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Altitudinal dynamics of glacial lakes under changing climate in the Hindu Kush, Karakoram, and Himalaya ranges

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A B S T R A C T

The environmental challenges posed by global warming in the Himalayan region include early and rapid melting of snow and glaciers, creation of new lakes, and expansion of old ones posing a high risk of glacial lakes outburst flood (GLOF) hazard for downstream communities. According to various elevation ranges, 3044 lakes were analyzed basinwide in the Hindu Kush-Karakoram-Himalaya (HKH) ranges of Pakistan using multisensor remote sensing data of the 2001–2013 period. An overall increase in glacial lakes was observed at various altitudinal ranges between 2500 and 5500, m out of which noticeable change by number was within the 4000–4500 m range. The analysis carried out by glacial-fed lakes and nonglacial-fed lakes in different river basins indicated variable patterns depending on the geographic location in the HKH region. The correlation analysis of parameters like lake area, expansion rate, and elevation was performed with 617 glacial lakes distributed in various river basins of the three HKH ranges. Lake area (2013) and elevation showed a negative relationship for all basins except Hunza, Shigar, and Shyok. The correlation between the expansion rate of lakes and elevation was on the positive side for Swat, Gilgit, Shigar, and Shingo basins—a situation that may be attributed to the variable altitudinal pattern of temperature and precipitation. In order to explore such diverse patterns of lake behavior and relationship with influential factors in the HKH, detailed studies based on using high resolution image data coupled with in situ information are a prerequisite. Although an increase in lake area observed below 3500 m would be favorable for water resource management, but could be alarming in context of glacial flood hazards that need to be monitored critically on a long-term basis.

1. Introduction

The glacial region of Hindu Kush–Karakoram–Himalaya (HKH) is often referred to as the 'water tower of Asia' as it stores large volumes of water in the form of ice and snow and releases water gradually over a long period during the dry seasons (Messerli and Ives, 1997). Because of observed rapid changes in the high-mountain cryosphere, projections about future developments of different components of the environmental system are of growing importance (Haeberli and Hohmann, 2008). According to the Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC, 2013), global temperature has risen by 0.85 °C since 1880, and surface warming may reach 3.7 °C between 2081 and 2100 if greenhouse gas emissions stay roughly on their current path. The changes in ice occurrences and corresponding impacts on physical high-mountain systems could be among the most directly visible signals of global warming. This is also one of the primary reasons why glacier observations have been used in climate system monitoring for many years (Haeberli, 1990; Wood, 1990). The retreat of glaciers observed in most regions of the Hindu Kush Himalaya (Ives et al., 2010; ICIMOD, 2011; Bolch et al., 2012) has given rise to the formation of numerous new glacial lakes and the expansion of existing ones (Komori, 2008; Rasul et al., 2011; Scherler et al., 2011). The number of glacial lakes has been reported to have increased in the majority of high-mountain areas at global level (e.g., Mergili et al., 2013; Emmer et al., 2014). This increase in lakes has been attributed to glacier retreat since the end of the Little Ice Age (e.g., Zemp et al., 2006; Haeberli et al., 2007). The rapid expansion of existing or newly created lakes indicates possible development of the glacial lakes outburst flood (GLOF) hazard (Richardson and Reynolds, 2000). The sudden increase in the frequency of glacial floods in recent years demands an in-depth investigation of the current/prevailing situation of glacial lakes in the context of changing climate in the Himalayan region. In mountainous regions where routine data collection is often hampered by highly inaccessible terrain and harsh climatic conditions, remote sensing based observations prove to be critical for the monitoring and assessment of cryosphere. Monitoring of glaciers and glacial lakes and assessment of GLOF impact downstream can be done quickly and rather reliably through RS data interpretation and analysis (Richardson and Reynolds, 2000; ICIMOD,

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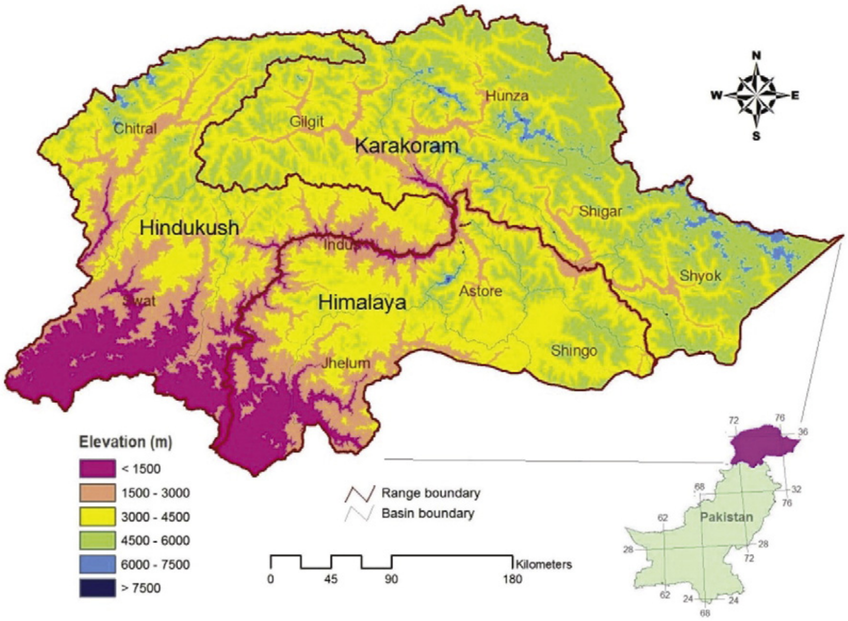

Fig. 1. Location of the Himalayan ranges and river basins in northern Pakistan.

2011; Ashraf et al., 2014). Gardelle et al. (2011) presented a regional assessment of glacial lake distribution and evolution in selected sites of the Hindu Kush–Himalaya using temporal Landsat satellite imageries of 1990, 2000, and 2009. As glaciers and glacial lakes are related to water resources and water-related natural hazards, they need to be monitored to assess their potential hazard and their resource value.

The primary focus of the present study is to evaluate the changing status of the glacial lakes by elevation in different subbasins of the HKH region using satellite remote sensing technique. Attempts have been made to explain the significance between different geophysical parameters of the lakes and elevation.

2. Geographic setting

The study area of the upper Indus basin comprising three Himalayan ranges (i.e. Hindu Kush, Karakoram, and Himalayas) stretches over 128,731 km^2 within longitudes 70°57′–77°52′ E and latitudes 33°52′–37°09′ N in northern Pakistan (Fig. 1). Elevation ranges from <1000 m in the south to >8500 m toward the northeast. About 28% of the Hindu Kush, 71% of the Karakoram, and 34% of the Himalaya areas lie above 4000 m elevation. Pleistocene to Recent glacial moraines, fluvioglacial deposits, loess, glacial lake deposits, and ancient rock terraces as well as fluvial terraces are commonly seen in the upper reaches of the Chitral, Swat, Hunza, and Indus valleys (Kazmi and Jan, 1997). The region has two distinct rainy periods, i.e., one in summer and another in winter. In addition to the influence of global weather systems, mountain climates are also influenced on the medium and local scale by elevation, valley orientation, aspect, and slope (Awan, 2002). The bulk of snowfall derives from westerlys during the winter half of the year (Hewitt et al., 1989). The deep and extensive bottoms are characterized by aridity, while the high mountains close by receive heavy precipitation, indicating high association of precipitation with extreme altitudinal variability. Over the last several decades, many GLOF events have occurred that resulted in devastating impact on the socioeconomics and natural resources of the Himalayan region (Ashraf et al., 2012). >90 outbursts from impoundments behind glacial ice dams have been identified in the HKH region. The 17 largest and most destructive were on the upper Indus River (Hewitt and Liu, 2010).

3. Data and methodology

Glacial lakes were delineated in different river basins of UIB (Fig. 1) using Landsat ETM plus images of 2001 and Landsat 8 OLI images of 2013 (Table 1). The RS analysis was supplemented by Google Earth imageries and the topographic maps published by the Survey of Pakistan on a 1:250,000 scale for this region. The Landsat 8 images are terrain corrected, having spatial resolution of 30 m for multispectral bands 1–7, 9, and 15 m for panchromatic band 8 and 100 m for Thermal Infrared Sensor (TIRS) bands 10–11 resampled to 30 m to match the multispectral bands. Digital elevation model (DEM) data of the 90-m Shuttle Radar Topography Mission (SRTM) was used to estimate the altitudinal characteristics of glacial lakes.

According to various elevation ranges, 3044 lakes were analyzed river basinwide in the three HKH ranges using multisensor remote

Table 1
Landsat imageries used for 2001 and 2013 glacial lake inventories of UIB.

Period	Scene id	Path/row	Type	Date
2001	L71148035_03520010721	148/35	Landsat 7 ETM+	21 Jul 2001
	L71148036_03620010518	148/36	Landsat 7 ETM+	28 May 2001
	L71149034_03420010930	149/34	Landsat 7 ETM+	30 Sep 2001
	L71149035_03520010930	149/35	Landsat 7 ETM+	30 Sep 2001
	L71149036_03620010930	149/36	Landsat 7 ETM+	30 Sep 2001
	L71150034_03420011007	150/34	Landsat 7 ETM+	7 Oct 2001
	L72150035_03520011007	150/35	Landsat 7 ETM+	7 Oct 2001
	L72150036_03620011007	150/36	Landsat 7 ETM+	7 Oct 2001
	L71151034_03420010928	151/34	Landsat 7 ETM+	28 Sep 2001
	L71151035_03520000909	151/35	Landsat 7 ETM+	9 Sep 2000
	L71151036_03620010928	151/36	Landsat 7 ETM+	28 Sep 2001
2013	LC81470352013268LGN00	147/35	Landsat 8 OLI	25 Sep 2013
	LC81480352013211LGN00	148/35	Landsat 8 OLI	30 Jul 2013
	LC81480362013195LGN00	148/36	Landsat 8 OLI	14 Jul 2013
	LC81490342013202LGN00	149/34	Landsat 8 OLI	21 Jul 2013
	LC81490352013282LGN00	149/35	Landsat 8 OLI	7 Sep 2013
	LC81490362013282LGN00	149/36	Landsat 8 OLI	9 Oct 2013
	LC81500342013209LGN00	150/34	Landsat 8 OLI	13 Jul 2013
	LC81500352013209LGN00	150/35	Landsat 8 OLI	28 Jul 2013
	LC81500362013257LGN00	150/36	Landsat 8 OLI	10 Jun 2013
	LC81510352013280LGN00	151/35	Landsat 8 OLI	7 Oct 2013
	LC81510362013184LGN00	151/36	Landsat 8 OLI	3 Jul 2013