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Final Report

Congratulations on the completion of your project that was supported by The Rufford Foundation.

We ask all grant recipients to complete a Final Report Form that helps us to gauge the success of our grant giving. The Final Report must be sent in **word format** and not PDF format or any other format. We understand that projects often do not follow the predicted course but knowledge of your experiences is valuable to us and others who may be undertaking similar work. Please be as honest as you can in answering the questions – remember that negative experiences are just as valuable as positive ones if they help others to learn from them.

Please complete the form in English and be as clear and concise as you can. Please note that the information may be edited for clarity. We will ask for further information if required. If you have any other materials produced by the project, particularly a few relevant photographs, please send these to us separately.

Please submit your final report to jane@rufford.org.

Thank you for your help.

Josh Cole, Grants Director

Grant Recipient Details	
Your name	Sonam Wangchuk
Project title	Hazard assessment of Luggye glacial lake: an alternative long term approach for conserving aquatic habitat, Punatshang Chhu, Bhutan
RSG reference	20064-1
Reporting period	June, 2016-June 2017
Amount of grant	£4930
Your email address	Somwangchotc9091@gmail.com
Date of this report	June 23, 2017

1. Please indicate the level of achievement of the project's original objectives and include any relevant comments on factors affecting this.

Objective	Not achieved	Partially achieved	Fully achieved	Comments
Estimating debris-free glacier and debris-covered glacier area changes from 1972-2015 using Landsat satellite data			✓	The automatic technique for segregating debris-free and debris-covered glacier exist, however it is time consuming task to work for a lengthy period (100 years). Here providing training to colleagues and students may be possible to reduce work load.
Temporal changes of glacial lake using normalised difference index (NDWI), lake volume estimation using empirical relationship				Same as above comment
Areal changes of Luggye glacial lake just before outburst in 1994				
Estimating Luggye glacier terminus retreat length per year from 1972-2015				
Finding correlation among glacier variables				
Analysing meteorological datasets in and around the study region				
Photographs of Luggye glacier and glacial lakes				Excellent photographs were taken which would serve as future datasets for hazard assessment
Awareness and sensitization program				Results were able to deliver to a wide audience during the international conference on challenges of Anthropocene held at Sherubtse College. I was even able to find a collaborator to continue my work on this topic and subject.
Estimating glacier mass balance				Needs expertise as well as software capable of making reliable digital

				elevation models (DEMs)
GPS measurement of down front and up front lake and lake area				Due to the steep slope around the lake and lake connected to a glacier, we could not make a complete round of the lake taking GPS, however we were able to take GPS measurement at the outlet of the lake.
Dam breach modelling and downstream impact assessment modelling				Was attempted this time but could not complete as more time may be required.

2. Please explain any unforeseen difficulties that arose during the project and how these were tackled (if relevant).

It was the first time for me and my colleagues to make such a field visit to a remote place in Bhutan. We climbed around 5700 m above the sea level. Altitude sickness was very likely, we even risked our lives. One of my colleague was almost caught with altitude sickness, he was able to recover taking domestic and home-made sweets of cane sugar which was recommend by our field assistant and porter. We had to take break and catch our breath for adapting to a rising elevation as when journey progressed. We also faced difficulty in cooking food (half boiled food). We often had to supplement ourselves with nodules and biscuits along the way.

3. Briefly describe the three most important outcomes of your project.

Assessing hazard of glacial lakes has various parameters to be considered. In this work: 1) Excellent pictures of Luggye glacier and glacial and GPS measurement at the outlet of the lake were taken which would definitely serve as reference data sets for hazard assessment in the future; 2) The detail analysis of changes of glacier and glacial lakes were accomplished for 40-year periods; 3) Result was shared with a wide audience during the international conference. Details of the figures, tables and write-ups are attached as well for the references.

4. Briefly describe the involvement of local communities and how they have benefitted from the project (if relevant).

In this project, there was no direct mass involvement of local communities in my work, however I was able to hire few colleagues along with me for the field visit. They got an opportunity to see glacier and glacial lakes besides financial benefits and sightseeing. Moreover, I hired porter including seven horses from Punakha and was able to benefit financially. During the international conference, students from various regions of Bhutan were present who were highly interested in glaciers and glacial lakes. Few students even presented on change assessment of glacial lakes which I was able to comment and provide feedback as a chair of the technical session.

Many thanks goes to RF for providing me a fund which enabled me to grow as an expertise in this subject.

5. Are there any plans to continue this work?

I consider this work as incomplete work. Definitely it needs more works such as depth measurement for dam breach modelling and downstream impact assessment which I may have to seek another funding sources. The work shall be continued till comprehensive study is being achieved and results are fully delivered.

6. How do you plan to share the results of your work with others?

The results of my work shall be shared during the gatherings such as conferences/workshops. Even organizing of mass awareness and sensitisation events and programmes are possible provided enough fund.

7. Timescale: Over what period was The Rufford Foundation grant used? How does this compare to the anticipated or actual length of the project?

The grant was utilised from August, 2016 to June 2017. The majority of grant was utilised during the field visit (September, 2016) which I had to hire field assistants, porter and seven horses. Hiring porter and horses were not easy task as we planned and proposed. Even hiring local people to take us to the field was very expensive. Overall I experienced a very expensive field visit.

8. Budget: Please provide a breakdown of budgeted versus actual expenditure and the reasons for any differences. All figures should be in £ sterling, indicating the local exchange rate used.

Item	Budgeted Amount	Actual Amount	Difference	Comments
Hiring 7 horses and daily porter charges plus hiring vehicle (to and fro) till the end point of the road.	1130	1250	120	Hiring 2-3 horses is not favourable as villagers own minimum of 7-8 horses. They are not willing to travel taking 2-3 horses provided it's a risky and troubling route. They travel in a group. It could be also due to their source of income as well as their business strategy. I had to spend most of the grant here. As a result I found this field visit very expensive. Hiring vehicle was also found expensive because of rough road/feeder road.

Foods, refreshments and accommodation for 5 persons for 21 days including whole journey. Payment for two field assistants and hiring local person charges. Buying field materials: field shoes, jackets bags, sleeping bags, and medicines	1556	1941	385	We have carried enough rice bags and dried vegetables. We could not eat enough food as it was half cooked at the high altitude. As a result, we had to mostly depend on the instant foods such as nodules, biscuits and juice. Therefore buying even a nodule was triple the standard price. Even refreshments served were double or triple the original price. Therefore, I have learned we have to carry enough instants foods and refreshments instead of rice bags next time to cut the expenditure. Buying safety boots were also found expensive.
Buying GPS and hiring tents and cameras	578	500	78	Actually we planned to buy cameras and tents but we landed up hiring and paying hiring charges as it was cheaper in this way.
Conference travel, Seminar/awareness and accommodation	1085	565	520	Entire result of the work was presented during the international conference held at Sherubtse College, I could not organized separate meetings as I would have definitely suffered from shortage of fund. However, I am fully satisfied and convinced with the audience present and discussions we had.
Internet packages and services	-	550	550	I also had to adjust fund for internet packages charges which was not proposed in the proposal. I had to mostly rely on 4G network for downloading data and papers which was quite expensive.
Local travelling expenses for discussion and report writing and +/- (5%) expenses	581	195	386	Had to use taxi and public transportation facilities for discussion and report writing.
Total	4930	5001	71	

9. Looking ahead, what do you feel are the important next steps?

In this current project period, most of the glacier variables (glacier area, lake area, glacier terminus change, physical observation of lake conditions, photographs, and climate variables) were able to analyse. For the comprehensive hazard assessment of Luggye Lake, bathymetric measurement of lake, hazard map, dam breach modelling are very important. I am looking forward to complete this remaining tasks with some additional funding.

10. Did you use The Rufford Foundation logo in any materials produced in relation to this project? Did The Rufford Foundation receive any publicity during the course of your work?

The Rufford Foundation logo was used where and when necessary. It was mainly incorporated during the report write ups. Rufford Foundation was all the time acknowledged for the funding for the study. Any materials produced and used as a result of funding were properly acknowledged. Rufford Foundation will be acknowledged for any articles, presentations or materials produced as result of funding in the future too.

11. Please provide a full list of all the members of your team and briefly what was their role in the project.

1) Sonam Wangchuk- Project leader
2) Sonam Gyeltshen- Hired field assistant
3) Krishna Prassad Bastola- Hired field assistant
4) Karma (Forester)-Field assistant plus field guide
5) Thinley (Tshogpa-Local village representative), porter
5) Prof. Jarek Zawadzki-Collaborator, article and abstract write ups and discussion.
6) Cheten Dorji-Study design and collaborator

12. Any other comments?

Field visit to a high altitude is demanding in terms of financially as well as risk taking. The journey and work is not as simple as reflected in the proposal. In future, such work should be supported by ample fund and all the people involved in a field visit should be subjected to providing local insurance scheme by a project leader/fund provider for unfortunate accidents and fatalities.

Period	Terminus retreat (m)	Retreat rate ($m\ a^{-1}$)
1972-1976	-91.493±84.852	-22.873
1976-1987	-446.766±67.082	-40.615
1987-1990	-189.471±42.426	-63.157
1990-1995	-259.500±42.426	-51.900
1995-2000	-156.913±42.426	-31.383
2000-2005	-232.987±42.426	-46.597
2005-2010	-295.727±42.426	-59.145
2010-2015	-215.959±42.426	-43.192

Table 1. Terminus changes of Luggye glacier

Lake						Debris-cover glacier				Clean ice glacier		
Year	Area	Area change		Change rate	Area	Area change		Change rate	Area	Area change		Change rate
	(km²)	km²	%	% a⁻¹	(km²)	km²	%	% a⁻¹	(km²)	km²	%	% a⁻¹
1972	0.400±0.163				1.609±0.542				5.101±0.636			
1976	0.314±0.150	-0.086	-21.500	-5.375	1.770±0.632	0.161	10.006	2.502	4.669±0.649	-0.432	-8.469	-2.117
1987	0.913±0.076	0.599	190.764	17.342	1.911±0.331	0.141	7.966	0.724	4.651±0.331	-0.018	-0.386	-0.035
1990	1.049±0.077	0.136	14.896	4.965	1.611±0.221	-0.300	-15.699	-5.233	4.680±0.307	0.029	0.624	0.208
1995	0.965±0.075	-0.084	-8.008	-1.602	1.710±0.254	0.099	6.145	1.229	4.578±0.669	-0.102	-2.179	-0.436
2000	1.096±0.082	0.131	13.575	2.715	1.544±0.300	-0.166	-9.708	-1.942	4.278±0.321	-0.300	-6.553	-1.311
2005	1.262±0.094	0.166	15.146	3.029	1.052±0.260	-0.492	-31.865	-6.373	4.106±0.274	-0.172	-4.021	-0.804
2010	1.337±0.107	0.075	5.943	1.189	1.380±0.234	0.328	31.179	6.236	4.250±0.318	0.144	3.507	0.701
2015	1.581±0.112	0.244	18.250	3.650	1.382±0.215	0.002	0.145	0.029	4.156±0.267	-0.094	-2.212	-0.442

Table 2. Luggye glacial lake area changes and glacier surface area changes

Period	MED (m)	STD (m)	SE (m)	NPI	EEC (m a^{-1})	EMB (mw.e.a^{-1})
2001-2007	-15.8	15.52	0.78	398	±2.63	±2.59
2007-2015	-18.21	22.14	1.23	398	±2.28	±2.25
2001-2015	-27.63	21.15	1.06	398	±1.97	±1.96

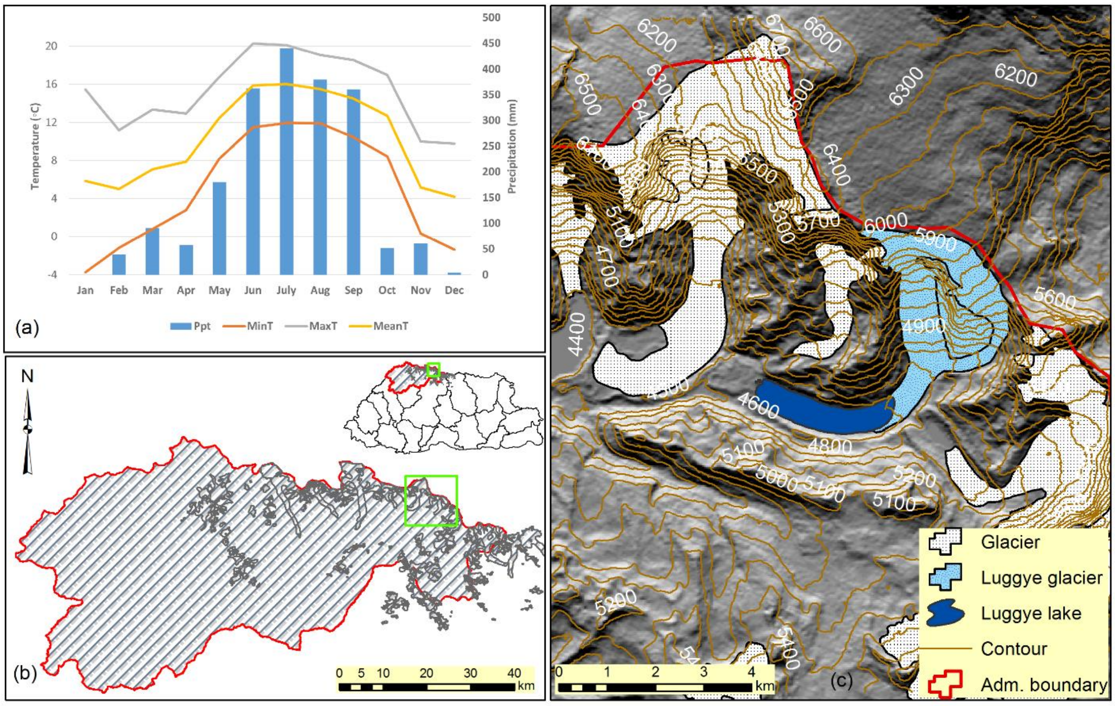
Table 3. Statistics for respective elevation differences in off-glacier region and associated uncertainties for elevation change and mass balance. MED: Mean elevation difference; Average; STD: Standard deviation; SE: Standard error; NPI: Numbers of pixels included; EEC: Error of elevation change; Error of mass balance.

	Area (km^2)	Max Depth (m)	Avg. Depth (m)	Volume (x10 m^3)	PFV(x10 m^3)	Survey date	Reference
	1.17	126.00	49.90	58.30	15.21	Sep-Oct 2002	Yamada et al. (2004)
	1.10	100.41	56.38	50.31	14.35	2002	Present Study
	1.306	109.01	58.79	65.07	16.98**	22-Sep-94	Present Study
					17.20**	1994	Fujita et al. (2008)
Error (%)	5.98	25.49	-11.49	15.88	1.31		

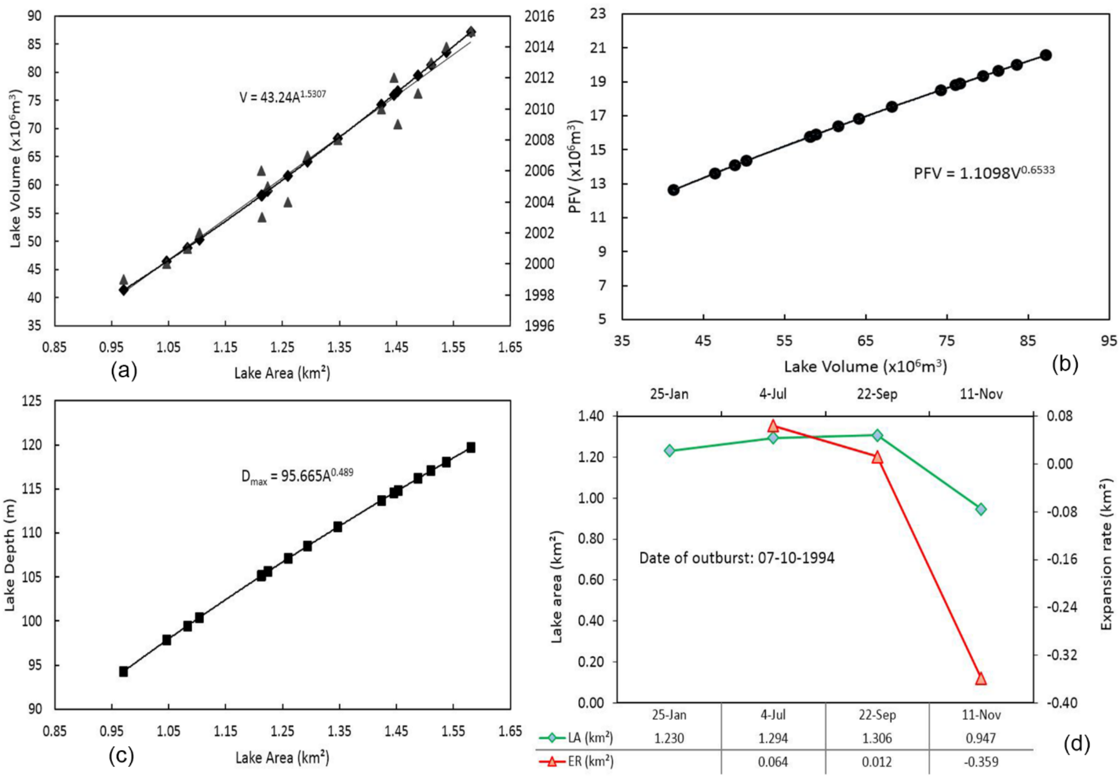
Table 4. Comparison of statistics between in situ measurements and Landsat data. ** indicates comparison between actual flood volume in 1994 and PFV calculated using empirical relationship V=43.24 A1.5307

Period	Down wasting rate (ma^{-1})	Specific mass balance ($mw.e.a^{-1}$)
2001-2007	3.54±2.63	2.54±2.59
2007-2015	3.37±2.28	2.80±2.25
2001-2015	2.81±1.97	2.17±1.96

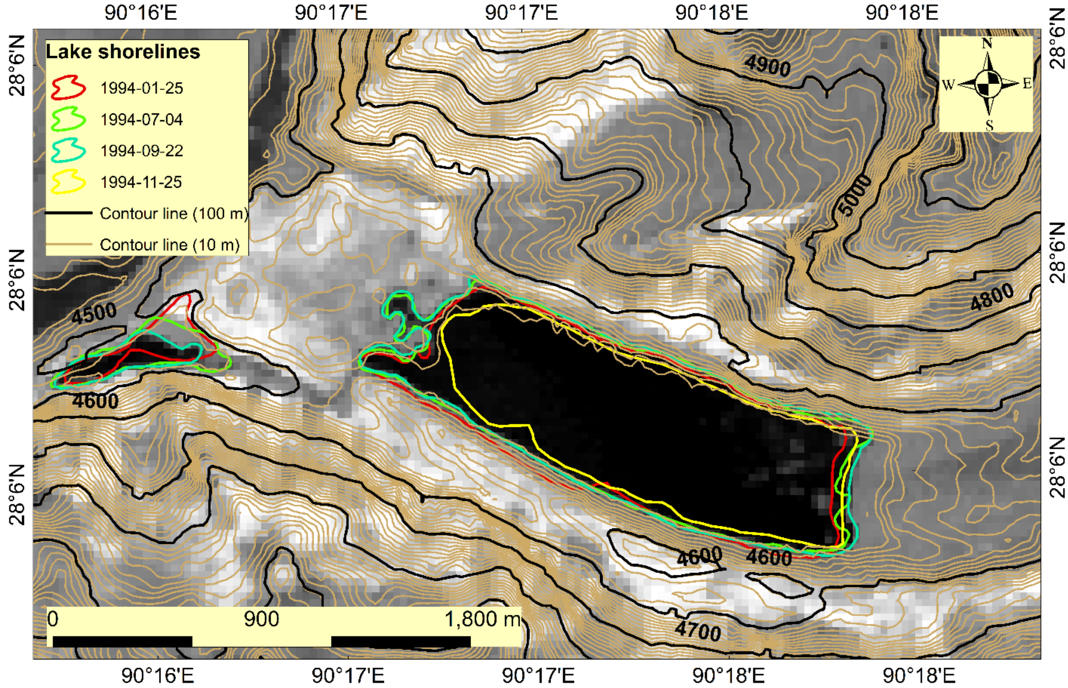
Table 5. Rate of elevation change and mass balance of Luggye glacier



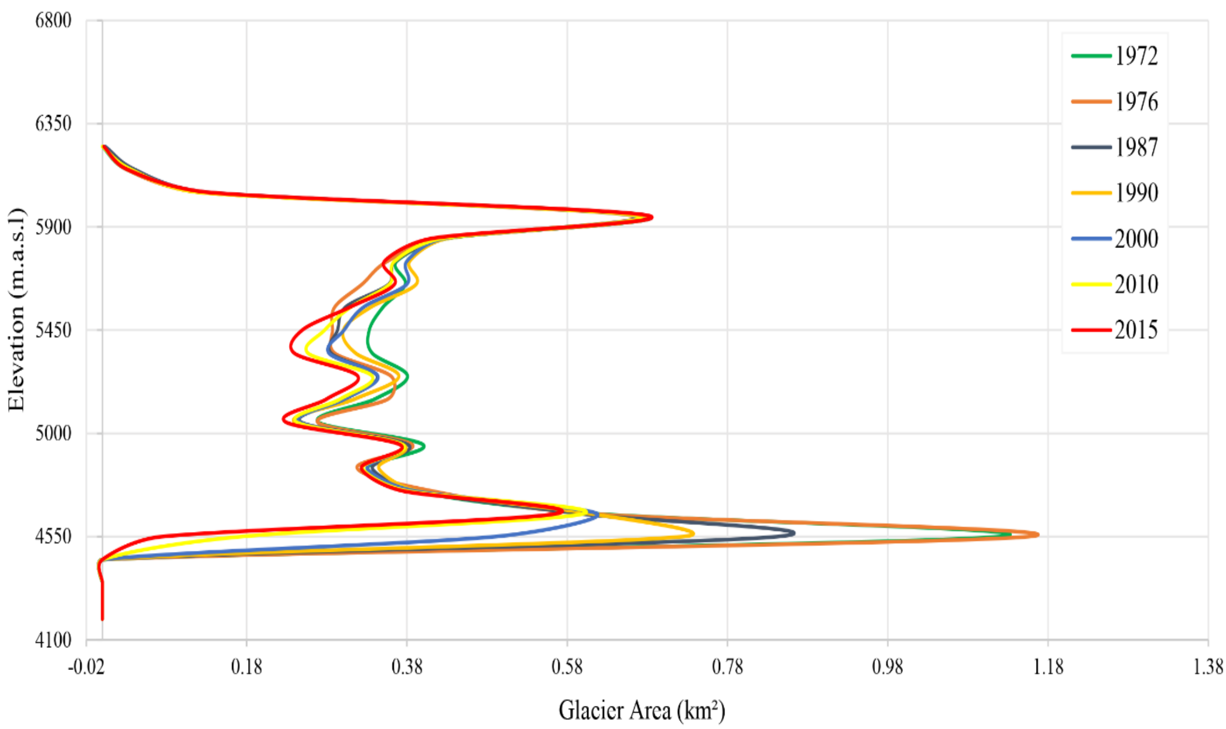
Study area



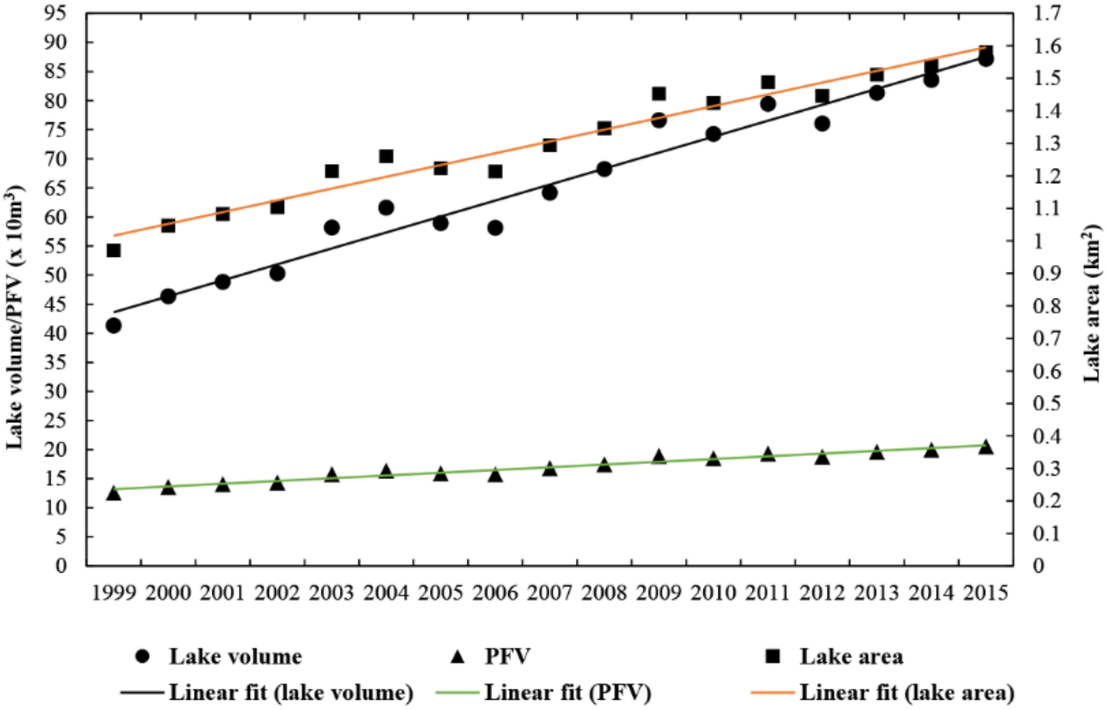
Empirical relationships (a, b, c). d) Lake areas and expansion rates in the year of outburst (1994)



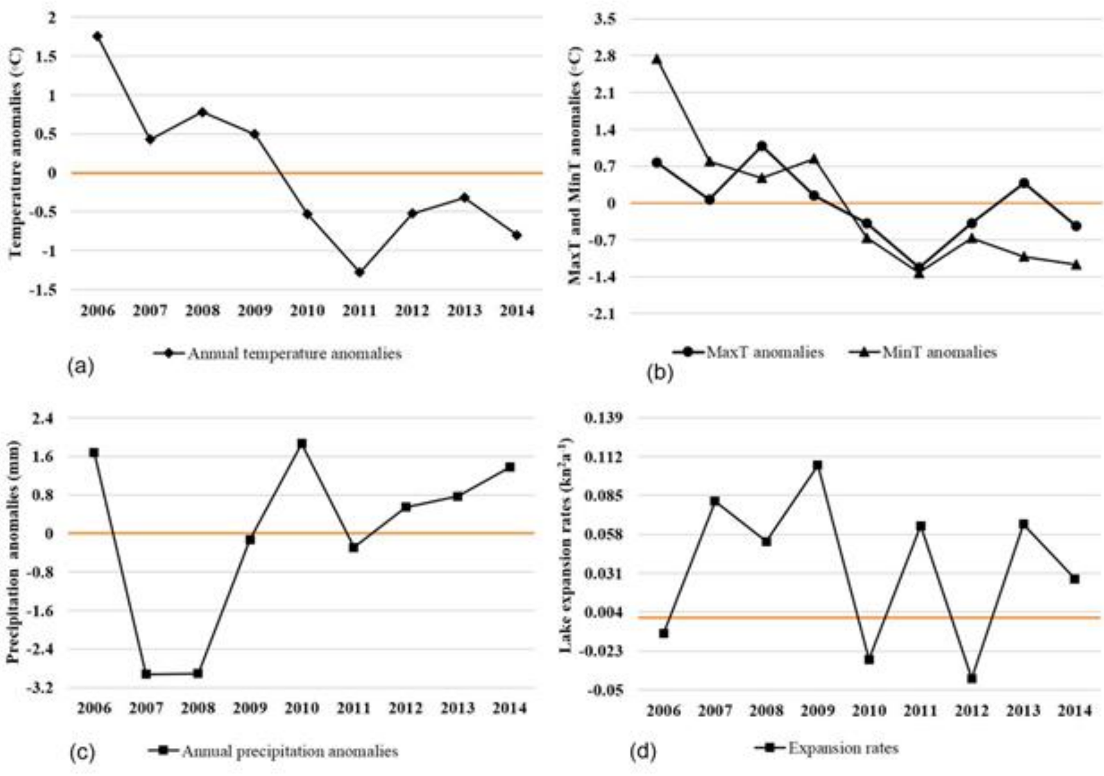
Variations of Luggye glacial lake in 1994



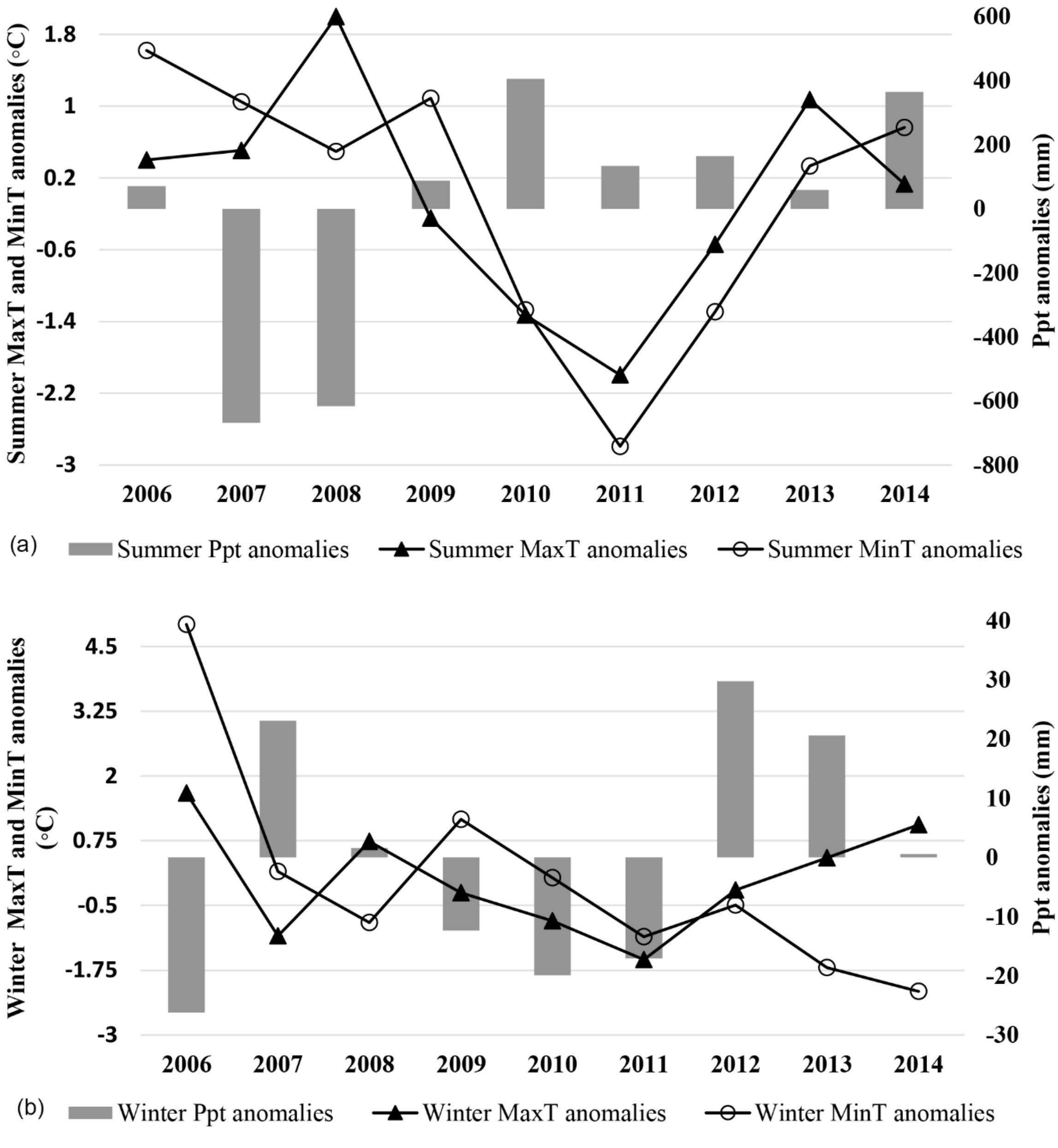
Hypsographic curve of variations of Luggye glacier between 1972 and 2015



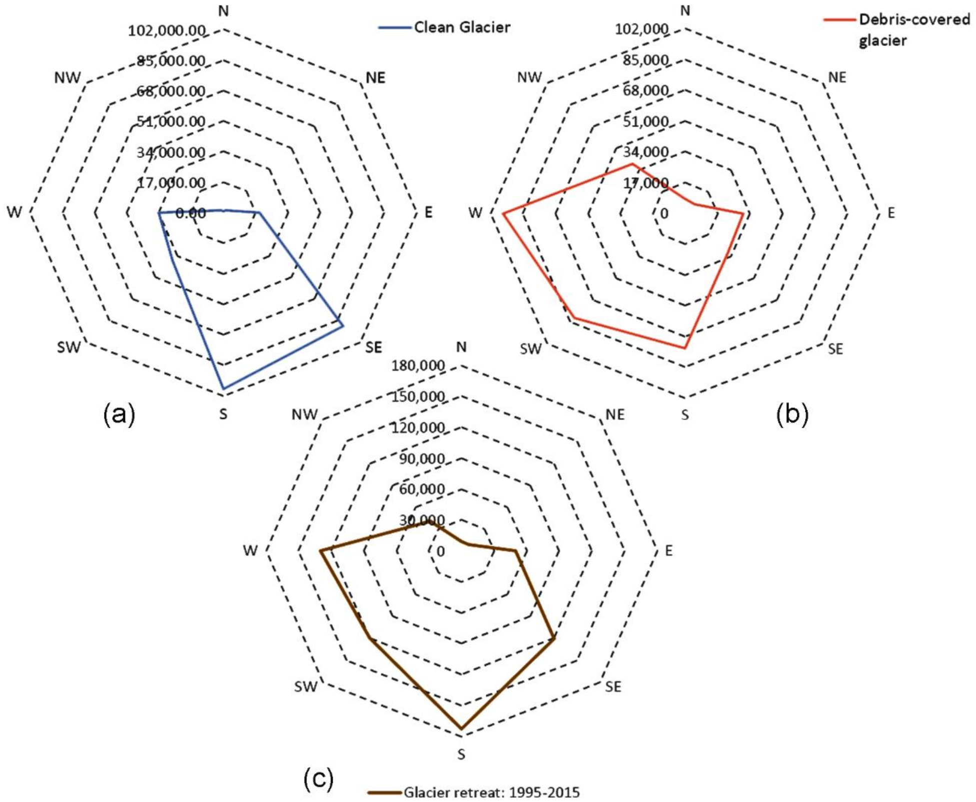
Variations of Lake Area, lake volume and potential flood volume (PFV) between 1999 and 2015



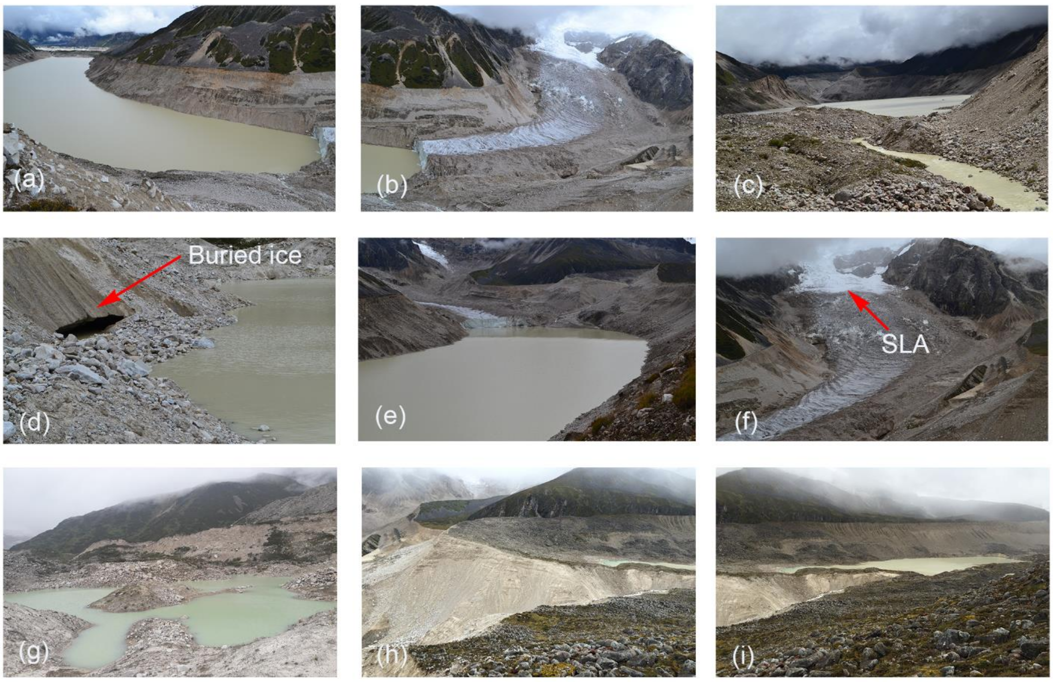
Precipitation and temperature trends and anomalies (2006-2014)



Summer and winter temperature and precipitation trends and anomalies



Aspect diagram of Luggye glacier retreat



(a) Luggye lake, (b) Luggye glacier, (c) Lake outlet, (d) buried ice, (e) Luggye lake and glacier, (f) Snow line altitude, (g) Supraglacial ponds, (h) Eroded moraine, (i) Upstream lake

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Satellite sensing of Luggye glacier mass balance since 2001 and variations of Luggye glacial lake over the past four decades, Bhutan Himalayas

Abstract

Luggye glacial lake is one of the most rapidly expanding moraine dammed glacial lakes in Bhutan Himalayas. Despite a previous catastrophic record of outburst, it is prone to burst again because of enormous volume of water and significant rate of expansion. This study reveals the factors controlling the accelerated expansion of Luggye glacial lake and changes of Luggye glacier using multi-temporal Landsat satellite images (1972-2015), ASTER digital elevation models (DEMs) and meteorological data (2006-2014). Between 1972 and 2015, the surface area of lake has increased by 1.18±0.19 km2 (229.07%) and expanded at the mean rate of 0.03±0.005 km2 a-1. The surface area of Luggye glacier has diminished by -1.17±0.64 km2 (-21.52%) and the south facing glacier has suffered major loss in an area. The terminus of Luggye glacier has retreated at the average length of -43.93±2.21 ma-1 between 1972 and 2016. A strong negative correlation (r=-0.83), at high statistical significance level (p<0.005) exists between areal increase of Luggye lake and clean glacier surface area loss. The study also reveals significant mass loss (2.17±1.98 mw.e.a-1) and down wasting rate (2.81±1.97 ma-1) of Luggye glacier. Thus, the substantial mass loss of glacier due to increase in the annual mean, maximum and minimum temperatures accompanied by slower accumulation as a result of reduced precipitations could have resulted in accelerated expansion of Luggye glacial lake in the last few decades.

Keywords: glacier mass balance, glacial lake, ASTER, Landsat, Bhutan Himalayas

Introduction

The recent glacier area in Bhutan Himalayas is reported as~642±16.1 km2 (Bajracharya, Maharjan, & Shrestha, 2014). The overall area of glacier has decreased although number of glaciers have increased due to fragmentation into small glaciers rather than new development (Veettil et al., 2015; Bajracharya et al., 2014; Karma et al., 2003). A clean glacier has shown retreating trend resulting in increase of debris-covered area in southern side of Bhutan Himalayas and upward shift in equilibrium-line of altitude (Veettil et al., 2015; Bajracharya et al., 2014). The mass balance record through satellite measurements and subsequent modelling indicated mass loss of Bhutanese glacier (Gardelle et al., 2013; Rupper et al., 2012). Furthermore, in-situ measurements have shown greater mass loss than neighbouring glaciers ranging from -1.12 to -2.04 m w.e. a-1 (Tshering & Fujita, 2016).

Simultaneously with an increasing trend of clean glacier loss and a resulting increase in the debris-covered area in Bhutan Himalayas (Veettil et al., 2015; Bajracharya et al., 2014), the formation and development of glacial lakes were noticed on the debris-covered glacier surface and glacier terminus (Ageta et al., 2000; Iwata et al., 2002; Komori, 2007; Ukita et al., 2011). Specifically, the formation of supraglacial lakes on debris-covered glaciers was restricted on the gradients of glacier less than 20 (Reynolds, 2000). Further research has revealed that supraglacial lakes tend to connect each other and grow into large lakes rapidly (Ageta et al., 2000; Iwata et al., 2002; Sakai, 2012). Compilations of studies (Ageta et al., 2000;) revealed three types of glacial lakes in Bhutan Himalayas: supraglacial lakes which are present on the surface of debris-covered glacier, they are often transient due to their small volumes, however they tend to connect each other growing into large lakes. It is the initial stage of most large lakes present in Bhutan Himalayas (Komori, 2007). Moraine dammed glacial lakes: They are known by various names such as proglacial lakes, ice-proximal or ice-contact lakes. They are characterised by large water volumes potential of glacial lake outburst floods (GLOFs), are often stable in terms of expansion and are in-contact with glacier ice. Unconnected lakes: These lakes are devoid of surrounding glaciers. They are stable and located in cirques or glacial troughs.

Luggye glacial lake is a moraine-dammed glacial lake. It was initially developed as supraglacial ponds on the surface of Luggye glacier in 1960s. Now Luggye glacial lake has entered into the third stages of glacial lake development which is indicated by stable expansion (Ageta et al., 2000; Komori, 2007). It is one of the biggest and rapidly expanding moraine dammed glacial lake in Bhutan Himalayas which has the previous catastrophic record of outburst in October 7, 1994 (Ageta et al., 2000; Mool et al., 2001; Komori et al., 2012) amounting the GLOF volume of 17.2±5.3 x106 m3 (Fujita et al., 2008; Fujita et al., 2013).The depth and volume surveyed by Yamada et al. (2004) in 2000 revealed mean depth of 49.9 m, deepest depth of 126 m and water volume of 58.3 x 106 m3.

Despite the enormous water volume, and expected GLOF because of incomplete failure of SLA (Steep Lakefront Area) during 1994 outburst (Fujita et al., 2013), a thorough study exploring the connection between Luggye glacial lake expansion and Luggye glacier changes is still lacking. In this study, we report in detail changes of Luggye glacier and glacial lake between 1972 and 2015 using Landsat satellite observations. Secondly, we present in-depth inter-annual variations of Luggye glacial lake and Luggye glacial terminus since meteorological data are available (i.e. 2006-2014). Thirdly, we discuss both the potential factors controlling the rapid expansion of Luggye glacial lake and likely future transformation of Luggye glacial lake.

Study area and data

The study area is Lunana, located in northern part of Bhutan Himalayas. Numerous sizes and types of glaciers and glacial lakes are present there. In particular, Luggye glacial lake is located at 280 05' 33.5" N, 900 17' 53.5" E in Pho Chu sub-basin. It is one of the main glacial lakes directly feeding Punatshang Chhu River. Luggye glacier is associated with both clean and debris-cover glacier, it has a direct contact with Luggye glacial lake.

Landsat datasets were imported from USGS archive (http://earthexplorer.usgs.gov/) website. Landsat Level-1T data products are radiometrically and geometrically terrain corrected data. The instrument has a spatial resolution of 30m except 60 m for Landsat-1, 2 and 3. Data were selected on the basis of minimum cloud cover and unfrozen lake surface to enhance the performance of NDWI (Normalized Difference Water Index) index and visual aid. In order to determine glacier elevation and mass changes, 1 ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) scene from 2001, 2007 and 2015 were used. ASTER has four visible/near-infrared bands (VNIR) each having 15m resolution. Additionally, it has a nadir band (3N) and backward-looking band (3B) with a stereoscopic capabilities for generating DEM. Climate data (2006-2014) around the study region was provided by the Department of Hydro-Met Services, Ministry of Economic Affairs, Thimphu, Bhutan. The satellite data used in this study are shown in the Table.

Methods

Mapping of clean-ice glacier, debris-covered glacier, glacier terminus, and Lake Area

Due to the unique spectral property of debris-free glacier in the region of electromagnetic spectrum, there are well-developed algorithms for classifying clean glacier from other features. In this study, a semi-automatic technique using band ratio was implemented. It is a well implemented method for studying clean ice with slight variations (Paul & Kääb, 2005; Paul & Andreassen, 2009; Bolch, Menounos et al., 2010; Paul, 2000a; Paul, 200b; Paul, Huggel et al., 2002; Paul, Kääb et al., 2002; Bolch & Kamp, 2006). In our case we followed two steps: firstly clean ice glacier was segmented using TM bands 4 and 5 and band 5 and 6 for landsat-8 OLI/TIRS. Secondly we manually digitized the segmented area depicted in figure…as an example which was obtained as a result of band ratio. In the region of ice divide we did not follow specific technique instead we used a base glacier polygon obtained from the GLIMs website. The same steps were repeated for all the analysed images. In contrast to the mapping of clean-glacier, automatic mapping of debris-covered glaciers is limited because of similar spectral property that of rocks and sands. Earlier studies have used spectral information, slope and vegetation information (Paul et al., 2004), extensive geomorphometric information (Bolch & Kamp, 2006), supervised classification and principal components analysis (Ghosh et al., 2015) and decision tree and texture analysis for quantifying debris-covered glacier region (Racoviteanu & Williams, 2012). However, these methods have certain superiority and limitations. In our case we used a band ratio method proposed by Alifu & Jhonson (2015) which incorporates thermal information of debris-covered glacier as follows: band 6/ (band 4/band 5) for TM and thermal band 1or 2/ (band 5/band 6) for OLI. The technique facilitated distinct segmentation of supraglacial debris from periglacial debris due to difference in the thermal response, however, we have noticed that it has over-emphasized the supraglacial debris region compared to the images taken during the filed visit and high resolution Google Earth images (Fig.). Therefore, the method was accompanied by slope information and manual interpretation. We have used slope less than 180 as the potential debris-covered region and considered for calculation of areal debris-covered region. The integrity of threshold slope was further verified with the high resolution Google Earth images and photos taken during the field visit. The rock outcrop present in the glacier was excluded from the areal glacier surface calculation.

To track the changes of glacier terminus at the upfront of the lake, a set of parallel strips with 50 m interval each was drawn along the direction of glacier flow. After that points were collected from the intersected point of glacier terminus outline and strips for every analysed images. The average distance between the points of two different years was calculated and considered as the average glacier retreat length. The same idea is implemented in Thakuri et al. (2016) and Koblet et al. (2010). The outline of the glacier terminus was manually acquired from the false colour composite (FFC) of a satellite image. To calculate SLA a true and false colour composites were used. The accumulation and ablation region of glacier was convinced by the fact that accumulation region appears brighter due to perennial snow than the ablation region in both true and false colour satellite images. With this knowledge 12-20 points were collected from the manually interpreted equilibrium region of snowline with an aim to collect elevation information. The elevation for each point was derived from the 1 sec STRM DEM. The SLA was calculated as the average elevation (Bajracharya et al., 2014).

For determining the surface area change of the lake Normalised Difference Water Index (NDWI) was used in this study. It is a well implemented method for detecting water bodies (Mcfeeters, 1996). The method was successfully applied for delineating glacial lakes in the high mountains (Huggel et al., 2002; Bolch et al., 2010). It is defined as follows: NDWI= (band 4 - band 2) / (band 4 + band 2). The technique is often complemented by NDWI threshold and DEMs (Bolch et al., 2010; Li & Sheng, 2012). With respect to our study we first segmented the lake surface using the formula defined above and then manually digitized the lake surface area for all analysed images. Where performance of NDWI was poor, it was accompanied by manual interpretation. The manual interpretation was necessary for the winter scenes as the lake surface was frozen.

Glacier elevation change and mass balance

To compute the elevation and mass change of glacier, 90m resolution ASTER DEMs were constructed for the year 2001, 2007 and 2015 respectively using ENVI DEM extraction module. 20-30 GCPs were manually assigned on identifiable objects (e.g. mountain peaks, rocks and river crossings) in image to ensure proper co-registration of stereo image pair. For determining elevation and mass change between 2001-2007 and 2001-2015, 2001 DEM was used as a reference DEM. A DEM pair was properly co-registered following the method of Nuth & Kaab (2011) and DEM differencing method (Bolch et al., 2011; Thakuri et al., 2016) was used to compute the glacier elevation change. Elevation difference greater than 7.5ma-1 was considered as possible outliers (Nuth & Kääb, 2011; Nuimura et al., 2012) and hence eliminated from the data. The remaining data gaps were interpolated by kriging. For the mass balance estimation, a density of 880 kgm3 was assumed.

Uncertainty measurement

There are numerous ways of considering sources of uncertainties for the glacier parameters measurements derived from remote sensing imagery. The main elements to the contribution of uncertainty are linear resolution of image and co-registration error (Hall et al., 2003, Ye et al., 2003; Wang et al., 2010). In our case co-registration error was not considered as the potential source of an error as changes were compared on the basis of entity not pixel by pixel. Another valid reason for eliminating influence of co-registration error was geometry of the level-1 Landsat products which were consistent in the study region. Therefore, uncertainty in mapping or delineating Lake Surface and glacier surface were calculated as the product of half the liner resolution of sensor and its perimeter (Salerno et al., 2012; Fujita et al., 2009) except for the scene from 1995. For 1995 scene full linear resolution of image and its perimeter were considered for uncertainty calculation of clean ice because image was partially covered by cloud and error was assumed be more conservative (Gardelle et al., 2010). The changes in the lake and glacier surface area were calculated according to the error propagation rule: root sum of squares (rss) of individual mapping error in each scene (Thakuri et al., 2014; Thakuri et al., 2016).The uncertainty of measuring glacier terminus length in each scene was calculated as of Hall et al. (2003) but we did not include co-registration error as discussed above.

Results and Discussions

Lake surface area

The initial development of Luggye glacial lake took place as supraglacial ponds in 1960's (Komori, 2007). Ponds have substantially merged and developed into one of the largest moraine-dammed glacial lakes in Bhutan Himalayas. The lake has continuously grown and reached maximum area of 1.306 ± 0.114 km2 in September 22, 1994. The lake area shark by 17.5 % (0.974 ± 0.07 km2) after the catastrophic outburst in October 7, 1994. Analysis of satellite data indicated that the lake has regrown and attended the area of 1.58±0.11 km2. The surface area of lake has increased by 1.18±0.19 km2 (229.07%) and expanded at the mean rate of 0.03±0.005 km2a-1 between 1972 and 2015. It is a 62.21 % increase in area since outburst in 1994. Although mean expansion rate seems remained constant for decades (Komori et al., 2004; Komori, 2007), temporal expansion rates are highly variable from period to period. For instance, recent period (2010-2015) showed highest expansion rate (0.048 km2a-1) compared to other periods. Furthermore, a major expansion has occurred between 2007 and 2008 with the expansion rate of 0.105 km2a-1. Such unusual expansion rate has to be noted while assessing hazard. A catastrophic outburst of Luggye Lake in October 7, 1994 could be because of surge in expansion rate as indicated. There is a clear development of hollow at the lower end moraine of Luggye Lake indicated by significant changes in the shoreline position and it has expanded at the significant rate of 0.01 km2/month between January and September, 1994. If such unusual development and rapid expansion rates are noted through satellite image. It is crucial to take mitigation activities. The area of a lake and expansion rates, unusual development in a lake (e.g. drastic change in shoreline position) are the primary indicators of danger which could be studied through remote sensing. The unusual development or formation of typical feature is not noted in this study. However, the possibility of danger could not be ignored due to the recent significant expansion rates.

Volume change of Luggye Lake

The empirical relationship (V=43.24 X A 1.5307) between lake volume and area was developed by Sakai (2012) based on the record of available bathymetric measurements of glacial lakes in Himalayas, where, V is volume of a lake [x 106 m3], A is area of a lake [km2]. The maximum and mean depth of a lake can be determined as well by a following relation: $Dmax$=95.665 X A 0.489 (Sakai, 2012), Dm=55A 0.25 (Fujita et al., 2013), where, $Dmax$ and Dm are maximum depth and mean depth (m). The potential flood volume (PFV) can be determined by a following relation: PFV=min [Hp; Dm], where, Hp is a potential lowering height based on the steep lakefront area (SLA) defined by threshold angle 100 (Fujita et al., 2013). The volume, PFV, maximum depth, minimum depth of Luggye Lake since 1999 was calculated using empirical relations discussed above. For determining PFV, an assumed potential lowering height (Fujita et al, 2013) without any change in the shoreline position following outburst was used. For the accuracy assessment, 2002 Landsat satellite data was compared with the in situ data of 2002 (Yamada et al., 2004). The relationship indicated that areal increase of lake corresponds to increase in the volume of the lake, lake depth, and PFV respectively. The volume of the lake has increased from 39.78x106m3 to 87.17x106m3 between 1994 and 2015. It is a twofold increase in volume of lake the since 1994 outburst. The latest PFV expected is 20.55x106m3 in case of outburst. The PFV can be calculated by the relation PFV = 1.1098V0.6533, if volume of a lake is known.

Variations of glacier terminus and shoreline positions

The Luggye glacier terminus has retreated at the average length of 43.93 ma-1 for the last 4 decades (1972-2015). The total terminus length retreated is 1888.8 m. The terminus has retreated at the highest rate of 63.157 ma-1 between 1987 and 1990 followed by 59.145 ma-1 between 2005 and 2010. The retreating length/rate is consistent with the other studies in Himalayas (Thakuri et al., 2016; Basnett, Kulkarni, & Bolch, 2013). The glacier with Proglacial Lake at the terminus suffers major loss in glacier length because of enhanced retreating due to calving mechanism (Basnett et al., 2013). The lowest retreating rate of terminus was observed between 1972 and 1976 (22.87 ma-1) followed by 31.38 ma-1 between 1995 and 2000. The recent (2010-2015) average retreating length is 43.19 ma-1. It has slowed by 34.6 % compared to a previous (2005-2010) retreated length (59.15 ma-1). The directions of expansion are from the northeast and northwest front of the lake. Northeast front expansion is more prominent than northwest front expansion as northeast front of the lake is attached with Luggye glacier.

Variations of glacier area

In the current study period (1972-2015), the area of clean glacier has decreased by 19.69% (-0.945 km2) at the average rate of -0.022 km2a-1 (0.46 %a-1). These results are consistent with the observations in Himalayas (Wang et al., 2011; Thakuri et al., 2013). However, different temporal intervals indicated different retreat and advance rates. For two temporal periods (1987-1990, 2005-2010), there was a slight advance in area at the rate of 0.21%a-1 and 0.70 %a-1 respectively. The maximum retreating rate (-2.12 %a-1) was observed between 1972 and 1976 followed by -1.13 %a-1 between 1995 and 2000. The recent (2010-2015) retreating rate is -0.44 %a-1. A negative correlation (r=-0.83) exists between clean ice glacier and lake and is statically significant (p=0.005). For debris-covered glacier, the overall trend between 1972 and 2015 indicated decrease in the area (0.23 km2) which is -14.12%, at the average rate of 0.005 km2a-1 (-0.33 %a-1). Similar variations in rates to those observed on clean glaciers were noticed for different temporal intervals. For almost one and a half decades (1972-1987), the area of debris-covered glacier has increased at the average rate of 0.02 km2a-1 (1.25 %a-1). For three periods (1987-1990, 1995-2000, 2000-2005), the debris-covered area has decreased which is likely due to degeneration of area because of lake growth as indicated by moderate negative correlation (r=-0.6), however, the relationship is not statically significant (p=0.08). Since 2005, the debris-covered area has increased at the average rate of 0.033 km2a-1 (3.14 %a-1). Clean glacier and debris-covered glacier has shown moderate positive relationship (r=0.68) and is not statistically significant (p=0.04). The south and west facing glacier has suffered major loss in an area.

Glacier elevation and mass balance change

For the investigated time periods (see Table 2), the surface of the Luggye glacier has lowered by at the average rate of -2.81±1.97 ma-1. The highest surface lowering rate (-3.54±2.63 ma-1) was observed for the period 2001-2007. A slight decrease in the surface lowering rate was observed during 2007-2015 but negative change in elevation was noticed in the accumulation region. Overall, a significant surface lowering was observed in the ablation region for all observed time intervals than accumulation area which could be due to action of a lake and presence of debris on the glacier surface (Naito et al., 2012). The comparisons of our results corresponds well with the in situ measurements carried by (Naito et al., 2012) in the same region. However, comparison of surface lowering rate with glacier devoid of glacial lake (Tshering and Fujita, 2016) indicated much higher lowering rate. The mass balance estimation also indicated that Luggye glacier has experienced a mass loss of -2.17±1.96 mw.e.a-1 between 2001 and 2015. The mass loss has slightly accelerated during 2007-2015 compared to previous period. The values are slightly higher than reported by Tshering and Fujita (2016) in the different study region but in Bhutan Himalayas, probably because of glaciers connected to a glacial lake. Accelerated glacier mass loss and surface lowering rate for glacier connected to glacial lakes were observed in other region as well (Bolch et al., 2011; Nuimura et al., 2012; Thakuri et al., 2016).

Changes in annual precipitation and temperature trends as potential driving factor for rapid lake growth

The lake growth and acceleration of surface lowering and mass balance loss of glacier could be due to changes in the patterns of precipitation and temperature. Although long-term climate data is not available for the study region, nevertheless, an analysis of temperature and precipitation pattern between 2006 and 2014 has indicated a robust influence on the health of glacier and glacial lake. As shown in the figure----the time periods for temperature and precipitation trends can be divided into two intervals: I. Period 2006-2009, II. Period 2010-2014. Period I is dry and warmer compared to period II which is wet and colder. Interestingly, the expansion rates can be also classified as same. In period I, positive expansion rates were noticed in which reduced precipitation and increased temperature (dry and warm) could have resulted in higher expansion rates and surface lowering. In contrast, variable expansion rates were noticed during period II which is possibly due to fluctuations in temperatures. A conservative model result also indicated that the 10C rise in temperature would result into glacier retreat until about 25% of Bhutan's glacierized area disappears (Rupper et al., 2012). Bhutanese glaciers are monsoon-affected and are more vulnerable to temperature change (Karma et al., 2003). The influence of climate parameters on glacier variables were noticed in other regions as well (Basnett et al., 2013; Thakuri et al., 2013) which aligns our finding.

Report through field visit

Through field observation, we confirmed that Luggye glacial lake is potentially dangerous due to the following reasons:

I. Large lake size and enormous volume of water; comprehensive Landsat satellite images analysed since 1999 indicated that current water volume (87.17x106m3) is approximately twofold larger than 1994 (after outburst). In period of studies, the lake area has expanded at the average rate of 0.03 km2 a-1.

II. Active expansion fronts of the lake; the upper portion of Luggye glacial lake has a direct contact with exposed Luggye glacier ice in which enhanced glacier retreat is expected due to calving. Moreover, buried ice cave was noticed at the lower portion of moraine dam. Thus, disintegration of ice core can undermine the structural integrity of the moraine dam (Richardson and Reynolds, 2000). Numerous ponds were present on the surface of moraine at the lower portion of Luggye glacier. In total 6 ponds were observed during our field visit.

III. Vulnerability of dam due to erosion of moraines; prominent and extensive evidence of erosion of dam wall was observed around the lake which may generate surging wave due to mass movement into the lake as discussed below. The colour of the lake has changed to light brown indicating vigorous erosion of moraine wall.

IV. High probability of mass movement into the lake; a small glacial lake is present at the headwater of Luggye lake. Satellite images have shown expansion is not significant here, however this area seems to be vulnerable as recent erosion of terminal moraine can be seen. The depth and volume are still not known for this small lake, however, there is a significant likelihood of rock fall and landslide into the lake which may generate tsunami-like wave capable of triggering outburst.

Conclusion

Due to a climate warming alpine glaciers and glacial lakes are subjected to rapid change. In this study, a relationship between accelerated expansion of Luggye glacial lake and changes of Luggye glacier was explored using multi-temporal Landsat satellite images (1972-2015) and ASTER digital elevation models (DEMs). Overall result showed Luggye glacial lake has rapidly expanded and area of glacier has continuously lost for decades. In specific, clean ice glacier area has retreated by -0.95±0.69 km2 (-18.53%) at the rate of -0.02±0.02 km2a-1 (-0.45%a-1). The south and west facing glaciers have suffered major areal shrinkage. During the fourth analysed decades, the total length of terminus retreated was around 1888.8 m. The volume of the lake has increased approximately twofold, since 1994. Furthermore, Luggye glacier has also displayed mass loss and surface lowering. We conclude that rapid growth of Luggye glacial lake is due to areal shrinkage and negative mass balance of Luggye glacier induced by fluctuations in climate parameters over time. Since expansion rate and volume of Luggye glacial lake water are essential trigger for possible outburst, we strongly recommend to monitor them through situ work, supplementing by systematic remote sensing observation.

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