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RESEARCH ARTICLE

Emerging Role of Remote Sensing For Monitoring Glacial and Surface Water Changes in Nepal

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Abstract

Objectives: This study showcases the use of remote sensing technology for monitoring evolutionary patterns of mountain lakes under climate stress in the mid-hills and hard to reach glacial terrains, ranging about 650-8055 meters above the mean sea level in the Gandaki region of Nepal. **Method:** Spatiotemporal trends were analyzed from Landsat (Thematic Mapper (TM), Enhanced Thematic Mapper (ETM +) and Operational Land Imager (1988 to 2018) satellite images using Normalized Difference Water Index (NDWI). Surface water content for three mountain glacial lakes (Kapuche, Dona and Tilicho) and two mid-hill lakes (Phewa and Begnas) were evaluated. **Findings:** Longitudinal data analysis of NDWI surface water pixels between 1988 and 2018 showed contrasting features in the two study terrains – the glacial lakes have expanded (NDWI for Dona and Kapuche increased by 29% and 182% respectively). Over the same period, the mid-hill lakes have receded (NDWI for Phewa and Begnas reduced by 2.05 % and 0.85 % respectively). On the other hand, the annual temperature increased 0.158ºC in the glacial region over the same period. The warmer temperature was considered the driving factor for the melting of glaciers, resulting in increased runoff. The increased surface water in the glacial lakes is attributed mainly to climate change impacts on glacier thickness reduction, whereas the diminishing lake area in the mid-hill belt is attributed mainly to sediment disposition and evaporative losses. **Novelty:** The study demonstrates the potential global application of remote sensing technology for in situ pervasive monitoring of the spatiotemporal climate change impacts on topographically complex landscapes. Our findings pave the way for the formulation of appropriate policy measures for sustainable management of land resources to reduce the drastic impact on surface water changes.

Keywords: Glacier Lakes and Surface Water; Landsat; NDWI; Climate Change; Complex Landscape of Nepal

1 Introduction

Retreating and thinning of glaciers are clear indicators of the impact of climate change. This transformation has profound implications for ice-sheets in Antarctica and Greenland, and high mountains region of Asia, including Karakoram and the Hindu Kush Himalayan belts [1,2]. The monitoring of glacial lakes has gained significant attention due to the increasing impacts of climate change, which have accelerated glacier mass loss and expanded glacial lake sizes in high-altitude Himalayan region [3].

As glaciers, lakes and snow cover are the important sources of global water resources and a sustainable world environment, monitoring them is highly imperative [4,5]. In situ monitoring of the glacial lakes is difficult due to their complex topography, combined with erratic weather patterns of the high Himalayan region. Remote sensing (RS) combined with dedicated geospatial analysis using GIS have proven to be cost effective and viable tools for exploring such landscapes [6,7]. Remote sensing satellite data is capable of routine observations of large scale spatiotemporal changes in the ecosystem [8]. Satellite imagery has already been extensively applied over the past few decades to monitor patterns of glacier shrinkage [9]. Application of spatial analysis tools using time-series remote sensing satellite images have reported diverse monitoring capabilities – for example, glacial area extraction [10]; land use change and soil erosion [11]. Numerous methods have been applied for the extraction of surface water and glaciers, such as - applied automated glacier extraction index (AGEI) [12]; Normalized Difference Water Index (NDWI) [10]; Modified Difference Water Index (MNDWI) [13] ; Normalized Difference Snow Index (NDSI) [14]; Water-resistant Snow Index (WSI) [15].

Recent advancements in remote sensing technology have significantly improved the monitoring of glacial lakes in Nepal, leading to improved assessment and management of Glacial Lake Outburst Floods (GLOFs) [6]. High-resolution satellite imagery from systems like Gaofen, Sentinel and Landsat, alongside synthetic aperture radar (SAR), allows for detailed and frequent monitoring of glacial lakes, even under cloud cover environment [16,17]. The application of deep learning/AI techniques and deep convolutional neural network has further refined the extraction and mapping of glacial lakes [17,18]. New frameworks integrating remote sensing data with GIS indeed enhance hazard models and risk assessments significantly [19,20]. Studies from 2000 to 2020 reveal a notable increase in glacial lake area and number, emphasizing the dynamic changes and growing GLOF risks [17,20]. Previous studies have reported rapid expansion of the glacial lake [2,5] resulting in serious problems for downstream communities of mountainous regions [21]. Advancements in technology play a pivotal role in supporting policy development and disaster management, crucial in the context of mitigating the impacts of climate change on these sensitive environments [22,23]. However, gaps remain, including the need for long-term monitoring, comprehensive risk models, and a better understanding of climate impacts. Future research should focus on integrating multi-source data, improving predictive analytics, and enhancing international collaboration to address these issues [20,24,25].

As mountain lakes in the Himalayan region are at the nexus of climate change and anthropogenic pressures, there is a growing need for additional research on the evolution of a pervasive monitoring system to aid effective policy formulation for the sustenance of lake ecosystems. This is essential for the long-term environmental protection of the ecologically sensitive Himalayan region while ensuring sustainable human-centric land use development. Several studies [2,5,7,20,21,26–29] have monitored the changing glacier lakes and water cover changes of Himalayan and other clusters. Mainly, previous studies have primarily focused on macro-scale assessments of glacial lake dynamics, often overlooking detailed spatial and temporal variations across diverse topographies [30] . Unlike traditional methods that rely on limited temporal data or lack comprehensive spatial analyses [23], our approach utilizes three decades of Landsat imagery (1988-2018), coupled with the Normalized Difference Water Index (NDWI). This methodological framework enables precise quantification of surface water changes and facilitates the identification of potential GLOF hazards. Comparative analysis with existing literature underscores our study's unique contributions. While previous research has highlighted general trends in glacial lake expansion, our study provides detailed insights into localized variations and their implications for environmental management [31].

In this study, we have applied remote sensing technology for monitoring evolutionary patterns of mountain lakes in relation to the impacts of climate change. The analysis applied Normalize Difference Water Index (NDWI) as a metric to identify the alteration in the expansion of glacial lake using longitudinal time-series Landsat images. The study correlated the trends in NDWI with temperature data to specifically examine the effect of climate change on altered surface water patterns in hard-to-reach glacial terrains of the Gandaki region.

2 Methodology

2.1 Case Study Description

The study area is located in the Gandaki Province of Nepal (28° 14' to 28° 98' northern latitude and 83° 66' to 84°82' eastern longitude), comprising mid-hill and mountain regions of the Gandaki river basin (Figure 1). The area spans across low elevation valleys in the south to high elevation snow-capped mountain ranges in the north, ranging between 650-8055 meters with unique topographical features. However, the glaciers in the north and the lakes in the mid-hills have been harshly impacted by the changing climatic condition, threatening the sustenance of the natural environment and its ecosystem services in the last few decades [32]. It has made the region highly vulnerable in terms of multiple disasters such as GLOF, landslides, floods and snow and water induced disasters. The lower part comprises of two mid-hill lakes, including Begnas (elevation: about 650m) and Phewa (elevation: about 742m), Kapuche is one of the youngest lower altitude glacial lakes of Nepal (elevation: about 2546m); Dona is oval in shape (elevation: about 4250m), Tilicho lies in the higher altitudes (elevation: about 4,919m). All these places hold remarkable touristic significance.

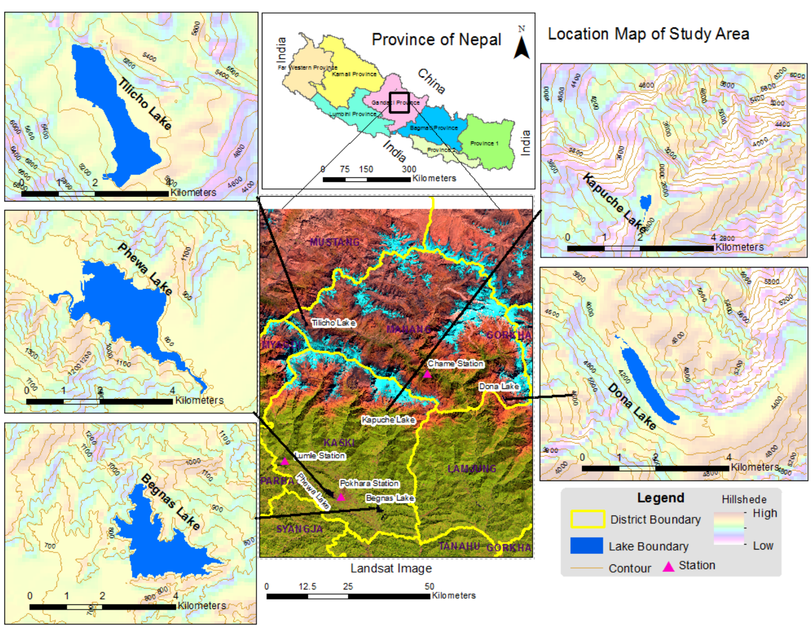

Fig 1. Case study site map showing the location of all the five lakes

2.2 Data acquisition and analysis

For the evaluation of surface water and snow/glacier condition of the study area, maximum cloud free Landsat time series level 1 data (Landsat 5 TM: hereafter Thematic Mapper; Landsat 7 Enhanced Thematic Mapper Plus (hereafter ETM+), Landsat 8 Operational Land Imager (hereafter OLI) were acquired for the years 1988 and 2018 from the US Geological Survey (USGS) website (https://earthexplorer.usgs.gov) (Table 1). Performance of Landsat Level 1 and Level 2 data (ETM+ and OLI) was conducted by Pinto et al [33]. The following image collection criteria were applied in order to improve the accuracy of the analysis: (1) maximum cloud free satellite images of study area (typically < 10 % of the image); (2) minimum snow content (between October – December). All the images were registered and their accuracies were verified considering <0.5 pixel RMS errors. The digital number (DN) of Landsat Level 1 data values of all images were converted into radiance and further atmospheric corrections of all the images were conducted using ENVI software and map was prepared in ARC GIS. In addition, all the images and Shuttle Rader Topography Mission (SRTM) digital elevation model (DEM) with 30m resolution were projected in UTM Zone 45°N for the extraction of water content. Furthermore, high spatial resolution images from Google Earth (http://earth.google.com) of multiple dates, topographical maps published by the Survey Department, Government of Nepal, 1998 (scale 1:25000) [34] and Glacier data developed by The International Centre for Integrated Mountain Development (ICIMOD) 2010 (https://servir.icimod.org/datasets), were collected for accuracy assessment.

Table 1. Time series Landsat 5, 7 and 8 imagery applied (Path/Row 142/040)

Year	**1988**	**1991**	**1995**	**1999**	**2002**	**2005**	**2009**	**2013**	**2016**	**2018**
Months	19-Oct	12-Oct	8-Nov	13-Dec	3-Nov	18-Oct	29-Oct	24-Oct	1-Nov	7-Nov
Sensor	TM	TM	TM	TM	ETM	TM	TM	OLI	OLI	OLI

2.3 Feature extraction

Landsat imageries are widely used data sources for calculating water indices [10]. Delineation of the water surfaces/lakes was conducted using NDWI [10]; and the mean pixel value was evaluated in GIS NDWI a satellite remote sensing method used to delineate water bodies and assess water content in vegetation and soils. It plays a critical role in hydrological studies (e.g. waterbodies delineation), environmental monitoring, land use change, drought assessment, glacial lake outburst flood (GLOF) monitoring [4,10,21]. NDWI has been considered superior to other methods because of its sensitivity to water features, simplicity of use and it uses commonly available bands in most of the satellite sensors. Hence, it is more popular among the remote sensing researchers. Equation (1) and Equation (2) show how NDWI is calculated from the remote sensing data derived from the sensors TM and OLI of Landsat imageries.

$$NDWI^{TM} = \frac{Blue\,(Band\ 1) - SWIR\,(Band\ 5)}{Blue\,(Band\ 1) + SWIR\,(Band\ 5)} \tag{1}$$

$$NDWI^{OLI} = \frac{Blue(Band\ 2) - SWIR_1(Band\ 6)}{Blue\,(Band\ 2) + SWIR_1(Band\ 6)} \tag{2}$$

Our study region extended from subtropical climatic zone of mid-hill region to the high-altitude alpine/tundra region. In order to characterize the distinct features of the water bodies in these two regions (all-time water surfaces in the mid-hill regions and the glacial lakes in the high-altitude Himalayan zones), extraction of water was conducted using atmospheric corrected Landsat TM, ETM + and OLI images. As a first step, cloud free Google Earth images for 2017 were used for the evaluation of lake extent, mainly boundary delineation of the water area of all the five lakes [12]. Thereafter, positive water pixel value (0 to 1) was evaluated using NDWI. The NDWI value ranges between -0.1 and +1 at the water level, high value representing in positive value close to the water value and negative value representing bare soil, vegetation and other natural features. The topographical variance of the entire region map was prepared and presented for all the maps (outputs provided later in the result section). The extracted pixels were classified into two different parts, water and non-water, according to their respective thresholds. The mean pixel value of all lake boundary was presented in the result section. For the water body extraction process, initially, the positive threshold values were set for all years' images and Blue and Short wave Infrared (SWIR) band was applied, following [10]. During the analysis, some mixed values were observed in remote sensing satellite data which were further verified during the accuracy assessment. A similar type of threshold value could not provide a higher performance for the water extraction in large area [4] and flexibility was applied for threshold setting.

2.4 Collection of Metrological data and analysis

Longitudinal metrological data between 1988-2017 was acquired from three recording stations – Chame (altitude 2680m), Lumle (altitude 1740m) and Jomsom (altitude 2744m) (source: Department of Hydrology and Meteorology, Government of Nepal). These were used to estimate the maximum and the minimum temperatures in the studied glacial lake area and water level was calculated. This station data was used for the evaluation of annual change in temperature and to examine the relation between water level change scenarios and the relative change in temperature.

2.5 Accuracy assessment

During the extraction of water content from satellite imagery analysis, some mixed pixels create uncertainty[10] in the water content estimate. This was overcome using true water boundaries, digitized using high resolution Google Earth images and water extraction results using Landsat images. The error number of classified data was tested based on the accuracy model and defined sample points. Water content and non-water content error values were evaluated for each pixel and sub pixel accuracy in the classified images. The maximum number of sample points were well distributed in two categories - main water content and non-water content (mixed area). The accuracy assessment factors pose challenges due to the complex topography and uncertainty was determined by image resolution and mountain shadows, cloud coverages[31]. In this study the overall accuracy, producer accuracy and user accuracy were evaluated for each year's indices. Further validation was conducted by using high resolution Google Earth images and glacial lake inventory data for 2010, developed by ICIMOD (https://servir.icimod.org/datasets).

3 Results and Discussion

3.1 Water content extraction and analysis

Our analysis found the following peculiar patterns of changes in NDWI values for the studied lakes – increment for the two glacial lakes (Dona and Kapuche); reduction for the two mid-hill lakes (Phewa and Begnas); almost constant for Tilicho. We have derived NDWI values over the time span of 30 years i.e. 1988 to 2018 AD. Based on the NDWI values, two mid-hill lakes namely Phewa and Begnas showed decreasing trend. In 1988, Phewa Lake sum-up to 4399 pixels numbers while Begnas Lake constituted 3168 pixels. These values decreased to 4309 and 3141 pixels respectively in 2018. As per our analysis, the overall (from 1988 to 2018) decreasing rate of water pixels, for mid-hill Phewa and Begnas Lake is 2.05 % and 0.85 % respectively. Up to the year 1999, both of the mid-hill lakes decreased at a higher rate i.e. 3.6 % and 1.12 % respectively. However, based on the NDWI water pixel values, the glacial Kapuche and Dona Lake expanded from 38 to 108 and from 755 to 1020 pixels respectively between 1988 to 1999. The annual growth rate of Kapuche and Dona was 124.29% and 0.79% respectively between 2002-2009. Overall, both the glacial lakes shows and expansion trend from 1988 to 2018. The Kapuche was barely noticeable until 2005, increased after 2005 and reached 107 pixel value in 2018. The increasing trend of Tilicho Lake was observed mainly from 1988 to 1999 and thereafter it stabilized, with relatively constant overall NDWI over the study period (Table 1).

Table 2. Total water pixels inside the boundary of the selected five lakes

Year	Phewa Lake	Begnas Lake	Tilicho Lake	Kapuche Lake	Dona Lake
1988	4399	3168	3775	38	755
1991	4336	3148	3722	92	801
1995	4329	3176	3747	72	872
1999	4238	3130	3780	108	1020
2002	4280	3138	3728	10	944
2005	4300	3134	3739	0	987
2009	4261	3136	3776	97	996
2013	4213	3075	3742	108	973
2016	4341	3112	3699	107	975
2018	4309	3141	3670	107	974

*Dona Lake also called Thulagi lake

We further evaluated the NDWI mean values for the five lakes and the following peculiar patterns of change in NDWI values for the studied lakes were found – reduction for the two mid-hill lakes (Begnas and Phewa); increment for the two glacial lakes

(Dona and Kapuche); almost constant for Tilicho. The mean value for Phewa lake was 0.82 in 1988 and it decreased by 0.54 and the decreasing trend was increased after 2016. The estimated NDWI in 1988 and 2018 respectively for Begnas was 0.77 and 0.57. Interestingly, Kapuche Lake became prominent after 2009 but its NDWI had been consistently increasing from 0.51 in 2009, reaching 0.63 by 2018. Tilicho Lake showed a 0.94 mean pixel value in 1988 and a relatively constant NDWI over the study period and reduced by 0.82 in 2018. NDWI mean values for Dona Lake increased from 0.56 in 1988 to 0.79 in 2018 (Figures 2 and 3). Overall trends showed an increasing water area in the upper Himalayan region, largely associated with temperature rise attributed to the increasing impact of climate change on the melting of the glaciers. On the other hand, decreasing water levels in the Mid-hill lakes were considered to be impacted directly by anthropogenic factors. Time-series mean pixel values (NDWI) for extracted water and snow/resources mean values are presented in Appendix 1, while all individual NDWI maps between 1988 and 2018 are presented in Appendix 2.

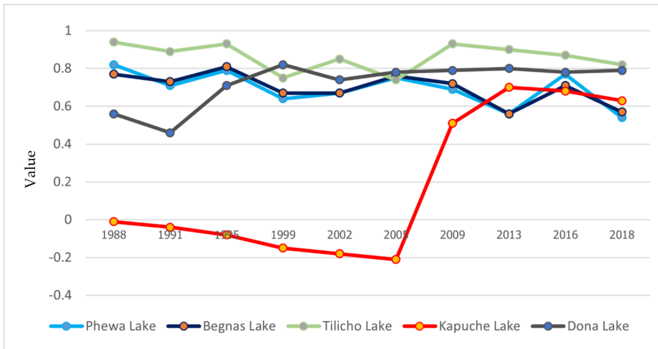

Fig 2. Time-series graph for the NDWI mean pixel values in each extracted water and snow/resources

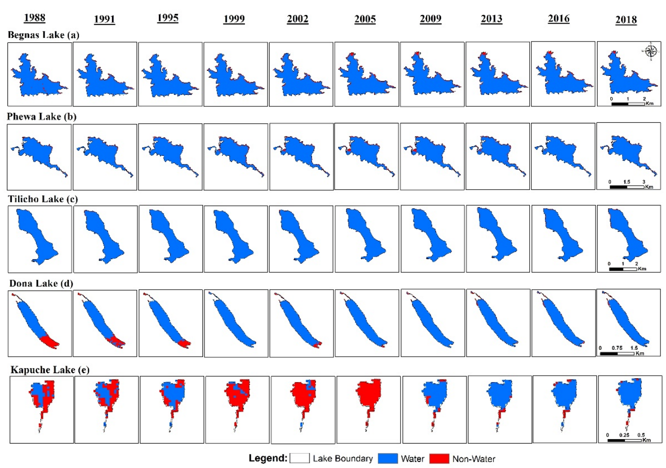

Fig 3. Water content caps of selected five lakes NDWI: (a) Begnas Lake, (b) Phewa Lake, (c) Tilicho Lake, (d) Dona Lake, (e) Kapuche Lake

3.2 Climate Change analysis

The temperature trends of both the upper Himalayan and the mid-hill regions were evaluated using the data from the three weather stations in the Basin – Chame (altitude 2680m amsl); Lumle (altitude 1740m amsl); Pokhara (Airport) (altitude 827 m amsl), all showed an increasing trend of air temperature (DHM) (Appendix3). We have evaluated the correlation of climate change and NDWI for Phewa lake and Begnasha like with Pokhara station, Chame station for three lakes i.e Kapuche, Dona and Tilicho. Our temperature analysis of 29 years data (1988 to 2017) clearly shows the annual mean temperature is raised by 0.0123 degree C and the rainfall is reduced by 49.856 mm per year.

We have studied the relationship between mean NDWI pixels values and the average annual temperature of all the five water bodies of the study area. Among them, the lakes at higher altitude regions (Kapuche and Dona lakes) showed a positive correlation between mean NDWI pixels values and the average annual temperature, whereas the lakes in the mid-hill regions (Begnas and Phewa lakes) showed a negative correlation between NDWI and the average annual temperature. Tilicho Lake, which is also located at a higher altitude region also showed a negative correlation. This correlation supports the increasing water content in the Kapuche lake and Dona Lake due to climate change impact, more specifically the increasing trend of average atmospheric temperature which is the result of global warming caused by several anthropogenic activities. Our analysis of 29 years temperature data (1988 to 2017) clearly shows a rise in the annual mean temperature by 0.0123 degree C over this period. Based on the correlation analysis between average annual temperature and NDWI mean pixel values for the five lakes; Dona Lake and Kapuche lakes have positive correlation having correlation coefficient of 0.356 (R square value 0.492) and 0.356 (R-square value 0.127) respectively (Figure 4**a**-**b**). Similarly, the correlation of the other three lakes (i.e. Phewa, Begnas and Tilicho) showed a negative relationship with correlation coefficient values at -0.2327 (R-square 0.054, -0.3795 (R-square 0.047, - 0.249 (R-square 0.062)) respectively among mean NDWI pixels values and mean annual temperatures (Figure 4 **c**-**e**).

Another study[35] which is related to land use land cover change, specifically urban expansion and its future prediction, shows the remarkable expansion of built up areas that were sourced from cultivated lands. Such expansion of urbanization is also linked to higher population growth, exploitation of natural resources, encroachment to water bodies (lakes), etc. The decreased water content pixels in the Phewa lake and Begnas lake are the well evidence examples.

This result supports the output we derived from NDWI analysis of Dona Lake and Kapuche lake where the snow/ice covered lake areas are decreased and the water content (water cover area) of lake increased. Hence, the impact of anthropogenic influences on land use land cover change and the changes in the climatic patterns (increasing trend of average temperature) on water resources is well supported by this study.

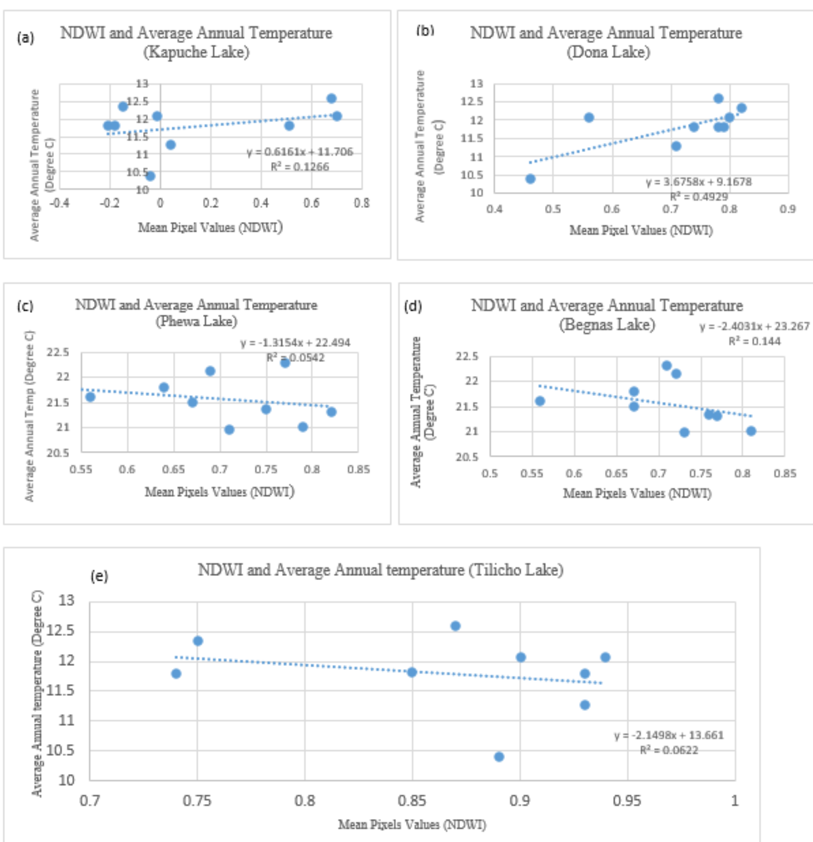

Fig 4. Relationship between Mean annual Temperature and Mean Pixel values (NDWI) in five lakes of study area (a) Kapuche Lake (b) Dona Lake (c) Phewa lake (d) Begnas Lake (e) Tilicho Lake

Based on the analysis, the extent of water content is found to be increasing in glacial lakes and reducing in the mid-hill lakes. Particularly, the increased water surface in the higher altitude zones (Dona Lake and Kapuche Lake) and the reduced water surface area in the lower altitude zones (Phewa lake and Begnas lake) are the clear evidences of climate change impacts due to increasing temperature trends.

NDWI index showed contrasting trends in water resources levels – an increment in high mountain areas and a reduction in the downstream region. This corroborates with a previous study indicating high mountain region of Asia, specifically the Himalayan region of Nepal, are being drastically impacted due to climate associated change [36]; large masses of glacier and snow have been melting in Nepal due to climate change impact [25]. The average rate of temperature in the mountain region had been rising, implicating potential for GLOFs leading to loss of life and properties in the downstream regions [37].

The temperature trends of both the high-altitude and the mid-hill zones, were monitored at the three weather stations in the Gandaki region – Chame, altitude 2680m amsl; Lumle, altitude 1740m amsl; Pokhara (Airport), altitude 827 m amsl, all show that air temperature are on the rise, more specifically due to the temperature dynamics over the last thirty years (DHM) (Appendix 5). The corresponding impacts of the maximum and minimum temperature rises on the glaciers and water surface are direct and significant. Increased temperature at the higher altitude zones [38] causes the melting of glaciers, ice and snow, which ultimately increased the free water surface in glaciers lakes and waterbodies of the region. Similar to our findings, increasing numbers of glacial lakes and expanded lake areas are witnessed in the Himalayan region [5,7,23,25]. According to a previous study, the total area of glacial Lake expanded by 17.11% from 1990 to 2010 [39] and our study demonstrated a similar trend in this period. And the similar trend was observed in Imja Tsho lakes the total volume of this lake increased about 140% within two decades between 1992 and 2012 and the area of Thulagi (Dona) also increased after 1995 [28].

Moreover, the climate change impact is evidenced by the increased water pixels of the studied lakes. This might be because of the shrinking snow fed area and loss of water through evaporation of the Tilicho Lake in the later decade. However, influences of the increased trend of mean annual temperature due to climate change is clearly evident in Dona Lake and Kapuche lake where the strong positive correlations between mean water pixel values and temperature suggested the increased glacier melt leads to the increased water surface of the lake area. Hence, these evidences can strongly support the impact of climate change on glaciers melt and increased water surface areas in high altitude regions of Nepal, which is associated with the increased risk of GLOFs. Imja glaciers 34 m a^{-1} and Lumding 42 m a^{-1} retreated from 1976 to 2000 with acceleration in the rates, reaching up to 74 m a^{-1} for both [40]. The surface area of small supraglacial lakes in Nepal during 1950s/2060s have been increasing and have expanded within 1.33 sq.km and 1.79 sq.km respectively by 2017 [41].

In contrast, in the middle and lower altitude zones, the increased temperature decreases the water surfaces (lake and water bodies) by excessive evaporation of water. In addition, a combination of natural and anthropogenic factors can be associated with the reduction in Phewa lake, such as sedimentation of Harpan khola in the lake, invasive growth of water hyacinth, landslides in the aftermath of the Gorkha earthquake followed by the monsoonal floods and urbanization (e.g. infrastructure development activities- in particular, rapid mushrooming of lake-shore restaurants on its eastern shore [32]. Similarly, in the case of Begnas lake too, as a consequence of climatic variation, several streams have dried up and surface water in the lakes has been declining. The impact of anthropogenic influences on land use land cover change and the changes in the climatic patterns (increasing trend of average temperature) on water resources is well supported by this study. Additionally, land cover change, urbanization and multi hazard risks impacted the natural resources [42] of mid hill. If the same trend continues, it is predicted that Phewa Lake will lose its storage capacity by 80% in the next 110 – 347 years because of the earthy material or sediments deposition [32]. Thus, we have successfully demonstrated the potential role of remote sensing as a tool for monitoring glacial lake expansion under climate change impact at a meso-to-macro scale in vulnerable, hard-to-reach mountain regions.

One limitation of the analysis identified in this study is that only medium resolution Landsat satellite images were used for the extraction of water content for all the five lakes studied. There may be potential uncertainty in the determination of the actual portion of glacial lakes and water extraction accuracy using NDWI [4]. We are aware this uncertainty is a manifestation of several factors, including climatic variations, intensity of snowfall, topographic complexity, etc. Further, the ground truthing was not possible owing to the inaccessibility of the remote sites over the investigation period, which has limited our capacity to eliminate changes. The study has completely relied upon remotely sensed satellite imagery and did not engage in collection of any primary data for evidencing the climate change impact on lake surface water changes through field observation; this was considered outside its scope. In the future, water resource management, conservation and monitoring within the basin is essential using effective scientific tools and techniques, particularly in the face of a changing climate [43].

4 Conclusion

This study demonstrated the capability of remote sensing technology in monitoring climate change impact on the evolution of mountain lakes. It evaluated the surface water content for three mountain glacial lakes (Kapuche, Dona and Tilicho) and two mid-hill lakes (Phewa and Begnas). Based on the derivation of the water indices from longitudinal remote sensing data analysis between 1988 and 2018 using a combination of surface water pixel and NDWI, we have shown the following two emerging patterns of climate change on mountain lakes in Nepal: a) increase of water surface and/or neo-formation of glacial lakes in the upper Himalayan regions (NDWI for Dona and Kapuche increased by 29% and 182% respectively); b) decrease of water surfaces in the existing lakes in the lower mid-hill regions (NDWI for Phewa and Begnas reduced by 2.05 % and 0.85 % respectively). The former can be associated with climate change impacts, whereas the latter can be interpreted as the outcome of sediment disposition, accelerating evaporation losses under warmer conditions, and urbanization-related anthropogenic factors. These findings can have severe implications for land-locked country like Nepal, which has strong economic dependence on its water resources for energy and agricultural needs.

Further investigations are warranted involving large-scale lake areas under different geographical and environmental conditions for developing statistically sound climate change impact, water quality and other environmental challenges in mountain areas using multispectral satellite data, combined with other sensor data.

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