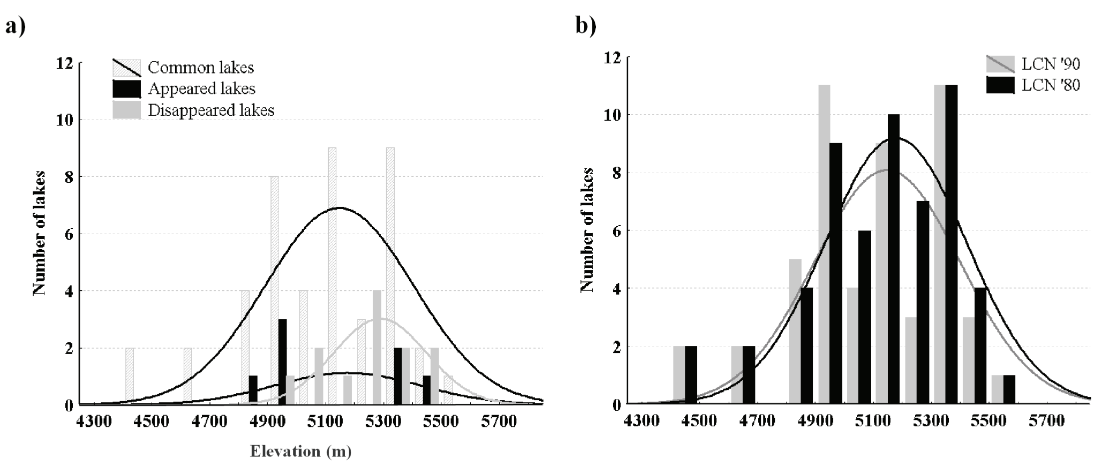

Fig. 5. Frequency distribution of the lakes relative to their elevation. **a**) Comparison between the lakes present at both historical times, the newly formed lakes in 90s map, and those which disappeared from 80s map. **b**) Frequency distribution of the lakes present on the two maps.

Tab. 5. Variations in lake areas in relation to the different classification types (*AE* = Area Error; *OE* = Error due to omitted tracing of the lakes; *TOT_E* = Total Error).

Classification LCN '90s	Total number of lakes	Glacier coverage	New lakes	Lakes in both maps	Disappeared lakes	Surface difference		*AE*	*OE*	*TOT_E*	Increased lakes
	N	%	N	N	N	km²	%	%	%	%	N (%)
					1	-0.004					
Supraglacial lakes	7	85	1			0.008	23.0	*±10.4*	*-1.8*	*(-10.6;+10.4)*	
				5		0.036					
Proglacial lakes	3	70		3		0.210	40.5	*±15.6*	*0*	*(-15.6;+15.6)*	26 (96)
Lakes not directly connected with glaciers	17	19			1	-0.004	5.2	*±4.9*	*-0.9*	*(-5.0;+4.9)*	
			3			0.082					
				13		-0.032					
Lakes located in basin without glaciers	36	0			10	-0.047	-3.9	*±7.4*	*+13.6*	*(-7.4;+15.5)*	13 (36)
			3			0.010					
				23		0.025					
Total	63		7	44	12	0.284	15.4				39
Mean		46						*±5.5*	*+1.3*	*(-5.5;+5.7)*	(62)

One such example is lake Imja Tsho, which expanded by 41%, but also LCN 4, which expanded by 45.5% (from 0.011 to 0.016 km^2). Unfortunately it was not possible to test the significance of this consideration because there are only 3 lakes of this type.

The Supraglacial lakes also showed significant increases in area, of 23.0 (-10.6; +10.4)%. It should however be considered that this last mentioned lake type is not representative of all the Supraglacial lakes present on the two maps, but only of those that became such during the studied historical period. In fact, as noted previously, because Supraglacial lakes were not included in the LCN '80s cadastre, they have consequently also been excluded from the LCN '90s cadastre, with the exception of those that were differently classified in the first cadastre and only became Supraglacial later by effect of the glacier's advance. Wilcoxon's-T test indicates that the observed increase is significant (p <0.05).

Among the most notable increases, there is that of LCN 44, which went from 0. 013 km^2 to 0. 029 km^2 (123%). More modest increases (5.2%, -5.0; +4.9) were shown by those lakes which, though not directly connected with a glacier, are nevertheless situated in basins which have glacial cover. Here, too, Wilcoxon's-T test indicates that the observed increase is significant (p <0.05). Finally, lakes without glacial cover in their catchment experienced reductions in their size, with an average area variation of -3.9%, although the magnitude of the associated error (-7.4%;+15.5%) means we cannot rule out that there might actually have been an area increase. Notice also that 12 lakes belonging to this category are not present in the LCN '90s, and therefore if these lakes had not been mapped (*OE* = +13.6%) in the '90s there would have an area increase also for this category too, as in the other cases described previously. What is more, Wilcoxon's-T test indicates that the observed reduction is not significant.

The last column of table 5, finally, shows that 62% (39 out of 63) of the examined lakes showed an increase in their area (0.42 km^2), and that this increase is principally accounted for by lakes situated in glacial basins (96%). This percentage declines to 36% for lakes situated in non-glacial basins, indicating that the majority of the population belonging to this type experienced a reduction in area, in some cases to the point of disappearing altogether.

An additional consideration relating to the area variations can be made by looking at the presence or absence of an outflow (Tab. 6). A full 81% of the lakes which showed a reduction in area have an effluent, a clearly high percentage with respect to those that showed a surface increase (32%). The changes in surface area are not only a function of the lake size, its altitude, and the presence of a glacier as described above, but are also strongly linked to the structure of the surface network, which influences the greater or lesser ease of water drainage.

Tab. 6. Type of area variation occurring for the studied lakes, relative to the presence of an effluent.

	Number of lakes (N)	Lakes with effluent (N)	Lake with effluent (%)
Decreased	16	13	81
Disappeared	12	1	8
Increased	28	9	32
Appeared	7	4	51
Total	63	27	43

One possible explanation for the observed changes could be the temperature increases recorded precisely starting from the 1980s, as noted in Shresta *et al*. (1999) for Nepal, and in Salerno *et al*. (2008) for the area near SNP. All the stations situated near SNP and the Kathmandu series, from the end of the 1950s to the early 1990s, show an increasing temperature trend, with also a rise during the 1984-1992 period. The divergent behaviour of the different types of lakes appears to bear out this hypothesis. The temperature rises may have favoured glacier melting, with a resultant increase in the flow of water feeding the lakes, thereby producing a positive hydrological balance for 96% of the lakes situated in glacial basins. Further supporting this hypothesis is the fact that the majority of the lakes which do not include a glacier in their basin showed a reduction in their area, often disappearing (83% of the lakes that disappeared were situated in basins without glaciers). In this case the temperature rise may have favoured increased evaporation, not compensated by any increased water inflows, thereby producing a negative hydrological balance with a consequent reduction in the lake areas. However this climate hypothesis requires further confirmation. In fact it should be remarked, in this connection, that the majority of studies on high elevations suffer from the absence of high altitude data, which makes it problematic to extrapolate the changes observed at weather stations to the lakes. Additional confirmation, for both precipitation and temperature, could be indirectly obtained through dendrochronological studies (Cook *et al*. 2003) or reanalysis data (Kistler *et al*. 2001), extending back into the past to the 1950s. That said, starting from 1994, there is data available from the weather station operated by Ev-K2-CNR at 5100 m, which can be used to determine the cause of any changes between then and the present day configuration of the lakes.

7. CONCLUSIONS

Updating the lakes cadastre for the north-eastern part of Sagarmatha National Park revealed the changes occurring in the population of lakes between the 1980s and the 1990s. Even within the short time period considered, there was a considerable statistical significant increase in the lake area (average 15.4%; median 12.5%), particularly at higher altitudes (>4900 m). Proglacial lakes were those with largest area expansion (40.5%), followed by the Supraglacial lakes (23.0%), while the smallest increases (5.2%) occurred in those lakes that, though not directly connected with a glacier, are nevertheless situated in lake basins where glacial cover is present. Finally, the lakes without glacial cover in their catchment showed a slight reduction in area (-3.9%), although in this case there is a higher margin of error, due to the small size of the lakes and the fact that the majority of lakes which disappeared are concentrated in this category. One possible explanation for the observed changes could be the temperature increases recorded precisely starting from the 1980s both for the overall for Nepal and for the area near SNP even though, as discussed, this climate hypothesis requires further confirmation.

The variations in lake areas appear to be a valid indicator of climate changes. In the near future, it will be possible to spatially extend the above analysis to the entire area of SNP, as well as back in time to the 1950s using the Khumbu Himal map (Schneider 1967), and up to the present day using satellite images, thereby obtaining a more representative sample of the lakes, and examining the area changes over a longer span of time.

However the LIS tool, integrating multiple information layers, whose development was undertaken with this work, should not be limited in its scope to investigation of the morphological aspects of the lakes. Rather, the intention is for the LIS to serve as a platform for integrating results from diverse research disciplines. The ultimate aim of creating a GeoDataBase, able to collect together morphometric, chemical and biological data and describe their evolution spatially and over time. The LIS has moreover been designed to be compatible with a GIS that is being developed on behalf of Ev-K2-CNR by IRSA-CNR and ISE-CNR in collaboration with ICIMOD, CESVI and IUCN for Sagarmatha National Park, within the framework of the HKKH Partnership Project (Basani *et al*. 2007) that is developing a Decision Support System for the protection of the natural resources of SNP.

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REFERENCES

Ageta, Y. 1976. Characteristics of precipitation during monsoon season in Khumbu Himal. *Seppyo*, 38: 84-88.

Ageta, Y. 2000. Expansion of glacier lakes in recent decades in the Bhutan Himalayas. In: Proc. Workshop *Debris-Covered Glaciers*. Seattle, Washington, USA, September 2000. IAHS, 264: 165-175.

Agrawala, S.,V. Raksakulthai, M. van Aalst, P. Larsen, J. Smith & J. Reynolds. 2003. *Development and climate change in Nepal. Focus on water resources and hydropower*. OECD, Paris, France: 64 pp.

Anthwal, A., V. Joshi, A. Sharma & S. Anthwal. 2006. Retreat of Himalayan Glaciers-Indicator of Climate Change. *Nature and Science*, 4(4): 53-59.

Antoninetti, M., M. Pepe, G. Iabichino, C. De Vito & G. Tartari. 1998. Environmental information system of Khumbu-Himal areas. In: R. Baudo, G. Tartari & M. Munawar (Eds), *Top of the world environmental research. Mount Everest-Himalayan ecosystem*. Ecovision World Monograph Series. Backhuys Publ., Leiden: 264-284.

Barry, R.G. & R.J. Chorley. 1992. *Atmosphere, Weather & Climate*. 6th Edition. Routledge, London: 392 pp.

Basani, M., F. Salerno, E. Cuccillato, B. Bajracharya, G. Daconto & S. Thakuri. 2007. Decision support tools for mountain ecosystem management: bringing together hard and soft system approaches. In: Proc. *Ecosummit 2007*. Elsevier. Beijin, Cina.

Battarbee, R.W., J.-A. Grytnes, R. Thompson, P.G. Appleby, J. Catalan, A. Korhola, H.J.B. Birks, E. Heegaard & A. Lami. 2002. Comparing palaeolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. *J. Paleolimnol.*, 28: 161-179.

Battarbee, R.W., N.J. Anderson, E. Jeppesen & P.R. Leavitt. 2005. Combining palaeolimnological and limnological approaches in assessing lake ecosystem response to nutrient reduction. *Freshwat. Biol.*, 50: 1772-1780.

Baudo, R., G. Tartari & E. Vuillermoz (Eds). 2007. *Mountain witnesses of global changes. Research in the Himalaya and Karakoram: SHARE-Asia Project*. Elseviers, Amsterdam, Developments in Earth Surface Processes, 10: 342 pp.

Bertoni, R., C. Callieri & M. Contesini. 1998. Organic carbon and micro-organisms in two Nepalese lakes. In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. Mem. Ist. ital. Idrobiol., 57: 99-106.

Bevington, P.R. & D.K. Robinson. 1992. *Data Reduction and error analysis for the physical sciences*. 2nd Edition. McGraw-Hill, Inc., Usa: 328 pp.

Bortolami, G. 1998. Geology of Khumbu Region, Mt. Everest, Nepal. In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal). Mem. Ist. ital. Idrobiol.*, 57: 41-49.

Brown, L.E., D.M. Hannah & A.M. Milner. 2007. Vulnerability of alpine stream biodiversity to shrinking glaciers and snowpacks. *Global Change Biology*, 13: 958-966.

Byers, A. 2005. Contemporary Human Impacts on Alpine Ecosystems in the Sagarmatha (Mt. Everest) National Park, Khumbu, Nepal. *Annals of the Association of American Geographers*, 95(1): 112-140.

Cook, E.R, P.J. Krusic & P.D. Jones. 2003. Dendroclimatic signals in long tree-ring chronologies. *Int. J. Climatol.*, 23: 707-732.

Gosso, E., G. Tartari, S. Valsecchi, S. Ramponi & R. Baudo. 1993. Hydrochemistry of remote high altitude lakes in the himalayan region. *Verh. Int. Ver. Limnol.*, 25: 800-803.

Gspurning, J., R. Kostka & W. Sulzer. 2004. Applicability of available Geodata in high mountain environmental research - Examples from the Khumbu Himal Area (Nepal). In: Proc. *19th European & Scandinavian Conference for ESRI Users*. Copenhagen.

Haeberli, W. 1990. Glacier and permafrost signals of 20th century warming. *Annals of Glaciology*, 14: 99-101.

Hutchinson, G.E. 1957. *A treatise on limnology. Geography, Physics and Chemistry*. J. Wiley & Sons, 1: 1015 pp.

Higuchi, K., Y. Ageta, T. Yasunari & J. Inoue. 1982. Characteristics of precipitation during the monsoon season in high-mountain areas of the Nepal Himalaya. Hydrological Aspects of Alpine and High Mountain Areas. In: J.W. Glen (Ed.), *Hydrological Aspects of Alpine and High-Mountain Areas*. International Commission on Snow and Ice (ICSI) Symposium, Exeter, UK. IAHS/AISH Publication, 138: 21-30.

HMGN. 1997. *Survey Department of His Majesty's Government of Nepal in cooperation with the Government of Finland*. Official Nepali map.

ICIMOD/UNEP. 2001. *Inventory of glaciers, glacier lakes and glacial lake outburst floods, monitoring and early warning system in the Hindu Kush-Himalayan Region*. ICIMOD/UNEP (Ed): 247 pp.

Inghilleri, G. 1974. *Topografia generale*. UTET, Torino.

IPCC. 2007. Climate Change 2007: *Impacts, Adaptation and Vulnerability. WG2-Ecosystems, their properties, goods and services*. Cambridge University Press: 212-272.

Iwata, S., T. Aok, T. Kadota, K. Seko & S. Yamaguchi. 2000. Morphological evolution of the debris cover on Khumbu Glacier, Nepal, between 1978 and 1995. In: Proc. Workshop *Debris-Covered Glaciers*. Seattle, Washington, USA, September 2000. IAHS, 264: 3-11.

Joe, T.K. & S.C. Rai. 2005. *An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China*. WWF Nepal Program. March, 2005: 70 pp.

Kamenik, C., R. Schmidt, G. Kum & R. Psenner. 2001. The Influence of Catchment Characteristics on the Water Chemistry of Mountain Lakes. *Arctic Antarctic and Alpine Research*, 33(4): 404-409.

Karlsson, J., A. Jonsson & M. Jansson. 2005. Productivity of high-latitude lakes: climate effect inferred from altitude gradient. *Global Change Biology*, 11: 710-715.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woollen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H.van den Dool, R. Jenne & M. Fiorino. 2001. The NCEP-NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. *Bull. Amer. Meteor. Soc.*, 82: 247-268.

Krishna, A.P. 2005. Snow and glacier cover assessment in the high mountains of Sikkim Himalaya. *Hydrol. Process.*, 19: 2375-2383.

Lami, A. & G. Giussani (Eds). 1998. *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. Mem. Ist. ital. Idrobiol., 57: 235 pp.

Lami, A., P. Guilizzoni, A. Marchetto, R. Bettinetti & D.J. Smith. 1998. Paleolimnological evidence of environmental changes in some high altitude Himalayan lakes (Nepal). In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. Mem. Ist. ital. Idrobiol., 57: 107-130.

Lami, A., G.A. Tartari, S. Musazzi, P. Guilizzoni, A. Marchetto, M. Manca, A. Boggero, A.M. Nocentini, G. Morabito, G. Tartari, L. Guzzella, R. Bertoni & C. Callieri. 2007. High altitude lakes: limnology and paleolimnology. In: R. Baudo, G. Tartari & E. Vuillermoz (Eds), *Mountain witnesses of global changes. Research in the Himalaya and Karakoram: SHARE-Asia Project. Elseviers, Amsterdam*. Developments in Earth Surface Processes, 10: 155-170.

Larson, G.L., A. Wones, C.D. Mclntire & B.B. Samora. 1994. Integrating Limnological Characteristics of High Mountain Lakes into the Landscape of a Natural Area. *Environ. Manage.*, 18: 871-888.

Lehmann, E.L. 1975. *Nonparametrics: Statistical Methods Based on Ranks*. San Francisco, Holden Day: 457 pp.

Löffler, H. 1969. High altitude lakes in Mt. Everest region. *Verh. int. Ver. Limnol.*, 17: 373-385.

Mani, A. 1981. The climate of the Himalaya. In: J.S. Lall & A.D. Moddie (Eds), *The Himalaya: Aspects of change*. Oxford University Press Delhi: 1-15.

Müller, F. 1980. Present and Late Pleistocene Equilibrium Line Altitudes in the Mt Everest Region-An Application of the Glacier Inventory. *IAHS-AISH Publication*, 126: 75–94.

Pradhananga, T.B. 2002. Topographic survey branch with remote sensing. In: Proc. 23nd *Asian Conference on Remote Sensing*. Kathmandu.

Rao, Y.P. 1976. *Southwest Monsoon. India Meteorological Department*. Meteorological Monograph, New Delhi: 366 pp.

Salerno, F., G. Bruccoleri, E. Buraschi & G. Tartari. 2006. *GIS dei corpi lacustri e dei ghiacciai del Parco Naturale Sagarmatha (Nepal)*. Rapporto IRSA-CNR–Ev-K2-CNR, Brugherio: 34 pp.

Salerno, F., G. Tartari, E. Buraschi, G. Bruccoleri & C. Smiraglia. 2008. Surface area variations of Sagarmatha National Park (Nepal) glaciers in the second half of the 20th century by comparison of historical maps. *J. Glaciology*, 18(187): (in press).

Schneider, E. 1967. Begleitworte zur Karte Khumbu Himal und zur Namensgebung. In: *Khumbu Himal, Ergebnisse des Forschungsunternehmens Nepal-Himalaya*. Band 1, Liefg. 5, München. S.: 430-446.

Sharma, S. 2001. The Ganges Crisis – Government lacks strategic plan. In: Proc. *Int. Conf. on Freshwater*. Bonn, Germany: 3-7.

Shresta, A.B., C.P. Wake, P.A. Mayewski & J.E. Dibb. 1999. Maximum Temperature Trends in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal in the Period 1971-94. *J. Climate*, 12: 2775-2787.

Smiraglia, C. 1998. Glaciers and glaciology of Himalaya. In: R. Baudo, G. Tartari & M. Munawar (Eds), *Top of the World Environmental Research: Mount Everest – Himalayan Ecosystem*. Backhuys Publishers, Leiden: 65-100.

Sommaruga, R. & R. Psenner. 2001. High-Mountain Lakes and Streams: Indicators of a Changing World. *Arctic Antarctic and Alpine Research*, 33(4): 383-384.

Tartari, G., L. Previtali & G.A. Tartari. 1998a. Genesis of the lake cadastre of Khumbu Himal Region (Sagarmatha National Park, East Nepal). In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. Mem. Ist. ital. Idrobiol., 57: 139-149.

Tartari, G.A., P. Panzani, L. Adreani, A. Ferrero & C. De Vito. 1998b. Lake cadastre of Khumbu Himal Region: geographical–geological–limnological data base. In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. *Mem. Ist. ital. Idrobiol*., 57: 151-235.

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Tartari, G.A., G. Tartari & R. Mosello. 1998c. Water chemistry of high altitude lakes in the Khumbu and Imja Kola valleys (Nepalese Himalayas). In: A. Lami & G. Giussani (Eds), *Limnology of high altitude lakes in the Mt Everest Region (Nepal)*. *Mem. Ist. ital. Idrobiol.*, 57: 51-76.

Tonolli, V. 1969. *Introduzione allo studio della limnologia. Ecologia e biologia delle acque dolci*. Ed. Istituto Italiano Idrobiologia, Verbania Pallanza: 387 pp.

Ueno, K., K. Toyotsu, L. Bertolani & G. Tartari. 2008. Stepwise Onset of Monsoon Weather Observed in the Nepal Himalayas. American Meteorological Society. *Monthly Weather Review*, 136: 2507-2522.

Wetzel, R.G. 2001. *Limnology. Lake and River Ecosystems*. 3rd Edition. Academic Press, San Diego: 1006 pp.

Wilcoxon, F. 1964. *Some Rapid Approximate Statistical Procedures*. Lederle Laboratories, Pearl River, New York: 59 pp.

Yamada, T. & C.K. Sharma. 1993. Glacier lakes and outburst floods in the Nepal Himalaya. In: J. Young (Ed.), *Snow and Glacier Hydrology*. Proc. Kathmandu Symp., November 1992, IAHS, 218: 319-330.

Zimmermann, M., M. Bichsel & H. Kienholz. 1986. Mountain hazards mapping in the Khumbu Himal, Nepal. *Mountain Research and Development*, 6(1): 29-40.