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Resilience in a Changing Climate

Cryosphere Monitoring and Management in Bhutan: Technical Note

Prepared in Collaboration between the
Royal Government of Bhutan and the World Bank

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Building Resilience through Capacity for Cryosphere Monitoring in Bhutan:
A Technical Note

Contents

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Acronyms

CBDRM	Community Based Disaster Risk Management
CSD	Cryosphere Services Division, National Center for Hydrology and Meteorology
DDM	Department of Disaster Management, Ministry of Home and Cultural Affairs
DGPC	Druk Green Power Corporation
DHMS	Department of Hydromet Services, Ministry of Economic Affairs
DoA	Department of Agriculture, Ministry of Agriculture and Forests
EWS	Early Warning System
GIS	Geographic Information System
GLOF	Glacier Lake Outburst Flood
ICIMOD	International Center for Integrated Mountain Development
IMD	India Meteorological Department
JAXA	Japan Aerospace Exploration Agency
JICA	Japan International Cooperation Agency
MODIS	Moderate Resolution Imaging Spectro-radiometer
NASA	National Aeronautics and Space Administration, United States
NEC	National Environment Commission
SWE	Snow Water Equivalent
UNDP	United Nations Development Programme
WWF	World Wildlife Fund

Executive Summary

The present report provides a cryosphere perspective on Bhutan's water resources, monitoring needs, and climate services. Main concerns are with glaciers, snow, permafrost, and related cold climate conditions. These are increasingly important as resources, but also in potentially large problems related to climate change and development plans.

A primary goal of this inquiry is to identify and assess existing capacities, data sources, and projects on-going, or in the pipeline. It seems fair to say, however, that, there are no satisfactory arrangements for *any cryosphere components, or their contributions to water resources* -- with the singular exception of a glacial lake outburst floods (GLOFs) program. The hydro-meteorological networks and instrumentation that exist were not been set up with snow, glacier or cold climate functions in mind.

There is a need to develop a comprehensive sense of just how snow, ice and attendant processes enter Bhutan's water system. This arises from, and is related to the "Water Act of Bhutan" (RGoB, 2011), in which relevant agencies are committed to '*integrated water management*' (see also NEC, 2016). The range and scope of cryosphere phenomena need to be recognized, as they contribute to Bhutan's water cycle and affect national aspirations.

The report begins with an updated over view of the scope and status of Bhutan's cryosphere (Section 1). It draws attention to the science behind cryosphere phenomena, the (unsatisfactory) state of knowledge of the Himalayan cryosphere, and on-going debates about that. Cryosphere hazards are addressed, how they arise, and possible impacts of climate change on them. In keeping with integrated water management, a multi-hazards approach is proposed, to extend and balance the exceptional work to date on GLOFs. Bhutan's relevant, existing capacities are then reviewed in relation to the cryosphere (Section 2). Subsequent sections deal with requirements for effective cryosphere monitoring, the Cryosphere Service Division (CSD),[1] and climate services it could offer to other groups.

It needs emphasis that, even the limited evidence available leaves little doubt that Bhutan's glaciers are in a precarious state (Karma et al, 2003; Iwata 2010). There are enough data to show serious and rapid losses. All observations point to relatively rapid thinning and retreat of almost all ice masses, and in sub-regions of Bhutan's high Himalaya. Estimates suggest a reduction by at least one quarter of the glaciered area since 1980. For the future one highlights the absence of stable, let alone advancing glaciers, the rapid and complex growth of glacial lakes.

There are also widespread, if mainly anecdotal, reports of reduced snowfall or shorter duration of snow on the ground. They are being related to a drying up of spring-fed streams and groundwater. These are critical concerns for agriculture, high pastures, forest ecology, and watershed management, and may become so for growing municipalities. Here is where 'climate resilience' becomes most necessary, but that hinges upon much more and better actual data for snow and ice.

Another recent report, known as the "Road Map" (World Bank, 2015)[2], already gave a comprehensive analysis of the state of Bhutan's hydro-meteorological services. It was a joint effort by various branches of the Government of Bhutan and a World Bank team. They also emphasized the importance

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[1] Earlier this was the Snow and Glacier Division under the Bhutan Department of Hydrology and Meteorology.

[2] World Bank, *Modernizing Weather, Water and Climate Services: A Road Map for Bhutan*, Prepared in Collaboration between the Royal Government of Bhutan and the World Bank Group, Washington D.C., 2015.

of snowfall and glaciers, the GLOF hazard, and potentially adverse impacts of climate change. It was recommended these become the special responsibility of a recently founded Crosphere Service Division (CSD).

However, the Road Map report did not go into specifics of cryosphere monitoring or assess the capacity needs of CSD in relation to cryosphere science or technicalities. The present report undertakes a detailed assessment of these issues and proposed recommendations on how to strengthen cryosphere monitoring and services.

Broadly, the cryosphere identifies environments where water is in solid form much or all of the time, especially in snowfall, glaciers, permafrost, frost action, and floating ice in rivers, lakes, and seas. These can comprise major stores of fresh water. They enter water resource concerns mainly through changes of phase. Melt waters are of primary interest, and how they partitioned by hydrological processes into runoff, especially stream flow, infiltration and groundwater, evapotranspiration and so forth.

In Bhutan, core cryosphere areas are in the highest, northern or 'Great Himalayan' region. They cover less than 10% of the country but nevertheless involve a great concentration of ice. Seasonal snowfall and freeze-thaw occur across most of the Inner Himalaya, comprising up to 40% of the country. More than a dozen stations provide some sort of snowfall readings, but their locations and procedures appear unreliable. None provides the all-important measures of snow water equivalent (SEW). In the high Himalaya, wind and avalanche redistribution of snow have major glaciological and hydrological roles. So do the incidence of ground ice and permafrost, frost days and freeze-thaw cycles. There is no on-going work on monitoring these aspects.

As a whole, rainfall dominates soil moisture, runoff and river flows, groundwater replenishment, and flood risks. However, Bhutan's larger rivers have significant snow melt (nival) and glacier components. It seems likely glacier ablation and snow melt can dominate flows in early and late summer. Though actual data are lacking, snow melt and its infiltration make a contribution to groundwater and spring-fed streams. Also, snowfall and freeze-thaw play critical watershed and ecological roles for forests, alpine plants, wildlife, and the agro-pastoral sector. There are, as yet, few actual data to quantify any of these functions. Likewise, in the heavily forested Inner Himalayan areas, intercepted snow needs to be considered, sublimation of snow and ice in perennially frozen areas, and in winter. The proliferation of glacial lakes affects stream flow, sediment yields, and evaporation losses, as well as generating outburst flood risk. Climate warming is likely to alter each of these factors.

For the glaciers, some useful inventories of ice cover and glacial lakes exist, but in need of refinement and repeated updating. There have been more than a dozen research projects on glaciers and associated expeditions. Their findings could be usefully pulled together and compared, but are patchy in time, place and quality. Monitoring requires planning in terms of an overall strategy, criteria for the selection of glaciers and preferred observations – only some of which has yet been settled. Few glaciers are identified for long term monitoring (glacier mass balance).

However, there is an acute need of continuous, medium and long-term records. A much more extensive network of observation sites is needed, especially in the higher, northern areas. A substantial capacity to receive and analyze satellite imagery should also be a major part of modern snow and ice monitoring, as yet unavailable to CSD.

It will be difficult but necessary to separate the actual contributions of different cryosphere functions. The main snowfall inputs at high altitude coincide with the heaviest rainfall in the rest of the country. The main yields from snow melt and glacier ablation occur immediately before and after the summer monsoon. Resolving these unknowns is surely of special interest for hydro-power, in particular due to its rapid, and projected expansion. Also, river waters are increasingly drawn upon by growing municipalities, and are the most likely sources for anticipated increases in irrigation agriculture. Beyond some very general modeling experiments, there is no sense of just how climate change has, or will, affect stream flow.

A major exception to the neglect of the cryosphere, involves glacial lakes and the GLOF hazard. Bhutan has something close to a state-of-the art capacity in this regard. Efforts by outside agencies, notably by ICIMOD and Japanese scholars, have provided inventories of glaciers and glacial lakes. Following the 1994 Lugge Tsho disaster, a substantial program of monitoring, mitigation, disaster preparedness, and community outreach has developed. There are two Early Warning Systems (EWS), for the Mochu-Punatshangchhu Basin and Pho chhu Sub-basin. These are located in the main facility inNCHM, not CSD. There are also EWS in 2 other sub basins in cenral Bhutan, Mangde Chu and Chamkhar Chu.

CSD lacks the funding, facilities, work space, instruments, and field logistics to begin a credible program. It continues to rely heavily on other units, outside assistance, and *ad hoc* initiatives. Some personnel are engaged in GLOFs program and in pilot glacier observing projects, or the. (Section 4). A small core of staff have extensive and invaluable experience of the specifics of Himalayan snow and ice, of the terrain, access and safety matters. Their input will be essential for choice of support facilities, instrumentation and equipment, and observation sites. CSD does not have the capacity to capitalize on past work. Existing weather and stream gauging stations are not set up to address cryosphere conditions and monitoring requirements. Strategies for snow and ice raise distinctive problems and principles. There are acute demands for access, siting, instrumentation, observing and network principles, communications, analytical tools, models, and information sharing. Few of these aspects of snow and glaciers work have been worked on.

With respect to climate services, there seems to be a heightened awareness throughout of potentially grave impacts of climate change on the glaciers. It is usually seen in terms of future water supplies, and the GLOF hazard. On the other hand, outside CSD there seems to be very limited awareness of cryosphere components, even those that clearly enter the concerns of other agencies. (See Section 5).

The main recommendations relate to;

i) Developing a cryosphere monitoring strategy in terms of integrated water, and watershed management, principles and priorities;
ii) Addressing the full range of cryosphere conditions in the Great and Inner Himalaya; a multi-hazards approach to cryosphere dangers and climate resilience and, above all;
iii) Urgent funding and substantive assistance for capacity-building, procurement, and staffing of the Cryosphere Service Division.

Chapter 1. The Bhutan Cryosphere: State of Knowledge

The cold areas of Bhutan are part of the high mountain cryosphere, specifically of the High Asian, sub-tropical varieties. The country's glaciers are in its northernmost 'Great Himalayan' region, as are perennial snow cover, permafrost and areas of intense periglacial processes. They cover somewhat less than 10% of national territory, above 4,000 m elevation, and in largely uninhabited areas. Their importance arises mainly because of the summer melt waters, which have growing significance for existing and planned hydropower projects. These core cryosphere areas and functions are also subject to threats from global climate change. The glacier area has diminished substantially in recent decades. Losses seem likely to continue and even accelerate. They have already affected the character, timing and quantities of water supplies, and hazards such as glacial lake outburst floods.

Immediately to the south, the Inner Himalaya is subject to seasonal snowfall and freeze thaw. Much of it is heavily forested and there are inhabited areas. Winter snowfall and freezing temperatures can reach down to 2,200 m, including the capital, Thimphu at 2,250m. Thus, almost 50% of the country has some cryospheric influences and cold environment parameters that will change and may be lost through global warming. Many anecdotal reports suggest Inner Himalayan snowfall and snow covers have also become less in recent years. In places springs and spring fed streams have dried up. A lack of actual observations and analyses clouds the full picture.

For the hydrological cycle and water resources, changes of phase are critical. The most important are seasonal melting of snow, and ablation of glacier ice. However, other parts of the water cycle are critical for watershed management and ecological health. Sublimation of ice and snow can play a significant role in high mountains. In the forested and alpine areas of the Inner Himalaya critical roles may be played by the interception of snow by trees, evapotranspiration, and the relative fractions of moisture that runs off, infiltrates into soils and enters ground water. These are as yet undetermined, but probably vary greatly with elevation, exposure, terrain, plant cover, and seasonal weather. Wind action and avalanches redistribute snow on a massive scale in the High Himalaya, again unmeasured (see 1.5.2 and 2). The significance of evaporation may be affected by the growth of glacial lakes (see 1.2). Other hydrological and environmental roles involve the seasonal duration of snow cover, soil and ground ice, frost days and freeze-thaw cycles. All of these are sensitive to climate change.

The geography of Bhutan's cryosphere needs to be considered. First, as part of the *mountain cryosphere,* conditions depend fundamentally on elevations, and elevation range. Second, while cryosphere conditions occur in almost continuous belts across the northern rim, their influence is divided up *as watersheds of major rivers.* Numerous Himalayan headwater streams are predominantly glacier and/or snow fed.

Hydrological components vary with altitude which, in combination with rugged terrain, affects the presence of snow, ice and melt waters, and their behavior. Crucial hydrological regimes occur within distinct elevation zones (Table 1). Perennial snow and ice features only occur above about 4,000 m. Bhutan's glaciers are situated between 4,100 and 7,500 m asl. Almost 90% of glacier surface area and mass lies between 4,500 and 6,500 m. The glaciers also have exceptional elevation ranges (or 'relief'). Many span over 2000 m vertically, and some more than 3000 m. In general, exceptionally high altitudes create major constraints on all forms of direct observation and measurement stations. Moreover, the elevations are much higher than most for mountain glaciers investigated elsewhere, if comparable to, or even exceeded in other major Himalayan ranges. This requires caution in transferring or adopting glacial concept and models from other regions.

Southwards, is the broad Inner Himalayan zone or 'middle mountains', mostly below 4,500 m. Climates are 'temperate', slopes heavily forested, valleys steep and narrow. From here come many reports of less snow, more rain, shorter winters, reduced or absent frost and drying up of water sources, increasingly attributed to climate change. Further south, and below about 1,500 m, is a humid, tropical zone.

The vertically organized cryosphere creates a series of east-west belts, increasing northwards in elevation and with more extreme conditions. However, their significance for water resource management also depends on the second geographical component. River systems serve to link and organize elevation zones (Figure 1.3). The relative scales of glacial and snowmelt (nival) contributions vary within and between different drainage basins. Punatsangchhu and Mandechuu have the largest glacier covers and share of glacier waters. All five major basins have some glacier inputs, and extensive areas of winter.

Table 1.1: **Bhutan cryosphere: provisional estimates of extent of glacial elements and limits** (after Mool et al. 2001; Iwata, 2010; Rupper et al. 2012; Bajracharya et al, 2014; Hewitt unpubl.)

Cover (area)	(km2)
• (PSI) Perennial snow and glaciers	2,900 – 3,120 [3](?)
• Glacier ice cover	1,317 – 1,930 (?)
• PSI + permafrost and periglacial	3,500 - 4,000
• Seasonal snowfall	8,000 – 10,000
Limits (elevations)	(m)
HIGHEST	
• Glaciers,	7,400
• Climatic snowlines/ELAs	5,200-5,350 (south flank) H.H.[4]
• 'Glacial lakes' ("dangerous") [5]	5,390 m
LOWEST	
• Permafrost (discontinuous)	4,800 (N-facing slopes) [6] 5,000 m (S-, and E-facing)
• Glaciers (termini)	4,100
• Rock glaciers (lowest active rims) [7]	4,310 (N-facing) 4,600 (S-facing)
• 'Glacial lakes' ("dangerous")	4,080 m
• Seasonal snowfall/frost, lower limit	2,100 m
Elevation range and zones	(m)
• Glacier basins	4,100 – 7,500[8] (span= 3400 m)
• 80% + glacier surface area and mass	4,500 – 5,500 (south flank HH)

[3] Mool et al. (2001) "snow/glaciers" 2,989 (7.5%), glaciers 1,370 km2; Rupper et al (2012) Bhutan glacial "watershed" 3,120 km2 +/-3%; "glaciers" 1,930 km2 (+/- 3%)
[4] HH = High or 'Great' Himalaya; Iwata, 2010; Bajracharya et al, 2014
[5] Mool et al. (2001)
[6] Iwata et al (2003) 4,800 m (N), 5,000 m (S and E).
[7] Estimated from satellite imagery, (KH 2016 unpubl.)
[8] Lowest, debris covered terminus (Lunana) may be stagnant. Highest peak, Kula Kangri (7,554 m)

	5,000 – 6,500 (Northern Basin)
• Ablation zones	4,100 - 5300
• rel. clean ice (scattered debris, dust and dirt)	4,600 - 5,300
• Rock Glaciers	4,300 - 5,300 (south flank HH)
• Periglacial	3,900 - 5000

"snowfall.[9]

Monitoring choices and scope should also reflect development, economic sectors, infrastructure and populations in the various river valleys.

1.1 Elements of the Hydrological Cycle

To date, efforts to conceptualize the cryosphere in terms of hydrological systems and water resources have been largely by inference not measurement. A monitoring program has to be set up in terms of the various water regimes of snow and ice, the conditions affecting them, established observation schedules, and representative spatial sampling. A sense is needed of just where snow, ice and attendant processes enter the overall water system. In relation to '*integrated water management'* (see also NEC, 2016), it requires attention to and ranking of the different cryosphere elements as they contribute to the water cycle as a whole (see 4.1).

What needs to be done is to explore specifics of each hydrological (sub-) regime that involves the cryosphere. Then it can then be shown how cryosphere monitoring can enter the broader concerns of water resources and watershed management, and where to identify glacial hazards and offer climate services.

In the past, the focus has been on water supply issues at or near places of consumption. These are surely important, but cryosphere constraints and processes have remained distant and, essentially, 'black boxes'. Even tracking glacier change only yields indicators of trends, whose meaning requires monitoring of a range of atmospheric, hydrological and ecological conditions. The many pathways, links and stores in snow and ice hydrology have not been explored and assessed. The commonly mentioned components of the cryosphere such as glacier, snow cover or permafrost, at best identify moisture stores. Hydrological parameters emerge from measurements of flows, changes of phase, and exchanges among the main cryosphere elements and into downstream areas. Below is an attempt to identify the major cryosphere elements and the controls of special concern in the Great and Inner Himalaya of Bhutan. Later sections will turn to monitoring strategies, problem solving and the services that could be offered.

1.2 Snow

Some snow may fall annually over almost 50% of Bhutan's area. The overall contribution of seasonal snowmelt to rivers, groundwater and spring-fed streams is less than rainfall. It may well be two or three times greater than that of glaciers, though less concentrated in space and time. Seasonal snowfall onto glacier ablation zones, and in off-ice, periglacial areas, may be substantial contributor to water yields from glacier basins. There are no actual data to confirm this impression. The highest snowfalls are in summer and in the High Himalaya. This snow is the primary input for glaciers, a key determinant of glacier mass balance. It means the glaciers are 'summer accumulation' types, largely

[9] It now appears, from recent maps, that Northern Basin is no longer viewed as part of Bhutan, and there are no plans for monitoring their or, as yet, any regional cooperation on that with China/Tibet .

fed by snow at high altitude when, at lower elevations, only rain occurs. Again, actual snowfall amounts and variability are unknown.

Winter season snowfall occurs over a much larger area, embracing most of the Inner Himalaya, and its heavily forested areas. Snowfall, infiltration and groundwater, or stream flow derived from them, are important for local water supply and influences on ecological and watershed conditions. That includes resident populations, agricultural and pastoral land uses.

Snowfall varies substantially across northern Bhutan and in the different main cryosphere environments. Variations in thickness and density of snow affect microclimates and ecological variables that, in turn, influence plants and, for example, ground burrowing creatures. To date, there are no observations to determine just how much snow falls or builds up in snow pack (2.2). It is not simply a question of how much snow falls, but how it is distributed.

In addition to elevation, snowfall is strongly influenced by terrain, micro-, and meso-climates, and storm systems (Barros et al, 2009). A glance at available satellite images shows the uneven distribution of snow due to effects of wind, avalanching, and seasonal conditions. In glacier basins, a large fraction of all snowfall is redistributed and modified by wind action and avalanching (see 1.5).

Variability leads to severe problems of representativeness for such measurements that are available. The problems with instruments for direct snow capture, snow surveys and satellite based monitoring are widely reported (see 3.3 iii). They tend to be least reliable in steepland terrain without forest cover.

1.3 Glaciers

Bhutan's glaciers are confined to the northernmost, highest areas of the Great Himalayan belt. Estimates of the glacier ice cover range from 1,317 km^2 (MoA, 1997; Mool et al. 2001), to 1,930 km^2 (Rupper et al. 2012). Some earlier estimates went as low as 900 km^2 and others as high as 3,500 km^2 (von Wissmann 1959; Fuji and Watanabe, 1983; Tsvetkov et al, 1998, 181). The latter may actually refer to what Rupper et al (op cit) call the "Bhutan watershed", the total area of perennial snow and ice they estimate at roughly 3,120 km^2. Recent inventories of glacier numbers range from 667 (Mool et al. 2001) to 885 (Bajracharya et al's 2013). An increase in numbers is partly attributed to break-up of previously larger ice masses due to climate change.

There are large variations in the extent of glaciers and related watershed attributes between different drainage basins (Tables 2.2 and 2.3). The survey by Mool et al. (2001) highlights morphological classes and provides an inventory of their numbers in different basins. Much the greatest area and mass was found in 'valley glaciers', mainly where the heaviest covers are concentrated. A distant second are their 'mountain glaciers', similar to valley glacier but smaller, steeper, and including cirque and niche glaciers. Then there are minor ice masses, great in numbers but scattered and small in total area.

Table 1.2 Distribution of glaciers in Bhutan by drainage basin
(modified after Mool et al (2001)

MAIN sub-Basin	Catchment (km2)	Glacier cover	(%)	Numbers
WANG CHHU		48.9	3.7	
Pa(ro) C.	*1,049*	*40.5*	*3.1*	*21*
Thim C.	*323*	*8.4*	*0.6*	*15*

PUNA CHANG C.		503.2	38.2	
Mo C.		*169.6*	*12.9*	*118*
Pho C.		*333.6*	*25.3*	*154*
MANAS C.		376.9	*28.6*	
Mangde C.		*146.7*	*11.1*	*140*
Chamkar C.		*104.1*	*7.9*	*94*
Kuri C.		*87.6*	*6.7*	*51*
Dangme C.		*38.5*	*2.9*	*25*
NORTHERN BASIN[2]		387.7	29.0	59
TOTALS		1316.7	100	677

Table 2.3 Some glacier dimensions in Bhutan by drainage basin (ibid)

MAIN sub-Basin	Glacier cover	(%)	Largest (km2)	Longest (km)	Elevations Highest	(M) Lowest
WANG CHHU	48.9	3.7				
Pa(ro) C.	40.5	3.1	11.3	7.74	7314	4200
Thim C.	8.4	0.6	5.1	2.25	5680	4840
PUNA CHANG	503.2	38.2				
Mo C.	169.6	12.9	13.2	8.1	6790	4080
Pho C.	333.6	25.3	49.3	20.12	6949	4120
MANAS	376.9	28.6				
Mangde C. (Tongsa)	146.7	11.1	44.1	10.56	7570	4570
Chamkar C.	104.1	7.9	26.7	8.87	6200	4800
Kuri C.	87.6	6.7	13.9	6.6	5765	4080
Dangme C.	38.5	2.9	5.6	4.4		
NORTHERN BASIN	387.7	29.0	99.8	12.7	7570	4710
TOTALS	1316.7	100				

It would be helpful in future to develop an up-dated inventory that includes glacier nourishment classes. There are few or none where conventional notions of accumulation apply; that is, direct nourishment by snowfall. The snowfall that nourishes most Bhutan glaciers has been redistributed, modified and deposited on the glacier surface by wind and/or avalanches. Most are avalanche-fed. Although we still lack tools to adequately measure this phenomenon, it has profound implications for what controls glacier hydrology, and how it will respond to climate change.

For a water resources perspective, Williams et al (2016) preliminary evidence from water chemistry is a helpful indicator. Their results suggest glacier outflows represent 76% of the water yield at and from above 4,500m. Along the larger rivers other contributions, mainly rainfall, substantially reduce this with distance downstream, making for just 30% at 3,100 m (ibid). A clear need is indicated to compare chemically determined contributions with better and up-dated statistics on glacier cover and the various other cryosphere elements.

It cannot be asserted too strongly that, even the limited evidence available, leaves little doubt that Bhutan's glaciers are in a sorry state (Karma et al, 2003; Iwata 2010). All observations point to relatively rapid thinning and retreat in almost all ice masses and sub-regions of Bhutan's High

Himalaya. A study of 103 Bhutan glaciers at the turn of the century found that 90 glaciers (87.3 percent) were retreating, 13 (12.7 percent) stationary, and none advancing (Karma et al., 2003). Some estimates show the glacier cover decreasing by 22 % between 1980 and 2010 (Wengdue, 2016). Retreats seem to be greatest in the southernmost glacier tongues and to decline somewhat northwards (Kaab, 2005). The true scope of losses can be masked by heavily debris-covered ice, widespread on ablation zones up to 5,000 m or more. Heavy debris covers reduce ablation rates there and slow the rates of ice decay low down (Sakai et al 2002). There is a greater concentration on southwest- facing ice tongues (Nagai et al, 2013).

This is in keeping with modeling that shows 'summer accumulation' type glaciers will be more sensitive to global warming. Bhutan seems to be among the countries most at risk. On satellite imagery, where there was active glacier ice a few decades ago there is now bare ground, or dead ice. Exceptional lowering and retreat has been recorded in the Lunana region (Naito et al, 2012). Something similar was observed at the 'Jichu Dramo' and nearby glaciers. For the period 1998 – 2003 annual surface lowering was estimated to be 2-3 m (Naito et al, 2006). In the same period retreat of the terminus was estimated at roughly 9 m annually (ibid).

In both areas diminishing ice is positively correlated with the growth of glacial lakes, a singular phenomenon, thought to aggravate the risk of GLOFs (Komori et al 2005' Sakai and Fujita, 2010; Tadoman et al, 2012; JAXA 2012). They are mostly around the termini of larger glaciers on the southern and northern flanks of the highest watersheds, notably again in the Lunana area (Figure 4).

There is little doubt these developments are a consequence of global climate change. Even relatively conservative models suggest large losses of ice cover will continue and, after an initial 'spike' as glaciers melt, a dramatic drop in their contribution a few decades hence (Rupper et al, 2012).

Another, possibly critical, role is of pollutants and particulates should not be ignored, especially black carbon transported to the glaciers by wind and in snowfall. Bhutan's atmosphere is affected by the most heavily polluted parts of the sub-continent.

To date, glacier size and survival is mainly a function watershed elevation. The healthiest glaciers have interfluves rising above 7,000 m. They have well-developed 'accumulation zones' with snow inputs continuing annually and in substantial amounts, although the termini are mostly retreating. Glaciers with watersheds below 6,000 m or so show signs of wastage throughout. In accumulation zones are many signs of ablation and re-freezing, of dirt and algae building up on the surface, and break up into smaller ice masses. Many smaller ice masses have no discernable accumulation zone (Tshering and Fujita, 2016). Once again, quantitative data to pin down the full scope and rates of these changes are missing. Rectifying that should be a core objective of a monitoring program. [10]

1.4 Special Problems for Glacier Hydrology

Like much of the Himalaya, Bhutan's mountain glaciers differ from the majority of those for which glaciology and glacier hydrology have been developed. It can benefit from cryospheric concepts and practices well-established elsewhere, but caution is needed. Bhutan's glaciers differ significantly from the world's best documented glaciers, especially so-called 'benchmark glaciers'. The latter were usually chosen to exclude or minimize steepness, high relief, and wind redistribution of snow, avalanches, icefalls, and debris-covered ablation zones. Yet these are typical of Bhutan's glaciered areas. Of course, they were excluded for good reason. They intervene in and complicate the climate-

[10] Further details on the hydrology of glaciers are outlined by Menzies (1995, chapter 6)

glacier relations on which conventional mass balance assumptions and measures are based. Most are difficult to measure. However, when they are definitive of the whole environment, they can hardly be ignored. Some of the key concerns are outlined below.

1.4.1. High Altitude Snowfall

Snowfall is a decisive factor in whether glaciers form, their size, distribution, and mass balance and, ultimately, the contribution to stream flows. Glaciers in Bhutan depend, firstly and above all, on snowfall at the higher elevations – snow in areas cold enough for it to survive from year to year. Its importance can hardly be over-emphasized. However, it is one of the least monitored and least well-understood aspects of these and other Himalayan glacier systems. Actual measurements from glacier basins are minimal.

Various publications and reports suggest snowfall above 4,000 m might be no more than 400 mm (w.e.) annually, suggesting an (unlikely?) decline of precipitation with elevation throughout (RGoB, 2015 p.18). Snowfall measurements from glacier basins are rare but a notable exception was for 1998-99, at an elevation of 5,245 m in the 'Lunana region'. (Naito et al. 2012). An annual (340 days) snowfall of 1,349 mm (water equivalent) was observed. The total amount may well have been 1500 mm (we) or more. The results seem to confirm terrain-, or 'orographically'-enhanced precipitation high up in glacier basins.

Given the huge sources of variation from year to year and watershed to watershed, it is impossible to say how representative this is, but it suggests there could be significant orographic enhancement of precipitation in the High Himalaya. Apparently this falls off again through the middle mountains (Rupper et al, 2012). From experience elsewhere in the Himalaya, more or less strong precipitation gradients could apply over *the more than 5000m elevation range* between the highest and lowest areas where snow occurs.

Conversely, there is Tshering and Fujita's (2016) report of a ten-year monitoring of a small, north-facing, clean ice ('Ganju La') glacier, just west of the Lunana area. A negative mass balance was recorded in the 4,900- 5,200 zone. These are also elevations where wind-, and avalanche transfers of snow prevail (see below). Evidently, in the whole decade there was *no net accumulation,* only seasonal snowfall and the glacier retreated throughout the period studied.

1.4.2. Wind Redistribution and Modification of Snow

Even a cursory scan of higher definition satellite coverage from Bhutan's high Himalayan watersheds, shows snow redistributed and modified by wind action throughout. It is shown in the prevalence of cornices along interfluves at the head of glacier basins, of bare windward slopes, and more abundant snow aprons down lee slopes. It is difficult to find sites in glacier basins unaffected by this. Cornices and aprons of wind deposited snow are also critical in priming avalanche activity (Figure 2.5). Glaciers with northerly exposure tend to be cleaner than those with southerly exposure, partly an effect of solar orientation, mainly of wind redistribution. Local wind fields may complicate this picture (Figure 2.6).

1.4.3. Avalanches and Avalanche-fed Glaciers

High altitude snowfall is also widely affected by avalanches. It seems likely more than 80% of actual 'accumulation' on glaciers is by avalanches. Thus, snow mass input to glacier ice differs from precipitation patterns. A great deal of the input may occur below where ELAs or firm limits apply on conventional concepts of mass balance. Avalanches descend from the walls surrounding ice masses and from icefalls, to carry and deposit snow far downslope.

Avalanching dramatically alters snow concentrations in quantity (or water equivalent) and pattern, compared to direct snowfall. This has important implications in accelerating rates of conversion from snow to glacier ice. Avalanched snow is extremely compacted, and what would otherwise take decades in 'firnification' is accomplished at once. The ways in which seasonal, weather and storm incidence affect the character of avalanches, will also influence their impact of the glaciers; if one of the least investigated aspects of glacier mass balance (Figure 1.7). Avalanching is also a major factor in debris content and build-up of supra-glacial debris, released from the ice lower down, and likely to be climate sensitive.

1.4.4. Ablation Zone Conditions and Supraglacial Debris

Decisive factors for ablation and water yields from these high mountain glaciers, are received solar radiation and the surface albedo, or reflectivity of ice. Temperature and seasonal snow cover are important controls over ablation season length, which generally decreases up-glacier, as sub-zero temperatures persist longer and there is more seasonal snow on glacier surfaces.

Debris covers have a strong influence on ablation rates and net yields of water through effects on albedo and insulation. Thick debris covers may have relatively high absorption rates for solar energy, but the debris slows the penetration of heat (Figure 1.8). Where debris thicknesses exceed one or two metres, there may be little or no ablation. Thin and scattered debris can greatly enhance absorption of solar energy and its transfer to the ice. Dirty but exposed ice typically has the highest ablation rates.

Heavy supraglacial debris is one of the most widely reported and discussed aspects of Himalayan glaciers (Hambrey et al. 2008; Milhacea et al 2008; Ming et al. 2009; Fujita and Nuimura, 2011; Hewitt 2014 ch. 5). Its occurrence follows especially from the role of avalanches and rock falls onto the glaciers. There tends to be a systematic increase of thickness and extent towards lower ablation zone areas. Their importance can be overestimated however, because they are the most accessible and first encountered parts of the glaciers. Typically, they are among the most conservative parts of glacier mass balance, and cause a marked *decrease* in ablation losses at elevations where, otherwise, the warmest conditions and longest ablation seasons occur (Figure 2.9). With climate warming, and ice area reduction, the relative amounts of heavy debris cover seem likely to increase.

As noted, a singular concern is how anthropogenic dust and soot can increase ablation in snow covered and glaciered areas. Bhutan is in, or close to, the heaviest Asian sources of air pollution that can generate smog or 'brown clouds'. Estimates suggest that 25- 35% of soot in the global atmosphere comes from China and India. There is exceptional risk of soot and dust fall-out, or rain- out. It may be a larger threat to ice survival than warmer temperatures. Monitoring needs to identify the relative importance of differing types and degrees of debris and dirt on glacier surfaces and snowpack, and track responses to climate change and air pollution.

1.4.5. Icefalls and their Roles

A large fraction of all the ice in Bhutan glaciers passes through one or more icefalls. They are among the most dynamic parts of glaciers, and second only to avalanching in accelerating the downslope movement of ice, snow and debris (Benn and Evans 1998 214-5; Hewitt, 2014). A glance at satellite imagery will leave little doubt as to the great numbers of icefalls in the middle and upper reaches of

Bhutan glaciers. They are, however, among the least studied features. Icefalls may occur at all elevations, but tend to increase, proportionately, as altitude and relief increase.

Icefall environments tend to be steeper, thinner, faster moving, and more crevassed ice (Figure 2.10). They are more open to ambient conditions. Their heavily crevassed nature makes them an important way in which snow and debris can be carried into the body of the glacier. For the same reason, where they occur surface debris is minimal, and ice exposed. It seems likely the prevalence of icefalls makes them an important factor in rates of response of these glaciers to climate change, although no work has been done on that.Where icefalls descend below the firm limit or perennial snow zone, ogives or transverse, arcuate bands may develop (Figure 2.11). They are waves or couplets of a light and dark bands that represent annual flow through an icefall, well-marked in satellite images. The ice below northerly-exposed icefalls tends to be cleaner than that below southerly exposed ones (Figure 2.12). This may partly reflect the relatively greater role of avalanche-, compared to wind-redistributed snow on the latter.

1.5 Permafrost, Rock Glaciers and Peri-glacial Processes

Permafrost, or ground in which temperatures stay below 0^{o}C for two consecutive years at least, is widespread in Bhutan above about 4,000 m. There are, however, no observations to confirm its extent and depth, the continuous and discontinuous areas. It is likely climate change has been having considerable effects on these dimensions, but no data are available. At present no plans have been made to rectify that. The same applies to periglacial features and processes and the hydrological roles of freeze-thaw or changing frost days. Getting a handle on these components is essential for integrated water management and a reliable view of the needs of climate resilience.

The clearest indications of the extensive permafrost presence are large numbers and diverse forms of rock glaciers (Figure 2.13). These are more or less lobate forms, their visible parts consisting of angular debris. They bear a resemblance to small, debris-covered glaciers. They are associated with a variety of cryospheric conditions, glacial, periglacial and slope processes mainly rock falls (Barsch and Jacob, 1998). They include glacier-, avalanche-, and talus- derived forms. It seems likely more than 2000 are present in the northern cryosphere of Bhutan, in the vicinity of the glaciers. In areas of recent deglaciation they may be inherited from glaciers, and even contain masses glacier ice (Figure 2.14). However, they differ in various respects, moving much more slowly than glaciers, centimeters rather than tens to hundreds of meters annually. There are important differences from a water resources perspective. Water yields are not as great as from glaciers, but most springs or streams coming from rock glaciers are clear. They are much preferred for drinking domestic animals and small scale farming.

1.6 Sublimation and Evapo-transpiration in Glacial and Nival Environments

Among the least known, but potentially large and climate-sensitive, parameters are sublimation and evaporation of snow. In forested mountain areas, snow-interception by the tree canopy has been shown to involve between 1/5th and ½ of received precipitation (Koerner, 1999). In mass and duration, the fraction of snowfall held by interception can be an order of magnitude larger, or more, compared to rainfall. Over the winter, sublimation in forested catchments may also remove substantial amounts of moisture.

Work on this topic has been almost wholly in sub-Arctic forests, but it seems likely that in sub-tropical montane forests like Bhutan’s, the quantities involved could be larger in absolute and relative terms, especially when cold coincides with an extended dry season. Forest age or maturity is a factor.

Substantial differences are reported between deciduous, coniferous and mixed forests (eds. Reynolds and Thompson 1988). In the sub-Arctic, snow processes appear more sensitive to atmospheric conditions than the state and variations in vegetation cover. The reverse may apply in rugged mountain environments, and where forest fires are an important factor, as in parts of the Inner Himalaya of Bhutan.[11]

With temperatures expected to rise in the inner Himalaya through the coming decades, in winter especially, sublimation and evaporation seem likely to increase, possibly at the expense of run off. [12] In the absence of observations these factors remain to be checked out. Joint efforts with the Forest Department, and in relation to biodiversity concerns, seem warranted (see 4.2).

1.7 Cryosphere Hazards

The Bhutan cryosphere is subject to a range of hazards. Some originate directly from glacial processes. Others, such as earthquakes and storms, may trigger glacial hazards as part of more complex events. Conversely, these other hazards may adversely affect cryosphere conditions.

The greatest investment in glacial hazards to date and, indeed, in cryosphere research, has been for glacier lake outburst floods (GLOFs). The geologist, Augusto Gansser (1983; 1990) brought them to international attention. Little was done about the problem until after the 1994 event, the most destructive on record (Watanabe and Rothacher 1996). The damages and loss of life brought a new and urgent focus on these hazards.

Substantial investigations were undertaken, and programs for monitoring, mitigation, disaster preparedness, and community outreach. GLOFs have received special attention. Images of the spectacular series of glacial lakes that developed in Lunana region since the 1970s, came to epitomize Himalayan GLOF hazards (Iwata et al 2004). Attention was on the rapid growth, volatility and potential interactions of some of these lakes (Watanabe and Rothacher, 1995; Häusler et al. 2000; Richardson and Reynolds 2000; Karma et al, 2008). Generally they have been identified with climate change and the risk seen to be increasing (Richardson and Reynolds 2000; Ives et al, 2010). Inventories of glacial lakes were prepared (Mool et al. 2001b; Iwata et al, 2oo2; Tadono et al, 2012). Some 2,674 glacial lakes were counted. The vast majority are very small.

Danger potential was also linked to morphological classified into lake types. Mool et al (2001, 105) found that "…glacial lakes can be grouped into three types: glacial erosion lakes, glacial cirque lakes, and moraine-dammed lakes. The former two types…do not generally pose an outburst danger….moraine-dammed glacial lakes have the potential for bursting." Some 562 lakes were found to be at, close to, or otherwise associated with glaciers, seen as the most general indicator of risk (ibid). Some 174 lakes were found at distances of less than 50m from a glacier.

In all, 24 'dangerous lakes' were identified (Figure 1.15). Assessments in 1995 added considerably to knowledge about the degree of stability of several of the larger glacial lakes in Bhutan (Watanabe and Rothacher 1996). Mitigation measures have been quite extensive (Hausler et al, 2000). That no further destructive GLOFs have yet come from the designated "dangerous lakes" reinforces a sense of events that are rare, singular, and complex.

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[11] From 2010 to 2014, the Forest Department reports an average of 45 damaging forest fires affecting almost 20,000 acres (Bhutan Renewable resources statistics, 2015)

[12] Although rainfall has declined at a number of stations across Bhutan (NECS 2016, 41)

Almost all reports assert that these GLOF risks derive mainly from on-going climate warming, and are increased by glacier retreat and associated ice wastage. The number and size of lakes at or close to glacier margins have indeed increased, some with alarming rates of growth. They change of shape and potential for interactions.

However, evidence to date even suggests GLOF incidence, especially large destructive ones, has actually been declining. Known large GLOFs were more frequent before the 1970s, than since. From efforts to extend the record based on geomorphic evidence it was observed;

> "….17 of these [GLOFs] occurred between the 19th century and the 1960s. On the other hand, there were *only four cases* of outburst incidents in the last 40 years. Hence, the frequency of outburst occurrence does not seem to have increased."(Komori et al (2012), p.68 emphasis added).

As Mool et al (2001) pointed out for their pioneering study, most of the lakes deemed "dangerous" were already in existence more than 40 years old before the inventory. Those of continuing concern are now another quarter- century older. We must take account the warnings in various studies about the difficulties and costliness, if not, impossibility of tracking the conditions and processes said to create dangerous lakes (Ives et al, 2010).

Meanwhile, decades without serious events add to uncertainties about the scale of risk and conditions that bring actual GLOFs A small 'GLOF' of 2015, did came from a moraine dammed lake, but was originally was thought triggered by a small earthquake, and later attributed to heavy monsoonal rainfall (Orlove 2016). Then there is a broader questions of floods. Over the past decade riverine floods, including flash floods, have come from other sources than GLOFs, mainly rainfall-related.

Today, something close to a state-of-the-art capacity exists. It includes the early warning systems (EWS) for the Mangde Chu and Chamkhar Chu river basins. Towards the end of the 1990s, the Raphstreng Lake outlet was artificially lowered by five meters an outlet was made out of. Similar work has been undertaken to lower Thorthormi Lake outlet.

This is also on-going work. It includes re-assessment of all the glacial lakes deemed 'dangerous'. An important on-going role of CSD staff is to check the status of glacial lakes that have been classed as "dangerous" in the past in particular when after decades, in some cases more than a century, no GLOF has been observed from them. At the same time, there are GLOF risks in other headwater streams and along other rivers than the two currently monitored.

Chances of the repetition of anything close to the 1994 event needs constant vigilance. The quality of the work and sense of pride in the achievements of mitigating and forecasting GLOFs is warranted. Nevertheless, staff involved in Bhutan are also concerned both that readiness will diminish or be replaced by skepticism because of the decades between events – a common problem with disaster preparedness. Also there is the problem of other, possibly equal if not greater, hazards and cryosphere issues being neglected.

Chapter 2. Existing Status of Hydro-Meteorological Services and Cryosphere Monitoring

A recent report, known as the "Road Map" (RGoB, 2015)[13] provided a comprehensive review of Bhutan's hydrometeorological services. It was a joint effort by various branches of the Government of Bhutan and a World Bank team. The importance of snowfall and glaciers was emphasized, and the GLOF hazard. Both were described as urgent, partly because of development pressures, mainly because of potentially adverse impacts of climate change (p.3).

However, the Road Map did not deal with specifics of snow and ice monitoring. These are the focus of this report. First an overview is given of climate services in place, partly based on the Road Map or updating it. A more specific and detailed break-down is given of cryosphere conditions and monitoring needs (3.1 – 3.6).

2.1 Weather and Stream Discharge

As a whole, the Road Map concluded that weather and river gauging stations are inadequate (RGoB 2015; Ch.3). Existing networks were not seen as fully able to meet requirements for any aspect of water resources or region of the country. The two key aspects of cryosphere geography raised above, elevation range and for different drainage basins, are inadequately covered.

Most important, from a cryosphere perspective, stations were found to be virtually *non-existent in the High Himalaya*, and rare or absent *in most of the Inner Himalaya*. Almost all existing weather stations are sited below 4,099 m elevation (ibid p.36), well under the lowest reach of glaciers at approximately 4,300 m. There is nothing to track conditions at elevations one to three thousand meters higher, where the main ice masses occur. Yet here are meteorological and hydrological conditions decisive for glaciers, for perennial snow, and major areas of permafrost.

Furthermore, 75% of stations were identified as below 2,355 m (p.36). That puts most of them below the lower limit of winter snowfall and freeze-thaw. The stations that do exist in the Inner Himalaya are insufficient in numbers and geographical coverage. These problems apply both to Bhutan's state networks, and those supported by the Government of India.

Some useful temperature data are provided by two AWS stations, set up in 2003 at Pelela (3,420) and Yotongla Pass (3,353). They could be used for, say, tracking frost days and freeze-thaw cycles in the seasonally cold environments. That has yet to be done, and they are too low to adequately represent conditions where the glaciers exist. Potential benefits depend upon extending the network to higher elevations.

There are proposals to further extend the AWS network (Figure 3.3), but no indication that cryosphere conditions were taken account of in network design. Appropriate instrumentation and site-specific problems for measuring snowfall, snow water equivalents (SWE), soil temperatures and the like, need to be addressed (see 4.2.i).

Likewise, river gauging stations, except for some serving the GLOF EWS, are sited well below and distant from glacier termini (Figures 3.4, 3.5). They measure flows where glacial, nival, rainfall-runoff, and/or groundwater contributions are already mixed. Each of these can vary more or less independently from year to year, seasonally, and according to weather conditions. At present no

[13] RGoB and WBG 2015 *Modernizing Weather, Water and Climate Services: A Road Map for Bhutan*, Prepared in Collaboration between the Royal Government of Bhutan and the World Bank Group, Washington D.C., May.

methods or models are available to separate out the different components. Integrated water management requires that this be done reliably, and as the basis for tracking and forecasting impacts of climate change, not least for cryosphere variables (see 4.2.v). The Road Map summed up its concerns with the hydromet' network as follows:

> "…At the moment it lacks the basic infrastructure, such as reliable Internet connectivity… or adequate computing resources, to carry out its tasks. Its ground monitoring system is mainly manual, and there is a need to invest in real-time stations and telemetry in a sustainable way. Meteorological measurements are under-represented at the higher elevations, where access is difficult and the climate is forbidding…

It was recommended that improving the network density be part of a follow-up consultancy (p.40). Some measures and new equipment have already been provided atNCHM. As yet, however, the needs of cryosphere monitoring have not been addressed (see 3.2).

For the latter, it will not be enough merely to extend the existing network and its communications systems. Network parameters and representativeness need to be re-examined. New or modified instrumentation will be necessary *at existing* as well as new sites, to serve the kinds of measurements needed for snow and ice. Alternative sites, instrumentation and network design need to be considered for the special character and constraints of cryosphere conditions. Below, some of the major concerns are addressed first before turning to the existing status of CSDand its operational requirements.

2.2 Snowfall and Snow pack

As outlined above (1.2), snow is the most considerable of cryosphere contributors to Bhutan's water resources. In terms of monitoring and baseline information it is also *the most neglected*.

The amounts and geographical variations are unknown. High altitude snowfall that feeds the glaciers, is not measured anywhere (1.4.1). There are a few, probably unreliable, observations of seasonal snow covers in the Inner Himalayan and its forested catchments.

At some 18 stations 'manual snow observations' are maintained (Figure 3.6). Apparently they are, at most, once daily checks of snow depth (Road Map p.41). All stations except one are below 4,000 m elevation. Intermittent snow depth measurements are made at a few weather stations and sites at mountain passes in the Inner Himalaya. Only one is above 4,000 m, Soe, at 4,387 m.

In mountainous catchments, of course, it can be difficult or impossible to deduce snow water equivalent from snow depth (1.4.2). Apparently, no station is presently set up to monitor the most critical variable in hydrological terms, the 'snow water equivalent' or SWE.

The Road Map reported 'snowpack' measurements at one station, and there were plans to add three more. The three AWS sites at Yotongla Pass (3353 m), Pilela Pass (3420) and Soe (4387) provide hourly precipitation. Apparently, they are not set up to measure snowfall, only rain[14]. It would be helpful if snow measurements could be added. Even more important is to extend the station network for greater geographical coverage and elevation range. In all cases there is a singular need for SWE measurements (see 3.3.ii).

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[14] The Road Map (p.42) says these stations are set up as "Automatic Snow Stations" but that seems not to have happened, nor have the "plans to install at least three such stations in 2014-15 in the high altitudes of Wangchu and Manas basins". The plans appear to be on hold.

2.3 Glaciers

Investigations of Bhutan's glaciers have included more than a dozen research expeditions, essentially summer field projects. Most initiatives have been by researchers from outside the country. It may be useful to pull together and compare their observations over time and by location. (Apparently a large collection of reports is housed in the library of the Department of Geology and Mines).

There have been several useful inventories of Bhutan's glaciers and glacial lakes (Fuji and Watanabe, 1983; MoA, 1997; Tsvetkov et al 1998, 181 Mool et al. 2001; Rupper et al. 2012; (Bajracharya et al's 2013;). Methods and coverage suffer from a lack consistency and in some, older, less precise data. More critically, they were carried out without addressing the needs and objectives of a monitoring system.

The Road Map refers to two glacier monitoring stations (ibid p.41-43). Presumably one was Meta Tshota glacier in the headwaters of Mangde Chu Sub-basin. It was studied for a few years in collaboration with Brigham Young University and Columbia University. The program stopped in 2014. The other seems to be Thana Glacier upstream of Chamkhar Chhu basin. In the last two years members of CSDhave visited it in two short summer expeditions with international partners (ICIMOD 2016). Such projects give invaluable experience for CSDmembers, and there is a plan to adopt Thana as a "benchmark glacier" (see 3.4).

As it stands, however, knowledge of glaciers is unavoidably patchy in time and space. Large parts of the glaciered area have never received attention or, at most, exploratory satellite-based surveys. It is not clear that a comparative assessment of these and other glaciers has been made in relation to an overall plan for effective and representative monitoring. Mass balance investigations are of most direct interest for water resources and impacts of climate change. A comprehensive survey is needed to address this objective and decide which glaciers, watersheds, and sub-basins of the main rivers, might best satisfy it. Accessibility is a major concern, but not the only one, Glaciers or sub-basins that represent different hydrological environments within the Great Himalaya must be chosen. That includes ways to address problems of high altitude snowfall, wind redistribution and avalanching, icefalls and debris covered ice. Plans must consider the fact that all, or nearly all, otherwise suitable glacier basins, have areas rendered too dangerous by crevassing, icefalls, avalanches and rock fall. Choices must include whether and how far remote sensing, or snow and ice chemistry can be substituted for or checked against field measurements. More generally, the Road Map emphasized that:

> "…While regional institutions are partnering with the DHMS to monitor decadal shifts in glaciers in the Bhutan Himalayas, the DHMS needs to strengthen *its own capacity in cryosphere monitoring and early warning systems,* given its mandate…" (p. 49, emphasis added)

2.4 Permafrost, Rock Glaciers and Freeze-thaw

The Road Map urged attention to the cryosphere as a whole. However, only snow and glaciers were explicitly mentioned. Permafrost has been largely neglected. To date there have been few and patchy efforts to identify its extent and state. There is no work to trace the incidence and intensities of periglacial processes, of frost days, or freeze-thaw. Temperature data from existing stations could help, but they hardly cover, nor are set up for, the range of frost environments. This could require measuring temperature profiles in different local microclimates, soils, and as a function of snow cover.

There has been little mention even, of the many rock glaciers (Iwata et al, 2003). Yet they have some hydrological significance, and could help identify and track the impact of climate change on permafrost behavior.

There appears to have been no mapping of periglacial areas and hazards; nor assessments of the place of freeze-thaw and melt water contributions to groundwater, springs and base flows. These are always important for forest cover, ecology and agro-pastoral communities and are all likely to be sensitive to climate change. They are parameters that CSD should surely address, and will be shown to have particular relevance in climate services it could offer to other divisions (see 4.3). They have to be part of an actual, integrated water and watershed management program.

2.5 Climate Change - Hazards and Uncertainties

Climate change is repeatedly mentioned as a concern in reports (Rupper et al, 2012). Its importance seems widely accepted, and was brought up in discussions (see 3.1 and 4). There is some general, mainly inventory-type information, to suggest the scope of changes to date. As already noted, the loss of glacier cover is exceptional and reports of reduced snowfall cause for alarm. However, there is virtually *no adequate research or tracking* to give definitive assessments or to predict future trends and impacts on uses. The absence or unrepresentative nature of existing observation networks compromises assessment of cryosphere conditions and melt water sources.

Studies and monitoring of glacial lakes have addressed important aspects of glacier change. Specifically that is for the two areas where the GLOF hazard is considered severe (1.7). However, coverage is incomplete as yet. The relations between climate, glacial lakes and other glacier conditions confound theory with unexpected changes. As yet there is no specific agenda to track the controlling variables. All that can be urges is a constant need to refine and update past observations and inventories, and develop a credible program of glacial multi-hazards reportage.

It is the case that other cryosphere hazards – avalanches, rock falls, debris flows, and freeze-thaw -- have been largely neglected. For the most part climate change is viewed in terms of increases in, or introduction of new, hazards such as forest fires and effects of disease on tree cover. Of late, the more frequent and serious floods have come with heavy rains or in flash floods. Conversely, there are widespread reports drying up of spring-fed streams and groundwater, critical for agriculture, pastures, forest ecology, and watershed management. This is where 'climate resilience' may become more critical, and needs to be informed by effective monitoring of snow hydrology.

There is also an informed consensus that climate change impacts may be confused with other sources of change arising, for instance, in different sectors and populations, and must be taken into account. In general, the approach being favored is towards a more balanced, multi-hazards assessments and preparedness. It is more in keeping with the integrated management strategies for water resources (3.4).

Chapter 3. Snow and Glaciers Division Capacity and Needs

The Cryosphere Service Division (CSD) is the focal agency for the purpose of this report. According to the Road Map:

> "The CSDis tasked with monitoring the country's snowpack and glaciers. Its programs are aimed at tracking the accumulation and melting of snow and glacial fields… preparing policies and plans related to snow and glaciers, managing and maintaining the monitoring network, and undertaking surveys across the country… (p.61)

It was also proposed that their work become the basis of a "long-term program for monitoring of Bhutan's cryosphere" (p.73). This implies observing the full range of cryosphere conditions, as outlined above, at least as they enter water resources issues and hazards. As already noted, however, the Road Map did not go into any of the scientific, technical or logistical issues that beset such programs.

The Road Map also concluded that, although set up in 2013, SGD lacked most of the personnel, facilities, training, and funds necessary to begin planning, let alone implementing a monitoring program (2015, p.61, Table 22). That remains virtually unchanged as of the end of 2016. CSDis barely operational. A small core of staff with experience of glaciers and snow is continuing some minimal summer field work: a pilot study for glacier mass balance at Thana Glacier, maintaining of the GLOFs set-up, and a reassessment of glacial lakes formerly identified as dangerous. They could begin working through program objectives, establishing scientific and logistical equipment and other concerns, outlined in the Road Map. Until they have a budget and time lines for facilities to be made available, their hands appear tied, the work, at best, marking time. Only the GLOFs program is well-developed, most of it conducted outsideCSD. Earlier some of the most experienced staff were housed in Department of Geology and Mines, partly because that is where equipment, data bases, remote sensing and other facilities were available. However, glaciology division under department of Geology and Mines has been merged with Snow and Glacier Division of DHMS under NCHM as Cryosphere Service Division. As a result, all staffs under glaciology division of DGM were transferred to CSD under NCHM

3.1 Consultations with Stakeholders

Consultations with stakeholders in Bhutan were undertaken as part of the preparation of this report and focused on existing programs, immediate and longer term aims, capacity building needs, and potential services of *cryosphere* monitoring to other agencies.

On the basis of the discussions, the elements of an operational monitoring program for cryosphere variables, is defined below (3.2). Consultations were also held with staff from six other agencies, likely to be among the main users of cryosphere information (see Section 5).

While the 2015 "Road Map" report addressed many important issues in terms of cryosphere monitoring in Bhutan, it did not delve into the science behind the cryosphere phenomena and inferred threats from climate change. The issues CSD staff and most others responsible for actual operations brought up, concerned technical and logistical issues of mountain cryosphere monitoring. These are all critical matters for implementation. From the discussions it seemed there is a need to:

a) Define more fully the scope, goals and specifics of cryosphere monitoring (3.2).

b) Urgently address CSD's lack of most of the equipment, facilities, office and laboratory space, and of personnel, necessary for an adequate cryosphere monitoring program.
c) Identify ways to provide a more comprehensive view of what services should be expected of CSD, to whom and how they can be delivered.

On the one hand, work to date has been uneven in scope and information generated. On the other hand, it offers a basis on which to build, and with one great advantage. There is a nucleus of staff in, or heading to, CSD who are experienced and knowledgeable of conditions in Bhutan's snow and ice environments. They have already, or could soon be trained to, tackle many of the operations required. They may well need outside assistance, some expert consultants, and training. But their on-the-ground experience will be essential for deciding the most appropriate strategies and for Bhutan to take ownership of this program. Some of the essential items are summarized below.

3.2 Operational Requirements for Cryosphere Monitoring by SGD

In terms of more comprehensive goals for the division, staff propose organizing their work under the umbrella of water systems or, more specifically, water budget. This would emphasize the contributions of different cryosphere parameters and environments. It is in accord with the national emphasis on integrated water management in The Water Act of Bhutan[15]. The requirements of a cryosphere monitoring program going forward must, however, address conditions outlined in Sections 1 and 2 above.

It is important to note that 'contribution' is not only about volume. Relatively small yields may be critical in particular seasons or habitats. Water quality may be an issue, notably in the distinction between turbid glacier melt, and clear water from snow, ground water springs or rock glaciers, or where contamination may develop.

In the high mountain context, field investigations and instrumentation raise major questions of safety, reliability, logistics, access and local support (or lack on them). Instrument robustness, protection and performance have to be determined. These change in different seasons. Snowfall stations and snow courses, for example, will be effective mainly if carried out in winter, but raise special questions of access and logistics. Trade-offs must be made between precision, reliability, and cost of particular instruments; affordable numbers of them and data management. Especially important but challenging, is to combine field visits, research and measurement projects, say, in glacier basins of the high Himalaya, with remote sensing and data streams from installed permanent monitoring stations.

A patchwork of investigations in the past, and the special program for GLOFs have been outlined. However, no existing set-ups measure, or can measure, the various forms of snow and ice identified. This requires appropriate instrumentation, constraints on site and network design, analytical and modeling tools, and ways to transmit and store data.

It is suggested that the monitoring program should address each of the following elements, trying to integrate and balance them in an overall strategy:

i. Extending the hydrometeorological network
ii. Field programs I: Snowfall in the High and Inner Himalaya

[15] See National Environment Commission 2016 *"National Integrated Water Resources Management Plan, 2016"* Royal Government of Bhutan, 144 p

iii Field programs II: Glaciers in the High Himalaya
iv. Indirect methods I: Remote sensing and GIS
v. Indirect methods II: selective sampling for snow, ice and water chemistry
vi. Indirect methods III: mapping the range of cryosphere conditions including glacier, permafrost and periglacial landsystems
vii. 'Data mining'; of existing station records, satellite coverage, and past expeditions
viii Glacial hazards and disaster preparedness

Something of the scope of these elements is outlined below.

3.2i Extending the hydro-meteorological network.

Further weather stations are needed to track conditions above 4,000 m, and in glacier basins. A denser network is also needed in the Inner Himalaya. Additional, improved or new instrumentation should be explored at existing weather stations. This should be, at least, for snowfall, evaporation and freeze-thaw between 2,500 m and 4,300 m. Also, the system of stream gauging stations needs to be extended to take account of headwater streams with predominantly glacial, nival, and/or glacio-nival flow regimes.

Grabs [16] (2016) suggests minimum criteria for site selection for such stations include:
1) Representativeness with regard to snow and glacier hydrological regimes
2) Existing or planned development potential downstream developments in the basin
3) Accessibility of the station site; seasonal, but year round where feasible
4) Availability and access of local staff or that can be employed as (part-time?) observers
5) Logistics for supplying of the stations with fuel, food, essential maintenance items, etc.,
6) Communications set up; possibility to establish radio, mobile phone, automatic transmission of data, etc.

Eventually some standard set up and configuration for data logging and/or automatic transmission should be chosen. Initially, however, it would be a mistake to opt for any one standard type of station for cryosphere variables, and start installing it. The process needs to be experimental. A range of equipment types and configurations, site and setting-specific conditions, need to be tried out for one or two seasons at least, before committing to a common set up and network. This has hardly been done for the high Himalaya anywhere. It should be approached cautiously, getting advice where it exists, to avoid unnecessary waste and losses. Existing stations may need to be moved if observations turn out to be compromised by local conditions.

Difficulties of finding good gauging sites in or near glaciered terrain warrant experiments with various methods of discharge measurement (dilution for example). Eventually, a stage recorder may be sufficient for many sites, once intensive, short-term measurements can establish discharge rating curves. The respective contributions of snowmelt, glacier ablation, etc., might be deduced, but will probably need experiments with water chemistry and isotopes to separate out different components. This may make it possible to calibrate existing stations to track longer term variability in relation to climate change.

3.2.ii Field programs I: Snowfall in the High and Inner Himalaya

[16] Modified after Wolfgang Grabs "Inception report (for Nepal)" p.6 where he also outlines criteria for CryoNet set up.

The use of snow gauges and snow courses was outlined above, although the objectives and criteria for them have to be spelled out. At-a-site observing stations will require choices among snow gauges, snow pillows, automatic or manual depth measurements, depending on local conditions. In snowier areas, snow pits will also be useful. Sites and network will need to link up with remote sensing, and such local observers as can be engaged. Existing observations (manual stations etc.) should be assessed and decisions made about whether to retain, upgrade or abandon them.

The problems of accurately capturing the snow that actually falls must be addressed. All available instruments have weaknesses – snow gauges, snow pillows, snow pits and snow courses. Special problems arise in choosing and testing different instruments. Difficulties tend to be compounded in mountainous areas. Special care and skill are needed to identify good sites and obtain reliable results hence, again, an experimental approach. The likelihood that a given snow collector or site will be accurate declines as wind speeds increase. Usually this results in 'under-catch' but, in lee-sheltered terrain, may overestimate actual precipitation.

A system of *snow surveys* should be implemented for several drainage basins from west to east in the Inner Himalaya. Accessible and suitable snow course lines and settings ill need to be identified. These will be useful in forested catchments taking advantage of sheltered clearings:

> "…The goal of the snow survey is to obtain an accurate measure of Snow Water Equivalent (SWE) at predetermined locations... Snow courses typically have between five and ten measurement points spread out over one or more straight-line transects. Transects can be short, or several hundred meters in length. Some snow courses are coincident with recording or data-transmitting weather instrumentation; many others stand alone in very wild and remote locations. Most snow courses are measured once per month throughout the winter (accumulation) and spring (ablation) seasons, though some may be measured at different frequencies… (Osterhuber, 2014)[17]

The surveys will require core samplers for depth and SWE (eg 'Mount Rose'). Choices will depend on winter and spring access. Staff should explore use of snow shoes and/or (cross-country?) ski equipment and training.

It is essential to have measurements that determine snow water equivalents (SWE) for snowfall, snow-on-the ground, and to forecast their melt water contributions. While remote sensing can be used to track snow cover, by season and in the longer term, sensors are not yet generally available to determine snow depth, let alone SWE. In part, the preferred system of snow courses in forested catchments should include setting some of them up at permanent weather stations to cross check with snow gauge performance.

Where snow is a few tens of centimeters deep or more, *snow pits* should be dug at courses and other sites

> **"…** A snow pit is a trench exposing a flat, vertical snow face from the snow surface to the ground. It allows you to study the characteristics of the different layers of the snowpack that have developed as the snow has changed due to compaction and weather changes. Snow pits are routinely used in mountainous areas to determine if one layer might slip on another causing an

[17] Osterhuber, R. 2014 *Snow Survey Procedure Manual*, The Resources Agency of California Department of Water Resources California Cooperative Snow Surveys http://cdec.water.ca.gov/cgi-progs/products/SnowSurveyProcedureManualv20141027.pdf

avalanche. Snow pits also help researchers measure the water content of a snow pack. This is essential in flood prone areas, and it is essential in those dry areas where the snowpack provides water for the coming year…. "NASA (n.d. p.1)

Public resources for snow pit procedures include Harrison (1994) and NASA (n.d.) [18] which outline methods, equipment, safety concerns, data set-up etc. Snow can exhibit great differences in density according to thermal, humidity and wind conditions even during snowfall, but especially through modification on the ground. It packs down through its own weight and through freeze-thaw, which can generate ice layers, and sublimation/condensation as indicated by 'depth hoar'.

As already emphasized, in the high mountains wind action and avalanching redistribute much of the snow that falls. They also transform its physical properties, notably densities which are much higher than direct snowfall or undisturbed snowpack. Debris content tends to be higher, thermal properties may be modified, and freeze-thaw may come into play. None of these parameters has yet been considered, let alone measured in Bhutan's glacier basins, to which we now turn.

3.2.iii Field programs II: Glaciers in the High Himalaya

Himalayan glaciers pose huge problems for adequate monitoring. Glacier monitoring will require a combination of field based experiments in selected glacier basins, linked to remote sensing tools such as digital elevation models, cross-correlation feature tracking, and glacier mapping.

Selection must be based firstly on drainage basins involved. Most probably, preferred glaciers will be in the two basins with the heaviest ice covers. The size, conditions and climate response of Bhutan's glaciers also seem to depend very much on watershed elevation and should be chosen accordingly.

From a monitoring point of view each gradient, elevation zone, and downslope interaction affects measurement problems and prospects. Accessibility, suitable sites, seasonal and spatial sampling requirements can require a different mix of methods in given basins. To date, the expectation has been that several individual glaciers will be chosen for repeated surveys to determine mass balance. Some plans recommend establishing "benchmark" glaciers to track mass balance changes. Thana Glacier is being considered based on type of glacier, condition of the glacier tongue (presence of calving), area and accessibility. However, experiments with mass balance studies to date are very preliminary, and confined to its lower ablation zone. SGD still needs to come up with a plan assessing a spectrum of glaciers to represent Bhutan's Great Himalaya region.

Care is also needed because benchmark glaciers involve a strategy developed and successful in very different mountain conditions from the Himalaya. Conditions may make it impossible to monitor all the main determinants of mass balance for a single glacier. Glaciers from the highest watersheds might be chosen as larger, healthier and representing the broadest range of altitude-dependent conditions. But all seem to have some exceptionally steep and rugged parts. The ablation zone may be accessible, but in many cases the upper basin or 'accumulation zone" seems unapproachable because of heavy avalanching and steep icefalls. It may, in fact, be better to identify representative and favorable hydrological sub-environments on different glaciers.

[18] Harrison, W.L. 1994, Snow Pit Measurements and Avalanche Forecasting, Geography 526 Rm University of Utah http://www.inscc.utah.edu/~campbell/snowdynamics/reading/Harrison.pdf; NASA (n.d.) *Winter's Story, Student's Observation Network*, https://www.nasa.gov/pdf/186123main_SnowPitProcedures.pdf

The largest factor generating water yields from within glacier basins is usually ice ablation. Studies elsewhere in the Himalaya show snowmelt can be a large, usually secondary but sometimes dominant, factor in some basins, some parts of the year, and even for whole years. Heavier snowfall years can also tend to protect the ice and shorten ablation seasons. There seems to be no data on this specifically for summer accumulation regimes, and none at all for Bhutan's winter snowfall in the Great Himalaya.

Seasonal snowfall includes on-ice snowpack and avalanched snow in the ablation zone, and off-ice snowfall below the climatic snow line. It would be useful to know what fraction of seasonal melt waters involve freeze-thaw of snow and seasonal ice superimposed on the glacier. In Himalayan glaciers surface sub zones can involve extensive areas above the snow free ablation zone, varying through the ablation season and from year. From highest to lowest they can feature 'dry snow' and wet snow zones, percolation and superimposed ice zones (Menzies1995; Hewitt 2014 p.99). The importance of such zones was first explored in the Everest region by Mueller (1962).

Snowfall is again important, and poses distinctive problems in glacier basins. Water yields include several snow components from the high altitude snowfall in the accumulation zone, to seasonal snowfall onto ablation zones. There is also seasonal snowfall onto ice-free areas of the basin. In some parts it may be measured using methods appropriate to permanent fixed stations, snow courses, and/or in pits. The latter are best for accumulation zones if and where undisturbed snow can be found. Whenever a team is present, it is useful to measure new snowfall, including for individual storms, at several elevations and in on-, and off-ice sites, if possible.

In glacier basins a lot of snow falls in inaccessible or dangerous areas. The portions moved around by wind or avalanches are difficult or impossible to measure directly, if at all. It becomes important to find least disturbed sites, preferably snow pits for SWE and sampling snow and ice chemistry.

As in most of the Himalaya, unless monitoring strategies can be devised to resolve the many difficulties, and safely, not just benchmark glaciers but any mass balance may remain hard to achieve. Field work may be largely to support largely estimates extrapolated from limited data and through models. As such, this is where monitoring problems are far from just applying known, routine measurements. They converge with unresolved problems of research into Himalayan glaciers.

3.2.iv Indirect methods I: Remote sensing.

Satellite imagery has offered substantial advances and constantly improving methods to address the difficulties of information and tracking of the high mountain cryosphere. It is now the major source of work on high Asian glaciers (see Reference lists). Caution is needed, to ensure reliability through ground control. However, no credible monitoring program can any longer proceed without up-to-date facilities for satellite data reception and analyses. This applies to mapping of features and basin areas, a range of indirect measures of snow and ice hydrology such as snow cover, or wind and avalanched areas, or areas and surface conditions including debris-cover in ablation zones. SGD can hardly proceed without such facilities, and arrangements for updates and training needs. It will be important to establish which systems will be available and how to ensure regular reception.

Much of the basic mapping and analysis can be done from the sets of best images archived over the past decade or more. For tracking glacier change, glacial and other hazards in the Great and Inner Himalayan areas, something close to a real time facility will be needed.

Snow cover can be explored and tracked through satellite imagery, including the MODIS described as a Moderate Resolution Imaging Spectroradiometer (see http://nsidc.org)[20]. There are difficulties in obtaining reliable depth and water equivalent data in high mountains, and SGD will need to explore options available for its territory.

3.2.v Indirect methods II: selective sampling for snow, ice and water chemistry isotopes, particulates and contaminants,

Water chemistry isotopes will help in diagnostic of climate change and where it is coming from and water quality. It will need to be based on a system for sampling and analyses in various hydrological environments where snow, ice and melt water are important.

In a trial evaluation of geo-, and isotopic chemistry in the headwaters of Chamkar Chhu, Williams et al. (2016) measured the share of "glacier outflow contributions" during the monsoon season of 2014 The glacier component was from near the Thanagang Glacier terminus. There was a general reduction in the glacier contribution with distance down-river:

> "… glacier outflow contributions increased from 55% of streamflow in July to 76% of streamflow in September at 4500m... At the lowest-elevation site (3100 m), the glacier outflow contribution increased from 14% to 31% between July and September (p.347)".

They also note that, at lower elevation sites groundwater contributed 60-80% of discharge in July, and declined in the later monsoonal months. The project does show a promising use of chemistry for separating out different contributions, and likely effects of climate change. Questions remain as to how a broader network could apply or extrapolate such results to other basins, to a full-year profile, and to deduce the range of fluctuations in year-to-year conditions, and going forward.

3.2.vi Indirect methods III: mapping of cryosphere features, zones and hazards. It may seem 'old school', but a program of mapping, on the ground and from satellite imagery, is invaluable as a learning exercise, for reference tools, and to use in outreach information. Such mapping requires a thorough background in cryosphere conditions. Geomorphological mapping can help identify the lay- out and environmental relations of permafrost and periglacial features, talus, avalanche, glacial lakes, and rock glaciers, land cover and ecosystems. This could, for example, adopt a 'land systems' approach (Eyles, 1983; Evans, 2013). Hazards mapping is essential for risk zoning, land use planning and preparedness. Other divisions and the general public will benefit from seeing where features are, and how various parts of the cryosphere are laid out, relate to each other and the country a whole.

3.2.vii Data mining, desk work, gathering together all existing records of cryosphere-related conditions such as some 45 years of satellite coverage, temperature time series to explore and establish changes in the recent past.

3.2.viii Glacial hazards and disaster preparedness

How SGD will relate to and be involved in the existing GLOFs program remains to be agreed. However, there is a strong argument for them having multi-hazards approach. Other cryosphere hazards – avalanches, debris flows, freeze-thaw -- have been largely neglected. At SGD there was a consensus, echoed in the Disaster Resilience group, in favor of *a multi-hazard approach, broadening out and balancing the existing capabilities in the GLOFs area.*

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[19] U.S. National Snow and Ice Data Center

[20] U.S. National Snow and Ice Data Center

SGD will have specific concerns with, say, post-storm conditions and how these may affect floods, avalanches, debris flows and other landslide hazards. They will need to learn to identify how insufficient snowfall and snow cover can affect water shortages or the fire hazard. Forecasting for snow and ice tends to involve different time frames and lag times from weather forecasting and special relations to the latter. For example, there are specific lag times for ablation associated with ablation season weather events. Other things equal, late winter or spring snowfall can delay the onset of the ablation season or its upward advance. Poor winter snowfall and thin snowpack may allow an acceleration of the same.

For all hazards there is a need of repeat, systematic assessments and constant updates on the status of dangerous items, whether glacial lakes, unstable slopes or wild fire risk. For this, access to high definition satellite coverage in real time seems the only answer, and its use to direct emergency teams to sites appearing to present urgent dangers.

3.3 Implementation of SGD mandate

The most critical issue that emerged relative to cryosphere monitoring is the condition of SGD. Almost three years since it was established, it appears to lack most of the capacities and budget necessary to do its work. No discernable change is evident since the negative assessment in the Road Map. The latter suggested that staff be hired who are "…glacier scientists, snow hydrologists, and technicians … "(p.75). However, it seems that persons with these skills are few, outside the existing 5 or 6 already hired.

It was also pointed out that, while Bhutan's educational system is quite good at producing qualified engineers, there are no programs in the sciences essential for cryosphere work – in atmospheric, geologic, hydrologic, biotic sciences or glacial geomorphology. Facilities seem unavailable for training in skills such as remote sensing and GIS, disaster risk management, or chemistry and isotope analyses. It seems necessary to identify qualified engineers willing to go for training in schools out of the country. Of course, this means a further delay in addressing some aspects of the program. It may be possible to make arrangements with outside institutions to provide consultants qualified in relevant fields and/or interested in pursuing joint research projects – as long as they are direct to in-country needs.

SGD is supposed to be the agency carrying out cryosphere monitoring. So far it lacks most of the elements needed to do so. It lacks the necessary space, facilities, logistical and scientific equipment, and personnel required for a credible program. They do not even have their own transportation, seemingly essential for a strongly field and survey based division. Staff already assigned to SGD are marking time, remain in other divisions and, at best, continue in various inadequately equipped pilot projects, largely as independent activities. They need, specifically,

1) An agreed agenda and 'road map' of their own, to address the issues raised in this report.
2) An agreed budget sufficient for:
    i) A full range of monitoring instruments for the various phases of cryosphere.
    ii) Logistical, personal, and safety gear for field work in the high mountains, As of now they have no transportation of their own, which would seem to be a priority,
3) A facility dedicated to cryosphere-specific remote sensing, GIS and analytical lab.
4) An urgent process to hire or house at least the 13 staff originally assigned to SGD and chosen to explore the eight cryosphere elements listed above.

For CSD one can reiterate what the Road Map stated:

> "…The development of these forecast systems will require enhanced computing power, training, and a highly reliable, high bandwidth Internet connection along with connection to WIS. Most important, in coordination with user agencies… to upgrade its infrastructure and capacity to deliver demand-driven sector-specific climate services, such as agromet services, that can meet the weather and climate information needs of user communities in Bhutan".

If these needs are met, then it becomes possible to entertain other suggestions. They include collaboration with educational institutions in Bhutan. SGD could re-engage in bilateral or international collaborative efforts on the Himalayan cryosphere, or formalize existing ones, such as with ICIMOD.

It should be possible to establish an outreach and climate services desk at SGD. It would have the task of drawing together the status and findings of the monitoring program. This could be made available to, or developed in cooperation with other divisions, branches of government and the general public. What the services might be is the topic of the final section.

Chapter 4. Potential contributions of SGD to climate services and users

The Road Map identified at least 38 branches of government in Bhutan with links, or needs, relating to weather, water and climate services. Most of these include, or should include, snow and ice components but apparently have not yet done so. Also identified were about a dozen bi-lateral (e.g. IMD, JICA), regional (JICA, ICIMOD) and international (UNDP, WWF) organizations. They have or have had connections to, or a history of collaboration with, Bhutanese institutions. The main finding, however, was of a very limited or absent capacity to deliver key hydromet information, above all for snow and glaciers.[21]

The Road Map focused largely on the need and ability of DHMS to deliver forecasts, mainly for weather and climate, and weather-related hazards (p.49, their Table 16). However, these are largely services SGD will need to help in its own activities, rather than ones it can provide. Its services should highlight cryosphere conditions and related hydrological information, forecasts and hazards. In all, one expects information to do with the status of snow and ice, and those processes which control freezing and thawing of snow, glacier ablation, the routing and ponding of meltwaters. Cryosphere phenomena should be prioritized in terms of having specific economic and ecological relations, or particular uses for, say, forestry or wildlife, agriculture or tourism.,

Initially, interviews with staff of other divisions indicated a common awareness of potential problems from climate change impacts of snow and ice, and possible reduced or less reliable water supply. Everyone was aware of the GLOF risk and related measures for forecasting and warning. The various ways in which glaciers and snow enter their concerns had received little thought. There are still no established communication systems with CSD, though there may be some with the main office of NCHM.

In discussions, recognition did emerge of ways in which a range of cryosphere conditions affect the agencies interviewed, and some agreement about the benefits they could derive from SGD monitoring information. Some common interests involved winter snow cover, glacier and nival contributions to stream flow, ground water and spring fed streams. It became evident that cryosphere conditions affect the whole range of their interests in environmental, ecological, and watershed management, in drinking water and for different economic sectors. To a great extent the absence of observations is responsible for the limited awareness (see Sections 3 and 4 above). Until such items are actually being monitored, SGD can have little to say or offer to other agencies.

4.1 National Environment Commission Secretariat (NECS)

NECS is the focal point for water resource management in Bhutan. It has a special concern with how climate change may affect it. In discussions, environment specialist, *Karma C. Nyedrup* (KC), made it clear that NEC's priorities relate to an all-inclusive view of water resources. They had developed the Water Management Act (2011) and the Integrated Water Resource Management Plan (2016). The former drew up roles and responsibilities for agencies involved in water management and water priorities. Drinking water has the primary place, followed by irrigation, energy, and recreation. The management plan emphasized an approach in which all aspects of water be studied and treated in terms of sustainable supply.

[21] World Bank, 2015. Modernizing Weather, Water and Climate Services: A Roadmap for Bhutan., World Bank: Washington DC.

Lack of baseline data is a major problem in the Northern areas, where unusually vulnerable groups are said to exist. The issue of water shortage came up often, but based on anecdotal and personal reports. No study has yet been made to determine whether and why some water sources are said to be dying up. This is evidently where cryosphere elements such as snowfall, meltwater, evapotranspiration, and freeze-thaw are important.

Water used for Hydropower has been a major development of recent years, particularly dependent on flows in the main rivers coming from the Himalayas. Again, other than popular reports, KC was not aware of any investigations into sustainability of water yields from snow and ice, or specific consequences of climate change.

It was emphasized that water resources are state property. It seems NECS is particularly concerned that the rapid and massive economic impact of hydroelectric power might be diverting attention from other concerns. There is a need to balance the needs of multiple stakeholders involved in water management and use. It was concluded that all aspects of snow, ice and melt water have potential importance to the water management agenda, but needing to be adjusted for differing conditions by river basin, jurisdictions, and economic sector was being. A comprehensive study seems needed to detail the snow and ice information that SGD might supply. For NECS it would include, at least:

i) For watershed management: snowfall and snowpacks; snow interception by forest canopy, sublimation 'losses', infiltration, frost-heave and other periglacial erosion processes
ii) For water supply: snowmelt, snow and glacier melt water contributions to evapotranspiration, groundwater, spring fed streams and main rivers
iii) For drinking water and health; sediment transport from retreating glaciers, snow factor in dry season and drought-prone watersheds

4.2 Department of Agriculture (DoA)

(In particular, its specialists in watershed management, irrigation and biodiversity)

There is broad recognition of the importance of glacial waters and GLOF risk. Discussions emphasized the priorities of an integrated national water plan. It was agreed that here, especially, snowmelt water is a primary resource, directly, and in contributing to soil moisture, ground water and spring-fed streams. There is a serious need of data on ground water.

While floods on the main rivers, including GLOFs, can lead to downstream loss of some agricultural lands, most agriculture in the northern half of the country avoids major river valleys. These tend to be deeply incised, with steep valley walls, which agricultural communities avoid. A particular concern is with farm level water management in communities on higher ground of the Inner Himalaya. In such communities, the DoA is looking, especially, to expand winter cropping and orchards. This involves second, cool season crops such as potatoes, barley. Various orchard fruits are also of interest. Movement towards more supplementary irrigation is likely to further stress water resources. It is also anticipated that, eventually, there will be an expanding shift to dependency towards snow and glacial waters tapped from the larger rivers.

Communities dependent on spring fed streams, probably with an important snowmelt input, report drying up of sources. With respect to biodiversity in forest, pasture and alpine communities, it is evident that plants and wildlife are adjusted to snow cover, frost and freeze-thaw, and will be stressed and disadvantaged by the impact of climate change on these conditions.

In general, staff are concerned about the lack of monitoring and sharing information in the whole water sector. Essentially, it comes down to information on the same variables as NECS watershed management concerns (see 5.1). There is a clear need for more attention to monitoring and tracking what is happening to these aspects of cryosphere;

i) For watershed management: snowfall and snowpack; snow interception by forest canopy, sublimation 'losses', infiltration, frost-heave and other periglacial erosion processes,
ii) For water supply: snowmelt, snow and glacier melt water contributions to evapotranspiration, groundwater, spring fed streams and main rivers
iii) For relations to plant cover and wildlife: snowpack and avalanche hydrology projects.

4.3 Druk Green Power Corporation (DGPC)

Power corporation staff stressed the importance of snow and glacier contributions to the feasibility and sustainability of Hydropower. For the moment the primary use is of stream flows on the main rivers, which is also the main routing of water from snow and glacier melt. It means a direct need of actual data on glacial mass balance and snow survey. They urgently need data on melt waters from snow and ice to help with turbine designs.

Plans to date have relied on past studies based on assumption and models, rather than observations. There main concerns are with volumes of flow, what affects seasonal variations, especially, the low flow season in winter, and impacts of climate change. It is also realised that there are no data on other 'loses' or extraction affecting stream flows; notably, for snowfall nothing is known of forest interception, sublimation and evapotranspiration, infiltration and groundwater.

They report a decrease in hydropower in winter, which they attribute to declining glacial melt water yields. Given that they have no capacity of their own to study glacial and snow perimeters they are looking to the SGD, under NCHM, to give services covering these aspects.

There is also growing interest in small-scale hydropower stations to serve communities away from the main river valleys. It is felt that snow surveys, in particular, are essential to help plan for this, and track hydrological constraints. Apparently, predicting water yields here can be more challenging than for the main rivers. As with other divisions, there is an impression of decline or drying up of spring fed streams, which may relate to less snow and infiltration of snowmelt, perhaps due to climate change.

i) For water supply I: snow and glacier melt water contributions to main rivers, especially those involved in major hydel power planes.
ii) For water supply II; snow surveys in the inner Himalaya watersheds and estimates of their role in forest hydrology, evapotranspiration, groundwater, spring fed streams,
iii) For climate change: changing ratios of rain and snowfall and, especially, likely changes in winter and shoulder season flows.

4.4 Department of Disaster Management (DDM), Risk Reduction and Prevention Division

To date, the main focus has been on GLOF hazards. While recognizing their importance, it was indicated that they are exceptionally well-served while there is a need to examine other hazards, some with equal urgency. There are risks from the full range of cryosphere hazards, including avalanches, rock falls and landslips, debris flows, frost action and other periglacial erosion processes.

It is necessary to pay attention to hazards from other environmental conditions in cold areas; notably rainfall-driven floods, including flash floods, earthquake and forest fire.

RPP has found that, people living in Gasa and other Northern Districts identify glacial and snow related hazards as serious risks for their community. This was an important outcome of the Community Based Disaster Risk Management (CBDRM). It means people could benefit from a weather focus not just, as at present, on rain, but also on snow storms, hailstorms, and avalanches.

It is suggested there is urgent need to identify hazard mapping in the Northern parts needs to be done and DDM along with the community could cooperate with SGD in a hazards mapping program. In all, a multi-hazard approach is needed and;

i) For hazards identification and tracking: information of snow storms, snowfall and snow packs; freeze-thaw and related periglacial erosion processes,
ii) For hazards mapping: recognition of cryosphere phenomena, and, for example, geo-hazards that trigger, or are triggered by snow and ice.
iii) For preparedness generally, DDM needs technical backstopping and reports from SGD on cold climate conditions and shifting hazards due to climate change.

WWF gave particular emphasis to the state of forest and fresh water biomes. These will receive special attention in the next five years. They are operating on an assumption that monsoon rainfall accounts for 60% of inputs, snow and glaciers 40%. However, this is not based on measurements. They have also developed a model for sediment movement and retention downstream but, again, with no snowfall data used.

Although there is a strong push for sustainable watershed management and wild life protection, WWF is concerned about some developments that they feel have not been adequately assessed. The Chamka chuu, for example, would be the best candidate for the 'free-flowing' river principle, but it is already slated for hydroelectric power projects. Another potentially damaging activity is the "Chinese caterpillar' harvesting. This takes place in the alpine zone between May and July, and thousands of gatherers are involved. Apparently it is a very lucrative trade but there is no investigation of what ecological impact this is having in what is generally considered a fragile and vulnerable ecosystem...

WWF is also taking seriously reports of stream and springs drying up, including areas where snowfall is important. Again, no study or assessment has been done. As such they would welcome snow and glacier information from SGD to help in the development of water yield models.

i) For watershed management: snowfall and snow packs; frost-heave and estimates of sediment production of periglacial erosion processes,
ii) Snow data; urgently needed for the inner Himalaya watersheds and estimates of their role in forest hydrology, evapotranspiration, groundwater, spring fed streams
iii) For climate change: changing ratios of rain and snowfall and, especially, likely changes in the high forest and alpine zones

In sum, most other agencies seem to have at least as strong an interest in snowfall as in glaciers, and in the Inner Himalaya as much, or more than, the Great Himalaya. Their interest tends to be drawn to snowfall in all its aspects, from high altitude glacier nourishment to seasonal snow covers in forested and alpine catchments. This is particularly the case for those with responsibilities involving watershed management, agricultural support, conservation and biodiversity. They also have an interest in better intelligence on permafrost and periglacial conditions, and for hydrological components such as sublimation and evapotranspiration, infiltration and groundwater in snowy areas. There is need to address the, hitherto neglected, areas of permafrost, the hundreds of rock glaciers, the scope and intensities of freeze-thaw, and periglacial processes.

Chapter 5. Recommendations

main recommendations are as follows:

Analysis carried out in this report shows significant need to improve cryosphere monitoring and capacity building in Bhutan. This applies across the board in terms of capacity-building for scientific, transportation, logistical, safety, and personal (field) equipment. There are work space needs, for facilities, staffing, consulting, and training. To work on this, an available budget needs to be established, including funds to request help/advice on newer techniques, or aspects of the cryosphere not formerly investigated. An overarching concern is adequate support and safety systems for personnel deployed.

An important point is that hardly any of the equipment necessary for cryosphere monitoring is produced in Bhutan. It will have to be purchased internationally. That means scientific instruments, transportation, field logistics and personal gear, analytical and forecasting facilities, safety systems, consultants and training of personnel. Based on experience elsewhere, for anything resembling an adequate monitoring system, CSD requires millions of dollars to begin identifying and purchasing a basic set of equipment and facilities. Eventually, for a sufficient system, some tens of millions of dollars investment will be required. A phased approach can be taken to develop such a program starting with a USD 6-8 million USD investment that could be scaled up based on lessons learnt.

In identifying and choosing equipment, it would make sense to engage the existing staff. Specifically, there are half dozen or so with experience of the conditions, the logistical and local safety and operational problems where monitoring will occur. Once a budget is known they should be able to draw up a basic list of requirements and types of instrumentation. They will need assistance with WB procurement practices and, from time to time, guidance from experts in particular methods and technologies.

To emphasize, plans cannot ignore the special demands of high elevations and rugged terrain, of large seasonal variations and environmental extremes, and work in poorly accessible, thinly, or un-populated areas. They create exceptional stresses on equipment and safety of personnel. Thus, an experimental approach is advised, whether in adding to and extending existing station networks, or testing new equipment and developing practices appropriate for the Bhutan cryosphere.

It should be asked whether more than one full-time facility makes sense, perhaps one in Thimpu and at least one more in the east of the country. Eventually some forward field stations may be needed, but only after trial periods to gain experience of conditions. Longer term, NCHM should

1) Develop a cryosphere monitoring strategy as part of integrated, sustainable water resources and watershed management;
2) Address a monitoring program in relation to the full range of cryosphere conditions in the Great and Inner Himalaya;
3) Develop and Implement a multi-hazards approach to cryosphere dangers and climate resilience and, above all;
4) Ensure urgent funding, procurement, and substantive assistance for the Snow and Glaciers Division for the monitoring areas identified above.

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