*Proceedings of the Pakistan Academy of Sciences:*
*B. Life and Environmental Sciences* 54 (2): 125–132 (2017)

ISSN: 2518-4261 (print), ISSN 2518-427X (online)

Pakistan Academy of Sciences

Research Article

# Evaluating Glacial Lakes Behavior in the High Himalayan Ranges of Pakistan

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**Abstract:** The increase in frequency of glacial lakes outburst floods resulting from changing climatic conditions in the recent years demands understanding of the existing situation of glacial lakes behavior in the Hindu Kush-Karakoram-Himalaya (HKH) ranges of Pakistan. The dynamics of glacial lakes was studied in relation with physical characteristics of the lakes and their surrounding using base data generated through integration of geographic information system and remote sensing data of 2001 and 2013 periods. The relationship analysis between lake area and elevation revealed that large sized lakes may decrease in numbers with altitude. The expansion of lakes and elevation had shown a positive correlation for all three HKH ranges, significant ($P<0.05$) for Karakoram range only. The correlation between lake expansion and aspect was non-significant for all three ranges. Future studies based on high resolution image data coupled with in-situ information are required to explore specific behavior of glacial lakes under various influential factors in the high altitude Himalayan ranges.

**Keywords:** Glacial lakes, elevation, Hindu Kush, Karakoram, Himalaya

## 1. INTRODUCTION

There is a general shrinkage of glaciers under changing climate on a global scale [1-3]. The retreat of glaciers observed in most regions of the Hindu Kush-Himalaya [2, 4, 5] has given rise to the formation of numerous new glacial lakes and the expansion of existing ones [6, 7]. Gardelleet al. [8] presented a regional assessment of glacial lake distribution and evolution in selected sites of the Hindu Kush-Himalaya using temporal Landsat satellite imageries. Many glacial lakes are dammed by unstable moraines, as a result, they are susceptible to dam failures and once outburst floods occur, they may pose significant risk to downstream communities [9]. Sudden breach of the unstable moraine 'dams' of lakes results in discharges of huge amounts of water and debris-known as Glacial Lake Outburst Flood (GLOF). These glacial floods–usually generating from different altitudinal ranges of mountains, are receiving increased attention as a key climate change hazard in High Asia including Hindu Kush, Karakoram and Himalayan (HKH) mountains in Pakistan. The growing of few glacial lakes and occurrence of frequent glacial flood events in Chitral basin during the last 12 years [10] point toward serious impacts of climate change in the fragile glacial environment of the Hindu Kush range. There have occurred many GLOF events in the last several decades in the Himalayan region that resulted in devastating impact on the socio-economics and natural resources in the downstream [11]. The glacial floods are going to increase owing to growing warm conditions in future that demands investigation of glacial lakes dynamics in the high mountainous environment. The present study has been conducted to understand

Received, June 2016; Accepted, May 2017
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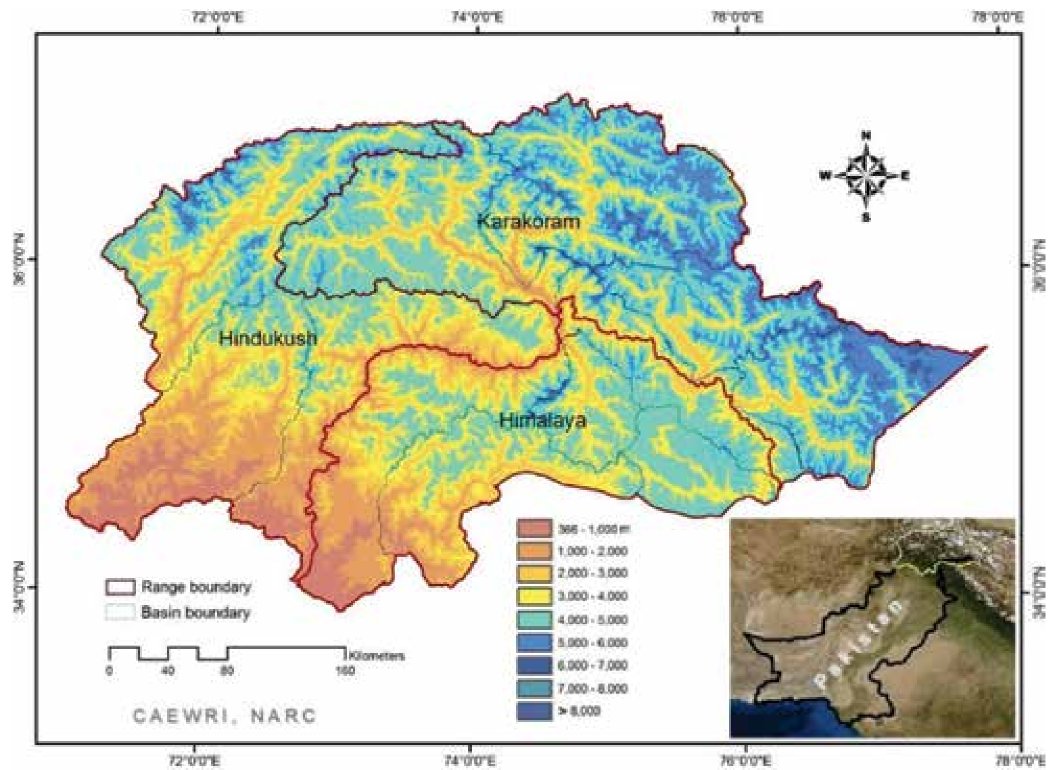


**Fig. 1.** Location of the three HKH ranges in northern Pakistan.

the relationship of glacial lakes dynamics in the HKH ranges of Pakistan through coupling remote sensing, geographic information system (GIS) and computational analysis.

The glacierized region of Hindu Kush-Karakoram-Himalaya (HKH) lies within longitudes 70º 57´ - 77º 52´ E and latitudes 33° 52´ - 37° 09´ N in Upper Indus basin (UIB) of Pakistan (Fig. 1). The study area stretched over 128,730 km$^2$in which 33% is contributed by the Hindu Kush, 40% by the Karakoram and the rest by the Himalaya range. About 5.3%, 22.6% and 3.1% areas in the Hindu Kush, Karakoram and Himalayas are glacierized [12].Generally the area exceeding 4,000 m upto about 8,500 m elevation contains most of the snow and glacial ice reserves of fresh water that nourishes the main Indus River system. The Indus irrigation system in Pakistan depends 50% or more on the runoff originating from snowmelt and glacial melt of the Hindu Kush, Karakoram, and Western Himalayas [13]. According to 2001 lake inventory, total of 2,420 glacial lakes were identified (area about 126 km$^2$) in the HKH ranges, out of which maximum lakes were contributed by the Karakoram (about 37%) followed by the Himalayas (34%) and the rest by the Hindu Kush range [12].

## 2. MATERIALS AND METHODS

In the present study, glacial-fed lakes that have their hydrologic connection with their mother glaciers were analyzed using temporal remote sensing data (2001-2013) of the HKH region. This category of lakes includes supra-glacial lakes and pro-glacial lakes: Supra-glacial lakes are developed on the surface of the glacier itself, growing by coalescence of small ponds, while pro-glacial lakes often grow downstream of steep glaciers, where water is collected behind former moraines [6, 14, 15].The lakes were delineated through on-screen digitization of the Landsat 7 ETM + (Enhanced Thematic Mapper plus) images of 2001 and Landsat-8 OLI (Operational Land Imager) images of 2013. The RS analysis was supplemented by Google Earth imageries and the topographic maps available on quarter million scale developed by Survey of Pakistan. The lakes were delineated sequentially in different river basins of the study area. Digital Elevation Model (DEM) data of Shuttle Radar Topography Mission (SRTM) 90m was used to estimate altitudinal characteristics of the glacial lakes. The spatial database of lakes like location coordinates, area and length was systematically developed for each river basin of the HKH ranges in GIS environment. The drainage direction of the glacial lake was specified as one of eight cardinal directions (N, NE, E, SE, S, SW, W, and NW) [16]. In geostatistical approach, attempts have been made to explain the cogency of tests of significance between different geophysical parameters by reference to hypothetical frequencies of possible statements [17]. Pearson coefficient '*p*' and correlation coefficient '*R*' were determined to measures the strength and direction of a linear relationship between different parameters.

## 3. RESULTS AND DISCUSSION

About 41% lakes (1255) were classified as glacial-fed lakes in the HKH ranges using remote sensing data of 2013 period –dominant in the Karakoram (702) followed by the Himalaya range (315), whereas the non-glacial fed lakes were maximum in the Himalayas (682) and least in the Hindu Kush range (484) (Fig. 2).Most of the large sized glacial-fed lakes lie in the Gilgit (Karakoram) and Swat basin (Hindu Kush) (Fig. 3). Three of such lakes e.g. Swat_gl 23, Gil_gl 418 and Gil_gl 156 exceed 1 km in length above 3500 m elevation (Table 1).

Among 617 selected lakes during 2001-2013 period, 149 belong to the Hindu Kush, 271 to the Karakoram and 197 to the Himalaya range. Their surface area ranged within 0.11-74.4 ha in the Hindu Kush, 0.2-85.5 ha in the Karakoram and 0.39-75.5 ha in the Himalaya range. They lie mainly within 2756-5166 m elevation –majority over 4000m elevation and toward northern aspect (i.e., NW, N, NE) in the three HKH ranges. In many cases, major/larger lakes are considered more susceptible to GLOF hazards [14]; however, surface area alone may not be a good indicator of GLOF hazards [18]. The rate of lake expansion in the Hindu Kush range varied between -0.44 to 0.99 ha $y^{-1}$. About 38.2% lakes indicated expansion, 54.4% shrinkage and the rest no change in area during 2001-2013in this range. In the Karakoram, expansion rate of lakes varied between -0.4 to 2.16 ha$y^{-1}$, about 49% lakes indicated expansion and 44.6% shrinkage in lake area. Similarly in the Himalayas, expansion rate of lakes varied between -1.1 and 0.69 ha $y^{-1}$, about 55.8% lakes indicated expansion, 34.5% shrinkage

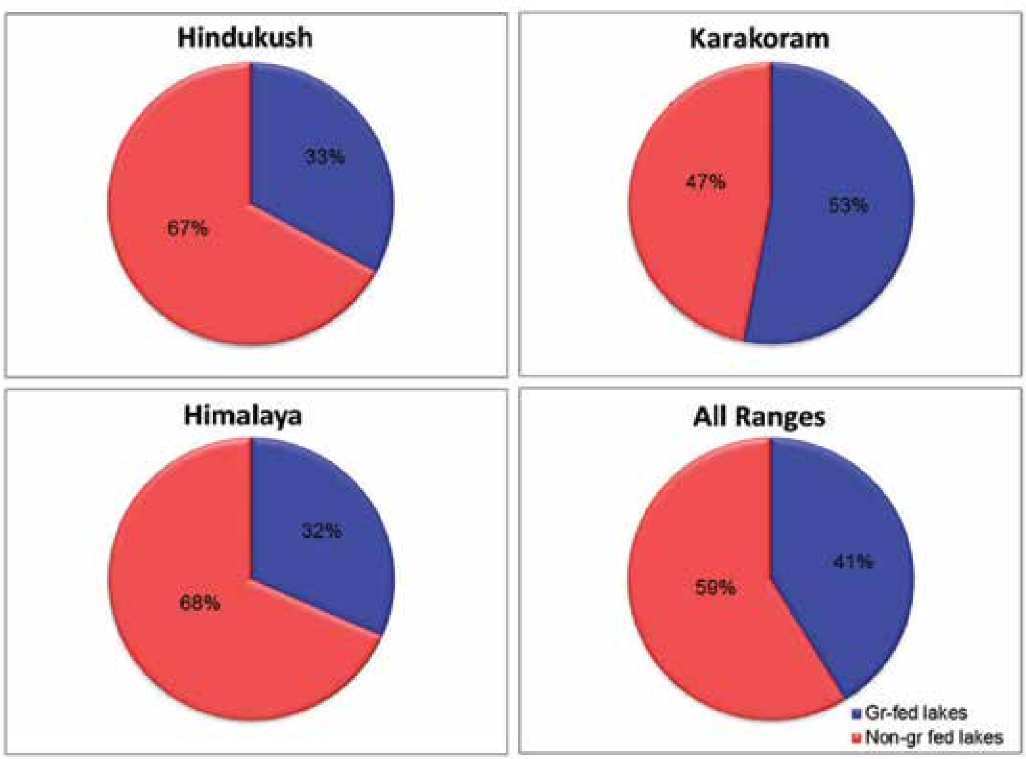


**Fig. 2.** Share of glacial-fed and non-glacial fed lakes in the HKH ranges.

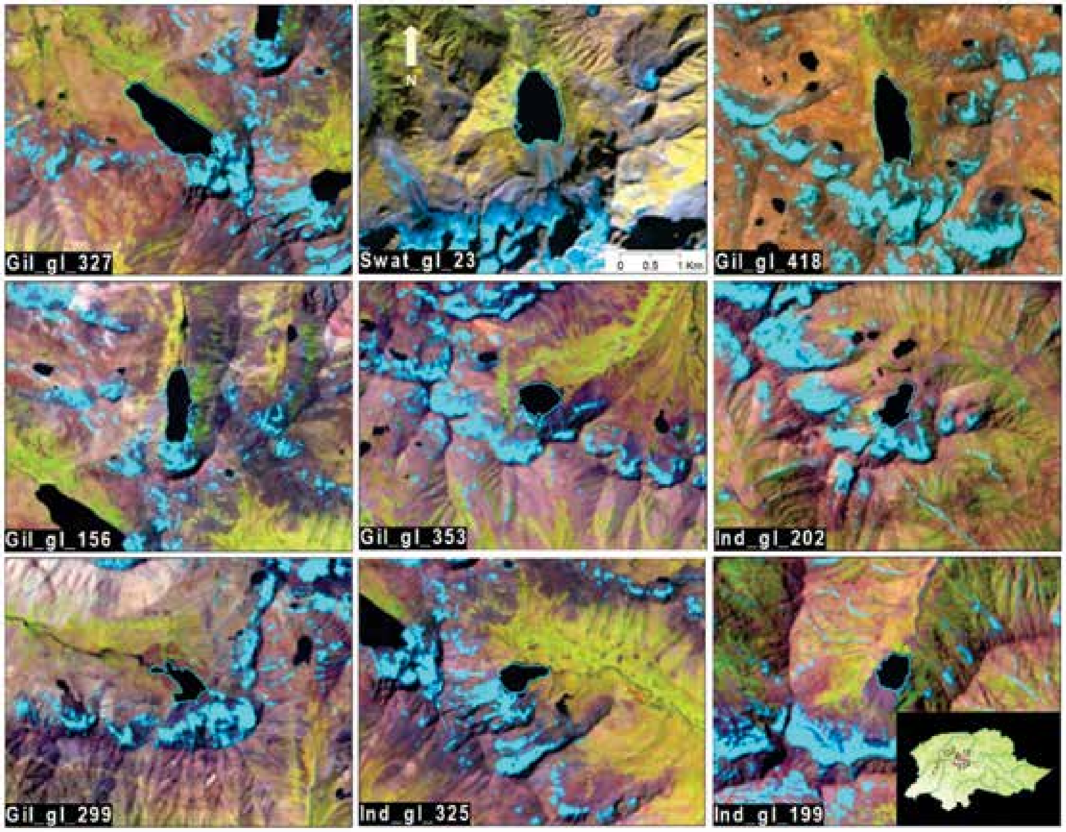


Fig. 3. Large sized glacial-fed lakes in the HKH basins (2013).

**Table 1.** Physical characteristics of some large glacial-fed lakes in the study area.

| Lake No. | Longitude | Latitude | Elevation (m) | Surface Area (km$^2$) | Length (m) |
|---|---|---|---|---|---|
| [1]Gil_gl_327 | 73 44' 43.846" E | 35 51' 52.572" N | 4143 | 0.855 | 650 |
| Swat_gl_23 | 72 20' 45.172" E | 35 22' 2.578" N | 3565 | 0.744 | 1,278 |
| Gil_gl_418 | 73 21' 52.990" E | 35 56' 43.009" N | 4149 | 0.71 | 1,600 |
| Gil_gl_156 | 73 45' 46.322" E | 35 52' 57.391" N | 4105 | 0.447 | 1,320 |
| Gil_gl_353 | 73 34' 34.740" E | 35 52' 48.372" N | 4059 | 0.292 | 304 |
| Ind_gl_202 | 73 15' 19.021" E | 35 44' 18.152" N | 4028 | 0.284 | 853 |
| Gil_gl_299 | 73 33' 25.896" E | 36 0' 38.735" N | 4245 | 0.272 | 143 |
| Ind_gl_325 | 73 46' 29.783" E | 35 51' 21.200" N | 3967 | 0.262 | 859 |
| Ind_gl_199 | 73 20' 38.437" E | 35 40' 30.848" N | 3425 | 0.256 | 563 |

[1]Gil= Gilgit; Ind= Indus

and the rest no change in area during the 12-year period. The rapid growth rate of lakes usually points toward possible development of the outburst flood hazard [15, 19-20].

The lake area, expansion rate of lakes and elevation have exhibited a mix relationship in different river basins of HKH ranges [21]. The lake area (in 2013) and elevation had shown a negative relationship for Hindu Kush, Karakoram and Himalayas, and collectively for all three ranges (Fig. 4). The situation indicates that large sized lakes may decrease in numbers with altitude or in other words, only small sized lakes can be found at higher altitudes in the HKH mountains. The relationship was non-significant ($P<0.05$) for the Karakoram range and appears to be stable for this range. The published research claims that the glaciers in Karakoram are less sensitive to warming than other glaciers in the world [22]. Because of extensive glacial coverage in this mountain range, mostly small sized lakes of supra-glacial type lie at a higher altitude than the glacier terminus [8]. In contrary to this, owing to less glacierized coverage and relatively higher warming conditions in the Hindu Kush and Himalaya ranges, lakes mostly of pro-glacial type expands in area near termini of the melting glaciers lying at lower altitudes. In the Himalaya region of Nepal and Bhutan, lakes are at the same altitude as the glacier termini, since they are in majority pro-glacial and are the exutory of the glacier catchments [8]. The correlation between lake expansion and elevation was positive for each HKH range and also collectively for all three ranges—the situation pointing toward increase in lake expansion with altitude in the HKH ranges (Fig. 5). The trends of this relation seem prominent for the Hindu Kush and Karakoram ranges as indicative from >0.1 correlation coefficient '*R*' values, significant at $p<0.05$ for Karakoram only. The correlation between lake expansion and lake area (2013) was positive for the Karakoram and the Himalayas while it was negative for the Hindu Kush range (Fig. 6). Overall this relationship was positive for whole three HKH ranges. In fact this diverse relationship of lake expansion with respect to lake size in different ranges occurred generally because of variations in lakes having area >10 ha or so and such lakes are not extensive in numbers. In other words, majority of small sized lakes exhibited no clear relation with their expansion rates in these ranges. According to Gardelle et al. [8], the expansion rate of supra-glacial lakes is always higher than the one of pro-glacial lakes which are not in contact with the glacier termini and contrary to this, pro-glacial lakes in contact with a glacier have a similar (or even higher) expansion rate than supra-glacial lakes).It seems that pro-glacial lakes in the Hindu Kush are away from the termini of their associated glaciers so are growing slowly as compared to those of Himalayas and Karakoram where the glaciers are in contact with their source glaciers. The correlation between expansion rate of lake and aspect, i.e., flow direction or orientation of lake, was non-significant for all three HKH ranges. As there can be local differences, diverse behavior of the glaciers exists in the Himalayan region e.g. glaciers are receding in the Himalayas and some are advancing as in the Karakoram [23-24], therefore

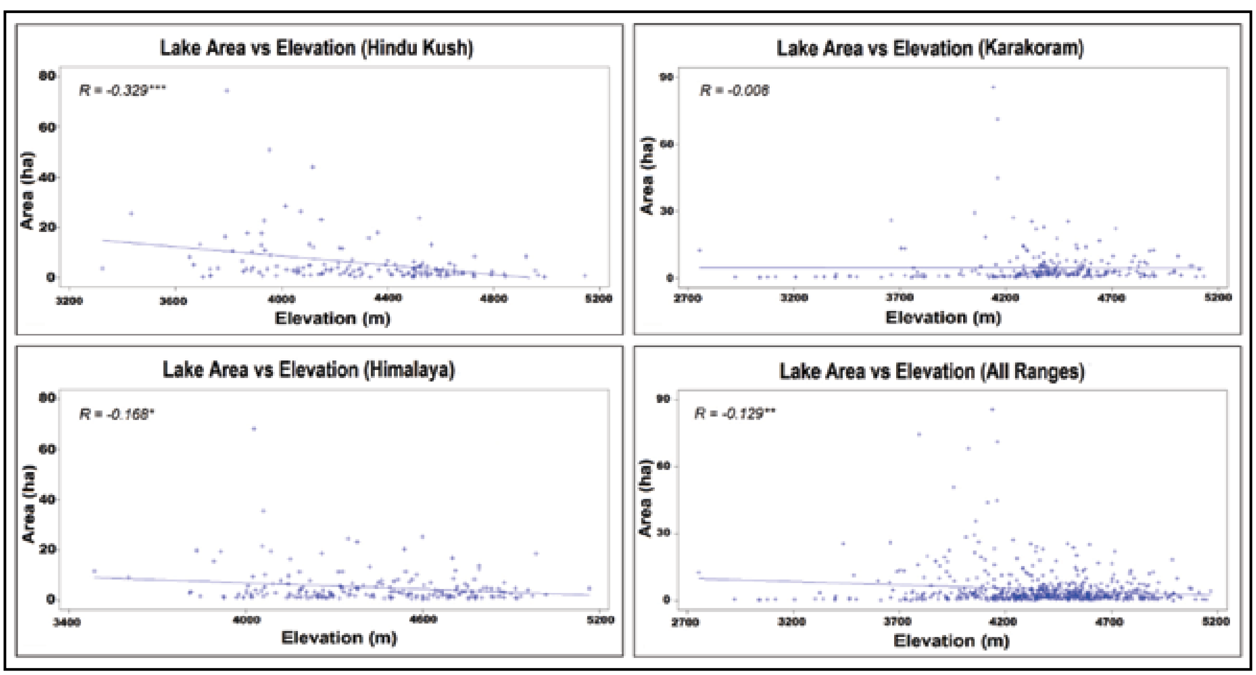


**Fig. 4.** Correlation of lake area and elevation in the three HKH ranges

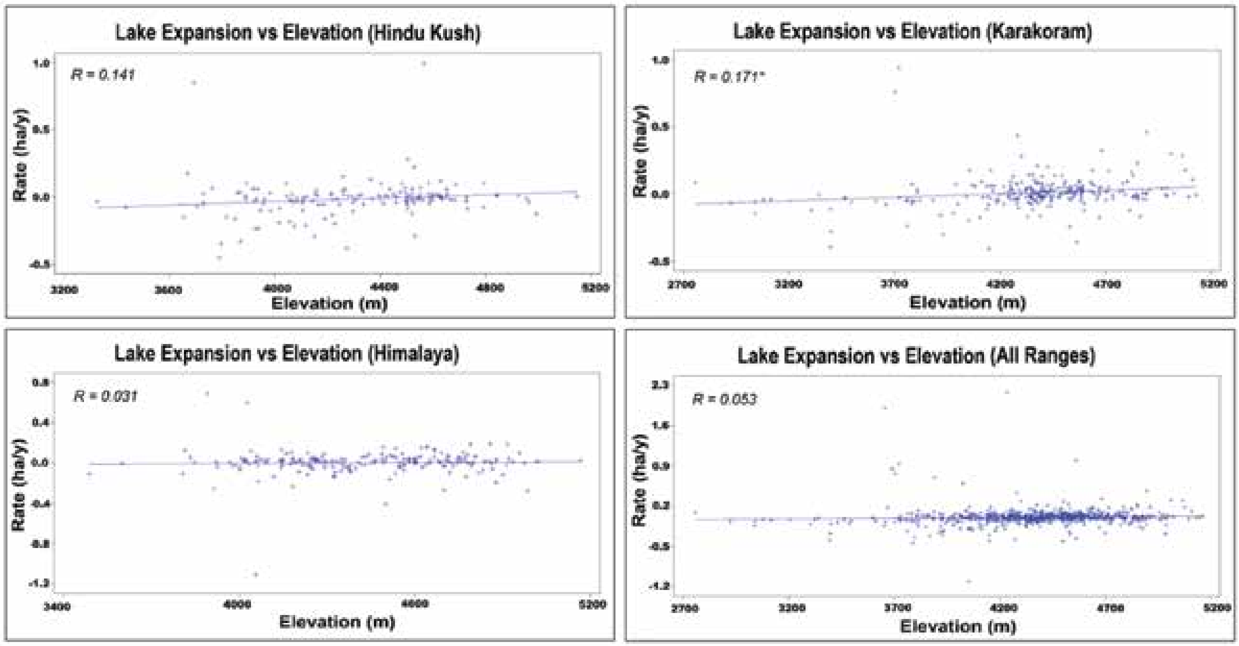


**Fig. 5.** Scatterplots of lake expansion vs. elevation in the HKH ranges.

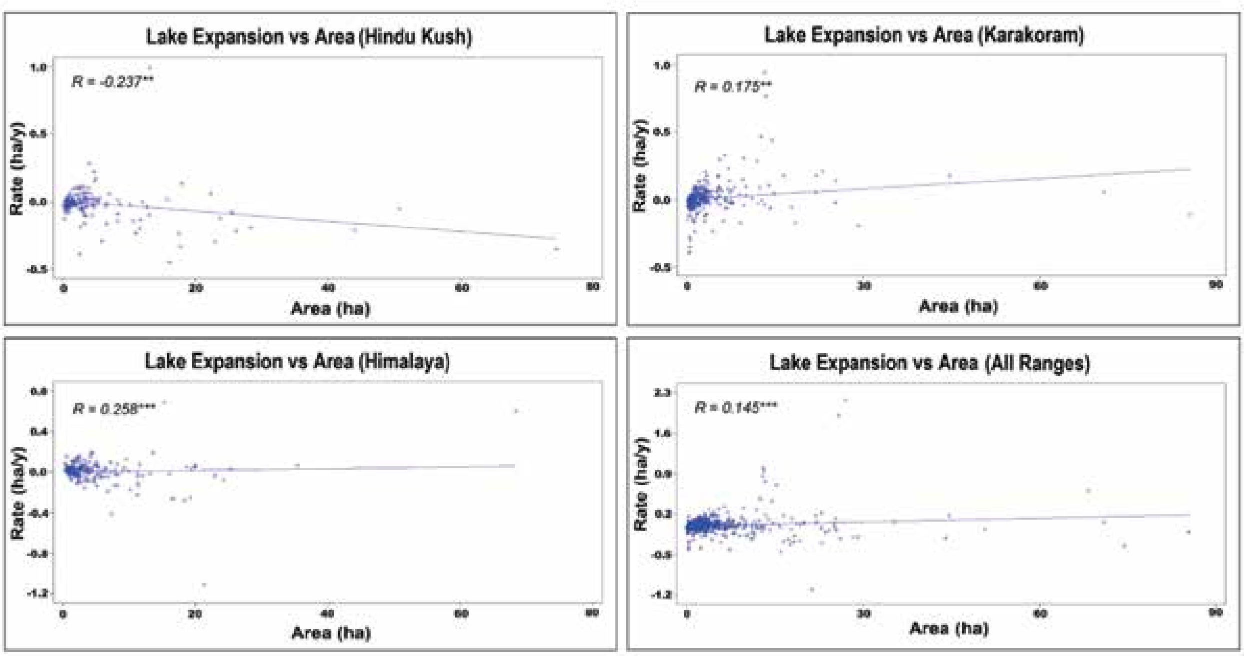


**Fig. 6**. Scatterplots of lake expansion vs. lake area in the HKH ranges.

the influence of climate on glacial lakes cannot solely account for lake variations [8].

## 4. CONCLUSIONS

The relationship analysis between lake area and elevation revealed that large sized lakes may decrease in numbers with altitude in the Himalayan ranges. The lake expansion and elevation indicated a positive correlation in the three HKH ranges, significant ($P<0.05$) for Karakoram range only. The correlation between lake expansion and aspect was non-significant for all three mountain ranges. Future studies based on high resolution image data coupled with in-situ information can provide in-depth insight of specific behavior of glacial lakes under various influential factors in the high altitude Himalayan ranges. The glaciers and glacial lakes need to be monitored to assess both their water resource potential as well as associated hazards in context of possible rise in warming conditions in future.

## 5. ACKNOWLEDGMENTS

The work was executed with the support of International Centre for Integrated Mountain Development (ICIMOD), Pakistan Meteorological Department (PMD) and GIS team of Climate Change, Alternate Energy and Water Resources Institute of National Agricultural Research Centre (NARC), Islamabad, which is highly acknowledged. We appreciate the anonymous reviewers and the editor for rendering valuable input for improving quality of this paper.

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