Inventory of glaciers and glacial lakes of the Central Karakoram National Park (Pakistan) as a contribution to know and manage mountain freshwater resource

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ABSTRACT

In this study, we reported valuable information on the cryosphere of the Central Karakoram National Park (CKNP, the largest protected area of Pakistan and the highest park all over the world). In fact, in addition to the glacier inventory, we also estimated the glacier volume and we modeled the amount of meltwater derived from glacier ice ablation during a 18-day summer period (23 July–9 August 2011, time window where also field melt measurements were performed thus enabling a crosscheck of the obtained results). Moreover, glacial lakes were considered as well; for these latter glacier features we also analyzed their potentially dangerous conditions. All these information are given considering the CKNP as a whole and in detail by dividing it into five basins (i.e. Shigar, Hunza, Shyok, Upper Indus and Gilgit). As regards the CKNP as a whole, 608 glaciers are found with a total area of 3682.1 ± 61.0 km^2, ~35% of the CKNP area. Analyzing in detail the five basins included in the CKNP area, they reflect the overall conditions regarding glacier distribution per size class, terminus elevation, length, and thickness. The widest basin (for number of ice bodies, glacier extent and ice volume) is the Shigar basin, where the largest glaciers are present (among which Baltoro Glacier), and the smallest one is the Gilgit basin. Finally, the highest number of debris-covered glaciers is located in the Shyok basin (62 glaciers). During 18 days in summer 2011, we quantified a total water magnitude of 1.54 km^3 derived from ice melting. Even if we considered a relatively short period, this water volume equals ~11% of the reservoir capacity of the Tarbela Dam. In addition to glacier information, we provided glacial lake occurrence, as these ephemeral water bodies can develop into actual glacial risk conditions, which makes it important to list them and to survey them over time. The information reported in this study would provide base for future monitoring of glacial lakes and GLOFs and for planning and prioritizing disaster mitigation efforts in the park. In fact, even if the Potentially Dangerous Glacial Lakes (PDGLs) identified in the park territory are only 2, they are located in a high vulnerable and fragile area and the recent history suggests us to survey over time these water bodies to avoid losses of human lives and destructions of villages and communities. Moreover, many other supraglacial lakes identified in the park area could develop into conditions of PDGLs thus suggesting to prosecute the lake monitoring and to develop early strategies for risk mitigations and disaster management.

KEYWORDS

Central Karakoram National Park (CKNP); CKNP glacier inventory; CKNP glacial lake inventory; Potentially Dangerous Glacial Lakes (PDGLs); Water resource.

INTRODUCTION

The Central Karakoram National Park (CKNP, Fig. 1) is the largest protected area of Pakistan (about 10,000 km² wide plus a further 7,500 km^2 buffer zone, WWF-Pakistan, 2007), born in 1993. It is located in the Northern Pakistan in the main glaciated region of the Central Karakoram. This area is situated in the High Mountain Asia (HMA), that represents the largest glacierized region outside the Arctic and the Antarctic, the so called "Third Pole", covering an area of more than 100,000 km^2 (Gardner et al., 2013) and hosting about 40,000 km^2 of ice bodies (glaciers, glacierets and perennial ice surfaces). The CKNP is the highest park all over the world, as it is characterized by extremes of altitudes that range from 2000 m a.s.l. to over 8000 m a.s.l., including K2 (8611 m a.s.l.), the second highest peak in the world. It falls into four administrative districts of Gilgit-Baltistan Region.

The study here summarized has been developed and carried out in the framework of the SEED Project. The SEED project was aimed at an integrative development of CKNP region through supporting the implementation and management of CKNP, improving local wellbeing and livelihood options. Although the population of Gilgit-Baltistan is relatively small, it is linguistically and ethnically very diverse. Twelve different languages tell us about the long, turbulent and rich history of the area, which manifests itself in numerous important cultural heritage sites.

However, for the people making a living in this part of Pakistan, remoteness from important education and health services and centers of commerce are the downside of the wild and untouched beauty of the province. Cash income sources are rare and in this harsh and dry mountain climate even subsistence agriculture is a feat and sickness can easily lead to serious chronic illness or death. All of these properties make people from Central Karakorum National Park living constantly at the brink of poverty. No surprise that the Poverty Reduction Strategy Paper (PRSP) of the Pakistan Government from 2004 lists rural regions in Gilgit-Baltistan province as having the 3rd highest poverty rate in the country, just after FATA and NWFP.

Gilgit-Baltistan has a unique and critical role to play in the sustainable development of Pakistan. Although the province spans a relatively small geographical area, it hosts the vital catchment of the Indus River, a key water source for Pakistan's irrigated agriculture and hydroelectricity production. Gilgit Baltistan also hosts the nation's most important natural forests, extensive mineral reserves, and a wealth of biodiversity. The dramatic scenery, some of the world's highest mountains and the rich cultural and archaeological heritage make Gilgit-Baltistan one of the most visited tourist destinations in the country.

The Central Karakoram National Park (CKNP) was officially notified as National Park in 1993. There was a tremendous pressure on the natural resources due to traditional usufruct rights of the local inhabitants, coupled with the additional need of visitors to the area. Unsustainable resource use and tourism practices were viewed as the key threats faced by the local ecosystem. Governmental and non-governmental organizations have been working at the local scale for over a decade in order to improve the economic, social and environmental situation of CKNP area. All the interventions have a common objective, but no framework that coordinates the different activities and strategies. International organizations and tourism companies do not have a legislative framework of reference, as the only law on parks is the Northern Areas Wildlife Preservation Act of 1975, which was not very effective. To tackle these deficits and achieve a better coordination of the different interventions towards the realization of CKNP, the project "Participatory Management and Development of Central Karakoram National Park (CKNP)" had been approved in June 2007 by the Northern Areas Administration; this 5 year initiative was supported by the HKKH Partnership Project, WWF Pakistan and the Karakoram Trust Project. The University of Milan was partner of both HKKH partnership and Karakoram trust project team. These initiatives were successful and useful to the development of the area but, due to a lack of funding, they were unable to produce the Park Management Plan, a fundamental tool to manage, preserve and promote the CKNP and its resources. To fill this gap was developed the SEED project, featuring the following specific aims:

1) building a strong, intrinsically scientific CKNP management, to contribute to the finalization and implementation of a management plan for Central Karakorum National Park;
2) supporting on livelihood assets and improvements of local people's wellbeing in and around the park, ensuring that they are not in conflict with, but support the park's conservation efforts;
3) Developing and supporting economy for the eco-sustainable tourism sector; for conservation areas, eco-sustainable tourism is the economic sector which is most consistent and compliant with the national park's vision, objectives and regulations.

To reach these goals the project's approach is to integrate research (and capacity building for intrinsic knowledge generation) with community development and ecosystem management. Thematically, the SEED project was focused on three main interconnected areas, which can be considered the main pillars of an integrated development of CKNP from the perspective of different prevailing approaches in the fields of macro-economic development, protected area management/entitlements, livelihood development and well-being.

Within this context, a great attention has been paid to the water resource in the CKNP area.

In fact, the CKNP holds the major source of fresh water in the Pakistan mainly due to glaciers, as they provide fresh water for civil use, hydropower production and farming (Bocchiola and Diolaiuti, 2013; Mayer et al., 2010). In fact, around half (2405 $m^3 s^{-1}$, Hasson et al., 2015) of the water in the Indus river originating from the Karakoram comes from snow and glacier melt (Immerzeel et al., 2010; Minora et al., 2015; Soncini et al., 2015; Senese et al., submitted), warranting a life to the immediate downstream Tarbela reservoir (the largest water storage structure in the country). The CKNP is therefore a key area for studying the effects of ongoing climate change on present and future meltwater discharge and a pragmatic assessment of the actual water availability from these watersheds is utmost necessary for ensuring the sustainable socio-economic development in the country.

In this study, we reported high-resolution and very detailed information on the water resource of the CKNP. In fact, in addition to the glacier inventory, we also estimated the glacier volume and we modeled the amount of meltwater derived from glacier ice ablation during a 18-day summer period. In addition to glacier information, we provided glacial lake occurrence, as these ephemeral water bodies can develop into actual glacial risk conditions (Potentially Dangerous Glacial Lakes, PDGLs), which makes it important to list them and to survey them over time. All these information are given considering the CKNP as a whole and in detail by dividing it into five basins (i.e. Shigar, Hunza, Shyok, Upper Indus and Gilgit, Fig. 1).

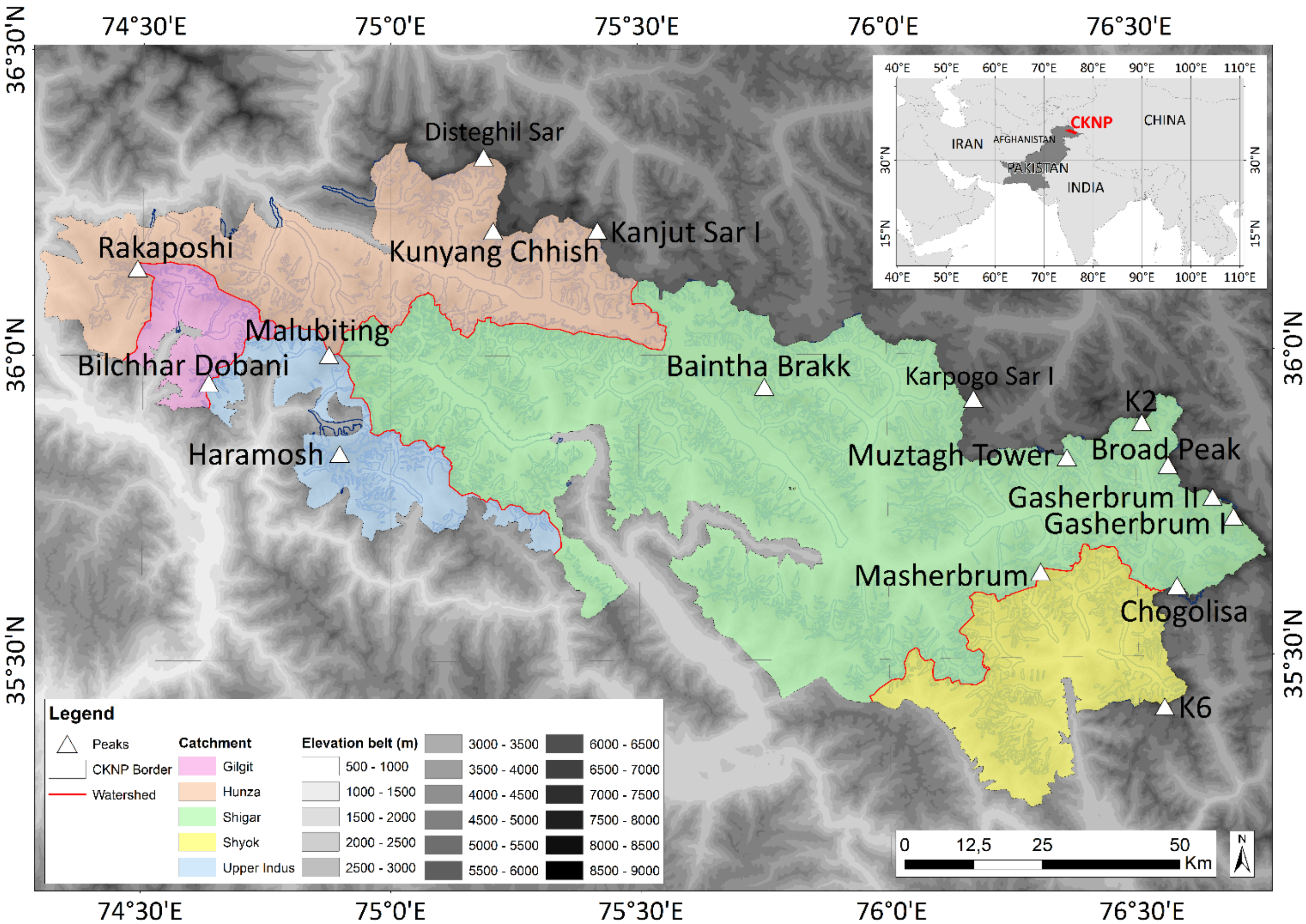

Fig. 1: The study area, the Central Karakoram National Park (CKNP) divided into five basins (i.e. Shigar, Hunza, Shyok, Upper Indus and Gilgit).

METHODS

To produce the inventory of glaciers of the CKNP and to estimate glacier volume (i.e. total fresh-water resource contained by CKNP glaciers) and meltwater, we considered i) the glacier boundaries in 2010 developed during the compilation of the CKNP glacier inventory, ii) supraglacial debris coverage and thickness in 2010 and 2011, respectively. In order to calibrate and validate our calculations, we coupled remote sensing investigations and physically based models with field observations collected during an expedition in summer 2011 on the Baltoro Glacier (the widest and representative ice body of the CKNP, 62 km long, widely debris covered). For further details regarding the approaches applied see Mihalcea et al. (2008a; 2008b), Minora et al. (2015; 2016) and Senese et al. (submitted).

The glacial lake inventory of the CKNP was derived from a general Glacial lakes inventory developed by PARC (Pakistan Agricultural research Council) and PMD (Pakistan Meteorological Department) in 2015 for the whole Hindukush-Karakoram-Himalayan (HKH) area. The occurrence of glacial lakes and their features refer to 2013. Field surveys were carried out in Hunza and Gilgit basins during 2013 in order to assess risk of flood hazards and investigate glacial environment. The criteria for identifying the Potentially Dangerous Glacial Lakes (PDGLs) are based on geo-morphological, geo-technical characteristics and records of past processes and events of the lake. For classifying a lake to be potentially dangerous, the lake physical conditions and features and its surroundings as discussed by Mool et al. (2001), Bajracharya et al. (2007), ICIMOD (2011) and PARC et al. (2015) were considered.

GLACIER INVENTORY

In the CKNP there are 608 glaciers (among which some of the largest Karakoram glaciers: Baltoro, Biafo, and Hispar, Fig. 2) with a mean size of 6.1 km^2. Their total area in 2010 is 3682.1 ± 61.0 km^2, ~35% of the CKNP area. This area represents ~24% of the glacier surface of the entire Karakoram Range within Pakistan (total area from Bajracharya and Shrestha, 2011). The Shigar glacierized area is the widest of the CKNP basins, covering more than half of the whole glacierized surface of the park (i.e. 2308.3 km^2, Table 1), and featuring the highest number of glaciers (i.e. 294 bodies, 48% of the total CKNP census, Table 1). In addition, four of the biggest CKNP ice bodies are located into this basin: namely Baltoro Glacier (604.2 km^2), Biafo Glacier (438.1 km^2), Chogo Lungma Glacier (265.0 km^2) and Panmah Glacier (264.2 km^2). Gilgit basin hosts the lowest number of glaciers (36, Table 1, corresponding to 6% of the whole CKNP glacier census) and the glacierized area is only the 2% (83.62 km^2, Table 1) of the total CKNP glaciation, thus representing the smallest one compared to the other basins.
Analyzing in details the widest basin (i.e. Shigar), on the one hand, as we found also for the other basins, the most part of glaciers (36.1% of all Shigar glaciers) features an area lower than 0.5 km^2, covering only 1.1% of the whole Shigar glaciation. On the other hand, glaciers larger than 50 km^2 cover the 70.8% of the whole Shigar glaciation. The mean glacier terminus elevation is found to be 4443 m a.s.l. (in agreement to the other four basins), ranging from 2740 to 5760 m a.s.l.
The total fresh-water resource contained in the CKNP glaciers was estimated ca. 532.37 km^3 and Baltoro Glacier is found to be characterized by the maximum volume value (128.79 km^3, Fig. 2). More than half of all CKNP glaciers (68.5%) contains a volume of water lower than 0.05 km^3, contributing only for the 0.98% over the total volume. In particular, ice bodies such as glacierets (with an area of about 0.02 km^2) feature the minimum volume equal to 0.0001 km^3.
The cumulated ice ablation from the CKNP in the time window 23 July–9 August 2011 (i.e. 18 days) was equal to 1.54 km^3 w.e., with a daily average of 0.09 km3 w.e. d^{-1}. As expected, the contribution from glaciers located into the Shigar basin is the highest one (0.92 km^3 w.e., Table 1).

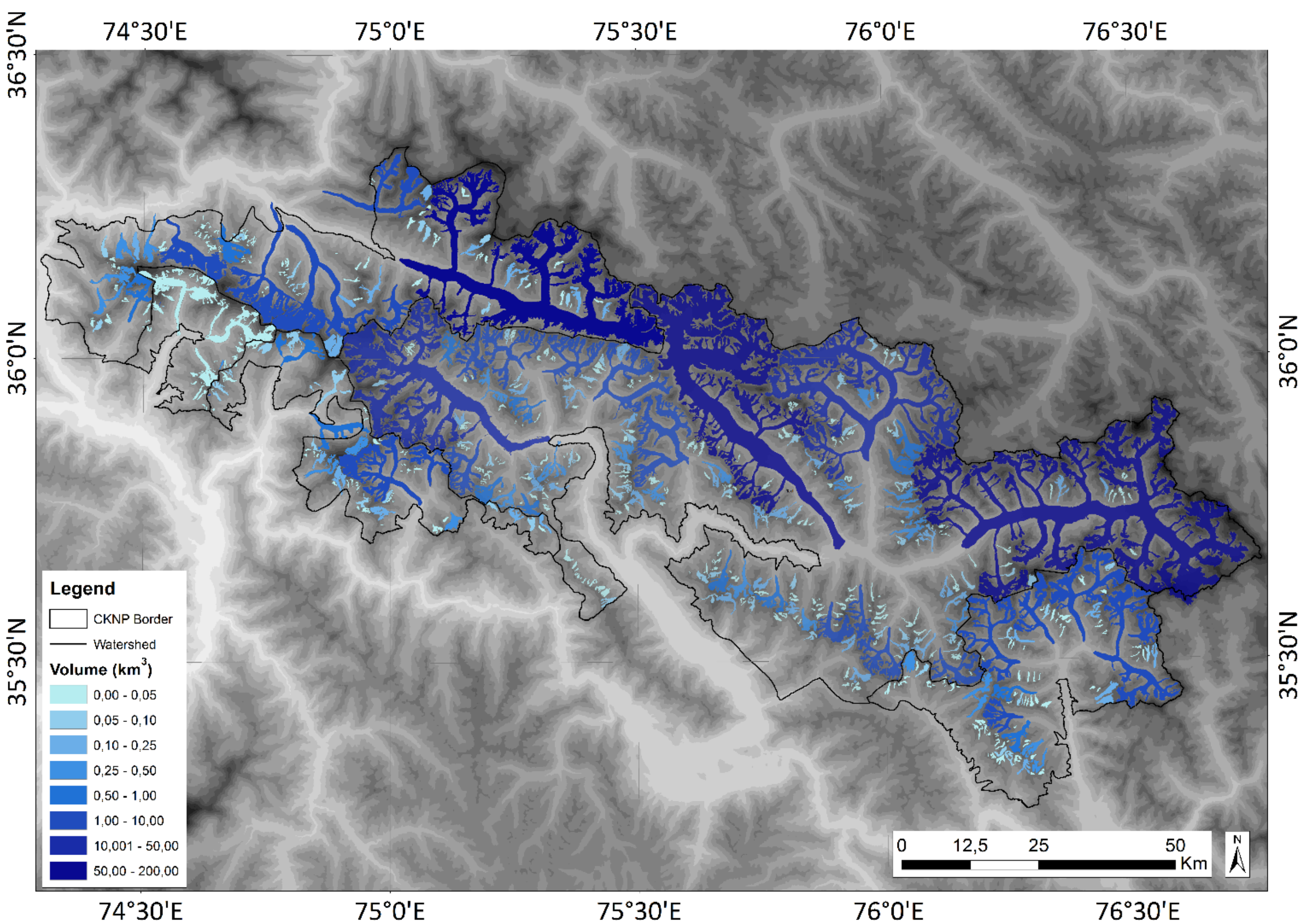

Fig. 2: Map showing the CKNP glaciers with information about the volume (km^3) corresponding to the total fresh-water resource contained in the CKNP glaciers.

Table 1. Summary of the inventory of glaciers and glacial lakes sorted into CKNP catchments.

Catchment	Area (km^2)	Number of glaciers	Cumulative glacier area (km^2)	Area of the widest glacier (km^2)	Glacier volume (km^3)	Volume of the largest glacier (km^3)	Cumulated meltwater in the time window 18 days long (km^3 w.e.)	Glacial lakes (number)	Glacial lake cumulative area (km^2)	PDGLs (number)
Shigar	6090	294	2308	604	392	129	0.92	109	2	0
Hunza	2099	123	766	369	98	70	0.35	57	1	0
Shyok	1224	94	335	67	27	7	0.13	30	0	0
Upper Indus	707	61	189	58	10	4	0.08	1	0	0
Gilgit	355	36	84	30	5	2	0.05	5	0	2
CKNP	**10476**	**608**	**3682**	**604**	**532**	**129**	**1.53**	**202**	**4**	**2**

GLACIAL LAKE INVENTORY AND PDGLS

In the CKNP area, 202 glacial lakes are located (Fig. 3) thus corresponding to about 7% on the total of 3044 glacial lakes listed for the Hindukush-Karakoram-Himalayan region (HKH). The park lakes feature a cumulative extent of 3.56 km^2 (Table 1, about 2.6% of the total glacial lake area in the HKH). Considering the lake type, in the CKNP the Supraglacial lakes prevail, they represent the 69.31% of the total number and they cover 2.04 km^2, then Blocked type lakes are abundant being 20.30% of the total number. The type distribution for CKNP gives a different picture with respect to the HKH general conditions. In fact, in the greater HKH region Erosion lakes prevails (857 water bodies, 28.2% of the total number), followed by the End Moraine Dammed lakes (791 water bodies, 26% of the whole number).

As in most cases major lakes are more susceptible of GLOF (Glacial Lake Outburst Flood) hazards than smaller ones, we analyzed lakes with a surface area greater than 0.02 km^2. The CKNP hosts 37 major lakes, corresponding to the 18.32% of the glacial lakes. Most part of these glaciers (64.86%) feature an area between 0.02-0.05 km^2. Overall 17 major lakes belong to Supraglacial type and 16 to Blocked type. In particular, only 2 PDGLs are found, both of them lie in the Gilgit catchment and are identified as supraglacial lake type (Fig. 3). These PDGLs have caused frequent flooding events in the recent past. In fact, the ephemeral lake developed at the surface of the Hinarchi Glacier possesses history of multiple breaching in the Bagrot valley of Gilgit basin. Also the other supraglacial lake in the Gilgit basin is growing rapidly due to melting of the associated glacier (i.e. Gargo Glacier) in the Bagrot valley thus posing threat of outburst flood hazard for downstream communities.

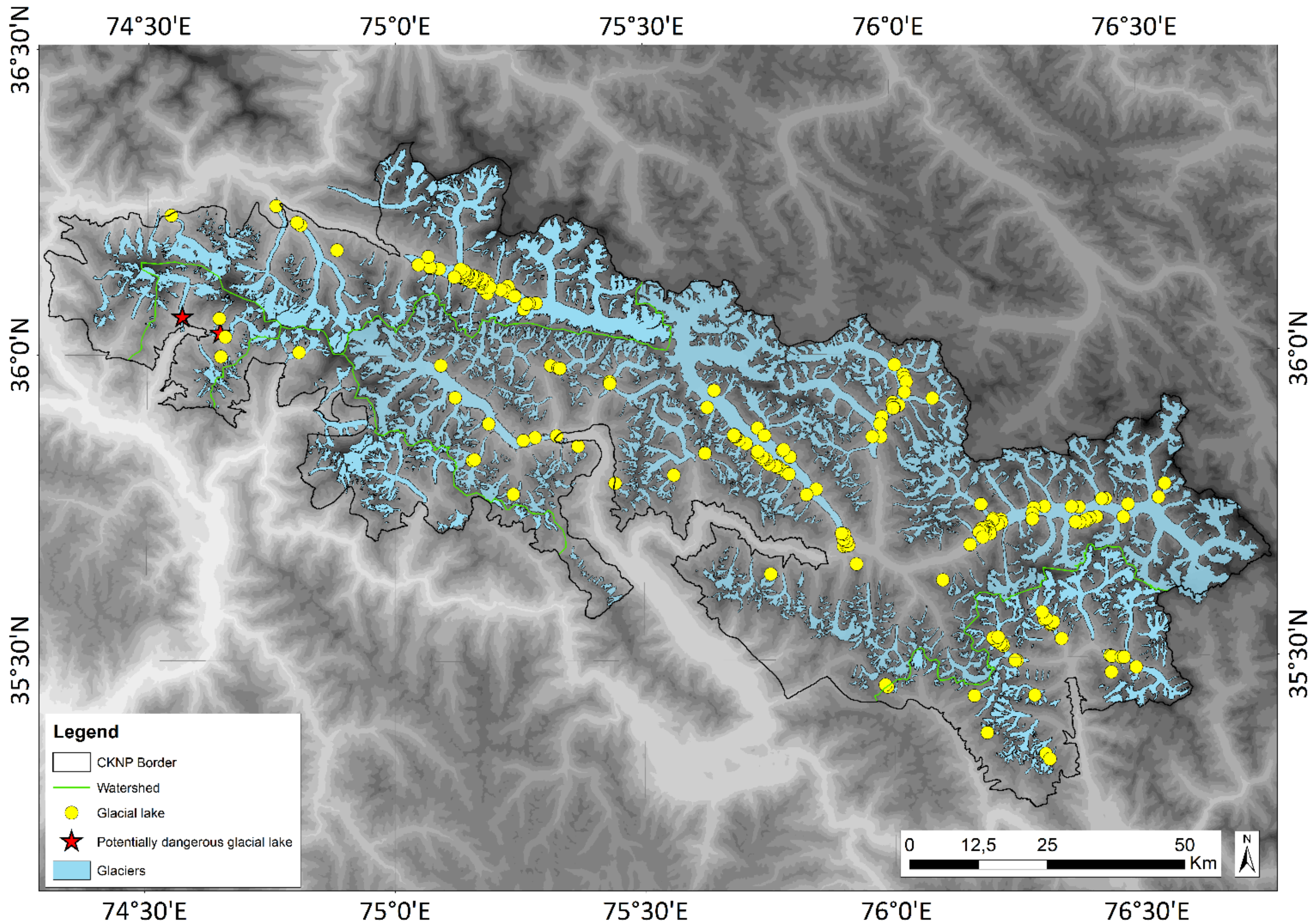

Fig. 3: Map showing the CKNP glacial lake inventory and PDGLs.

CONCLUSIONS

As regards the CKNP as a whole, 608 glaciers and 202 glacial lakes are found with a total area of 3682.1 ± 61.0 km^2 (~35% of the CKNP area) and 3.56 km^2, respectively. The total fresh-water resource contained in the CKNP glaciers was estimated ca. 532.37 km^3, with a maximum volume of about 130 km^3 (Baltoro Glacier). Analyzing in detail the five basins included in the CKNP area, they reflect the overall conditions regarding glacier distribution per size class, terminus elevation, and ice volume. The widest basin (for number of ice bodies, glacier extent and ice volume) is the Shigar basin, where the largest glaciers are present (among which Baltoro Glacier), and the smallest one is the Gilgit basin.

During 18 days in summer 2011, we quantified a total water magnitude of 1.54 km^3 derived from ice melting. Even if we considered a relatively short period, this water volume equals ~11% of the reservoir capacity of the Tarbela Dam (i.e. a huge hydropower plan located in Pakistan, 25,000 ha wide, 144 m high, 2743 m long and hosting a water volume of about 11 x 10^9 m^3). This value gives an idea of the role played by glacier melt in providing freshwater for Pakistan people (Fig. 4).

Fig. 4: People in the CKNP transporting giant glacier ice cubes to be used for deriving freshwater for civil use. This activity is performed daily in the summer season as most regions suffer dry conditions and limited freshwater availability.

In addition to glacier information, we provided glacial lake occurrence, as these ephemeral water bodies can develop into actual glacial risk conditions, which makes it important to list them and to survey them over time. The information reported in this study would provide base for future monitoring of glacial lakes and GLOFs and for planning and prioritizing disaster mitigation efforts in the park. In fact, even if the PDGLs identified in the park territory are only 2, they are located in a high vulnerable and fragile area and the recent history suggests us to survey over time these water bodies to avoid losses of human lives and destructions of villages and communities. Moreover, many other supraglacial lakes identified in the park area could develop into conditions of PDGLs thus suggesting to prosecute the lake monitoring and to develop early strategies for risk mitigations and disaster management.

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livelihood improvement and conservation through an integration of intrinsic scientific ecosystem management oriented research, indigenous practices for natural resource management and ecotourism principles to support the development and implementation of the CKNP. The present study was also carried out by early career researchers supported by DARAS (Department of Regional Affairs, Autonomies and Sport) of the Presidency of the Council of Ministers of the Italian Government through the GlacioVAR project (PI G. Diolaiuti).

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NOMENCLATURE

Symbol or Acronym	Meaning
CKNP	Central Karakoram National Park
PDGL	Potentially dangerous glacial lake
PARC	Pakistan Agricultural research Council
PMD	Pakistan Meteorological Department
HKH	Hindukush-Karakoram-Himalayan
GLOF	Glacial Lake Outburst Flood