BHUTAN HydroMet Journal

Volume: II

National Centre for Hydrology and Meteorology
Royal Government of Bhutan
Thimphu: Bhutan

June 2023

Bhutan Hydro-Met Journal, June 2023

Published by National Centre for Hydrology and Meteorology
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Thimphu: Bhutan
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Editorial Note

Bhutan HydroMet Journal was started in 2022 and the first volume of the journal was launched successfully on 28th June 2022 during the 8th Board Meeting of National Centre for Hydrology and Meteorology. With the objective to institute research culture in the field of hydrology, meteorology, climate studies and cryosphere both within and outside the Centre, the editorial team for the Bhutan HydroMet Journal is happy to bring out the second volume of the journal with four scientific articles. Although the Bhutan HydroMet Journal is in its second year of publication, the editorial team has made all effort to follow the standards of international scientific journals. The aim of this journal is to disseminate the science-based information generated through extensive research process to the readers and particularly to the planners and decision makers to enable them to take decisions and make plans accordingly. Therefore, we hope that through this journal the scientific communities, students, decision makers, planners and general public will be greatly benefited.

The editorial team would like to acknowledge all the support received from the management of the Centre in bringing out the second volume of Bhutan HydroMet Journal. We also would like to express our sincere gratitude to all the authors for their cooperation and tireless effort in finalizing their articles. We hope that the next volume (Bhutan HydroMet Journal, Vol.III) will have more scientific articles and we would like to assure that the team will work together towards enhancing the journal.

Karma Toeb

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Glacier Variation (terminus & surface area) in Bhutan Himalaya from 1990-2020 as deduced from three bench mark glaciers (Shodug, Gangju La and Thana) and their relative changes with other glaciers in the Himalaya.

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Abstract:

Glaciers in the Himalaya are important in sustaining lives and livelihood of the population in the region. However, the glaciers are undergoing drastic changes due to major shifts occurring in temperature and precipitation due to climate change. It is imperative to have a clear understanding of the behavioral characteristics of the Himalayan glaciers to support decision making of developmental activities in the country. This study compares the changes taking place in terms of terminus retreat and surface area on three clean type glaciers (Shodug, Gangju La and Thana glaciers) in Bhutan from 1990 to 2020 with the variation rate of glaciers from other Himalayan regions. Gangju La, Shodug and Thana glaciers in Bhutan have retreated their terminus by 225 m 196.4 m from 2004-2020, 225 m and 497.4 m from 1990-2020 respectively which reveals that these glaciers are retreating at an average rate of 12.27my^{-1}, 7.01my^{-1} and 16.58my^{-1} respectively. The finding show that the retreat has accelerated in recent times with clear indication of zonal difference in variation (increasing retreat trend from west to east within Bhutan depending on the location of the glaciers). The result also shows that Gangju La glacier has lost 29.89% of its total surface area in the last 16 years (2004-2020) and the surface area of Shodug and Thana glaciers decreased by 15.24% and 30.31% respectively in the last 30 years from 1990-2020. Glaciers in Bhutan are retreating at a higher rate relative to glaciers from other parts of the Himalaya.

Key words: Terminus retreat, Aerial shrinkage, temperature and precipitation, Himalayan glaciers, summer accumulation type of glaciers.

Introduction

Himalayan glaciers play an important role in terms of water resources which sustains livelihood of the local communities as well as generating revenue for the government. However, these glaciers have been undergoing drastic changes in terms of their surface area, ice volume and terminus retreat. Number of studies shows the glaciers in the Himalayas are retreating and shrinking in surface area (Fujita et al 2001; Kadota et 2002; Naito et al 2002; Bajracharya et al 2014; ; Thakuri et al, 2014; Kulkarni, 2014; Lama et al 2015; Das and Sharma, 2018). Studies have shown that glaciers located in eastern part of the Himalayas show higher retreat rate than the ones which are located more towards western part (karma et al, 2003). It has also been found that the glaciers in the Himalayas are retreating at an accelerated rate in recent times (Basnet et al 2013). Clean type and smaller glaciers were found to be more sensitive to climate (Pratap et al 2015; Huss and Fischer, 2016; Das and Sharma, 2018). It is of concern to note that Bhutan will experience a reduction of 10% in its glacierized area even if the climate continues with the mean of current value which will impact the meltwater flux by 30% and in the scenario of 1-degree Celsius additional regional warming, the glacierized area in the country would reduce by as much as 25% impacting melt water flux by 65% (Rupper et al 2012). Although many studies were carried out along the Himalayan range, data and information on Bhutan glacier still remains scarce and limited. According to the latest inventory of glaciers in Bhutan, there are 700 glaciers occupying an area of 34 km^2 which is about 1.6% of the total land area of Bhutan (NCHM, 2018). Therefore, this study investigates the recent variation in terminus and aerial shrinkage on 3 clean type glaciers in Bhutan from 1990 to 2020 and compare their changes with the glaciers from other parts of Himalaya.

Location of the 3 benchmark glaciers in Bhutan

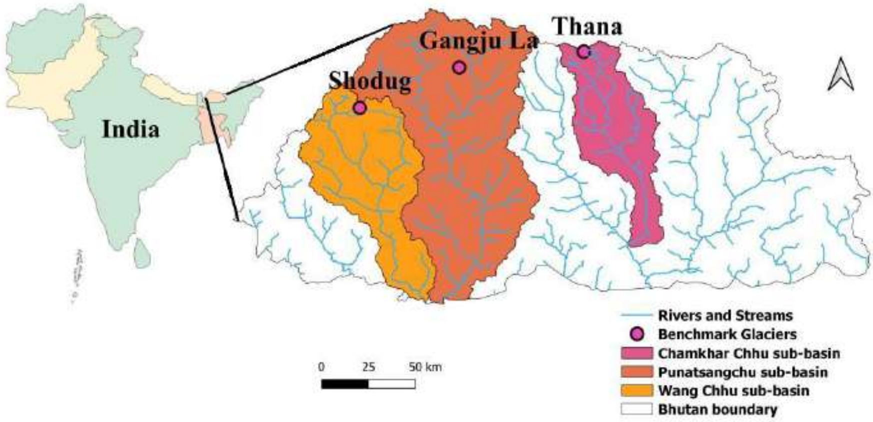

Figure 1: Location map of Thana, Ganju La and Shodug glaciers in Bhutan

The three (3) glaciers (clean type) considered for this study namely Thana, Ganju la and Shodug glaciers are located in Chamkhar chu, Pho Chu and Thim Chu sub basins respectively. They have been chosen to have uniform coverage across the northern frontier of the country and these glaciers are also benchmark glaciers in Bhutan identified for long term monitoring. Their locations are shown in Figure.1

Thana glacier, the largest of the three sample glaciers, has a surface area of 3 km^2. It is located in the headwaters of Chamkhar Chu in central Bhutan at 28.17ºN and 90.36ºE and has an elevation range of 5100 m to 5700 m. Thana glacier has a south-east aspect. Gangju la glacier is a small clean type glacier with a surface area of 0.202 Km^2 and is located at 27.94ºN & 89.95ºE in the headwaters of Pho Chu in western part of Bhutan (NCHM unpublished report, 2021). Gangju La glacier has a north easterly aspect. The glacier is located within an elevation band of 4900 masl to 5200 masl and lies to the west of Thana glacier. Shodug glacier is also a clean type glacier in the headwaters of Thim Chu and lies to the west of Gangju la glacier in western Bhutan. It has a surface area of 1.38 km^2 and located at 89.41ºE and 27.71ºN.

Data and method

Landsat TM (30m resolution) images for the years 1990, 1995, 2000, 2005, 2010 were used as base material to delineate glacier boundaries for Thana and Shodug glaciers. Since Sentinel products are available from 2016, sentinel 2 multispectral images (10 m resolution) were used to delineate glacier boundaries for the period 2020. These images are freely available at http://scihubcopernicus.eu . The details on the imageries used in this study are given in Table 1. For Gangju La glacier, no suitable satellite images of the area were available, however, ground based GPS data collected using GNSS were available for period 2004 – 2020 for Gangju La, 2016-2020 for Thana and 2020 for Shodug glacier.

Table 1: Details of imageries

Image	Image ID	Path-Row	Image Resolution	Acquisition Date
LandSat	LANDSAT/LT05/C01/T1_TOA/LT05_138041_19901216	WRS_PATH: 138, WRS_PATH: 41	30	1990-12-16
	LANDSAT/LT05/C01/T1_TOA/LT05_139041_19951221	WRS_PATH: 139, WRS_PATH: 41	30	1995-12-21
	LANDSAT/LE07/C01/T1_TOA/LE07_138041_20000930	WRS_PATH: 138, WRS_PATH: 41	30	2000-09-30
	LANDSAT/LT05/C01/T1_TO	WRS_PATH: 138,	30	2005-11-07

	A/LT05_1380 41_20051107	WRS_PATH: 41		
	LANDSAT/LT 05/C01/T1_TO A/LT05_1380 41_20100121	WRS_PATH: 138, WRS_PATH: 41	30	2010-01-21
Sentine l 2	SENSING_ORBIT_NUMBER : DECENDING, SENSING_ORBIT_NUMBER :33		10	2016-10-27
	SENSING_ORBIT_NUMBER : DECENDING, SENSING_ORBIT_NUMBER :33		10	2020-10-31

Method

To analyze the terminus status and overall aerial changes for three clean type glaciers in Bhutan and compare these changes with glaciers in other Himalayan regions, manual delineation approach was adopted for extracting the glacier boundaries for different years. Manual onscreen delineation method was opted over automated techniques mainly because of very few glacier samples (only three glaciers) and also considering minimum error compared to automatic delineation method (Lama et al 2015). Paul and others (2013) as cited in Das and Sharma (2018) has also shown that using automated techniques for glacier boundary mapping, bias significantly increases for glaciers with surface area < 1 km^2. All operations were carried out in Arc GIS and QGIS.

Result

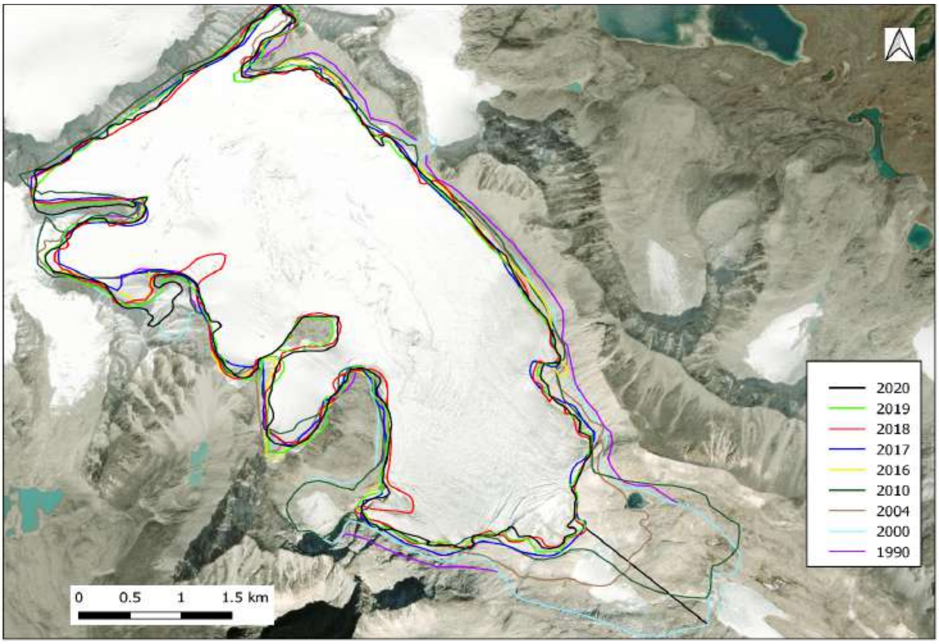

Figure 2: Terminus position and glacier boundary of Thana glacier from 1990 to 2020

Figure 2 shows the terminus position of Thana glacier from 1980 to 2020. For the analysis, only the data from 1990 were considered for consistency in the timeframe. Based on the analysis it was observed that the terminus of Thana glacier has receded 74 m from 1990 to 2000, 122.4 m between 2000 to 2010 and 301 m from 2010 to 2020. In total the terminus of this glacier retreated by 497.4 m in the last 30 years. This shows that on average, Thana glacier is receding at a rate of 16.58 my^{-1} (Table 2). Similarly, the surface area of Thana glacier was measured to be 5.028 km^2 in 1990 and within a span of 30 years the surface area of the glacier decreased to 3.504 km^2 which translate to 30.31% (Table 2) reduction with an annual average shrinkage rate of 1.01%.

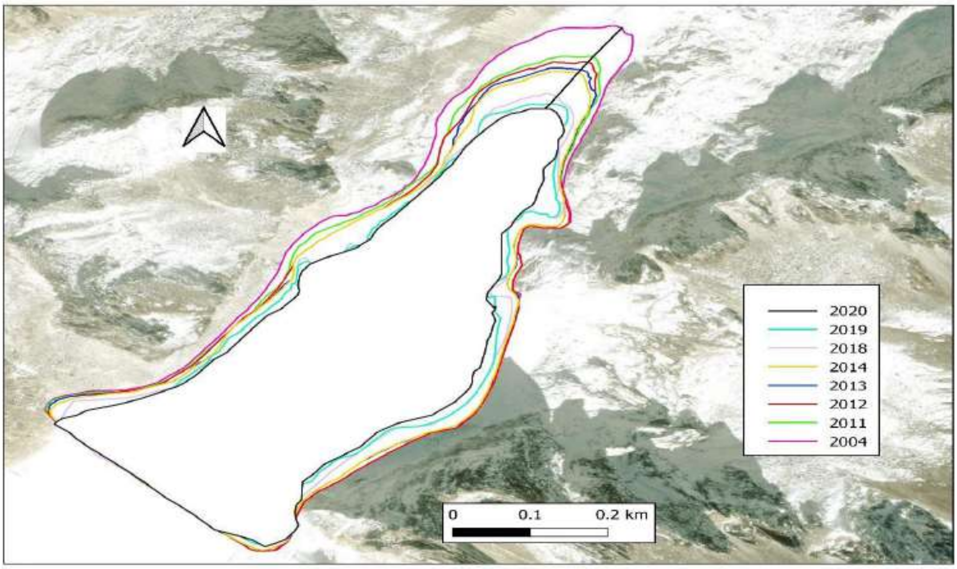

Figure 3: Terminus position and glacier boundary of Gangju la glacier from 2004 to 2020

Figure 3 shows the terminus position and glacier boundary of Gangju la glacier. Since no suitable images could be found for this glacier, the terminus positions marked in figure 3 are ground based data collected during the annual glacier monitoring field programs using GPS. That is also the reason for having data only from 2004 for this glacier. Based on the available terminus position data, Gangju la glacier has retreated its terminus by 196.4 m during the last 16 years (2004 to 2020) showing an average retreat rate of 12.27 my^{-1} (Table 2). In terms of surface area, the glacier surface area decreased by around 29.89% (Table 2) during the same period (2004 to 2020) resulting in an annual aerial shrinkage rate of 1.86%.

Unlike Thana and Gangju la glaciers, Shodug glacier has a complex terminus which is basically due to topography and terrain. Figure 4 shows the terminus position and glacier boundary of Shodug glacier. As seen from the satellite image (Fig.4), the glacier does not have a single tongue converging to a common lowest point but rather has a broad and irregular terminus area. Therefore the terminus retreat was estimated by measuring along three different lines in the terminus area (A-A'. B-B' and C-C' as shown in Fig.4). Along line A-A', the terminus of Shodug glacier receded by 225 m from 1990 to 2020 (30 years). The terminus position of the glacier retreated by 188 m along B-B' and along C-C' the terminus moved up by 218 m in the same period. The average retreat for Shodug glacier is calculated considering the retreat along the three different lines and was found to be 91.66 m for the period 1990-2000; 40 m for the period 2000-2010 and 78.66 m from 2010 – 2020 respectively.

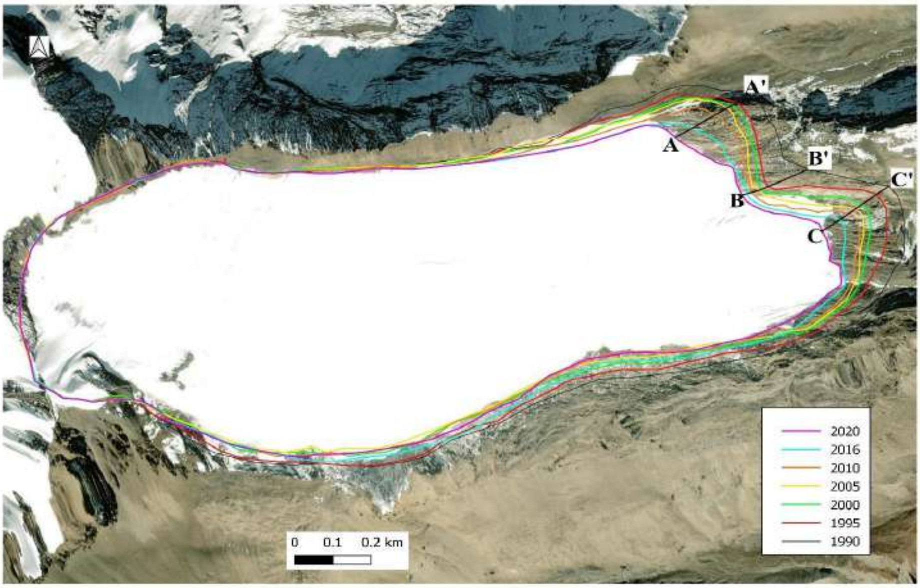

Figure 4: Terminus position and glacier boundary of Shodug glacier from 1990 to 2020

Based on the average retreat along line A-A', B-B" and C-C' the average retreat rate for Shodug glacier was estimated to be 7.01 my^{-1} during the last 30 years from 1990 – 2020 (Table 2). Retreat along line A – A' was found to have similar trend (Fig 5) with the other two glaciers (Gangju La and Thana) giving a retreat of 48 m, 55 m and 125 m for the period 1990-2000, 2000-2010 and 2010 -2020 respectively with an average retreat of 7.6 my^{-1}. Similar to other glaciers in Bhutan, Shodug glacier also has undergone changes in terms of area shrinkage. The glacier lost about 15.24% (Table 2) of its surface area in 30 years from 1990-2020.

Thana glacier lies to the east of both Gangju La and Shodug glaciers and is located in the headwaters of Chamkhar chu in Central Bhutan. Shodug glacier is the western most glacier among the 3 glaciers and is located in the headwaters of Thim Chu river in western Bhutan (Fig.1). On comparing the terminus retreat of the three glaciers, the result shows that Thana glacier is receding at a faster rate followed by Gangju La and Shodug glaciers (Fig.5). The findings also show that all the three glaciers studied for this article are showing accelerated terminus recession in recent times (for the period 2010-2020). Although Shodug glacier shows a different trend initially but agrees well with the recent increasing retreat of its terminus with the other two glaciers. However, retreat of terminus along A-A’ of Shodug glacier shows a similar trend with the other two glaciers (Figure.5).

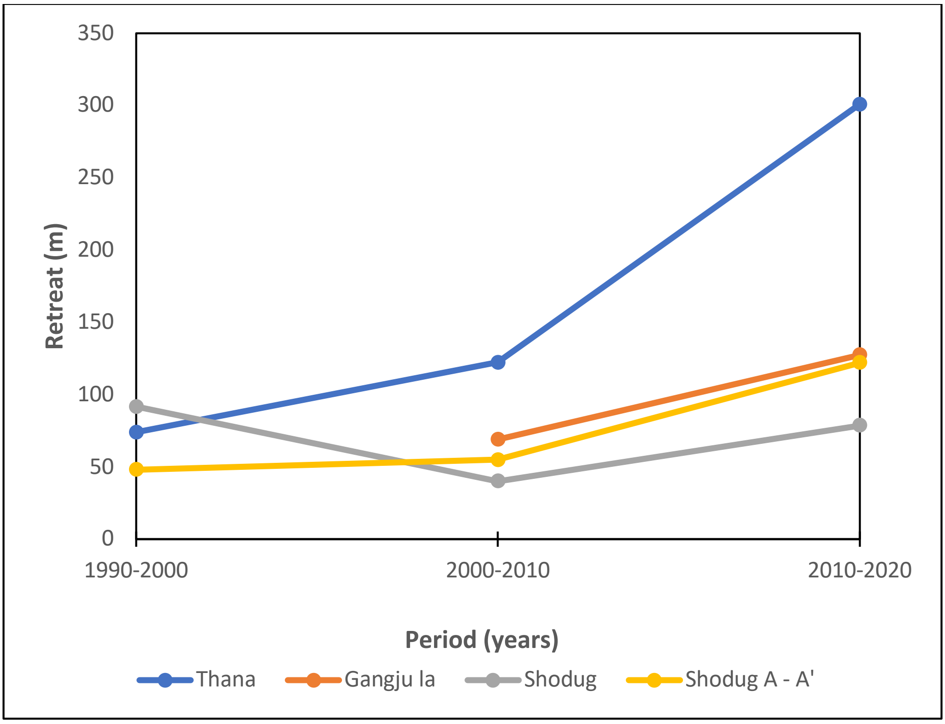

Figure 5: Terminus retreat of Thana, Gangju La and Shodug glaciers in Bhutan. (Grey line: average retreat of line A-A’, B-B; and C-C’ of Shodug glacier; Yellow line: retreat along line A-A’ which shows uniform retreat and trend similar to Gangju La and Thana glaciers).

Table 2: Terminus retreat rate and area change of Thana, Gangju La and Shodug glaciers in Bhutan

SL. No	Glacier Name	Time Period (Year)	Terminus Retreat rate (m/year)	Surface area change (%)
1	Thana	1990-2020	16.58	30.31
2	Gangju La	2004-2020	12.27	29.89
3	Shodug	1990-2020	7.01	15.24

Table 3: Comparison of retreat rate and aerial shrinkage of glacier in different region along the Himalaya

Region	Glacier Name	Period	Terminus retreat rate (m/year)	Aerial change (%)	Source
Western Himalaya	Central Karakoram	2001 - 2010	-	+0.6%	Minora et al 2013
	Pensilungpa	1993-2016	6.62	2.56	Garg PK et al 2021
	Jankar Chhu watershed	1971-2016	-	11.9±2 (clean ice)	Das & Sharma 2018
	Chorabari	1962-2010	6.4	11	Dobhal et al 2013
Nepal	Mustang/ Hidden valley	1980 – 2010	3.86 - 13.88	21.87	Lama et 2015
	Rikasamba	1989-2013	18	-	Stumn et al 2021
	Yala	1974-2016	8.2	-	
	AX010	1978-1999	5.21 (mean)	26.31	Fujita et al 2001

	Sagarmatha	1962 - 2011	6.1±0.2	13±3.1	Thakuri et 2014
Tibet (China)	Qomolongma & Xixiabangma area (north slope)	1966 - 2004	4 -9.5	-	Ren et al 2006
Sikkim (Eastern Himalaya)	Sikkim	1988 – 2018	10.82-23.44	1.32 – 41.7(calculated)	Guha.S 2022
	Sikkim	1989/90 - 2010	-	3.3±0.8	Basnet et al 2013
	Sikkim	2000-2018	-	19.78	Hazra et al 2019
	East Rathong	1976-2009 1997-2009	13.3 19.5	-	Luitael et al 2012
Bhutan	Shodug	1990 – 2020	7.01	15.24	
	Gangju La	2004 – 2020	12.27	29.89	This Study
	Thana Bhutan	1990 – 2020 1980 - 2010	16.58 -	30.31 23.3±0.9	Bajracharya 2014

Due to its vastness, the Himalayan arch is home to thousands of glaciers and because of its geographical extent, the behavioral characteristics of the glaciers vary from region to region. Status of the terminus and aerial shrinkage of glaciers along the Himalayan range is presented in Table 3.

Retreat rates and aerial shrinkage of the glaciers in different regions along the Himalayan arc were compared from various sources (Table 3). A retreat rate of 6.62 to 6.68 my^{-1} has been reported by different authors for the glaciers in western part of the Himalayas with few glaciers experiencing snout advance especially in the Karakoram region (Minora et al, 2013; Bahuguna, 2014; Das & Sharma, 2018; Garg et al, 2021; Guha S. 2022) while rates ranging from 3.86 to 18 my^{-1} were reported for the glaciers in Nepal (Fujita et al, 2001; Lama et, 2015; Stumn et al, 2021). On the northern slope in Central Himalayas, retreat rates ranging from 4 to 9.5 my^{-1} were observed (Ren et al, 2006) and in this study, glaciers of Bhutan Himalaya were found retreating with an annual retreat rate ranging from 7.01 to 16.58 my^{-1}. For the glaciers in Sikkim Himalaya which lies more to the eastern part of the Himalayas, retreat rates between 10.82 to 23.44 m per year was reported (Luitel et al, 2012; Basnet et al, 2013; Hazra et al, 2019; Guha S, 2022). An important feature observed while comparing the retreat rates of the glaciers along the Himalayan range is the increasing trend in retreat rates from west to east.

Discussion

(a) Variation in retreat and aerial shrinkage for Shodug, Gangju La and Thana glaciers in Bhutan

The three bench marked glaciers in Bhutan (Shodug, Gangju La and Thana) are all undergoing rapid change in terms of terminus retreat and areal shrinkage. The retreat rate of these three glaciers was found to range from 7.01 to 16.58 my^{-1} with an average retreat rate of 11.95 my^{-1} (average retreat rate of 3 glaciers) for the period between 1990 to 2020. The aerial shrinkage for the same glaciers was found to range from 15.24% to 30.31% with an average shrinkage of 25.14% (average shrinkage for the 3 glaciers for the same period). Karma et al (2003) reported a retreat rate of 7.36 my^{-1} (horizontal retreat rate) and an aerial shrinkage of 8.1% between 1963 and 1993 for debris free glaciers in Bhutan. Tshering and Fujita (2016) also reported retreat rates ranging between 8 – 17 my^{-1} with an average terminus retreat rate of 11 my^{-1} for Gangju La glacier and highlighted the accelerated mass loss for the period 2003 – 2014. Comparing the retreat rates and aerial shrinkage between 1963 – 1993 (karma et al, 2003), 2003 – 2014 (Tshering and Fujita, 2016) and the present study, the result indicates that the glaciers in Bhutan are retreating and losing mass at an accelerated rate significantly in recent time. Glaciers are excellent indicators of changes taking place in the parameters of the climate system (Das & Sharma, 2018). However, the response of a glacier to climate is complex in nature which is also governed by various factors such as size, aspect, gradient and type (Dobhal & others, 2013). Nevertheless, various authors attributed such trend of glacier variation in terms of terminus retreat and aerial shrinkage in the Himalayan region to changes in climate parameters particularly temperature and precipitation (Fujita et al, 2001; Ren et al, 2006; Basnet et al, 2013; Minora et al, 2013; Shangguan et al, 2014; Thakuri et al, 2014; Salermo et al, 2015; Das & Sharma, 2018; Garg et al, 2021). Analysis of temperature and precipitation from 15 meteorological stations in Bhutan for the past 21 years (1996 – 2017) reveals an increasing trend in temperature and slightly decreasing trend in precipitation (NCHM,2019). Therefore, in conformity with the findings of above references cited, it can also be suggested that the recent acceleration in terminus retreat and aerial shrinkage found on the glaciers in Bhutan can be due to the combined effect of increasing temperature and decreasing precipitation.

An interesting finding in the present study is the zonal variation of the terminus retreat rate between the glaciers located in western and those lying to the eastern region. Shodug glacier is located in the western part of the country and Gangju La glacier lies to the east of Shodug followed by Thana glacier which is located further east (Figure 1). All three glaciers lie in similar topography and at similar elevation range. Except for Gnagju La glacier which has a northerly aspect, both Shodug and Thana glaciers have southerly aspect. The average retreat rate of Shodug, Gangju La and Thana glaciers are 7.01 my^{-1}, 12.27 my^{-1} and 16.58 my^{-1} (Table 3) respectively indicating that retreat rate increases from west to east. Such zonal variation in glacier fluctuation was ascribed to mass balance characteristics of summer accumulation type of glaciers (Karma et al, 2003) which can also be closely linked to variation in zonal climate parameters. However, in the absence of data on zonal variation of temperature and precipitation within Bhutan, currently such linkage cannot be established in the present study. Non availability of climate data from the high altitude area in the country is also an impeding factor to develop such zonal correlation.

(b) Comparison of glacier variation in terms of terminus retreat rate and aerial shrinkage along the Himalayan range

Variation of glaciers in terms of terminus retreat rate and area shrinkage along the Himalayan range is presented in Table 3. It would be an ideal case if all the glaciers considered for comparison belong to the same type of debris free glacier since these types of glaciers are considered to be more sensitive to climate (Karma et al. 2003). With absence of data for debris free glaciers from certain regions, information and data from few debris covered glaciers were also taken into consideration to provide a holistic comparative perspective.

Based on the data from various sources compiled and compared in table 3, variation in terminus and area change is not uniform throughout the Himalayan range. In the western Himalaya and Karakoram region, variable glacier fluctuations were reported. Although the general notion of glacier losing mass through retreating and aerial shrinkage are reported (Das & Sharma, 2018; Garg et al, 2021), there were stagnant and even increasing glacierized areas reported (Minora et al, 2013; Bahuguna et al, 2014). Different authors related such variable glacier fluctuation phenomena in Karakoram and western Himalaya to different reasons. Bahuguna et al (2014) stated that the reason for 13 glacier advancement cases in the Karakoram region from 2001/2002 to 2010/2011 was due to the region being fed both by mid-westerlies and south-west monsoon. Minora et al (2013) related similar condition of glacier in stable or experiencing slight advancement in central Karakoram to slight drop in summer minimum temperature and general increase in winter wet days. For the glaciers experiencing decreasing area and retreating terminus in western Himalaya, higher mean air temperature and decreasing trend in precipitation are pointed out to be the main influencing factors (Das & Sharma, 2018; Garg et al, 2021).

For the Central Himalaya, data from a few glaciers of Indian Himalaya lying at the periphery of western Nepal, Nepal and southern Tibetan Plateau were considered for this study. Unlike in the case of Karakoram-western Himalayan region, most of the earlier literatures reported retreating, shrinking and stable glaciers in terms of terminus and surface area (Fujita et al, 2001; Karma et al, 2003, Ren et al, 2006; Bahuguna et al, 2014; Shangguan et al, 2014; Thauri et at, 2014; Salermo et al, 2015, Tshering and Fujita, 2016). Fluctuation and variation of glaciers in the central Himalayan region were related to various causes. Higher mean summer air temperature around glacier AX010 was pointed out to be the main reason for rapid shrinking of the glaciers in the 1990s (Fujita et, 2001). The zonal fluctuation of glacier terminus from west to east and north to south within Nepal was related to mass balance characteristics of glaciers lying in humid region under the influence of monsoon (Karma et al, 2003) and others associated such diminishing trend of glaciers in terms of terminus retreat and surface area reduction to combined impact of increasing temperature and decreasing precipitation in the region (Ren et al, 2006; Shangguan et al, 2014; Thakuri et al, 2014). Air temperature and precipitation were considered to be the two most common factors related to glacier fluctuation and Salermo et al (2015) argued that the weakening monsoon to be a more important factor and cause for glacier retreat and shrinkage in the central Himalayas.

As for the eastern Himalayas, available data from Sikkim and Bhutan on glacier variation reveals that in general glaciers in this part are receding at higher rate and therefore shrinking more than the glaciers in other parts of the Himalayan range (Table 3). The analysis of minimum temperature and precipitation from the meteorological station at Gangtok for the period 1987-2011 shows that summers are becoming hotter and winters are becoming warmer with no significant changes in precipitation (Basnet et al, 2013). Similarly, the record for 21 years (1996-2017) shows an increasing trend in temperature with a slight decreasing trend in precipitation in Bhutan.

General trend of glacier terminus retreat rate and shrinkage in area were found to increase from west to east along the Himalayan range (Table 3). As highlighted by Salermo et al (2015), temperature and precipitation are the two most important factors responsible for glacier fluctuation. Due to its large extent, the glaciers in the Himalayan range are under the influence of different climatic conditions. Glaciers in the Karakoram-western Himalayan range are under the influence of both westerlies in winter and south-west monsoon in summer favoring accumulation both in winter and summer. There were cases of increase in the number of winter wet days reported in the Karakoram-western Himalaya (Minora et al, 2013) which probably would have been the factor for advancing glaciers in the region. Although there were findings showing glaciers in this region have diminished in size, the rate of recession was found to be less than the glaciers located towards the eastern part of the Himalayas (Dobhal et al, 2013; Garg et al, 2021). On the other hand, glaciers in the central and eastern Himalayan region receives\ much of their accumulation from the south-west monsoon in summer which is why they are termed as summer accumulation type of glaciers (Ageta & Higuchi, 1984). Many findings reported cases of increasing temperature and decreasing precipitation trend in the recent times in the central and eastern part of the Himalayas (Fujita et al, 2001; Ren et al, 2006; Thakuri et al, 2014; Shangguan et al, 2014; Salerno et al, 2015). By geographical location, the intensity of the monsoon is higher in the eastern part of the Himalayas. Glaciers in this part of the region are found to be more sensitive to temperature change than the other types since it can cause change in precipitation phase which can affect both surface melting and surface albedo (Fujita & Ageta, 2000; Fujita, 2003) resulting in higher retreat rate and greater mass loss. Some of the glaciers in table 3 show inconsistency in this trend mainly due to nature of their type (large debris covered glaciers) which are controlled more by the non-climatic factors.

Conclusion

The objective of the study is to investigate recent glacier variation in Bhutan Himalaya based on the status of terminus retreat and surface area shrinkage and compare them with the glaciers in other parts of Himalayan range. Based on the findings from the study, the following are the conclusions drawn:

1. Terminus of Shodug and Thana glaciers have retreated 210.4 m and 497.4 m for the period 1990-2020 (30 years). Gangju La glacier has retreated its terminus by 196.4 m from 2004 to 2020 (16 years). The average retreat rate for Shodug, Thana and Gangju La glaciers are found to be 7.01 my^{-1}, 16.58 my^{-1} and 12.27 my^{-1} respectively.
2. The retreat rate of all three glaciers seems to have accelerated in the recent time (2000-2020) as seen from Figure.5.

3. In terms of surface area, all three glaciers in Bhutan Shodug, Gangju La and Thana glaciers have shrunk by 15.24%, 29.89% and 30.31% respectively in the same period mentioned above for the respective glaciers.
4. The findings also show some zonal difference in glacier variation within Bhutan. Thana and Gangju la glaciers which lie to the east of Shodug glacier show higher retreat rate implying an increasing trend in retreat rate from west to east.

Based on the available information on climate parameters (Temperature and Precipitation trend) for the last 21 years (1996-2017), such a trend in glacier variation can be attributed to increasing temperature trend and slight decrease in precipitation trend. In the absence of data and information on zonal differences in climate parameters, especially from the high altitude region in Bhutan at present, zonal differences in glacier variation within Bhutan is difficult to explain.

5. There are thousands of glaciers located in the whole Himalayan range. Due to regional differences in climatic conditions, glaciers respond and vary quite uniquely along the Himalayan range. Glaciers in the Karakoram and western Himalayan region were found to be either retreating at lower retreat rates or are in a stagnant state. There are glaciers even reported to be advancing. All or most of the glaciers considered in this study in the central Himalayan range are retreating and diminishing in surface area over the years and similarly the eastern Himalayan glaciers which includes Bhutan are experiencing an accelerated retreat rate recently. The Karakoram and western Himalayan region are under the influence of both westerlies and south west monsoon which are the primary nourishing sources for the glaciers. Although the normal temperature trend shows an increasing trend all along the Himalayan range, but some cases of drop in summer minimum temperature were also reported from the western Himalaya with an increase in the number of winter wet days. Therefore, low retreat rates and advancing cases of glaciers could be due to such climatic

trends in this area. On the contrary, the glaciers in central and eastern Himalaya are summer accumulation type of glaciers. The combined effect of higher sensitive nature of summer accumulation type of glaciers to higher temperature with weakening monsoon could be the causes for higher retreat rates and greater shrinkage of glaciers in this region.

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Verification of 24-hour Surface Maximum and Minimum Temperature Forecast in Bhutan for the year 2022

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Abstract

Weather forecast verification is carried out to measure the accuracy of forecasts by comparing observed data by weather instruments to operational forecasts. Verification of the daily 24-hour surface maximum and minimum temperature forecast for 20 forecasting points was carried out for the year 2022 using the Agro-meteorological data operated by the National Centre for Hydrology and Meteorology. The methods used for the verification in this study include mean error, root mean square error, and correlation coefficient.

The results show that for the year 2022, the maximum temperature was over-predicted for most forecasting points, with RMSE ≤ 2°C of 70.26%. The minimum temperature was slightly under-predicted, with RMSE ≤ 2°C of 84.05%, however with better forecast accuracy. Maximum temperature accuracy was higher in autumn and lower in spring, and minimum temperature accuracy is higher in summer and lower in winter. A lower magnitude of the forecast error for temperature was observed for the southern region. The results concluded a good correlation between the observed and forecast temperature.

Keywords: Temperature Forecast Verification, Mean Error, Root Mean Square Error, Correlation coefficient.

Introduction

The weather has a significant impact on many aspects of our lives. Accurate forecast benefits impact assessment of floods, drought, cold waves, heat waves and weather-related diseases. It also assists in the effective planning of day-to-day activities.

Advancements in weather and climate science, especially the significant developments in weather models, have improved forecast accuracy, resulting in an increasing demand for these services. Furthermore, to improve the accuracy, the verification of the forecast is crucial. According to the estimate made by the agribusiness, an agro-sector forecast can be put to economic use if it is 50–60% accurate (Seeley, 1994). Therefore, verification is essential for understanding the performance of operational forecasting to further develop forecast guidance to improve accuracy. Service users may have an incorrect perception of the reliability of forecasts, which can be understood by sharing appropriate verification information.

Weather forecast services in Bhutan started in 2007, as a unit under the Ministry of Agriculture then. Currently, as an autonomous agency of the Royal Government of Bhutan, the National Centre for Hydrology and Meteorology (NCHM) provides short-range (one-three days), pilot medium-range (up to 10 days), extended-range (monthly) and seasonal forecasts. For temperature forecast, NCHM uses many sources and models such as Weather Research and Forecasting (WRF) Model and Global Spectral Model (GSM). The WRF model has an average root mean square error (RMSE) of approximately 2-7 degrees Celsius for maximum and minimum temperatures (NCHM, 2020) . Since the Numerical Weather Prediction (NWP) models exhibit systematic errors in forecasts, mainly due to differences in topography on actual ground and the models, and approximation in the physical process of the models, the Kalman filter (KF) guidance is widely used to significantly reduce these errors (Galanis et al., 2002). The application of KF guidance (Kalman, 1960) for the post-processing of NWP model outputs using the observation data from the weather stations has been used by many meteorological organizations for a relatively long period of time. NCHM has recently started using the KF guidance for temperature forecasts. The application of such guidance is expected to significantly improve the accuracy of forecasts. Verification of forecast accuracy must be carried out to access the performance of such approaches in operational weather forecasting. Therefore, the main objective of this study is to validate using simple statistical methods, the accuracy of the surface maximum and minimum temperature for the next 24 hours for the year 2022 (1 January 2022 to 31 December 2022) by comparing the forecast data with the observation data from the 20 Agrometeorological stations (Class A), to provide guidance for operational weather forecasting for variables of surface maximum and minimum temperature.

Data

Observed Weather Data

In continuation of the surface temperature verification from 2018, this study accesses the surface maximum and minimum temperature of 2022 recorded by agro-meteorological stations (Class A) for the verification of the 24-hour maximum and minimum temperature. 2022 data was considered to evaluate the accuracy of temperature forecasts for the recent one-year period and access the accuracy of forecasts following the integration of KF guidance.

There are 20 Class A across the country (Figure 1), which are identified as forecasting points for weather forecasting for Bhutan. These stations are manned by field observers and reports data to the National Weather and Flood Warning Center (NWFWC) twice a day at 9:00 AM and 3:00 PM Bhutan standard timing (BST).

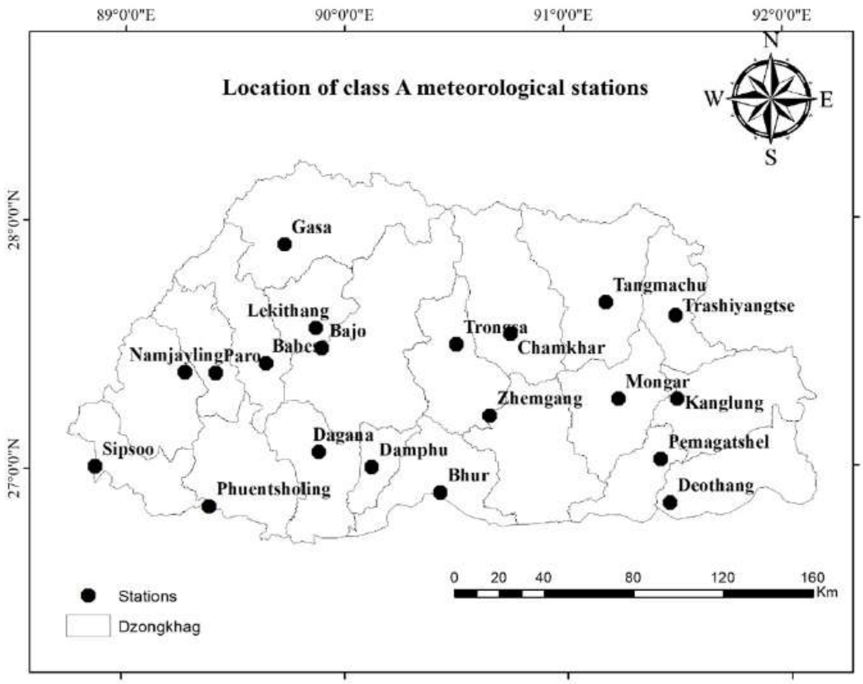

Figure 1: *Location of Agro-met (Class A) stations*

Forecast Guidance

NCHM uses many sources such as information from the Indian Meteorological Department, Thai Meteorological Department, user access websites for only National Hydrological and Meteorological Services and models such as Weather Research and Forecasting (WRF) Model and Global Spectral Model (GSM) for the 24-hour temperature forecast. WRF Environmental Modeling System (WRF-EMS) version 3.4 is a complete, full-physics, state-of-the science NWP model package that incorporates both the National Oceanic and Atmospheric Administration (NOAA) Environmental Modeling System and WRF model system into a single user-friendly, end-to-end forecasting system (Powers, et al., 2017). At NCHM, currently, WRF-EMS Version 3.4 Model is the only model available and runs every 6 hours for initial conditions of 00, 06, 12 and 18 UTC. The model has the capacity to run with a lead-time of 72 hours (three days). The model runs with a nested domain of 45 vertical levels and the parent domain and nested domain with the horizontal resolution of 15 km and 3 km respectively. The boundary initial conditions used for the model is from the Global Forecast System (GFS) model, which is a coupled model (atmosphere, ocean, land/soil and sea ice) with 64 vertical levels and has a horizontal resolution of 28 km. The Japan Meteorological Agency's GSM has a resolution of 0.1875 degrees (approximately 20 km) and runs with the lead-time of up to 11 days ahead covering the entire globe.

Numerical Weather Prediction models usually produce errors for forecast of near-surface weather variables due to the model's coarse topographic resolution, insufficient physical parameterizations, and cloud field uncertainties (Libonati et al., 2008). Therefore, NCHM applies the Kalman filter guidance to the WRF and GSM outputs to reduce such errors for the maximum and minimum temperature forecast for operational forecasting. This guidance is used by the forecaster to prepare the 24-hour temperature forecast.

Methodology

Continuous verification of temperature forecasts

In the continuous verification method, the forecast and observed data used for verification are a specific value of the variable, for example, temperature in ^{o} C (degree Celsius). Continuous verification scores can provide an overall measure of how the values of the forecasts differ from the observations and the forecast performance. Mean error (ME), root mean square error (RMSE) and correlation coefficient (CC) are common verification scores categorized under continuous verification approach (Stanski et al., 1989; World Meteorological Organization, 2014; Tiriolo et al., 2015). Similar methods were also used by (Subba et al., 2022) and (Sharma, et al., 2018) to verify the medium-range weather forecast for station points with observation data. These verification scores were coded in a Jupyter notebook (formally IPython notebook).

a) Mean error

Mean error (ME) or bias is the average of all the differences between forecast and observation over the verification sample. It represents a simple and informative score on the behavior

ur of the given variable. It is calculated either by averaging observation differences or by subtracting the mean observation from the forecast. Normally the bias is expressed as forecast minus observation, positive values indicate that the forecast is higher on average and negative values indicate that the forecast is lower on average. However, it is not an accurate measure, as it does not provide information on the magnitude of errors. It is possible for the bias to be 0 (perfect=no bias), but all the forecasts could actually have quite large errors. The value ranges from -∞ to +∞. The perfect score is equal to 0.

$$ME = (1/N) \sum (fi - fo) \quad \textbf{Eq (1)}$$

Where, fi = forecast data, fo = observed data, N= no. of data

b) Root mean square error

The root mean square error (RMSE) is a quadratic scoring rule, which measures the average magnitude of the error. Expressing the formula in words, the difference between forecast and corresponding observed values are each squared and then averaged over the sample. The square root of the average is taken. Since, the errors are squared before they are averaged, the RMSE puts greater influence on large errors than smaller errors, which may be a good thing if large errors are especially undesirable. The value ranges from 0 to +∞. The perfect score is equal to 0.

$$RMSE= (1/N) \sum (fi-fo)\ \hat{}2 \ \ldots\ldots\ldots\ldots \ \textbf{Eq (2)}$$

Where, fi = forecast data, fo = observed data, N= no. of data

As per World Meteorological Organization (WMO) guidance on performance assessment of public weather services, for the deterministic forecasts of values of continuous weather variables, one of the measure for measuring the accuracy is the "percent correct" of forecasts that are within some allowable range, e.g., within ±2°C or ±3°C (World Meteorological Organization, 2000). For this study, within ±2°C threshold is used to assess the accuracy of the forecast. (Sharma, et al., 2018) and (Kothiyal et al., 2017) used the same ≤ 2°C RMSE threshold as the "usable forecast" for the verification of continuous variables forecast.

c) Correlation coefficient

Correlation coefficient (CC) gives the measure of correspondence between the observations and forecasts. It is a good measure of association or phase error. It varies between -1 to +1; +1 being the perfect score. Correlation is perfect if the data points in the scattered plot all lie along any straight line with non-zero slope. Correlation is independent of the bias, so the line of perfect correlation need not pass through the origin.

$$CC = \frac{\sum(fi-f)(Oi-O)}{\sqrt{(fi-f)2}\sqrt{(Oi-O)2}} \ \ldots\ldots\ldots\ldots \ \textbf{Eq (3)}$$

Where, fi = forecast value, f= forecast mean value, fo =observed value, O=observed mean value

Result and discussion

Maximum temperature

The analysis of maximum temperature show that the average bias for all the stations was within ± 1 degree (Figure 2). Most of the stations over predicted the maximum temperature with the highest over prediction bias error of 1°C at Samdrup Jongkhar station. On the other hand, Punakha station has highest under prediction bias of average 0.8 °C. The average bias was negligible for Bumthang, Gelephu and Pemagatshel stations.

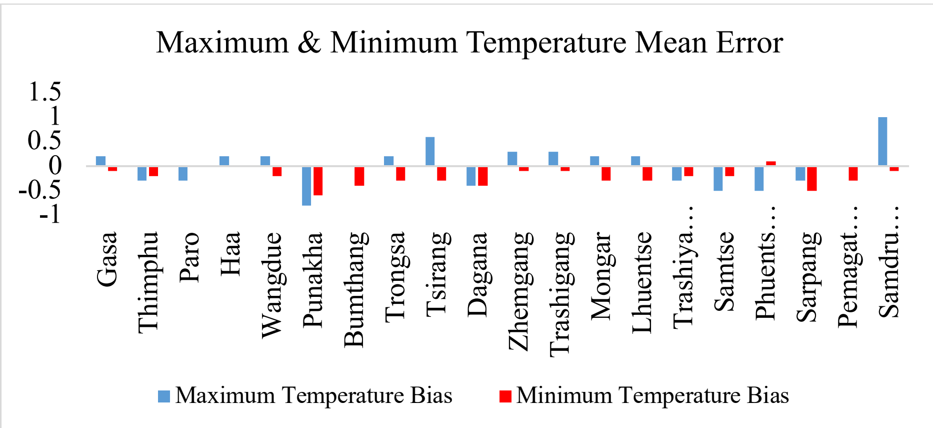

Figure 2: *Mean error of maximum and minimum temperature*

Overall, the forecast has a good correlation with the observation ranging above 0.70 for all the stations. Haa station has the highest correlation score of 0.89. Figure 3 shows a positive linear correlation association between the forecast and observed maximum temperature, which means lower (higher) forecast temperature values, tend to be associated with lower (higher) observed temperature. However, few dispersion is observed for most of the stations, which indicates that the bias between forecast and observed was higher for those data. The correlation was observed higher (>0.8) for the all stations in western and northern region (Figure 3). The difference of the accuracy and the correlation can be due to the complex topography and the microclimatic features in the different districts of the country, with the performance of the weather models and the KF guidance.

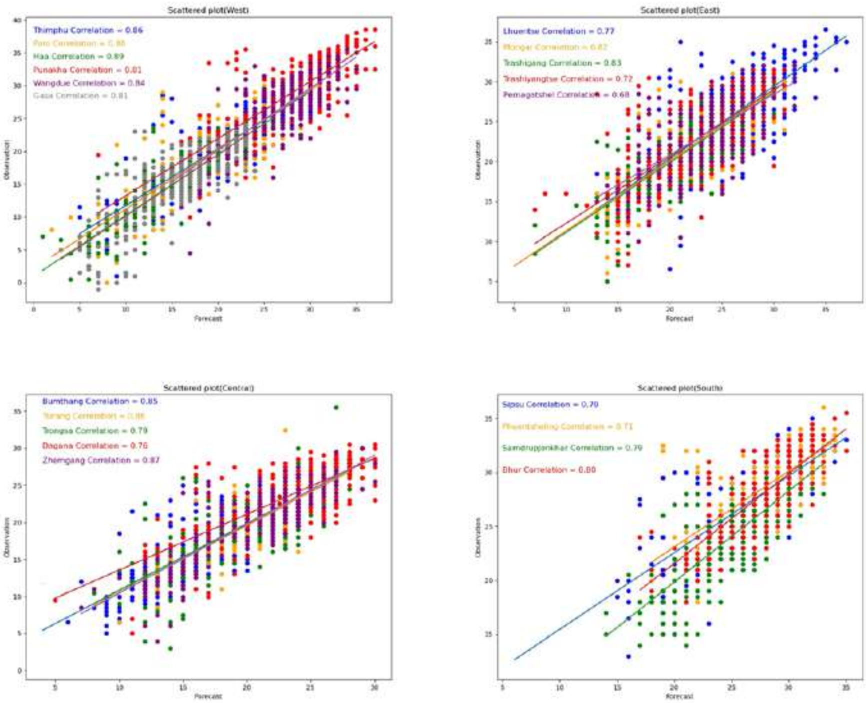

Figure 3: *Scattered plot of maximum temperature*

The annual RMSE of maximum temperature ranges from 2-3.5 °C for all the stations (Figure 4). Lhuentse station showed the highest RMSE with a score of 3.39. Region wise, the RMSE was observed higher for the eastern region (Lhuentse, Trashiyangtse and Pemagatshel). The 2022 accuracy analysis shows that the RMSE error ≤ 2 degree for maximum temperature forecast was 70.26% (Figure 5). The higher accuracy was observed in the autumn season with 79.1 % of the forecast within ±2°C followed by winter (68.03 %), summer (67.35 %) and spring season (66.58 %).

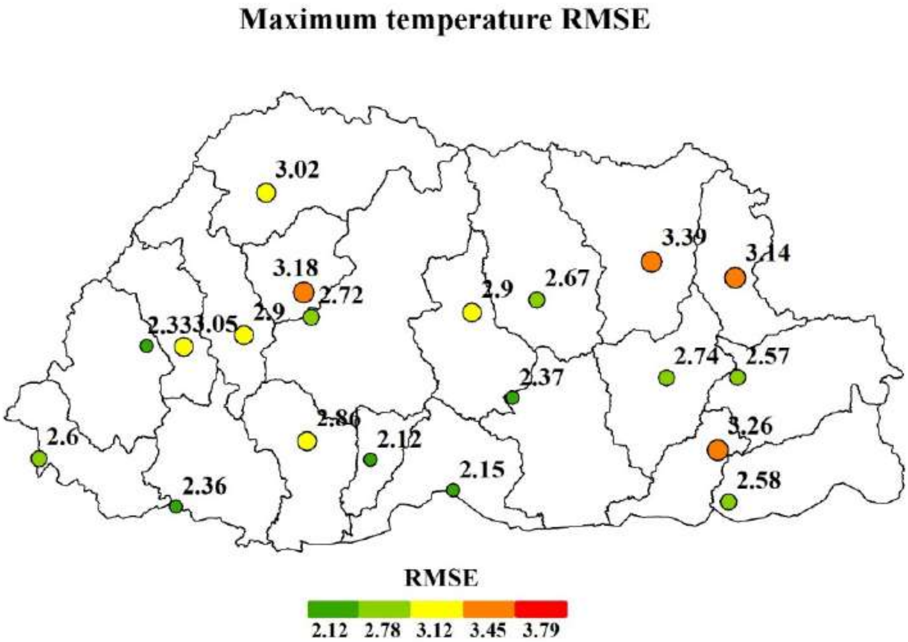

Figure 4: *RMSE of maximum temperature*

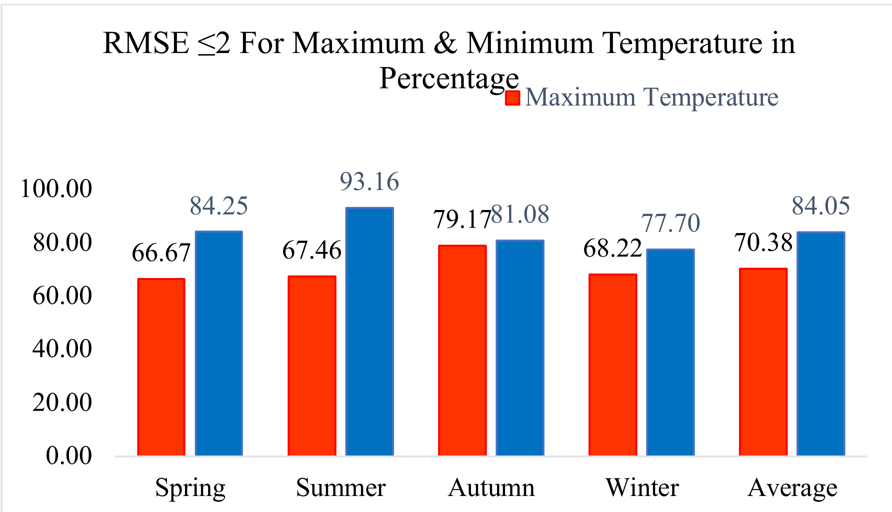

Figure 5: *RMSE value of ≤2 in percentage for maximum and minimum temperature*

Minimum Temperature

The minimum temperature of 24-hour weather for the year 2022 was slightly under-predicted for most of the station points with the highest average bias of –0.6 at Punakha station (Figure 2). Paro and Haa stations have the perfect score average bias of 0.0.

Overall, the forecast has a good correlation with observation above 0.90 for all the stations. Trashigang, Mongar and Pemagatshel station has the highest correlation score of 0.98. (Figure 6) shows a positive linear correlation association between the forecast and observed minimum temperature for most of the stations.

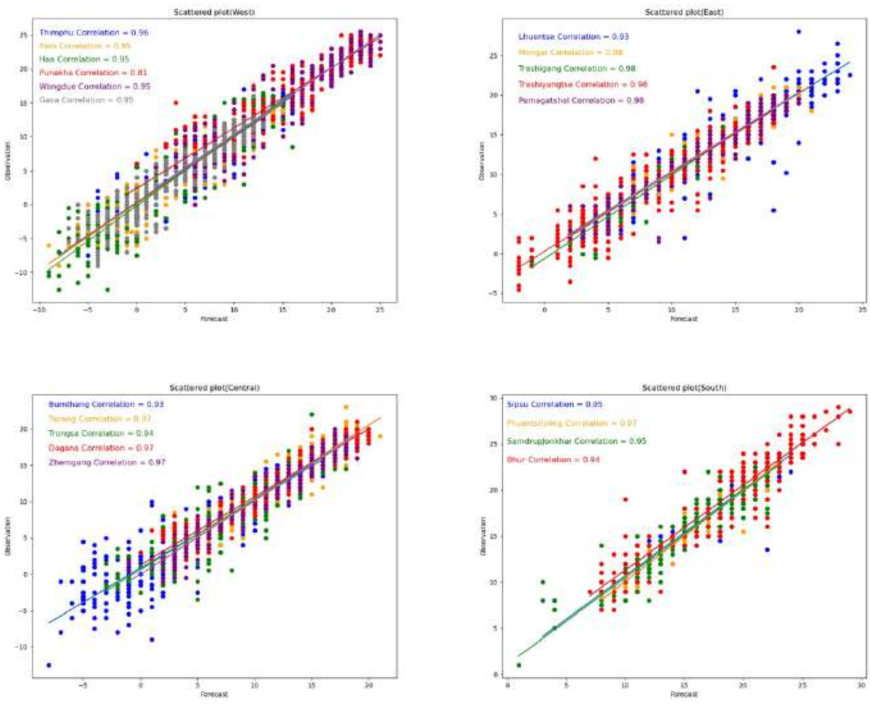

Figure 6: *Scattered plot of minimum temperature*

The RMSE for minimum temperature ranges from 1-2.5°C for year 2022. Almost all the stations in the western region (Thimphu, Haa, Paro, Wangdue and Punakha) observed RMSE greater than 2°C, whereas for the southern region, the RMSE was below 2 °C (Figure 7). Bumthang station has the highest RMSE with a score of 2.54 °C. The average minimum temperature forecast RMSE ≤2 degree for 2022 was 84.05% (Figure 5). Season wise, the minimum temperature was well predicted for the summer season (June, July, August and September) with 93.16%, of the forecast within ±2°C. Whereas, winter has the lower accuracy with 77.7%.

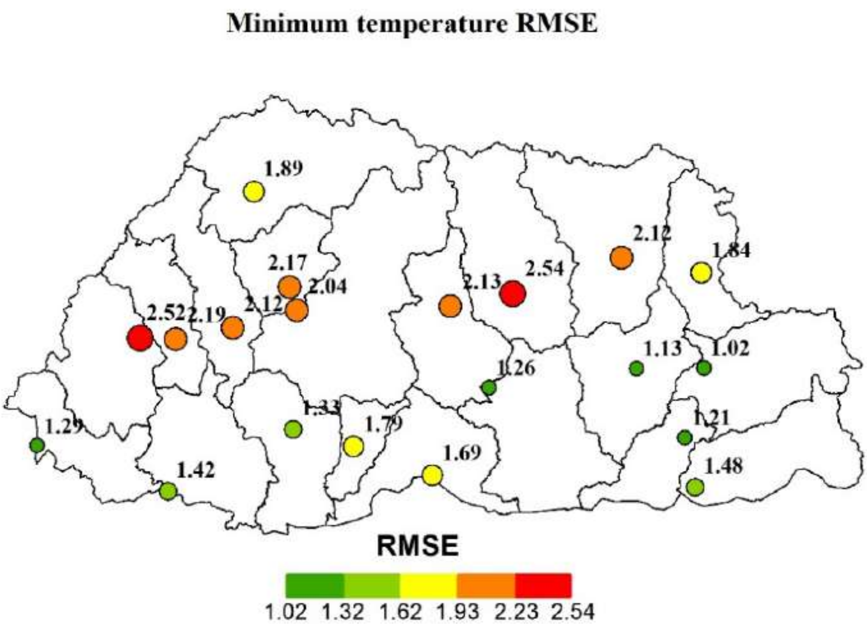

Figure 7: *RMSE of Minimum Temperature*

Conclusion

Reliable forecasts of surface temperature have a wide range of applications, in agriculture decision support, flood monitoring, tourism, heat wave monitoring, drought forecast, amongst others. The verification of 24-hour temperature forecast has been carried out for the individual station point using the past agro-met station data observed from the agro-met station for the year 2022. Verification of forecast enables the weather forecaster to identify the areas where the improvements are required.

The study showed the forecast has performed well in both maximum and minimum temperature in all the seasons for 2022. The accuracy for the minimum temperature was higher (84.05% of the forecast has RMSE <2) when compared with the maximum temperature (70.26%). It was observed that the maximum temperature was over predicted for Tashiyangtse station and under predicted for Punakha and Lhuentse stations with the average annual error magnitude of more than 3.1 degree. The results of the study indicate that the use of the Kalman filter has improved the forecast accuracy.

Further improvement of forecast accuracy can be explored through bias correction from the results of the study, which could address the over-prediction of maximum temperature at Tashiyangtse station and under-prediction at Punakha and Lhuentse stations, it is important to evaluate the performance of the forecast for these locations on a daily basis and implement bias correction techniques to improve accuracy. It is also recommended to enhance the weather models such at the Weather Research and Forecasting Model including data assimilation and parameterization, incorporating high resolution regional models, and advance statistical bias correction approach. Multi-model ensemble should be incorporated. Globally the ensemble of multiple weather model is regarded superior in most cases compared to single deterministic model. It’s also important to enhance data collection and monitoring through strengthening the infrastructure and resources for data collection and monitoring, including the maintenance and calibration of stations. This will contribute to the availability of high quality and accurate observations, leading to more reliable forecast verification and subsequent improvements. The verification study needs to be continued in the future as data becomes available.

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ASSESSMENT AND MAPPING OF WATER SOURCES IN BHUTAN: A comprehensive inventory and status of water sources used by the communities.

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ABSTRACT

The assessment and mapping of water sources in Bhutan records information on currently tapped water sources including their number, uses, types, status and general issues affecting them. Based on the issues of water sources drying around the country as reported through various sources and mainstream media, there was urgent need to assess the status of water sources and recommend appropriate interventions accordingly. A total of 7399 water sources currently used by communities were assessed and mapped through field visits and community consultations. The results indicate that springs are the main water sources, while 76% of the water sources recorded are used for drinking. The assessment also reveals that 0.9% of the water sources used in the past have dried up and 25.1% are in drying state. According to communities' view, climate change followed by forest degradation and deforestation are cited as the main drivers of water source drying up in Bhutan. The study also revealed that about 28% of the watersheds of water sources inventoried are degraded.

This study is an attempt to record and understand the status of water sources currently used and also to set up the baseline of the same. The need to conduct similar studies after certain interval in the future to assess the trend and validate the claims of water sources drying up along with impact of climate change and forest degradation and deforestation on water sources are discussed in this paper. Further, the study recommends relevant entities to initially focus on protection and management of water sources in drying state and associated watersheds and then proceed on to long term studies to enhance water source revival activities. Finally, the study advises relevant stakeholders to use the results of the same to make informed decisions and prevent wasteful expenditures in any water related activities.

Keywords: baseline, climate change, communities, drying water sources, current status

INTRODUCTION

Surface water in the form of springs, streams, lakes, rivers, ponds and marshes are the main water sources used by the humans. However, these water sources have now begun to dry up, and the problem is increasingly felt across the Himalayan region, (Sandeep Tambe, 2012); (Dendup, 2022). Population growth, urbanization, management issues, and limited stakeholder participation or multi-sectoral coordination issues (NEC, 2018) are expected to exacerbate the situation. While past attempts were made to inventory water sources (NEC,2018) and (WMD, 2019), these studies were incomplete and lacked comprehensive information, making it difficult to consider them a baseline for water sources in Bhutan. According to Bhatt (2015), almost 70% of water sources in the Himalayan region have decreased by half from their previous levels, with up to 5% of once-common waterfalls already having dried up. Despite this, the issue of drying up water sources, primarily springs, has not received sufficient attention, and it is exacerbated by the increasing demand for water, ecological degradation, and unsustainable land use practice. Although, Bhutan has abundant water resources with per capita water availability of 109,000 m^3 per year (NEC, 2016), there is imbalance in spatial and temporal distributions resulting in shortages in local areas. This is due to the fact that most of the rivers comprising of significant water resources in Bhutan run along the valley bottom and are not available for settlements, which are mainly located on the slopes. Settlements rely on smaller water sources, such as springs, streams, lakes, ponds, and marshes, which are reported to be drying up from many parts of the country leading to severe challenges for local people in obtaining water for their domestic consumption and irrigation (NEC, 2016). Additionally, the climate change is expected to have strong impact on water resources. The rise in temperature is expected to accelerate the retreat of glaciers, enhance the occurrence of extreme weather events, changing rainfall pattern with majority of rainfall occurring during the monsoon, and causing disasters such as floods and drying of streams (NCHM, 2019).

The situation is expected to worsen due to various problems such as increasing population, urbanization, management issues, and limited stakeholder participation or multi-sectoral coordination issues (NEC, 2018). In the past, attempts were made to inventory water sources (NEC, 2018),· (WMD, 2019); however those studies were carried out either in specific sites or incomplete and therefore information generated are inconclusive to consider as a baseline for water sources in Bhutan. Therefore, the present nationwide assessment and mapping of water sources attempts to list all the water sources currently tapped by the communities with the following specific objectives:

- To evaluate the types & current status of water sources, their uses and to take stock of the potential water sources in the vicinity of settlements,
- To assess and document the watershed conditions within which the identified water sources are located and,
- To build a baseline information of drying water sources and attempt to understand the causes for drying.

STUDY AREA

The assessment and mapping of water sources was carried out in all the 20 Dzongkhags covering 205 gewogs. The water sources include springs, streams, lakes, ponds and marshes, which are tapped by the communities for various purposes. Information collected include number, use, type, status, causes of water source drying and condition of the watersheds. The study also collected and analyzed available data and information of untapped water sources that have potential for the future use.

METHODOLOGY

Data collection

A structured survey questionnaire mixed with Focus Group Discussion (FDG) and Key Informant Interviews (KII) were used to collect the information on water use, status, water source drying and related issues from the communities. Types and amount of water sources were assessed through field surveys.

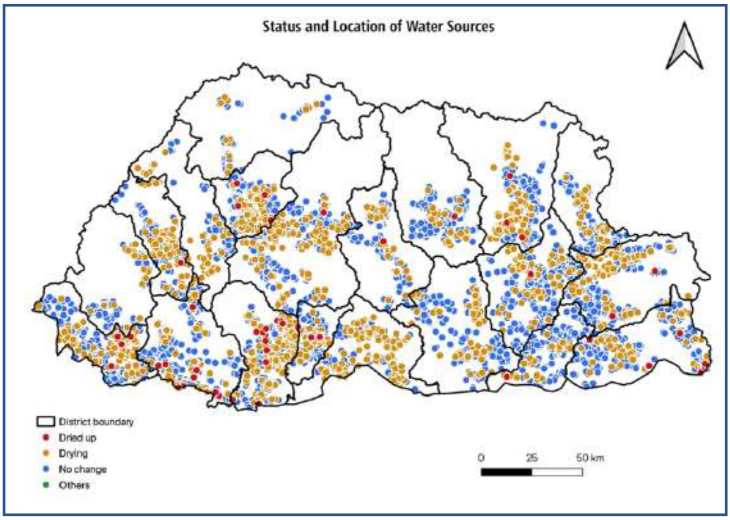

Figure1.***Status and location of water sources***

The coordinates of the water sources data were collected using GPS (Fig1). Based on the size of the springs, the discharges were measured using bucket, float, and current meters. GPS coordinates and water discharge measurement was done at the source or above the tapping points closest to the source to avoid double counting of the water sources due to additional tapping from the single source along the stretch. Information on the number of users per water source in terms of households was gathered through surveys, community consultations and confirmed through respective village heads and water caretakers.

The watersheds of each of the water sources were assessed individually or in a cluster. While independent streams or springs were assessed individually, the water sources that are within short distance from each other were grouped and assessed as one watershed. The number of watersheds to be assessed under each gewog or chiwog were delineated (desktop work) before the field work. Actual watershed assessment was done through field visit based on condition of the watersheds and downstream water use using the watershed classification guideline (WMD, 2016).

Data processing and analysis

GPS data was processed using ArcMap 10.2 and water sources were mapped on the Bhutan map. The information collected on water sources were computed in MS Excel spreadsheet and analyzed using pivot table. The data were for the whole country and inferences were drawn both at national and dzongkhag level based on appropriateness. Most of the results are presented in graphical form to allow easy comparison among dzongkhags or categories.

RESULTS:

Majority of the water used for drinking, irrigation and commercial purposes are obtained from surface water. These water sources include springs, lakes, streams, rivers, ponds and marshes. Assessment and mapping of water sources recorded 7399 water sources across the country. While assessment focused on water sources currently tapped for drinking, irrigation, commercial and other purposes, some potential water sources (269) that are in the vicinity of the settlement areas were also recorded. The assessment and mapping were carried in Spring (April-May) of 2021.

1. **Number of water sources used in each dzongkhag**

Among the 20 dzongkhags, Wangdiphodrang dzongkhag recorded the highest number of water sources (779) currently tapped for use followed by Dagana dzongkhag (719). Haa dzongkhag has recorded the least number of water sources (101). The number of water sources recorded under each dzongkhag is presented in figure 2.

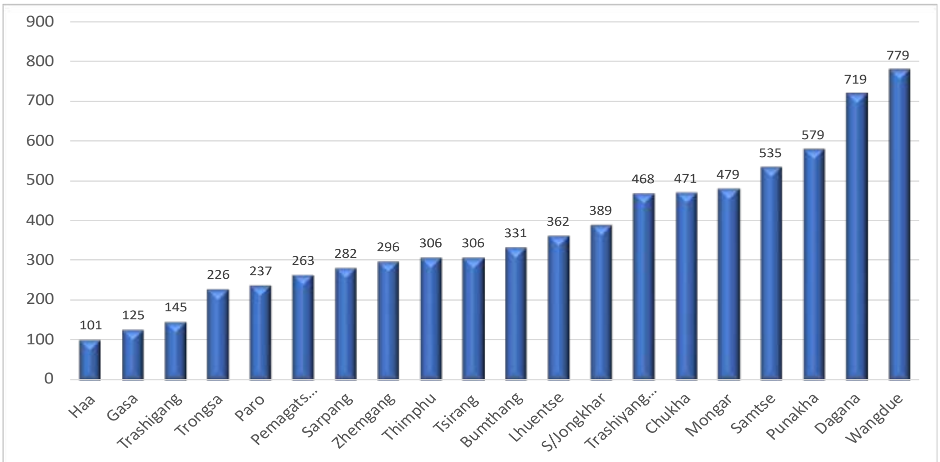

Figure 2: Number of water source in each Dzongkhag

2. Types of water sources

From the total of 7399 water sources mapped/surveyed, springs were found to be the highest water source type accounting to 67% (5001), followed by streams with 26% (1898), marshes 3% (200), ponds 2 % (168), rivers 1 % (81) and Lakes are currently tapped the lowest with 1% (51), (Fig 3).

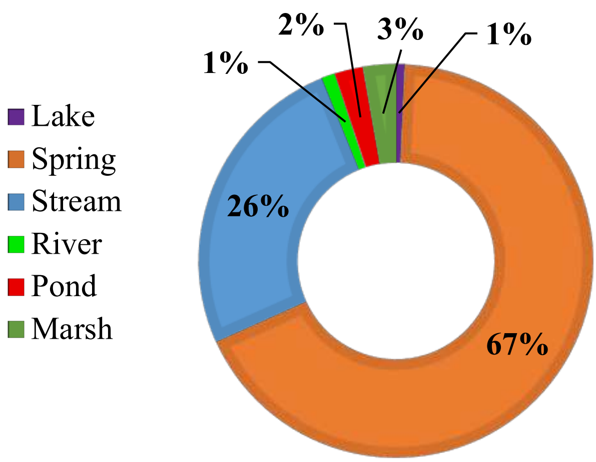

Figure 3. *Types of community water sources*

3. Uses of water sources

As shown in the figure below (Fig 4), there are overlaps in water use from single source and drinking is recorded as the highest use of water (5636) followed by irrigation (841). There are about 580 water sources that are used both for drinking and irrigation, while about 38 water sources are used for commercial purposes at the cottage and small industries scale. Survey also recorded 269 unused water sources that are potential for future use.

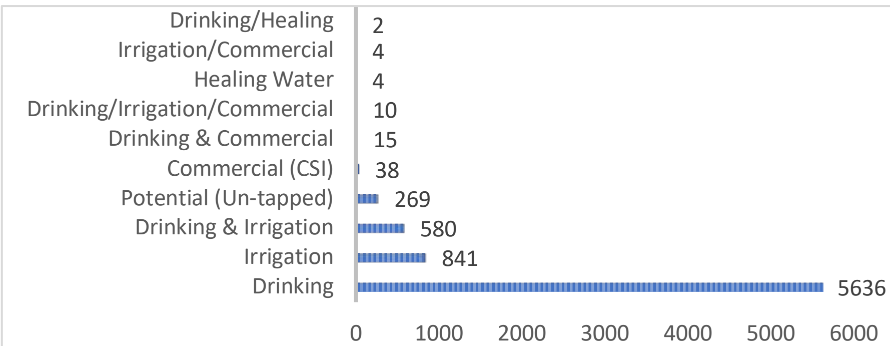

Figure 4. *Uses of water source*

4. Status of water sources

It was recorded that 0.9 % (69) of the water sources had been dried up over the years, 25.1 % (1856) are currently in drying up stage and 73.8 % (5457) are perceived to have not changed their discharge over the years. However, about 0.2 % (17) are not clear about their status and are marked as others (Fig 5). The distribution of water sources with different status located across the country are shown in figure 1.

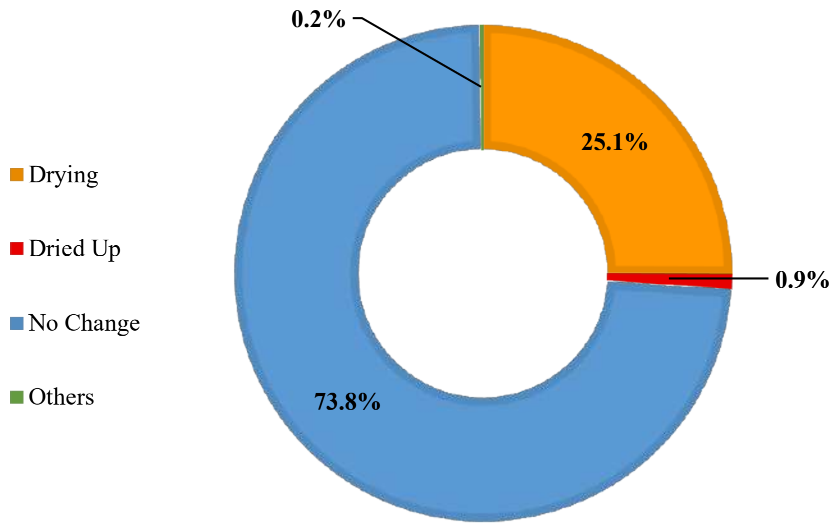

Figure 5. *Status of water source*

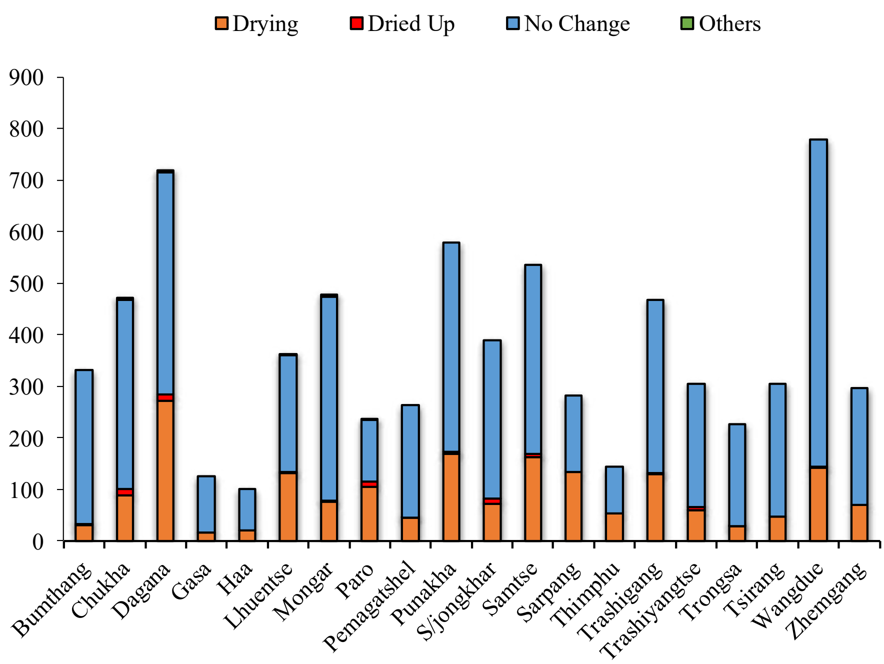

Figure 6. *Status of water source in each dzongkhag*

Among 20 dzongkhags, Dagana recorded the highest number of both dried up and drying water sources with 12 and 271 respectively, while Gasa dzongkhag recorded least number of drying water source with just 16 and no dried-up issues. The highest report on unclear status of water source was reported from Mongar dzongkhag (6) followed by Chukha and Dagana dzongkhags (4 each), (Fig 6).

5. General issues causing water source drying

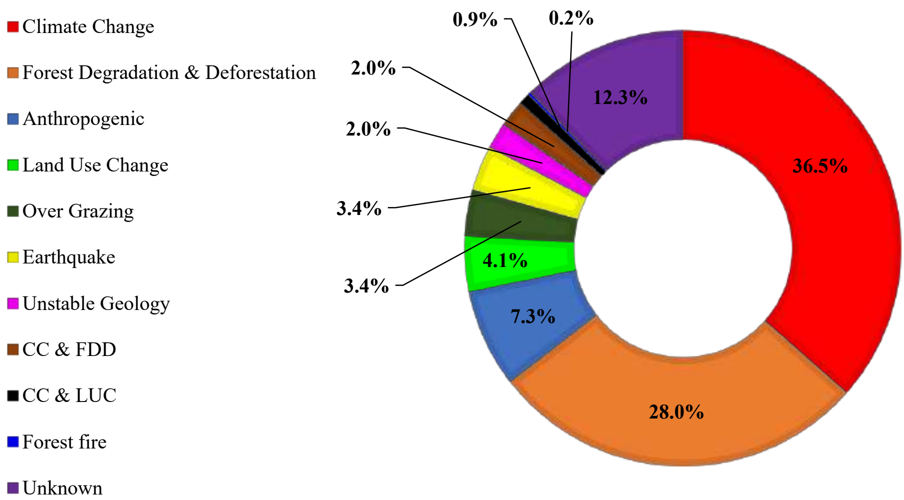

Figure 7. *Causes of drying water sources*

As per people's perceptions gathered through consultations and focus group discussions, impact of climate change (36.5%) followed by forest degradation and deforestation (28%) are cited as the major factors contributing to drying up of water sources in the country. The other issues perceived to be contributing to drying up of water sources are presented in the figure above. There are also water sources drying up in some areas in the country, for which the causes are not known (marked as unknown) by the people, (Fig 7).

6. Watershed assessment of water source areas

The assessment and mapping study also included assessment of watersheds where these water sources and their springsheds are located. The assessment of watersheds were carried out using watershed classififcation guideline 2016 and classified in to pristine, normal and degarded watersheds and the distribution of the same is as shown in the figure below (Fig 8).

Table 1 shows the extent of watersheds of water sources areas in different classification category. The watersheds of the water sources are delineated using the hydrological tool in GIS. It shows that the water sources mapped falls in 527 watersheds (of varying sizes) of which 149 (28.3%) watersheds are classfied as degraded in condition while only about 93 (17.6%) watersheds are in pristine condition. Rest of the 285 (54.1%) watersheds are in normal conditions as per the criteria described in watershed classification guideline (WMD, 2016).

Table 1: *No of watersheds in different class*

Dzongkhag	No of sub-Watersheds		
	Pristine	**Normal**	**Degraded**
Bumthang	2	5	8
Chukha	4	11	5
Dagana	5	9	7
Gasa	6	3	3
Haa	4	17	8
Lhuentse	4	19	7
Mongar	4	21	8
Paro	1	11	7
Pemagatshel	14	25	5

Punakha	2	6	6
S/jongkhar	8	20	10
Samtse	2	19	10
Sarpang	5	15	10
Thimphu	10	6	5
Trashigang	6	17	10
TrashiYangtse	3	11	5
Trongsa	2	18	6
Tsirang	6	13	11
Wangdue	2	24	12
Zhemgang	3	15	6
Total	93	285	149

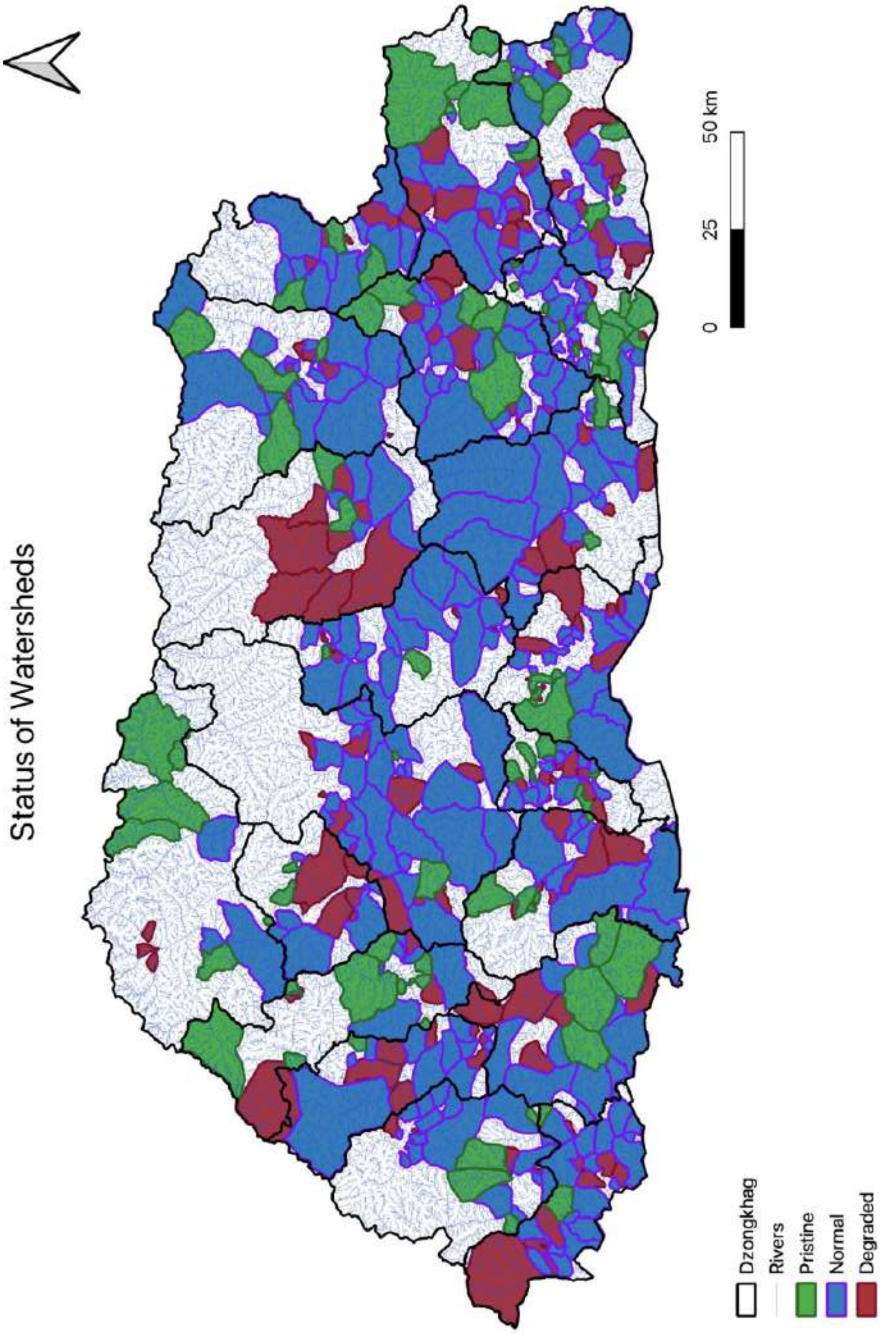

Figure 8. *Spatial distribution of the condition of the watersheds where water sources are located in the country*

DISCUSSION AND CONCLUSION

The study attempts to develop the baseline information on water sources currently used by the communities in Bhutan and their status. It also looked into documenting the location, uses, reasons for change (drying/dried up) and other details of the water sources to enable future studies to monitor the drying up issue. Although, the assessment recording these water sources at a single point in time may not ascertain if the water sources are drying up, but water shortage, especially for drinking and irrigation is a known issue and recognized by Royal Government of Bhutan (DES, 2020) and similar issues are reported in other Himalayan regions (Dendup, 2022); (Choekyi, 2022); (Kajal, 2021). However, to study the trend and validate the drying up claims, the assessment should be repeated after an interval of several years to find out if any sources currently existing has dried up or changed.

Various factors natural and manmade have caused water sources drying up in Bhutan as per the study and highlighted climate change impact as the major factor affecting them. The same is also reported as cause of water sources drying in Nepal (Dhakal, Bhattarai, Thapa, & Tiwari, 2020) and other Himalayan regions (Smadja, et al., 2015). Such trend along the Himalayan region is worrisome and Bhutan is already experiencing it (Wangchuk, Norbu, & Norbu, 2018). Additionally, the analysis of historical climate and climate projection for Bhutan from 1996-2017 by National Center for Hydrology and Meteorology (NCHM, 2019) further substantiates the perceptions as it also showed increasing trend in temperature and decreasing trend in rainfall. Further, the climate projection by the same study indicates increasing trend in temperature and decreasing trend in rainfall during 2021-2100 period under both RCPs 4.5 and 8.5 scenarios and is a grave concern for the sustenance of the livelihood of the Bhutanese communities.

In general, climate change is expected to have strong impact on water resources in the mountain areas (Buytaert, 2012 as cited in (Smadja, et al., 2015)), and even more so in the Himalayas where the rise in temperature, which is higher than the global average, has a significant effect on the cryosphere (Eriksson et al., 2009; IPCC, 2013 as cited in (Smadja, et al., 2015)). These increasing trend in temperature may intensify the hydrological cycle resulting in higher rates of evaporation and disturbance in rainfall pattern, which in turn may affect the spatial and temporal distribution of ground water resources (Shrivastava) and can ultimately impact on the water supply.

Forest degradation and deforestation are also perceived as having significant impact on water sources drying up in Bhutan as per the communities. The extent of the issue is substantiated by number of watersheds identified as degraded (28.3%) through this study. Being a country with high forest cover (71%) (DoFPS), forest constitute the main component of watersheds in Bhutan. Further, as springs are recorded as the main source of used water, forests in the watersheds have an important role as trees serve as natural sponges, collecting and filtering rainfall and slowly recharging the springs and are the most effective cover for maintenance of water quality. Therefore, the health of the forest in the watersheds have direct impact on water availability as well as quality (Clausen, 2016), (Lyons & Gartner, 2017) and overall condition of the watersheds and springsheds. Particularly for Bhutan, as the main input to springs is through monsoon rain received mainly from June through September, Bhutan's forests have massive function in catching this rainfall and recharging the springsheds. The cover and variety of trees and layers within forest help soften the impact of monsoonal rains, supporting natural soil and water conservation process. Besides, being located at high altitude and with constant exposure to clouds, forests in Bhutan are known to intercept fog, which contribute to increasing spring flows during the dry season (WMD, 2019). However, with increasing population, urbanization, management issues, and limited stakeholder participation issues impacting the water sources (NEC, 2018), there is risk that forest degradation and deforestation will worsen and further deteriorate the condition of the watersheds of our community water sources. As such, concerted efforts should be put in to manage the watersheds of the water sources with appropriate measures including development of springsheds for sustainable protection and conservation of water sources. In doing so, the effort will help mitigate the impacts of climate change and other natural and anthropogenic impacts causing water sources drying highlighted by communities in this study.

In conclusion, the findings of this study should enable watershed and other water related agencies to identify and recommend appropriate intervention measures for management of watersheds and springsheds to conserve the water sources in Bhutan. In the immediate future, the study recommends relevant agencies to focus on water sources in drying state and associated watersheds as nothing much can be done for those already dried up. These agencies can assess the water sources in drying up stage, develop their springsheds and appropriately manage the associated watersheds to prevent further drying up. However, in the long run, the agencies should proceed to carryout in-depth study/research on the relation between climate change, human activities and water flow to help come up with effectives measures to conserve as well revive the water sources that are drying up. Finally, the study also recommends relevant stakeholders to use the results of this study to make informed decisions and prevent wasteful expenditures on any water related activities.

ACKNOWLEDGEMENTS

The author would like to acknowledge the hard work put in by forestry staff involved in water source assessment and mapping in all 205 gewogs.

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DEVELOPMENT AND VALIDATION OF CHANNEL RATING EQUATIONS FOR AUTOMATIC WATER LEVEL STATION SITES

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Abstract

A discharge rating, widely known as a rating curve, represents a site-specific relationship between discharge and stage. It is generally used for the conversion of the stage measurements into corresponding discharge values, and vice-versa. The National Centre for Hydrology and Meteorology (NCHM) is involved in the development of discharge rating equations for the Automatic Water Level Stations (AWLS) since 2020. Steady-uniform flow conditions based on Manning's equation were initially considered. However, unsteady and non-uniform flow conditions are predominant in the natural river channels. Therefore, validation by employing a 1-dimensional (1D) unsteady flow simulation using the River Analysis System developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC-RAS) is conducted in 2022, and the simulation is calibrated with the measured spot discharge, and the corresponding stage and water surface elevation. The results demonstrated underestimation of discharge by the previously developed rating equations and the need for adequately detailed in-situ field data collection for greater reliability, accuracy, and performance of the rating equations at all stages of flow. With the well-established rating equations, rivers and streams with installed AWLS can have time-series discharge data. Over time, rating equations require updates, after abrupt changes in site conditions, to maintain the required levels of data quality and accuracy.

Keywords: Calibration, discharge, HEC-RAS, rating curve, stage, unsteady flow, water surface elevation

Introduction

River flow information is a crucial component in various aspects of surface water resources assessment, planning, and management. Generally, engineering designs and hydrological studies for the development of water-related projects and flood mitigation measures for flood disaster risk reduction mostly depend on the accuracy of river discharge data derived from rating curves. The most predominantly used field of rating curve is at the automatic water level station (AWLS) sites automatically collecting water level or stage (*h*) where direct discrete measurements of discharge or flow rate or streamflow (*Q*) are absent. A rating curve is a site-specific relationship [*Q(h)*] between stage and discharge used to generate a continuous discharge record from a time series of recorded river stages (Holmes, 2016; ISO, 2010) and vice-versa.

The characteristics of the rating curve are dependent upon the hydraulic resistance exhibited by the channel features being evaluated. The greater the resistance, the greater the depth of water needed to convey a given flow volume per unit of time. The resisting elements are collectively referred to as "control." A channel control includes all of the features such as the shape, size, slope, roughness, alignment, constriction, and expansion of the channel, which in turn create flow resistance (Al & Kennedy, 1970).

At the data-adequate hydrological stations, the rating curve is constructed by developing a relationship between the time series of the recorded discharge and stage, known as the direct method of rating development. It is often established by using indirect methods such as the use of simple hydraulic formulae such as Manning's equation (Leonard et al., 2000) which considers steady-uniform flow conditions. Natural streams and rivers, however, exhibit inherent unsteady and non-uniform flow conditions. Under such site conditions, the use of a simple steady-uniform state of Manning's equation does not guarantee an accurate estimate of discharge. In addition, rating curves are usually extrapolated, based on low and medium flow conditions, beyond the observed stage range and thus fraught with uncertainties and errors (Wara et al., 2019). Minimizing such errors is possible through direct discrete discharge measurements at various stages and flow conditions, which is labor and resource-intensive. Such limitations and uncertainties can be also reduced by selecting channel rating sites with relatively stable controls.

With significant technological advancements in the field of hydraulic modeling, the mentioned challenges are shown to be significantly reduced while also increasing the reliability and accuracy of rating curves for any open channel section with simple to complex hydraulic structures. Various studies (Reistad et al., 2007; Zheng et al., 2018) around the globe have used the River Analysis System developed by the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC-RAS) to develop and review rating curves. One such study by Wara et al. (2019) indicates that the rating curves calibrated and extracted from the HEC-RAS model are satisfactory and acceptable for deriving discharge across the range of stages at each river section.

The National Centre for Hydrology and Meteorology (NCHM) collects and archives time-series stage data from AWLS. Stage data by itself is of minimum value and usage. Through this study, NCHM aims to validate the preliminary rating curves and establish the stage-discharge rating equations for AWLS sites to generate time-series discharge data from the stage time-series data.

Channel rating sites

NCHM monitors 45 AWLS installed across the river basins in Bhutan. However, three AWLS sites of Chendebji in Trongsa, Khagang in Bumthang, and Khoma in Lhuntse (**Error! Reference source not found.**) a re selected for the validation of channel rating equations. The streams in the selected sites are easily accessible and wadable which enables thorough field data collection. Chendebji and Khagang AWLS have contact (bubbler) water level sensors working on the principle of hydrostatic pressure whereas Khoma AWLS has a non-contact (RADAR) sensor to record the water level (Table 2)

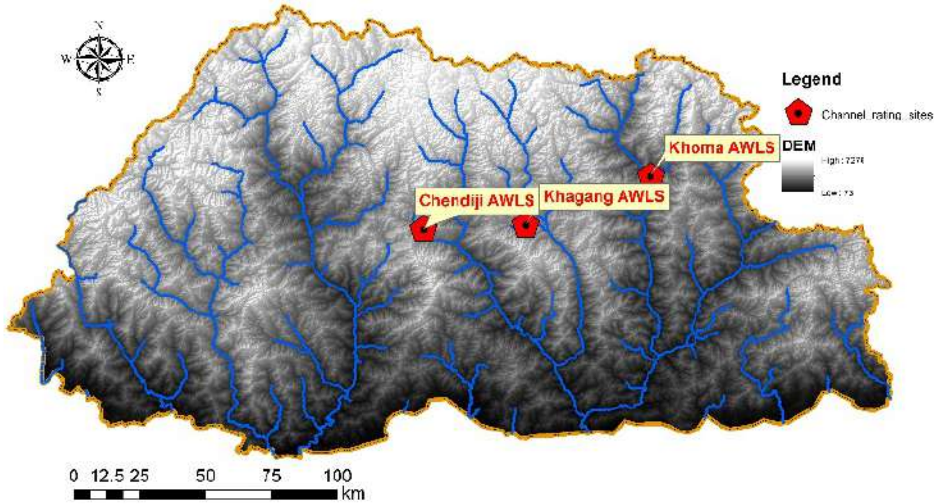

Figure 3: AWLS sites selected for channel rating

Table 2: Station metadata

Sl.No.	Station name	Location coordinates	Sensor type	Measured parameter
1	Chendebji AWLS	90.33635°E, 27.48799°N	Bubbler	Water level
2	Khagang AWLS	90.72831°E, 27.50174°N	Bubbler	Water level
3	Khoma AWLS	91.21045°N, 27.66408°N	RADAR	Water level

Data and methodology

In this study, a 1D unsteady mixed-flow regime of hydraulic modeling approach has been employed using HEC-RAS for simulation. This is in contrast to Manning's equation, which is an empirical formula previously used for the establishment of rating equations assuming steady-uniform flow conditions. The HEC-RAS model is based on a finite difference solution of the full Saint-Venant equations of mass and moment conservation allowing for a more realistic representation of the complex flow conditions in natural river channels (USACE, 2021).

Governing equations

Equations (1) and (2) represent the simplified forms of the mass conservation (continuity) and momentum conservation equations used in the 1D-unsteady HEC-RAS modeling simulation respectively.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_l \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (VQ)}{\partial x} + gA\left(\frac{\partial z_s}{\partial x} + S_f\right) = 0 \quad (2)$$

In the above equation, Q represents discharge, *A* represents total flow area, q_l represents lateral inflow per unit length, S_f represents friction slope, which is positive in the direction of flow, *g* represents acceleration due to gravity, *V* represents velocity from Chezy's equation, $z_s = z_0 + h$, where z_0 is the inverted elevation.

The two equations are solved using the four-point implicit box finite difference scheme developed for channels that are non-dissipative and stable in a semi-implicit form under unsteady flow conditions. The model can handle different conditions of sub-critical and super-critical flows while a mixed flow regime is employed in the study.

Geometric data collection and processing

1D hydraulic modeling requires adequate cross-section data that sufficiently represents the river and floodplain geometric conditions and characteristics of the AWLS sites. The channel and floodplain geometric information is derived from the surveyed cross-sectional data collected from sites for the three AWLS under study. Data on the river and flood plain cross-sectional profiles were collected from the field surveys using Trimble R10 global navigation satellite system with real-time kinematic (GNSS RTK) and Ceeline echosounder from CEE Hydrosystems (Figure

3) mounted on a boat. To minimize the augmentation of uncertainties in model results from the topographical data, each station is surveyed at least 200 meters downstream as downstream boundary conditions are critical in simulation. The collected cross-sectional data is processed in the geographical information system (GIS) software to generate digital elevation models (DEM) of individual stations which are then used in the model for simulations (Figure 4).

Figure 3: GNSS RTK and Ceeline Echosounder survey at AWLS sites: Khoma (left), Chendebji (Center), and Khagang (right)

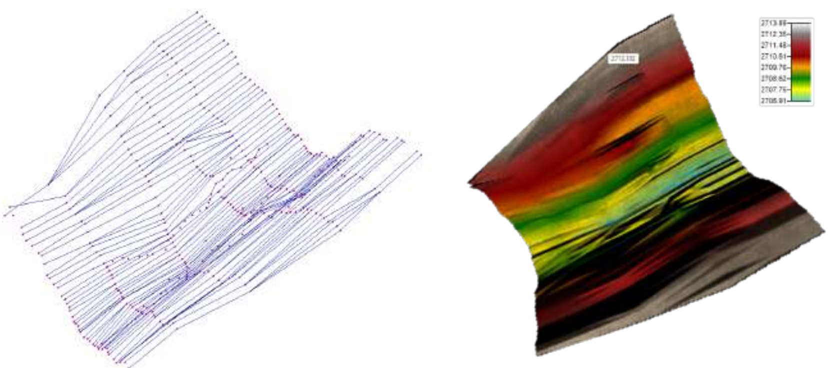

Figure 4: Processing digital elevation model

Determination of Manning's roughness, n values

Manning's roughness coefficient, *n* values for river channels and flood plains were initially determined from different methods generally employed in the studies of Böhm et al. (2002); Marcus et al. (1992); USACE, (2021). The former study presents various kinds of channel characteristics of varying *n* values with pictorial representations which are easier to visually compare with the present site conditions, while the latter recommends the use of established Jarret's (1984) equation for mountain streams which depends on two channel characteristics of hydraulic radius, *R* and friction slope, S_f. The USACE, (2021) provides a range of *n* values for different kinds of river channels. Figure 5 shows a typical cross-section with a channel *n* value of 0.035 and flood plains with 0.05 initially used.

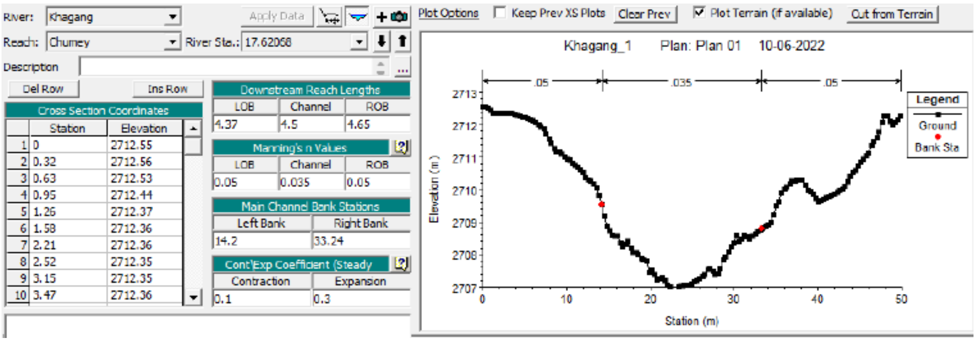

Figure 5: A typical river cross-section with different n values for channel and flood plains

Boundary conditions

Two boundary conditions are necessary for the 1D unsteady model using HEC-RAS, one each at the upstream and downstream cross-sections. The upstream boundary condition used in the study is a simple triangular hydrograph encompassing both the highest and lowest flows. The boundary condition employed at the downstream cross-section is the bed slope. Bed slope is calculated from the DEM generated from the surveyed in-situ river cross-section and profile data.

Calibration of 1D-unsteady model and rating curve

The calibration of the model and rating equation is carried out using a single spot discharge measurement and the water surface elevation (WSE) which is correlated with *h*. The *n* value is the main parameter used for calibration in matching the simulated WSE with the measured WSE and *h,* for the measured *Q*. Wherever unrealistic *n* value is determined after calibration, it is discarded and appropriate *n* from Böhm et al. (2002) after visual comparison of the site imageries is used. The stability of the model is achieved by ensuring an appropriate time step in addition to *n* values.

Result and discussion

The simulation results for the selected AWLS are as follows:

Khoma AWLS in Lhuntse

Validation of the rating equation for Khoma AWLS in 2022 resulted in a power equation (3). The comparison of the pre-rating equation of 2020 in red font with the validated rating equation (3) in black font graphically represented in Figure 6 demonstrates minimal difference indicating the pre-rating equation was satisfactory. However, since spot discharge measurement during the field visit in the year 2022 was not possible, the model and equation were calibrated using the historical discharge data measured employing the float method.

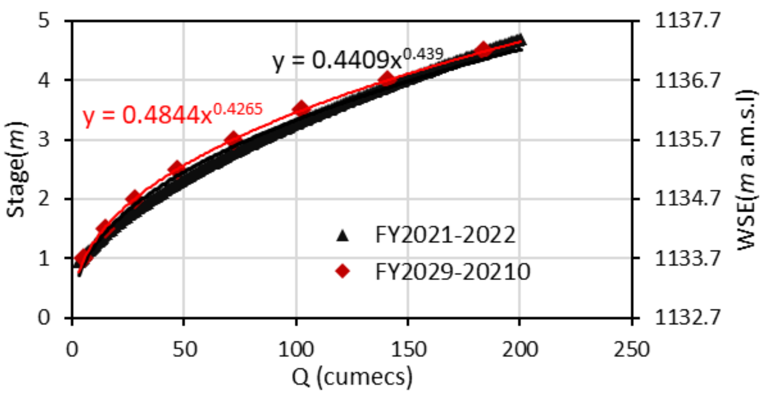

Figure 6: Validation of channel rating equation for Khoma AWLS.

The validated $Q(h)$ relationship of Khoma AWLS station is, $h = 0.4409Q^{0.439}$ (3)

Chendebji AWLS in Trongsa

The validated channel rating equation of Chendebji AWLS done in 2022 is shown in equation (4). Figure 7 compares the validated channel rating equations of 2022 which are generated from the calibrated 1D unsteady flow model in HEC-RAS using the measured spot discharge of 6.965 cumecs with the corresponding stage as well as WSE of 1.14m and 2423.106 m above mean sea level (a.m.s.l.) respectively, to that of 2020. However, the previous rating equation underestimates flow for the same stage due to the uncalibrated *n* value and mild slope considered in the steady-uniform flow state. The previous channel rating equation results in the flow of 3.476 cumecs for the stage of 1.14m which is underestimating 50.09%.

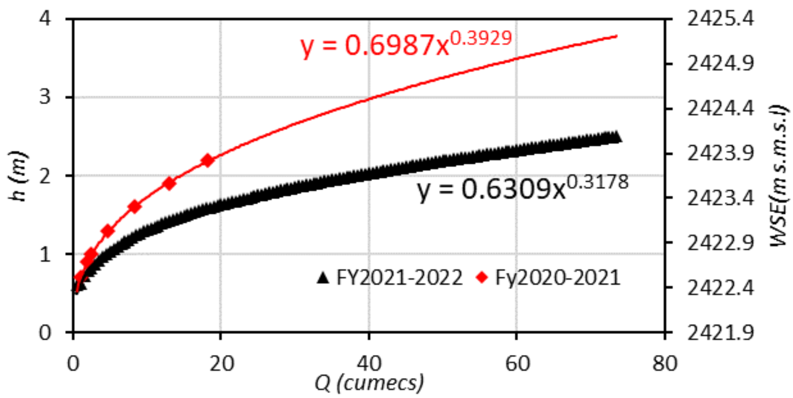

Figure 7: Validation of channel rating equation for Chendebji AWLS

The validated $Q(h)$ relationship of Chendebji AWLS station is, $h = 0.6309Q^{0.3178}$ (4)

Khagang AWLS in Bumthang

Equation (5) is the calibrated rating equation of Khagang AWLS using the flow of 1.828 cumecs with corresponding stage and WSE of 0.91 m and 2707.862 m a.m.s.l. respectively. The comparison of the channel rating equations (Figure 8) illustrates the underestimation of flow by the channel rating equation of 2020. Flow for the corresponding stage of 0.91 m is 0.981 cumecs which is an underestimation of 46.32%.

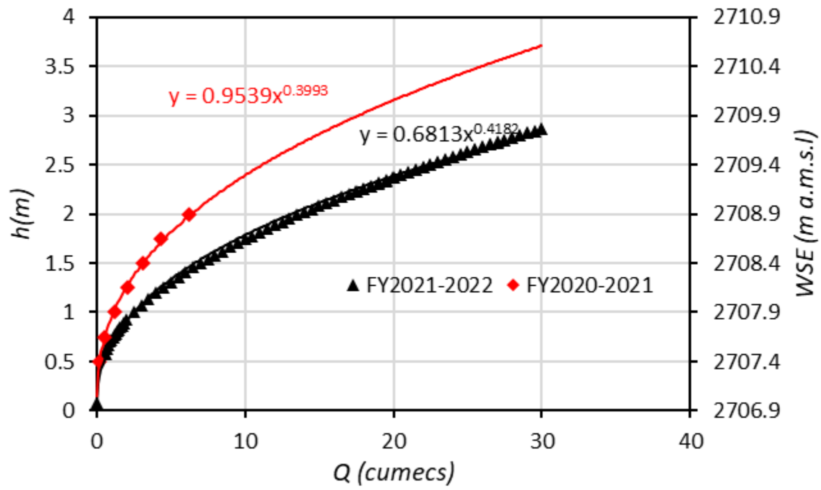

Figure 8:Validation of channel rating equation for Khagang AWLS

The validated $Q(h)$ relationship of Khagang AWLS station is, $h = 0.6813Q^{0.4182}$ (5)

Calibrated n values

The calibrated parameter, *n* values for different sites are shown in

Table 3. The values are substantially higher than what is recommended by the USACE, (2021). However, higher *n* values for the 3 AWLS sites under study conform with the studies of Manning's roughness in the mountainous rivers (Böhm et al., 2002; Marcus et al., 1992). A study on setting up of rating equation using HEC-RAS by Reistad, Petersen-Øverleir, and Bogetveit., (2007) also shows that the *n* values can be a lot higher in the sections where super-critical flow is observed which conforms well with the three AWLS sites under study which have mixed flow regime of sub-critical and super-critical flows.

Table 3: Calibrated n values with a channel bed slope

Sl. No.	Name of AWLS	Calibrated *n* value of the channel	Approximated *n* value of flood plains	Bed slope
1	Khoma	0.08	0.09	0.0025
2	Chendebji	0.068	0.075	0.00932
3	Khagang	0.0815	0.09	0.0125

Conclusion

The study validated the previously developed rating equations for AWLS sites using an indirect method of rating curve development using Manning's equation which considers steady-uniform flow conditions at the site. However, since flow conditions at sites are mostly unsteady and mostly non-uniform, 1D-unsteady HEC-RAS modeling was used in this study to validate the rating equations of the three AWLS sites. The results revealed that the previous rating equations mostly underestimated the observed discharge. The calibrated *n* values were found to conform with research conducted in geographically similar parts of the world. Since rating equations developed from the direct method are the most reliable and closest to the true value, collection of discharge data at different stages is recommended, especially for the high stage, for better calibration of the model and the rating equation. Moreover, re-validation of the rating equations at certain intervals of duration and post-flood events can help to ensure stability and in maintaining the rating equations updated. With the well-established rating equations, AWLS monitored by NCHM can generate time-series data for both water level and discharge.

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