Institutional Strengthening and Modernization of Hydromet and Multi-hazard Early Warning Services in Bhutan A Road Map for 2024–2034

Royal Government of Bhutan

Prepared in collaboration between the National Centre for Hydrology and Meteorology and the World Bank

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Acknowledgments

This roadmap has been prepared jointly by the National Centre for Hydrology and Meteorology (NCHM) and the World Bank as part of the implementation of the World Bank-supported project 'Strengthening Risk Information for Disaster Resilience in Bhutan'. It presents a potential pathway to strengthen the country's national hydrometeorological (hydromet) and multi-hazard early warning systems and services, based on the needs of the user community. The roadmap is based on a technical evaluation and assessment of the needs and capacities of the NCHM which, as the main service provider in Bhutan, issues meteorological and hydrological information, forecasts, and warnings.

Other government agencies that are responsible for the provision of advisory services to end users which incorporate factors affected by weather, climate, and hydrology are considered as key stakeholders of NCHM information and services. Some important stakeholders encompass around 20 government departments including those responsible for agriculture and livestock, water resources (especially hydropower and flood management), disaster management, public health, urban planning, human settlement, environment and climate change, energy, aviation, road transport, and tourism. This roadmap identifies gaps and challenges in the production and delivery of weather, climate, hydrological, and cryosphere information and services and proposes a strategy for improving the country's institutional capacity in support of saving lives, protecting property and livelihoods, and promoting social and economic development. The information for the preparation of the roadmap was mostly collected remotely, through authors' ongoing discussions with officials in the NCHM as well as during a technical mission to Bhutan when consultations were held with nearly all the stakeholders listed above. The roadmap is the result of a collaboration between the Royal Government of Bhutan and the World Bank Group.

The roadmap has been prepared under the leadership of Mr. Karma Dupchu, Director of the NCHM. Special thanks to Mr. Chimi Namgyal for proactively coordinating the information sharing from the NCHM for preparation of the roadmap and all the staff who critically contributed to this work.

The World Bank team includes Naho Shibuya (Task Team Leader), Arati Belle (Senior Disaster Risk Management Specialist), Dechen Tshering (Disaster Risk Management Specialist Consultant), Haleh Kootval (Senior Meteorology and Public Weather Services Specialist), Gerald Fleming (Senior Meteorology Specialist), Wolfgang Grabs (Senior Hydrology and Cryosphere Specialist), Anish Kumar (Senior Hydrology Specialist), and Madhavi Ariyabandu (Senior Gender Specialist). The team expresses sincere gratitude to Abhas K. Jha (Practice Manager, South Asia Climate Change and Disaster Risk Management Unit) for his guidance as well as peer reviewers, Anju Gaur (Senior Water Resources Management Specialist), Anna-Maria Bogdanova (Senior Disaster Risk Management Specialist), and Moussa Sidibe (Disaster Risk Management Specialist) for providing valuable comments and feedback.

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Hydrometeorological information is crucial in numerous economic development activities, protecting lives, and livelihoods. With the increasing frequency of extreme weather events and climate change, it is necessary to plan and implement economic activities that are resilient to impending disasters and adaptable to changing environmental conditions. With economic transformation as one of the main pillars for the 13th Five-Year Plan (2024–2028), focused on enhancing agriculture production, tourism, and resilient infrastructure, hydrometeorological data is crucial to projecting and understanding the possible changes in weather and water scenarios in the short- and medium-term. Therefore, investing in enhancing sector-specific hydromet services, including early warning services for weather and water-induced disasters, should be a top priority for the government to pursue a resilient development path.

The Ministry of Energy and Natural Resources is the lead for the 'Economic Cluster' of the Royal Government of Bhutan, responsible for driving Bhutan's economic transformation sustainably and responsibly. In line with this vision, the National Centre for Hydrology and Meteorology, as a crucial technical agency within the Economic Cluster, is mandated to provide hydromet services. For Bhutan, hydropower is its backbone when it comes to its economy. However, in recent years, glaciers in Bhutan have been melting at a rapid pace of 16 meters annually, posing a high risk to the sustainability of water resources and hydropower generation. While everyone knows that glaciers are receding, which is not good for Bhutan and the entire region, without scientific evidence, it is difficult to really understand what is happening and at what pace. Therefore, the National Center for Hydrology and Meteorology (NCHM)'s role as the only scientific agency studying and monitoring glaciers and glacial lakes is vital for the nation.

Furthermore, other significant economic activities of the country, especially agriculture, are highly dependent on weather and water. With the changing climate and increasing frequency of extreme events, the agriculture sector has become even more vulnerable to weather and water-induced disasters, posing a very high risk to the food security of the country at large and the livelihoods of our farmers. NCHM's role in providing adequate weather forecasts that are now being translated to agromet advisories is a notable achievement in the country that will benefit the entire farming community, about 125,000 people in 2022. The aviation sector is another crucial sector where meteorology information is becoming highly critical. As Bhutan expands its connectivity with plans to establish additional airports in Gelephug and improve its services at existing airports, it has become urgent for NCHM to step up its services in this sector.

While NCHM is enhancing its services to provide early warning services for weather and water-induced disasters and sector-specific services to critical economic sectors, this roadmap comes promptly to guide its investments. The roadmap gives a direction that will help in the optimum utilization of resources, which is important when there are so many priorities but resources are highly limited.

I commend the collaboration between the NCHM and the World Bank and their efforts in enhancing hydromet services for Bhutan, which is critical for the economic development of the country and equally crucial for protecting the lives and livelihoods of its population.

On behalf of the Ministry and the Royal Government of Bhutan, I would like to express our gratitude to the World Bank for their continued support in enhancing the country's resilience against natural disasters and climate change.

His Excellency Lyonpo Gem Tshering
Minister, Ministry of Energy and Natural Resources

FOREWORDS

The need for hydrometeorological services is gaining importance in Bhutan in several key economic sectors, including hydropower, agriculture, tourism, health, aviation, constriction, and disaster management. Studies show that investing US$1 in hydrometeorological services and Early Warning Services generally results in at least US$3 in socioeconomic benefits (defined as a 3:1 benefit/cost ratio) and often far more. Bhutan is highly vulnerable to several weather and water-induced disasters and climate change. As a result, investing in improving hydrometeorological information and services are crucial to achieving Bhutan's vision to develop its economy and social well-being in a sustainable and resilient manner.

The importance of enhancing hydrometeorological services was well-recognized by the Hon'ble Prime Minister during the National Disaster Management Authority meeting held on May 28, 2024, where the need to establish a National Centre for Hydrology and Meteorology Head Quarter, including National Weather and Flood Warning Centre and Scientific facilities, installing additional weather stations, and flood warning centers were identified as top priorities to ensure a robust response to natural disasters, in addition to deriving socio-economic benefits.

The National Center for Hydrology and Meteorology (NCHM) has come a long way as an institution, and there has been tremendous improvement in its services over the last few years. However, we are still challenged significantly with human resources, specialized capacities, ICT systems, and overall financial resources, which have hindered our ability to cater to the needs of the various sectors affected by weather and water. Based on the recent assessment as a part of the preparation of this roadmap, there are still significant gaps in upper air and weather radar coverage, models and analytics, weather and flood forecasting, and ICT, as a result of which tailored and integrated services are still at a nascent stage.

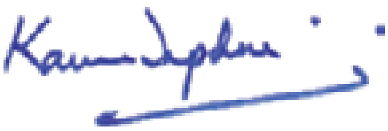
Similar to the roadmap that the World Bank supported development in 2015, this roadmap is a crucial document for NCHM to guide our prioritization of activities and investments in the medium- and long-term for enhancing the current capabilities of the NCHM to cater to the needs of other sectors.

This roadmap will guide the NCHM toward a more systematic basis for setting strategic and forward-looking priorities to improve its service delivery and contribute to the development of the national economy by producing location and sector-specific, well-articulated, and usable information not only on hazards but also on their impacts on target areas and population, and projected changes in weather and water parameters that are crucial for designing high-cost investments including hydropower and research and development in the agriculture sector.

Achieving this modernization program over 5–10 years in the roadmap requires anticipation and proactive measures to be taken by the NCHM with adequate funding and technical support on several fronts.

We anticipate a consequential positive impact on various economic sectors by advancing and optimizing our hydrometeorological services. The enhancements in weather and flood forecasting, which will help produce impact-based forecasting in collaboration with relevant sectors, climate change, glacial melt, and changes in river flow projections, will inform decisions to foster a more objective and efficient operational landscape in development activities. This scientific progress will empower key industries, enabling them to make data-driven decisions, enhance resource allocation, and fortify resilience against natural disasters and climate change. Through these advancements, our commitment is to contribute substantially to the economic sectors and enhance resilience.

On behalf of NCHM, I would like to thank the World Bank for the fruitful collaboration in developing this roadmap and the overall hydromet program that has been supporting NCHM for over a decade and is still going strong.



Karma Dupchu
Director
National Center for Hydrology and Meteorology

FOREWORDS

In the serene and majestic landscape of Bhutan, where the harmony between nature, people, and culture is deeply rooted in the national ethos, the importance of strengthening and modernizing hydrometeorological and multi-hazard early warning services cannot be overstated. Hydromet and multi-hazard early warning services play a crucial role in protecting lives, livelihoods, assets, and socioeconomic activity.

Modernized hydromet services is particularly important forBhutan, a country prone to floods, landslides, and Glacier Lake Outburst Floods. Hydromet services are also essential in promoting the country's economic development, particularly in climate-sensitive sectors like hydropower, agriculture, and tourism. Timely and accurate Hydromet data allows for efficient hydropower management, accurate weather forecasts for informed agricultural practices, and reliable weather information for the tourism and industry.

The Kingdom of Bhutan known for its pioneering Gross National Happiness philosophy, has always placed the well-being of its citizens and sustainable economic growth and the conservation of biodiversity and nature at the forefront of its development agenda despite the increasing unpredictability of natural hazards, which are exacerbated by climate change. This roadmap is a testament to the government's commitment to modernize hydrometeorological services for the country's sustainable and climate-resilient growth and development. It builds on a previous roadmap published in 2015 and serves as a strategic guide that aligns with the country's development vision, ensuring that resilience and sustainability remain central to its growth ambitions.

Our analysis shows that by investing $1 in hydrometeorological services and early warning system results in at least $3 in socioeconomic benefits. The roadmap outlines a series of innovative and pragmatic steps designed to enhance the National Centre for Hydrology and Meteorology (NCHM)'s service delivery by enhancing internal capacity with cutting-edge technology to collect multi-hazard risk information.

The path laid out in this document is ambitious, yet achievable. It calls for an integrated approach, bringing together all stakeholders, including government agencies, local communities, development partners, and the private sector, to create a robust system that can support the implementation of this roadmap.

As we look to the future, let us be guided by the wisdom of our past and the innovative spirit that this roadmap embodies. I would like to thank the donors who have financially supported the preparation of this roadmap through the Strengthening Risk Information for Resilience Project – namely the Climate Investment Fund (CIF) and the Japan-World Bank Program for Mainstreaming Disaster Risk Management in Developing Countries (administered by the Global Facility for Disaster Reduction and Recovery). The World Bank is proud to be a part of this journey and remains committed to support Bhutan to achieve sustainable and climate-resilient growth.

Together, we can ensure that Bhutan remains a beacon of resilience that plays a leading role in regional flood forecasting to warn not only Bhutanese communities but also downstream communities living along the Brahmaputra basin further South beyond the border.

Best wishes,

Abdoulaye Seck
Country Director for Bangladesh and Bhutan
World Bank

ABBREVIATIONS AND ACRONYMS

ADCP	Acoustic Doppler Current Profiler
ADSS	Agromet Decision Support System
AI	Artificial Intelligence
ARDMS	Automatic River Discharge Measuring System
AWLS	Automatic Water Level Station
AWOS	Automatic Weather Observing System
AWS	Automatic Weather Station
BBS	Bhutan Broadcasting Service
BCAA	Bhutan Civil Aviation Authority
CAP	Common Alerting Protocol
CDMS	Climate Data Management System
CPT	Climate Predictability Tool
CSD	Cryosphere Services Division
CWC	Central Water Commission
DGM	Department of Geology and Mines
DGPC	Druk Green Power Corporation
DHMS	Department of Hydromet Services
DHPS	Department of Hydropower and Power Systems
DL	Deep Learning
DLGDM	Department of Local Governance and Disaster Management
DoFPS	Department of Forests and Park Services
DoL	Department of Livestock
DoAT	Department of Air Transport
DoE	Department of Energy
DoW	Department of Water
DSM	Daily Scheduling Market
DSS	Decision Support System
ECMWF	European Centre for Medium-Range Weather Forecasts
EMSWRF	Environmental Modelling System Weather Research and Forecasting
EPS	Ensemble Prediction System
ERP	Extended Range Prediction
EW4ALL	Early Warning for All
EWS	Early Warning System
FDSS	Flood Decision Support System
FFGS	Flash Flood Guidance System

FMI	Finnish Meteorological Institute
FWS	Flood Warning Section
FYP	Five-Year Plan
GAW	Global Atmosphere Watch
GBON	Global Basic Observation Network
GCF	Green Climate Fund
GDP	Gross Domestic Product
GFS	Global Forecast System
GIS	Geographic Information System
GISC	Global Information System Centre
GLOF	Glacial Lake Outburst Flood
GoI	Government of India
GPC	Global Producing Center
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTS	Global Transmission System
HEC	Hydrologic Engineering Center
HFWS	Hydrological Forecasting and Warning Section
HMS	Hydrologic Modelling System
HPC	High-Performance Computing
HQ	Headquarters
HWRSD	Hydrology and Water Resources Division
ICAO	International Civil Aviation Organization
ICIMOD	International Centre for Integrated Mountain Development
ICT	Information and Communication Technology
IDF	Intensity-Duration-Frequency
IDF	Intensity-Duration-Frequency
IFMSS	Integrated File and Message Switching System
IMD	India Meteorological Department
ISO	International Organization for Standardization
IT	Information Technology
IWXXM	ICAO Meteorological Information Exchange Model
JICA	Japan International Cooperation Agency
JMA	Japan Meteorological Agency
MÉRA	Met Éireann Reanalysis
MHEWS	Multi-Hazard Early Warning Services/System
ML	Machine Learning
MoAL	Ministry of Agriculture and Livestock
MoAL	Ministry of Agriculture and Livestock
MoENR	Ministry of Energy and Natural Resources

MSD	Meteorological Services Division
NCHM	National Centre for Hydrology and Meteorology
NCMWRF	National Centre for Medium–Range Weather Forecasts
NCOF	National Climate Outlook Forums
NDMA	National Disaster Management Authority
NFCS	National Framework for Climate Services
NMHS	National Meteorological and Hydrological Service
NWFWC	National Weather and Flood Warning Centre
NWP	Numerical Weather Prediction
O&M	Operations and Maintenance
OPMET	Operational Aeronautical Meteorological Data
OHS	Occupational Health and safety
PWS	Public Weather Services
QMS	Quality Management System
R&D	Research and development
RAS	River Analysis System
RCSC	Royal Civil Service Commission
RGoB	Royal Government of Bhutan
RIC	Regional Instrument Center
RIMES	Regional Integrated Multi–Hazard Early Warning System for Africa and Asia
RTC	Regional Training Center
RUB	Royal University of Bhutan
SAHF	South Asia Hydromet Forum
SASCOF	South Asian Seasonal Climate Outlook Forum
SIGMET	Significant Meteorological Information
SMS	Short Message Service
SOP	Standard Operating Procedure
SWFP	Severe Weather Forecasting Programme
TAF	Terminal Area Forecast
TSRD	Technical Standard and Research Division
UKFCDO	United Kingdom Foreign, Commonwealth, and Development Office
UNDP	United Nations Development Programme
WAFS	World Area Forecast System
WCSD	Weather and Climate Services Division
WHO	World Health Organization
WIS	WMO Information System
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting
WWIS	World Weather Information Service

A note on how this Roadmap is organized

The organization of this Roadmap is along the following lines:

The **Executive Summary** provides an overview of the key points and recommendations

In Section One, the **Introduction**, some basic background is provided on the climate of Bhutan and the consequent natural hazards, and on the organization of the NCHM and its position within the government structures.

Section Two, the **Approach to Modernization**, describes a generic framework which is used to analyze the different elements within a National Meteorological and Hydrological Service and to determine their maturity according to a five-level scale, ranging from Low to Advanced.

In Section Three, the **Current Status of NCHM Services and Infrastructure**, the work of the NCHM is described and the generic framework outlined in Section Two is applied to the different elements within the organization to establish the baseline level of maturity for each.

Section Four is the **Roadmap for Modernizing and Strengthening NCHM's Services and Systems**. Divided into two time frames to align with two cycles of the Government of Bhutan's Five-Year Plan, this provides recommendations as to where investments in infrastructure should be focused and outlines the expected consequent improvement in maturity likely for each element of the organization. The recommendations are fully costed.

The **Conclusion** in Section Five offers some broader thoughts beyond the detailed recommendations, including some suggestions for innovations and also on the possible role of public-private partnerships within the weather enterprise in Bhutan.

The **Annexes** contain the detail of the costs and timelines associated with the modernization plans, as well as the implications for future staffing requirements.

Throughout the document some text is presented in Boxes.

> **Blue boxes** provide some examples of the needs of users for hydrometeorological information in Bhutan, underlining how the modernization efforts will help to address these needs.

> **Gray boxes** highlight especially important points or challenges for NCHM, or key recommendations for future development.

EXECUTIVE SUMMARY

Purpose of the Roadmap Development

This roadmap describes the current situation of hydromet service provision in Bhutan and proposes a short- and medium-term modernization approach. It provides an overview of the National Centre for Hydrology and Meteorology (NCHM), its financial and technical infrastructure, human resources, and information about the users of its products and services. To provide enhanced and fit-for-purpose services to its users, the roadmap proposes two development stages to help strengthen the capabilities of the NCHM to better deliver hydromet information, impact-based forecasting, and multi-hazard early warning services (MHEWS).

Building on the one prepared in 2015,[1] this roadmap supported the preparation of the 13th Five-Year Plan (FYP) and aims to inform the preparation of the 14th FYP in accordance with the National Hydromet Policy 2023. The 2015 roadmap proved instrumental in the institutional development of the NCHM. The NCHM leadership regards this roadmap as strategic guidance for strengthening the capabilities of the organization. The recommendations in this roadmap are intended to assist the NCHM in providing input to the national FYP development over the next two cycles of the governmental planning process. In addition, the roadmap is firmly anchored to other strategic documents, particularly the Hydromet Policy 2023[2] which was formulated in parallel with this roadmap.

Ultimately, the roadmap supports the Royal Government of Bhutan (RGoB) in ensuring the safety of the Bhutanese population and their livelihoods and properties and in protecting its economic investments against weather- and water-induced disasters. Various user communities and their needs are the principal drivers for the modernization of hydromet products and services in Bhutan. The roadmap aims to assist the NCHM to enhance its capabilities through gaining access to and utilization of up-to-date technologies and tools to produce the best possible forecasts within the technical and financial resources framework of Bhutan and deliver sustained, fit-for-purpose, and usable information and services. Addressing these issues will require that full consideration is given to including all meteorological, cryosphere, and hydrological elements of a modern, well-planned organization with goals, a clear strategy and sound implementation plan, and the means to achieve those goals. It will also contribute to ensuring water security for the country by providing reliable information and projections on the country's water resources, seasonally as well as a result of climate change. The modernization proposed in this roadmap intends to help the NCHM fulfill its public tasks by strengthening its institutional and technical capabilities and capacities.

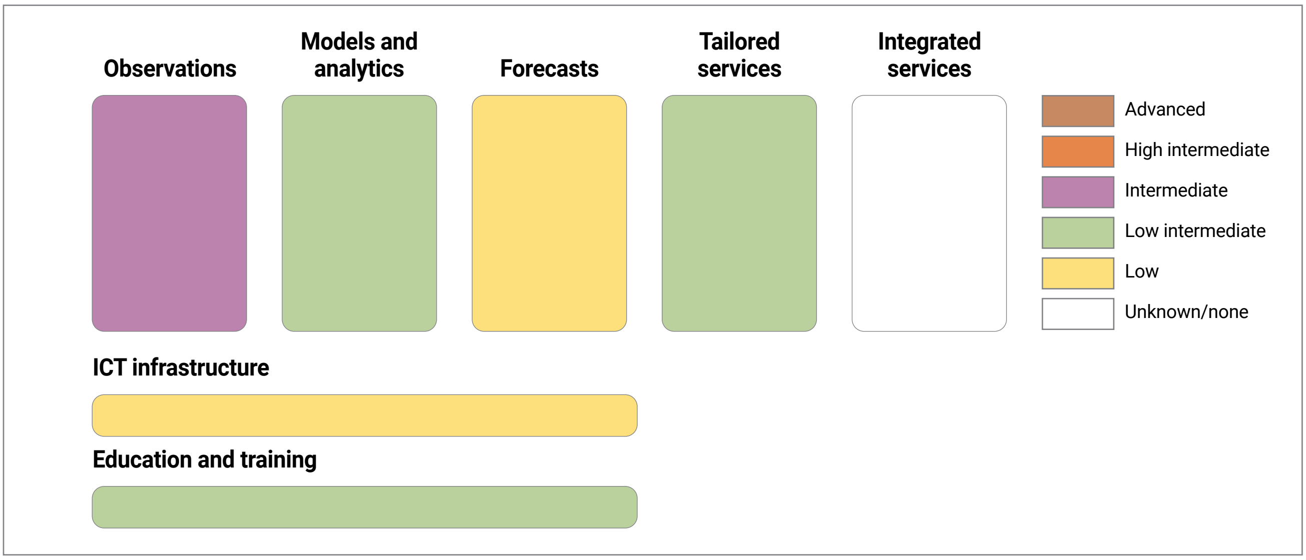
> **The overall benefit/cost ratio of modernization is expected to be 3.1, taking into account the high initial costs of modernizing the NCHM.** In general, investing US$1 in hydrometeorological services and early warning system (EWS) results in at least US$3 in socioeconomic benefits (defined as a 3:1 benefit/cost ratio) and often far more[3].

[1] Modernizing Weather, Water, and Climate Services: A Road Map for Bhutan

[2] The "Hydro-met Policy of the Kingdom of Bhutan, 2023" came into effect on September 18, 2023, and remain in force until amended or superseded.

[3] WMO, World Bank, GFDRR, and USAID. 2015. *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services*. Geneva: WMO.

Figure ES.1. Schematic of NCHM current value chain



The economic benefits of enhancements in the capacity and capability of the NCHM were analyzed in 2014.[4] The sectors covered in the study included energy, agriculture, tourism, aviation, disaster risk reduction and management, roads, public health, construction, insurance, natural resource management, and climate change monitoring. The potential socioeconomic benefits relating to the use of historical data, current observations data, weather and hydrological forecasts and seasonal outlooks, and EWSs were assessed as part of the study. However, these costs are mostly covered through development agencies and other forms of international cooperation. On the other hand, if the project costs in the beginning of the assessment period are excluded, then the benefit/cost ratio increases to 5.5. The yearly benefit/cost ratio increases substantially in 2025 (in the time frame of the study recommendations) up to 8–9, when the benefits of the historical data start to accrue. This illustrates what has been seen in many countries—the benefits arising from investment in hydromet services accrue primarily in the medium to long term.

4 Pilli-Sihvola, K., P. Namgyal, and C. Dorji. 2014. *Socio-Economic Study on Improved Hydro-Meteorological Services in the Kingdom of Bhutan*. Report prepared for the Strengthening Hydro-Meteorological Services for Bhutan (SHSB) Project. Finnish Meteorological Institute and Department of Hydro-Met Services.

Status of Hydromet Services and Key Challenges

The NCHM was established in 2016 as an autonomous scientific and technical agency responsible for hydrology, meteorology, and cryosphere science and services from the former Department of Hydromet Services. It is the main agency responsible for the generation of information and delivery of products and services on weather, climate, cryosphere, and water resources in Bhutan. The NCHM financial resources are provided by the RGoB, with additional extra-budgetary funds from donors, development partners, and the Government of India (GoI).

Using the hydromet value chain approach and activities in each link of the chain, the current capacity and maturity of the NCHM are illustrated in Figure ES.1. In meteorological terms, a value chain describes the general relationship between different activities in each system and subsystem, from the making of observations through to the application of forecast and warning services by users. The value chain conveys the important concept of the production of value (which only happens when the meteorological and/or hydrological information is used to make or influence decisions) and is a useful way of exploring the organization and performance of a National Meteorological and Hydrological Service

(NMHS). The meteorological value chain has five links: observations, models and analytics, forecasts, tailored services, and integrated services. Each link is the product of science and technology infusion, and each contributes to social and economic benefit.[5]

The NCHM does not have any meteorological stations that are of synoptic standard and data are manually transmitted to the headquarters (HQ). Of the 169 stations, there are 80 automatic weather stations (AWS), 20 Class A (agromet) stations, 65 Class C (climate) weather stations, and four automatic weather observing systems for aviation observations at airports. Class A stations are manually operated, in which the observers report to the HQ daily by telephone and monthly via postal service. Data from the rainfall stations are not necessarily used for hydrological forecasting. The NCHM does not operate a lightning detection network and it does not subscribe to lightning data services from a service provider. There are no global atmospheric watch (GAW) stations operating in Bhutan.

All 80 AWS installations are prone to frequent interruptions of service mainly due to challenges in communication and network connectivity. These challenges make identifying alternative communication channels a necessity.

Bhutan's precipitation network faces challenges in adequately representing higher elevations and remote areas. The majority of the stations are located at or below 2,999 meters, and a small percentage of them are at elevations equal to or higher than 3,000 meters. Thus, the higher elevations are under-represented compared with the lower elevations. Gaps in Bhutan's precipitation network are generally in the northern part of the country, which is remote, difficult to access, and at high elevations, although they represent a significant area of the country.

[5] Rogers, D., V. M. Staudinger, V. Tsirkunov, M. Suwa, and H. Kootval. 2022. *Affordability of National Meteorological and Hydrological Services.* Washington, DC: World Bank.

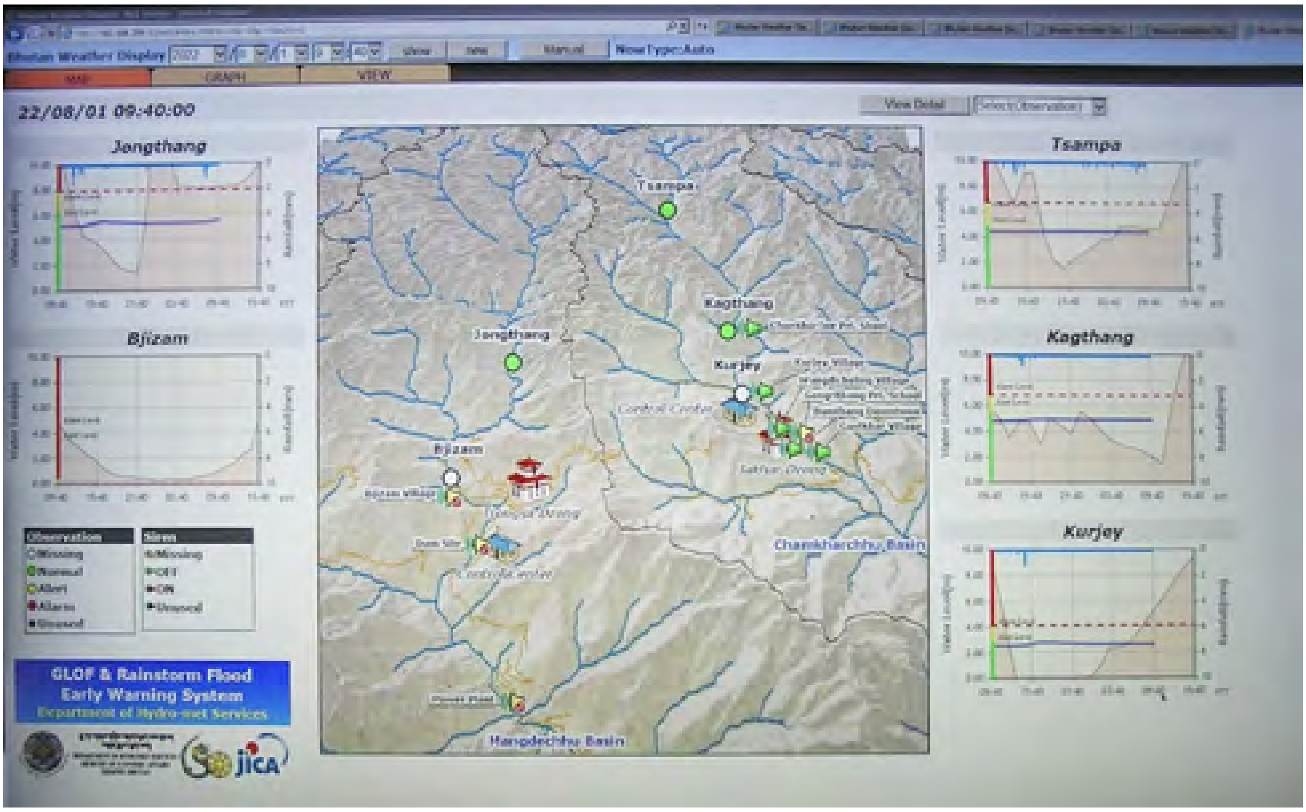
The NCHM's weather forecasts are deterministic, and currently they do not have the capability to produce probabilistic forecasts. Although no impact-based forecasts are produced, forecasts are written in simple form to help recipients with the interpretation of the weather systems. The NCHM currently runs the weather research and forecasting (WRF) model that produces forecasts for three days ahead. However, there is a need to work on parameterization schemes and data assimilation for improved forecasting skill. Manual verification of outlooks and temperature forecasts are carried out at the end of the year. However, there is no validation and verification system for the WRF model. There is a need for providing quantitative precipitation forecasts, rather than qualitative outlooks.

> **No data from AWS or other local observations are used for forecast preparation.** The observations are not put into the forecast model. Forecasters refer to the WRF model outputs as well as other products from regional and international centers as guidance to prepare their forecasts. In addition, data on rainfall, storms, and lightning are conveyed by telephone when a severe weather event occurs.

Based on a qualitative analysis, flood warning stations are located mainly along major rivers, and the network is sparse in smaller rivers. Several tributaries have no monitoring, especially at the international border with Tibet in northeastern Bhutan. There is a need to expand the network in ungauged catchments or supplement the monitoring system with modelling for small streams. The glacial lake outburst flood (GLOF) network should be expanded to cover the remaining basins.

At present, the early warning system (EWS) operates on the basis of detecting and issuing warnings, but the NCHM is planning to integrate flood forecasting with more lead time into the EWS. As part of services provided, the NCHM is

Figure ES.2. GLOF Early Warning System Display



also exploring the implementation of impact-based forecasting for weather and floods. The staff are capable of carrying out flow modelling and flood forecasting. The NCHM aims to extend the GLOF and rainstorm flood EWS to all river basins.

Cryosphere services are relatively new to the NCHM with limited technical expertise and human and financial resources. The NCHM focuses on monitoring glaciers through mass balance studies on benchmarked glaciers, monitoring glacial lakes for GLOF hazards, preparing and regularly updating glaciers and glacial lake inventories, updating the list of potentially dangerous glacial lakes, conducting studies on melt contribution from glaciers to surface runoffs in major river systems, and assessing hazards associated with cryosphere. The center provides data and information generated through the above activities as part of cryosphere services to the general public and line agencies. However, the center faces limited technical expertise, manpower shortages, and financial constraints.

NCHM does not conduct regional climate research or operational climate forecasting due to limited capacity and resources. Seasonal forecasts are issued for the summer and winter monsoons, based on the consensus statement from the South Asian Seasonal Climate Outlook Forums (SASCOFs). The NCHM participates in SASCOFs and since 2016 has been organizing National Climate Outlook Forums (NCOFs). The NCHM provides climate information services, including monthly and annual climate monitoring reports, seasonal forecasts, and annual statistical information and analysis of the climate extremes. In addition, as mandated by the National Climate Change Policy, the NCHM has been working on the climate projections for Bhutan and monitors climate change and climate variability. However, no regional climate downscaling and regional or subregional climate research is conducted by the center. Similarly, no operational climate forecasting (for example, monthly and seasonal) services exist due to insufficient capacity and resources.

Agromet advisories and forecasts services for farmers are at the nascent stage. The Department of Agriculture (DOA) under the Ministry of Agriculture and Livestock (MoAL) operates an Agromet Decision Support System (ADSS)6 with inputs from the NCHM. The NCHM provides three-day quantitative forecast to generate agromet advisories and agrometeorological information and forecast services for farmers in the form of seven-day outlooks obtained directly from the global/regional models. The center provides outlooks for both temperature and precipitation, but the farmers need quantitative precipitation forecasts and temperature. The NCHM does not have an operational seven-day forecasting system and relies on what is available from regional centers on the internet. No indexes are provided, and no crop modelling is performed. A drought monitoring and warning system is being implemented in a pilot phase. The NCHM does not operate an EWS for heat waves, cold spells, or frost formation.

While international meteorological data and information are required for flight planning and safe, economic, and efficient air navigation, the NCHM's capacity and resources are limited. The NCHM maintains and operates airport weather stations at all aerodromes of the country: Paro International Airport and three domestic airports. It provides meteorological information for international and domestic flights. Although the NCHM provides flight documentation to airlines, it does not issue Terminal Area Forecasts (TAFs) or Significant Meteorological Information (SIGMET) bulletins to airlines and does not receive Operational Aeronautical Meteorological Data (OPMET). The World Area Forecast System (WAFS) products are received on an operational basis by the NCHM. The NCHM is not ISO-certified for provision of aeronautical meteorological services.

[6] ADSS was developed under the World Bank-financed Hydromet Services and Disaster Resilience Regional Project and the Strengthening Risk Information for Resilience project.

The NCHM does not have a quality management system (QMS) in place to govern its management and technical operations. The NCHM recognizes, however, that the adoption of international data quality standards, methods of observation, communication, and data handling is of the utmost priority. Standard operating procedures (SOPs) were developed in 2020 for all operational activities of the NCHM; these need to be updated to reflect more recent changes in Divisional responsibilities.

The NCHM does not implement the WMO-No. 258 requirements for public weather service (PWS) personnel and thus does not meet the appropriate education and competency requirements. At present, there is no established mechanism for the training of NCHM staff, nor are there any institutional arrangements, involvement of academic institutions, or a curriculum of topics to be covered. Building capacity through training activities and cooperation with other WMO members is indispensable for the NCHM.

Proposed Modernization of Hydrometeorological and Multi-hazard Early Warning Services

This roadmap uses a system-of-systems approach to arrive at two scenarios for modernizing the NCHM. A modernization program for any NMHS should include three components: (a) enhancement of the service delivery system; (b) institutional strengthening and capacity building; and (c) modernization of the observation, information and communication technology (ICT), and forecasting infrastructure. This path has been followed in developing this roadmap. The proposed activities aim to strengthen the NCHM's institutional basis, enhance the capacity of staff, technically modernize the operational infrastructure and forecasting facilities, and advance the delivery of hydromet and multi-hazard early warning system to the population of Bhutan and sectors dependent on weather, climate, and water information. The short- and medium-term approaches are designed to contribute to the capabilities of the NCHM for producing and delivering (a) timely warnings of high-impact (for respective users) and hazardous hydromet events and their potential impacts and (b) weather and hydrological forecasts for operations and planning in weather, water, and climate-sensitive economic sectors, particularly agriculture, energy, transport, water resources, and disaster risk management.

The short- and medium-term approaches are interdependent and should be conducted in a phased manner to seamlessly build on each other and contribute to the overall goal of the modernization progress. Thus, the medium-term plan assumes the accomplishment of objectives in the short term and builds on them.

Short-Term Modernization (five years)

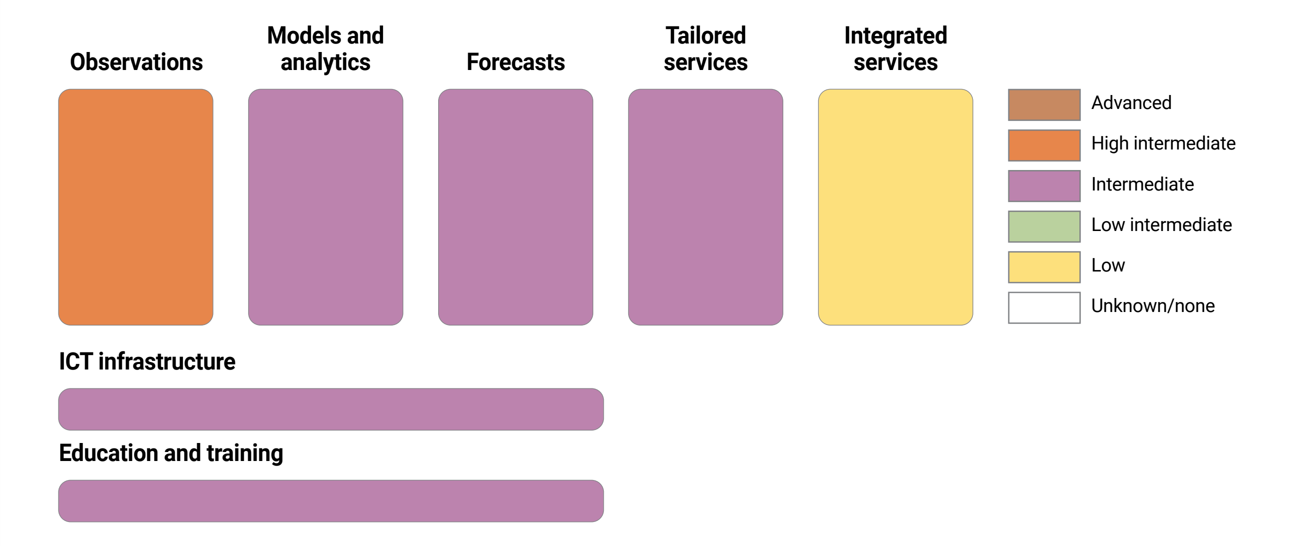
The estimated cost of implementation of the short-term modernization over the next five years is approximately US$14.9 million (to achieve the maturity levels as shown in **Figure ES.3**). This includes the construction cost of the new NCHM center of approximately US$2.8 million, operation and maintenance (O&M) costs (excluding labor costs) of approximately US$2.2 million and capacity-building costs of US$1 million. The short-term modernization presents investment needed to meet the needs of the most important user sectors such as disaster management, water resources, hydropower, and agriculture. Certain high priority activities are included in this approach, which are regarded as the most urgent to achieve critical minimal capabilities for improved meteorological and hydrological services.

- **The *observation* link after a five-year intervention will be at the** high intermediate **maturity level.** Observation network design is an ongoing and complex process with addition of new stations as required and the rehabilitation of existing stations. In making these decisions, many factors have to be considered such as access to stations, reliability, reporting accuracy, costs, O&M requirements, durability, and site specifications. Data management is a key element of an observation network for proper storing, validating, analyzing, and reporting of all data that are being generated and collected on a continuous basis.

- The ***models and analytics*** **link will be at the *intermediate* maturity level** through enhancing the forecasting procedures and practices to include access to, and use of, other regional and global models, especially the post-processing and calibration of global models to the conditions of Bhutan. Attention will be mainly focused on improving modelling capabilities in water availability assessment, flash floods, mudflows, avalanches, and GLOF risks in these areas as well as in overall impact-based flood forecasting. As part of this effort, developing and sustaining a catalogue of mountain lakes with outburst potential through use of high-resolution satellite imagery and application of geographic information system (GIS) tools is a crucial activity at this stage of modernization. This also relates to the mapping of high-impact and high-risk areas of devastating avalanches.

- **The *forecasts* link will be further enhanced to the *intermediate* maturity level with improvements and innovations.** It will build on current capabilities of forecasters by upgrading the tools for visualization and manipulation of data and products by forecasters, introducing the ensemble prediction system (EPS) and the concept of probabilistic forecasting, enhancing the understanding and full use of numerical weather prediction (NWP)/EPS data and products for short- to medium-range forecasts, introducing impact-based forecasting techniques, and nowcasting. Forecasting and assessing water availability for the agriculture and energy sectors, GLOF, flash floods and mudflows, and long-range streamflow are hydrological and cryosphere areas of focus for development and enhancement.

Figure ES.3. Schematic of the NCHM value chain after short-term modernization intervention



- The tailored services link will reach the intermediate maturity level. The services will be enhanced by paying closer attention to the users' needs and their level of satisfaction with services of the NCHM and collecting their feedback. Closer collaboration with the Department of Local Governance and Disaster Management (DLGDM) will be established, for example, in developing/strengthening joint SOPs and exercises. Improved services will be provided to the agriculture and energy sectors. Climate services will be enhanced by producing climate indexes and implementing plans for establishing a National Framework for Climate Services. Similarly, cryosphere services will be enhanced by the provision of water resource assessments from high-mountain snow and ice fields as well as avalanche and GLOF warnings. It should be fully recognized that tailored services may not be generated by NCHM resources alone but require a knowledge base to be established in close cooperation with institutes of higher learning, the science community, and the public and private sector organizations.

- **The *integrated services* link will be at a low maturity level.** Following the medium-term modernization stage, the *integrated* services will be developed in the form of impact-based MHEWS and impact-based forecasts. Agromet services will be codeveloped with the agriculture sector to include preparing various crop-specific advisories and analytical information. Similarly, the NCHM will codevelop hydromet services for the energy sector.

- **The ICT link will be at an *intermediate* level of maturity.** The *ICT* link will be further developed with an integrated system for data transfer, quality control, data storage, and management. All data will be in the standard format required for the functioning of an integrated meteorological and hydrological ICT system, allowing the retrieval of data in the format required by all staff and thus covering the requirements for improved data exchange between them. The visualization system, including hardware, software, and training for the forecast and services divisions, will be upgraded for integration of all meteorological, hydrological, and cryosphere observations and model data. Additional dissemination channels for enhanced provision of PWS and hydrological services will be established including mobile platforms and the use of the Common Alerting Protocol (CAP).

- **The *education and training* link will be at the *intermediate* maturity level.** This link will benefit from the introduction of more

Figure ES.4. The Headquarters building of NCHM is shared with other government agencies

structured training activities to complement the new techniques, hardware, and software introduced into the NCHM at its short-term modernization. These will include training of staff at the regional training and research institutions in meteorological and hydrological modelling techniques, impact-based forecasting, implementation and maintenance of the mobile app and CAP, and implementation of MHEWS.

To enable modernization and proper development of the organization, a new, purpose-built campus is required for the NCHM.[7] This should comprise specific buildings devoted to administration, operational service provision, technical laboratories, educational and meetings spaces, a variety of other support functions, and residential accommodation for sufficient staff that will guarantee resilient services. The campus should also allow for the siting of weather observing equipment, including provision for balloon launches to gather upper air data. It would clearly be impossible to accommodate all these diverse needs on the existing site (see **Figure ES.4**), and the space required will be such that a suitable site is unlikely to be found near the center of Thimphu.

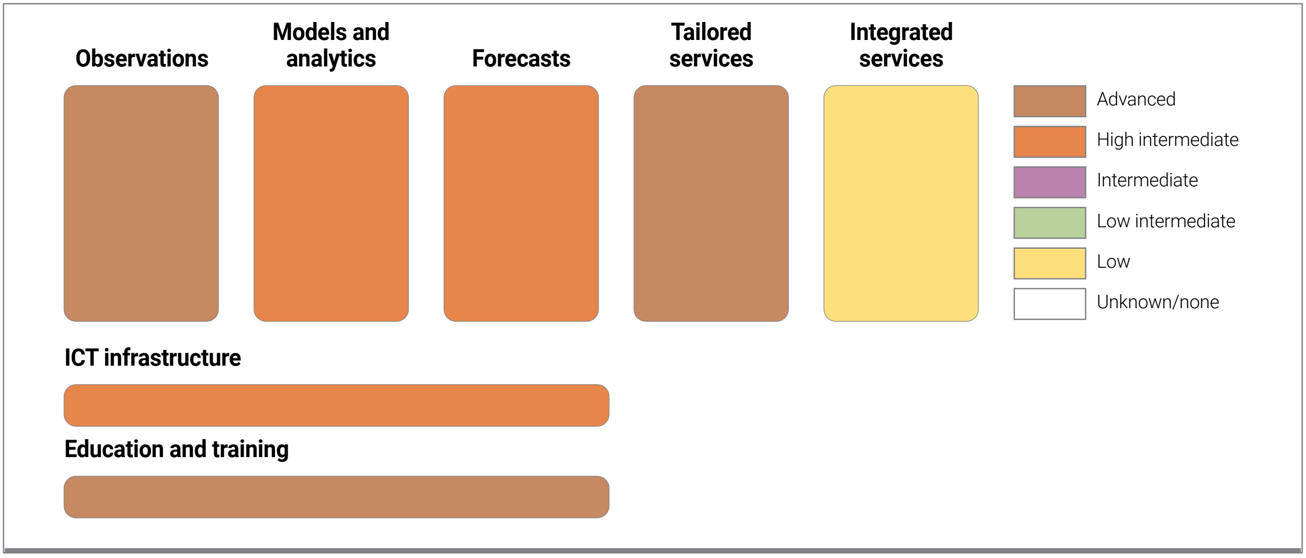
Medium-Term Modernization (10 years)

Under this approach, plans are made for a further five-year outlook (14th FYP). Investment is needed to enable developing and acquiring advanced capabilities for providing fit-for-purpose data, forecasts, and warnings services for the safety of the public and support to development of Bhutan's economy. This medium-term modernization plan is expected to cost **US$20 million** including O&M costs (excluding labor costs) of US$5.5 million and capacity-building costs of US$1 million.

- **The *observation* link will be at an *advanced* level of maturity** with the installation of two additional upper air stations, one weather radar to cover the Thimphu/Paro regions, 10 synoptic stations, and 10 AWS, all of which transmit data automatically and are fully integrated and

[7] Bhutan – Technical Guidance Note for Establishment of National Centre for Hydrology and Meteorology Head Quarter, National Weather, and Flood Warning Centre and Scientific Facilities (RGoB and World Bank 2023).

Figure ES.5. Schematic of the NCHM value chain after medium-term modernization intervention



ingested into a central ICT system. Cryosphere observations of permafrost are carried out at two locations. All historical data are digitized. The O&M budget is used for a proper life-cycle management of observation infrastructure and facilities. The investment for observations covers the cost of new observing equipment, tools, instrumentation, software and facilities, supply of spare parts, consumables, vehicles for field visits, fuel, the increased communication costs, power and other operating costs, and quality control/quality assurance procedures. All the stations are fully functional.

- **The *models and analytics* link will be at *high intermediate* level of maturity.** At this stage, a modelling group is established which is engaged in continuous research and development (R&D) and introducing innovations in modelling, with strong links to regional partners in developing, running, and exploiting advanced models. Model post-processing and calibration and data assimilation are now part of the routine operation of the NCHM. In addition, a 30-year reanalysis of the Bhutan climate using a limited-area model would aid the design of infrastructural projects such as roads, bridges, and dams. The data could also be used to drive hydrological models to estimate return periods for flood conditions. In terms of hydrology modelling and forecasting, techniques for medium- and long-term forecasts (including ensemble approach) are enhanced.

- **The *tailored services* link will be at the advanced level at this stage,** but further enhancements are still being made. Tailored services are now available to a wide cross-section of user sectors and further improvements are made in the dissemination mechanisms to communities. As part of its PWS, PWS/civil contingency advisers are deployed to provide links with user sectors, especially with DLGDM, to support the necessary preparatory and anticipatory actions to minimize the impact of hazardous hydromet events. Programs are developed and activities are organized to help increase the capacity of users to enable them to extract maximum benefits from data, products, and services provided by the NCHM, and raise understanding and awareness among the public, especially in remote and mountainous communities, on weather-related hazards and risks. This work is especially important as impact-based forecasts and warnings become the more commonly used forms of information shared with the public. At this stage, the NCHM uses its own TV studio facilities to broadcast forecasts and prepare content for online platforms. SOPs enable the NCHM to codify how alerts, warnings, and other operational products are issued. The SOPs also enable stakeholders to define their responses to the various levels of alerts and warnings. The ISO certification for aviation services and an organization-wide QMS are maintained.

- **The *integrated services* link will be further enhanced to an *intermediate* maturity level.** Opportunities are explored to develop a new business strategy for more sustainable operations by initiating public-private engagement such as fee-based service provision and outsourcing of certain activities such as modelling, ICT services, and software upgrading. MHEWS and impact-based forecasting intermingle leading to the development of impact-based MHEWS in close collaboration with DLGDM. Other integrated services are also developed, for example, in agriculture, urban and rural transport, construction, and health sectors by working closely with these sectors and coproducing services to meet their specific requirements.

- **The *ICT* link will be at a *high intermediate* level.** State-of-the-art ICT and computing facilities (within the technological, human resources, and financial capability of the NCHM) will occupy the ICT link. This includes a centralized data center comprising an Integrated File and Message Switching System (IFMSS), a forecaster visualization system to allow forecasters to view all relevant data, a Data Archive which allows holding of all raw data in medium term for quality control before the long-term storage of data, a climate data management system (CDMS) for long-term storage of quality-controlled weather data, and a sufficient number of servers, workstations, and personal computers. The planned move of the NCMH HQ to a separate campus, comprising specially designed buildings to house and support sophisticated ICT equipment, would be an important enabling element in achieving this level of ICT facility improvement. In addition, a service delivery platform and applications are established to disseminate and communicate products and information. A 'one-stop' users' portal for services, enabling easy and user-friendly access to serve all sectors from one location as well as mechanisms for collecting user feedback, is established.

- **The *education and training* link will be at an advanced level,** further strengthened to allow development of technical capacity and education through a professional training plan for NCHM personnel. On-the-job training of staff to support the implementation and application of upgrades for hydromet components, including issues around effective service delivery, is ongoing in a routine manner. More staff are trained at the regional and international training centers. Training in communication is provided routinely to all staff, especially those who interact with the public and with sectoral stakeholders. Continuing professional development of the managerial, scientific, and technical staff of the organization is the norm.

Innovation

Advances in scientific and technical innovations have been a cornerstone of the evolution of meteorology and hydrology over the past decades and these will continue. Artificial Intelligence (AI) – Deep Learning (DL), or Machine Learning (ML) techniques will enable Bhutan to access a range of products that will enhance forecasting techniques. The use of these techniques is a rapidly growing aspect of weather modelling and involves creating large member forecast ensembles, potentially extending the number of ensembles and downscaling both global and regional models to provide highly localized forecasts of rain and other critical weather parameters. The size and resolution of operational ensemble forecasts are constrained by computational resources, particularly in developing countries. ML techniques can be used to oversample numerical weather prediction distributions enabling more accurate representation of extreme weather events.

Local observations could be extended using ML techniques to address the extreme orography of Bhutan. One of the challenges faced by users of meteorological services in Bhutan is that the climate record is sparse and rather short in terms of time. The orography of Bhutan is very extreme, which makes it very difficult to construct a comprehensive and consistent record of the evolution of weather over the country, because of the relative lack of observations and the observations that are taken in a given location may not be representative of nearby areas. Local observations could be extended using ML techniques to create fields, which in turn can be used for bias correction of the ensemble and rapidly update the forecast cycle to create 0–6-hour hyperlocal predictions.

The implications for the NCHM would be to move their focus away from developing local-area NWP modelling and instead to focus on schemes to bias-correct, calibrate, and downscale global model data, and also to train some of their scientists in AI/ML techniques. It will also be important to develop a climate reanalysis dataset. Costs for these activities, including capacity building have been included in the estimates in Annexes III and V to this Roadmap.

Regional Cooperation

The NCHM is the cochair of the South Asia Hydromet Forum (SAHF). The SAHF, launched in 2018, brings together hydromet experts from all South Asian countries for sharing knowledge, building capacity, and aligning national-level technical assistance with regional engagement. The activities focus on (a) enhancing the Knowledge Hub (for example, fully operationalize the Forecasters Workbench including knowledge management and integration of regional and global model forecasts, cloud services for the Knowledge Hub, Data Exchange Platform, and allied information exchange/sharing platforms); (b) strengthening regional engagement (for example, Forecasters Forum, Working Group, Executive Council, and SAHF annual meetings established as a part of the SAHF); and (c) building capacity (for example, NWP, impact-based forecasting, observational network, and capacity enhancement). The SAHF is implemented by the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) and financed by the World Bank, initially with funding support through the European Union South Asia Capacity Building for Disaster Risk Management Program and by the UK Aid, administered by the Global Facility for Disaster Reduction and Recovery. Now, continued support is provided through the World Bank-funded Climate Adaptation and Resilience for South Asia and United Kingdom Foreign, Commonwealth, and Development Office.

The GoI and the NCHM cooperate in operating some hydromet stations and sharing of data. The GoI provides funds to the NCHM for the operation of 17 hydromet stations within Bhutan. Data of these stations are shared with the Central Water Commission in India for flood forecasting and warning in the part of India that is downstream of Bhutan. The network is a mix of manual and automatic stations using global system for mobile communications (GSM)-based telemetry. In addition, extended range prediction (ERP) for rainfall and temperature is prepared with support from the IMD.

There is strong collaboration with regional institutions such as BIMSTEC, RIMES and the International Centre for Integrated Mountain Development (ICIMOD). NMHSs are receiving more numerical weather products for both short term, medium and long range from BIMSTEC Centre for Weather and Climate (BCWC). RIMES has developed a Flood Decision Support System (FDSS) and an ADSS and provides capacity building to the RGoB agencies. The NCHM developed a streamflow prediction tool with ICIMOD and there have been activities to monitor snow and glaciers in collaboration with ICIMOD.

Photo credit: Dechen Tshering.

1. Introduction

1.1 Country Context

Bhutan, a landlocked kingdom in the Eastern Himalayas, is dominated by high mountainous terrain with four major river basins. Its elevations range from 7,500 meters in the north to under 100 meters in the south. The region is characterized by its many rivers, its isolated valleys that house most of the population, and the expansive forests that cover 70 percent of the land. Bhutan has four major river systems: Manas, Puna Tshang Chu, Wang Chu, and the Amo Chu (**Figure 1**). There are three transboundary rivers in Bhutan with China in the north and India in the south: Kurichhu, Amochhu, and Drangmechuu.

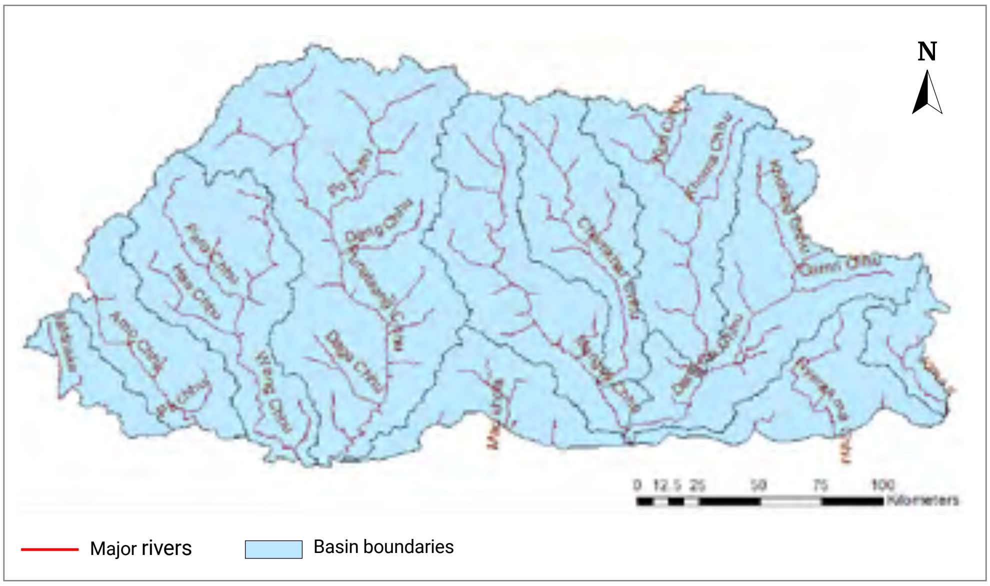
Bhutan's economy is highly dependent on climate-sensitive sectors such as agriculture and hydropower. Hydropower plants contributed to 13.4 percent and agriculture contributed to 6.8 percent to the country's gross domestic product (GDP) in 2022.[8] Half of the country's workforce is in agriculture, which is highly vulnerable given its concentration in rain-fed dryland and wetland farming. The rainfall in October 2021 affected 17 dzongkhags, 2,500 acres, and resulted in the loss of around 2,400 metric tons of crops. Bhutan's economy is shaped by hydropower development including the sale of electricity to India. While its abundant water resources created ideal conditions for hydropower development with total installed capacity of 2.3 GW out of a full hydropower generation potential estimated at 36.9 GW, the sector is also vulnerable to climate change, including changes in rainfall patterns, melting glaciers, and increasing occurrence of weather events.

[8] Statistical Year Book of 2023.

Hydropower. The Hydropower business has emphasized that it needs more observations of rainfall and river levels. There is a move to put hydropower units into smaller catchments, many of which are completely ungauged. Without good data on river flows, there is a reluctance to commit investment into hydropower infrastructure. This is why there is a need for more Automatic Rain Gauges and more / denser network of river gauges, all reporting in real time. There is a further need to be able to model river catchments more accurately so that (forecast or measured) rainfall amounts can be converted to expected river levels.

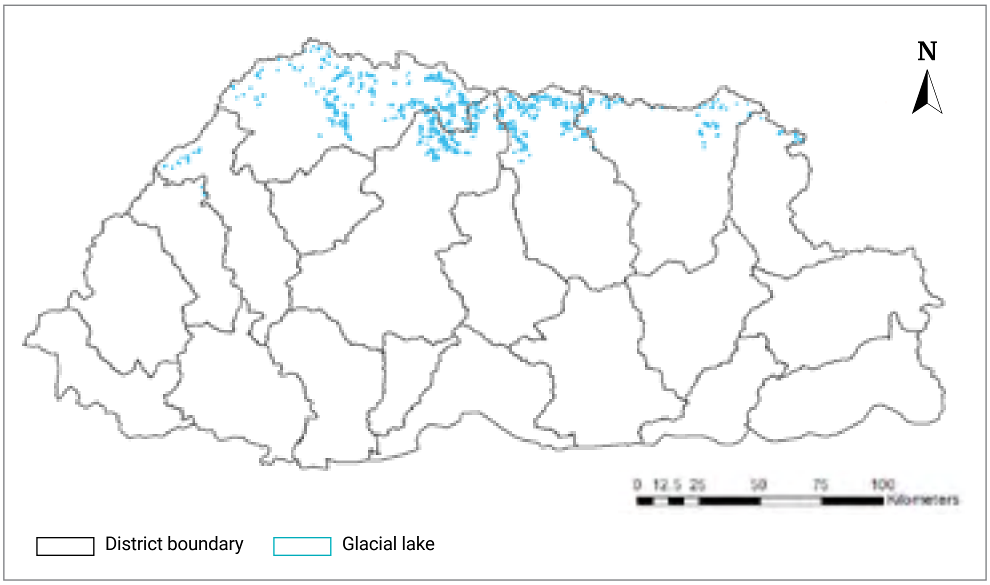
The Hydropower sector also has a great need for better statistics of possible extreme rainfall / flood events (both for severity and frequency). These statistics are needed as input into dam and other infrastructure design. The time frames (likely lifetimes of the infrastructure) are such that the statistics would need to incorporate climate change projections. A huge problem is that the length of the climatological record in Bhutan is short. Under the Innovations section below, there are some ideas as to how this deficiency might be overcome.

Figure 1. Major river systems in Bhutan



Source: Firoz Alama et al. 2016. "Sourcing Green Power in Bhutan: A Review."

Figure 2. Distribution of glacial lakes in Bhutan



Source: Bhutan Glacial Lake Inventory 2021.

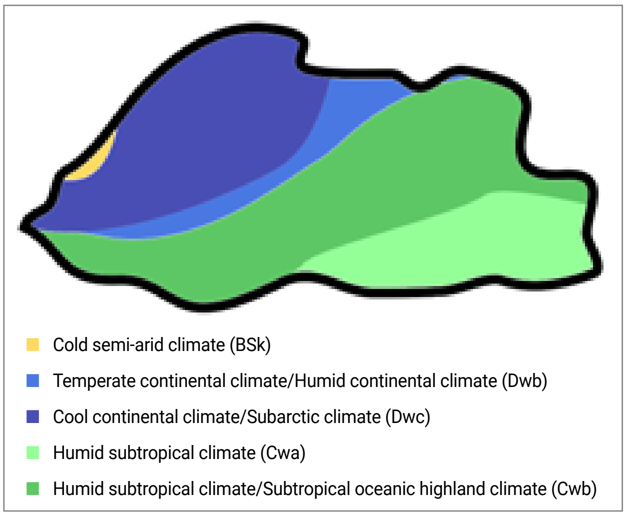
The country's dynamic glacial landscape necessitates regular inventory updates to monitor environmental changes and potential hazards effectively. Bhutan's northern glaciers, constituting 10 percent of the land in the 1980s, play a crucial role as a renewable water source for rivers. The 'Bhutan Glacial Inventory 2018' identifies 700 glaciers covering 630 km², representing 1.64 percent of Bhutan's total land area. The country is home to 3,027 high-altitude lakes, with 17 flagged as potentially dangerous for glacial lake outburst floods (GLOFs). A 2021 inventory reports 567 glacial lakes covering 55.04 km², all of which fall between 4,062 and 5,507 meters above sea level elevation with larger glacial lakes located between the elevation band of 5,000–5,200 meters above sea level (**Figure 2**).

Bhutan's non-glacial lakes, spanning 43 km² above 3,500 meters, constitute essential high-altitude wetlands and are an integral part of the river systems. They play a vital role in water storage and the mountain ecosystem and support government hydropower projects. The escalating risk of glacial melting due to climate change increases flooding hazards from GLOFs. Knowledge about snow cover, runoff, and avalanche risks in Bhutan is limited.

1.2 Climate

Bhutan's climate is as varied as its altitudes and is clearly affected just as much by monsoons as other countries in the region. The climate of South Asia is dominated by the monsoon: the timely arrival of the summer monsoon, and its regularity, are critical for the rural regions and food production. An increasing occurrence of extremely low snow years and a shift toward extremely high winter/spring runoff and extremely low summer runoff would increase the flood risk during the winter/spring and decrease the availability of freshwater during the summer.[9] Western Bhutan is particularly affected by monsoons that bring between 60 and 90 percent of the region's rainfall. The climate is humid and subtropical in the southern plains and foothills, temperate in the inner Himalayan valleys of the southern and central regions, and cold in the north, with year-round snow on the main Himalayan summits (**Figure 3**). Bhutan's generally dry spring starts in early March and lasts until mid-April. Summer weather commences in mid-April with occasional showers and continues through the pre-monsoon rains of late June. The summer monsoon lasts from late June through late September with heavy rains from the southwest. The monsoon weather, blocked from its northward progress by the Himalayas, brings heavy rains, high humidity, floods, flash floods, landslides, and numerous misty, overcast days. Autumn, from late September or early October to late November, follows the rainy season. It is characterized by bright, sunny days, little rainfall, and some early snowfalls at higher elevations. Droughts and forest fires can occur during this period—with devastating impact on agriculture, forests, and rural communities. From late November until March, winter sets in, with frost throughout much of the country and snowfall common above elevations of 3,000 meters. The winter northeast monsoon brings gale-force winds down through high-mountain passes.

Figure 3. Bhutan map of KÖppen climate classification[10]



The altitude range of 100–2,000 meters receives about 2,000 mm of total annual rainfall, the area between 2,000 and 4,000 meters receives about 1,000 mm total annual rainfall, and the northern region above 4,000 meters receives about 400 mm of precipitation annually in the form of snow. Temperatures vary according to elevation. Temperatures in Thimphu, located at 2,200 meters above sea level, range from approximately 15 to 26°C during the monsoon season of June through September but drop to between about -4 and 16°C in January. Most of the central portion of the country experiences a cool, temperate climate year-round. In the south, a hot, humid climate helps maintain a fairly even temperature range of between 15 and 30°C year-round, although temperatures sometimes reach 40°C in the valleys during the summer (**Figure 4**). The spatial variation of the mean temperature and precipitation for Bhutan for 1991–2020 is shown in **Figure 5**.

[9] Giorgi, F., et.al. 2011. *Higher Hydroclimatic Intensity with Global Warming.*

[10] KÖppen climate classification -Ali Zifan (2016) derived from World KÖppen Specification

Figure 4. Monthly climatology of minimum, mean, maximum temperature and precipitation in Bhutan (1996–2023)

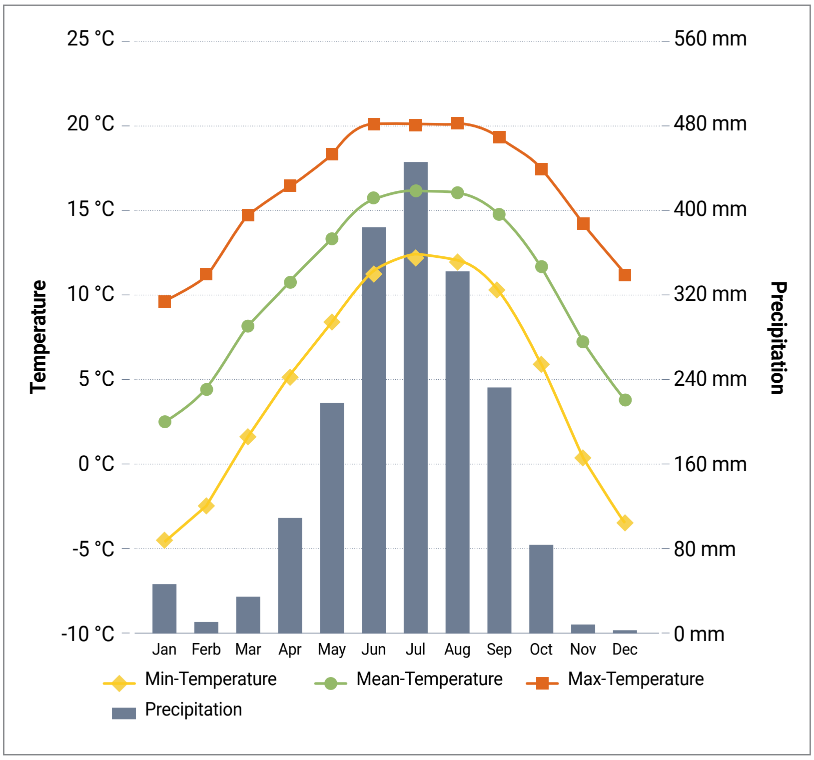
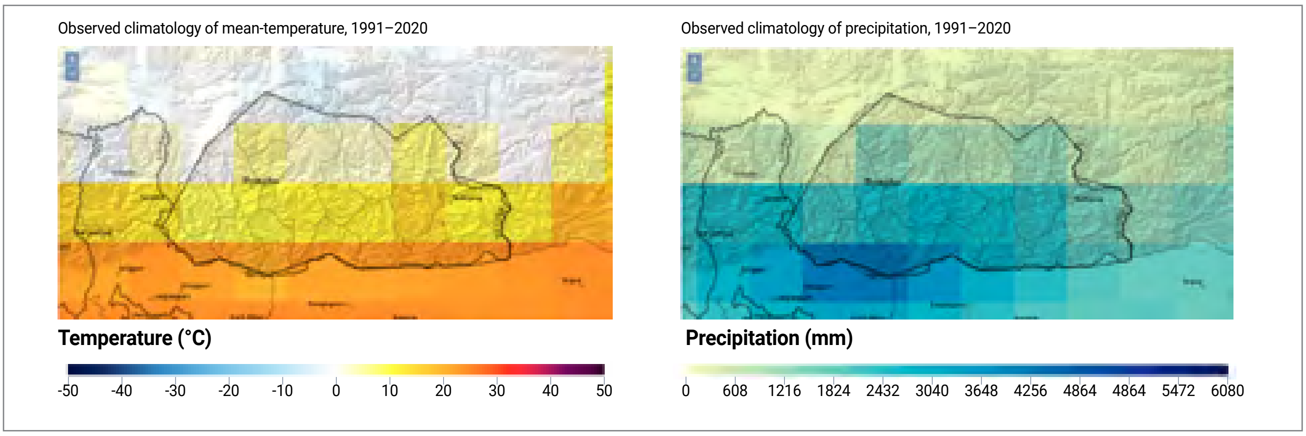


Figure 5. Observed climatology of mean temperature and precipitation in Bhutan (1991–2020)



1.3 Hydrometeorological Hazards and Their Socioeconomic Impacts

Due to the diverse ecological systems, variable terrain, and regional climate, disasters affect Bhutan and its people to a varying degree. Bhutan is exposed to flooding, landslides, GLOFs, wildfire, and windstorms. Among the climate-related hazards, flooding is the country's most significant. The risks associated with other climate-related natural hazards often found in Asian countries, such as drought and tropical cyclones, are relatively low, according to the INFORM 2019 Index. An exception is the 2009 cyclone Aila which caused massive flooding, resulting in estimated damages of US$17 million to properties and housing.[11]

Natural disasters and climate change threaten lives and livelihoods, requiring a robust and timely hydromet services delivery. Climate

[11] https://www.nchm.gov.bt/home/pageMenu/781

change could affect the intensity and frequency of hydromet hazards. It is expected to affect water resources through loss of storage in the form of ice and changes in precipitation and flow patterns, causing more floods and droughts. The risk of potential disasters induced by GLOFs is pronounced, as the country is home to 700 glaciers and 2,674 glacial lakes, of which 17 are expected to pose medium to high risks.[12] Climate change can reduce the income of the poorest 40 percent by more than 6.5 percent by 2030.[13]

Road Engineering. There is a significant and urgent need for better statistics for extreme rainfall/flood events to help with planning road infrastructure. Flooding and landslides are major causes of damage to roads. Design of drainage from roads is a challenge, as is providing proper support to road margins etc. Some snowfall is experienced so forecasts for this would be useful. Ice formation also occurs on roads during the winter months; between extreme rainfall, floods, snow and ice the annual economic and social impact of weather conditions of the road network in Bhutan is considerable. The quality of available data and the unfriendly formats of the data are currently available are significant issues.

1.3.1 Floods and Landslides

Flooding is responsible for the largest percentage of mortality and economic losses in Bhutan. For example, in 2010, flash floods and landslides affected nearly 4,800 households, and in 2012, flooding in Gasa caused damages of over US$5 million to infrastructure and housing.[14] The impact of flooding on health and livelihoods is expected to grow and could cost up to 4 percent of GDP by the 2030s.[15] Most of the country's infrastructure is located along drainage basins that are highly vulnerable to flooding caused by heavy monsoon rains and glacial melt. The urban areas are vulnerable to flooding and extreme heat in the south. In July 2023, devastating flash floods in Gelephu, Phentsholing, and Lhuentse damaged assets, including roads, public properties, and a bridge. They washed away 23 people and a section of the Yungichhu Hydropower Plant.

1.3.2 Glacial Lake Outburst Flood

The risk of GLOFs is a major concern in Bhutan. The October 1994 major GLOF event from the Luggye Tsho glacial lake caused extensive damage along the Punakha-Wangdue valley and created increasing awareness of the potential risks from glacier retreat and of GLOFs. Glacial retreat contributes toward the formation of supra-glacial lakes, which can burst, creating a GLOF and causing flash flooding with potential for significant damage in Bhutan's river valleys, where the highest concentration of the country's economic activity is based. This risk is highest in Bhutan's northern region and in areas near glacier and snow-fed lakes.

1.3.3 Drought and Extreme Temperatures

Erratic monsoonal activities are increasingly the cause of extreme windstorms during the spring and multiply the risk of forest fires during the drier winter seasons. Windstorms in the last two decades have caused severe damage to infrastructure and agricultural production. Projected reductions in winter rains in many districts under a changing climate, especially in the next three decades, are likely to compound the risk of forest fires. The slow onset of disasters, such as droughts, are less likely to make news headlines and are therefore less well recorded, but the impacts are often equally detrimental to farmers, who have limited means to mitigate the impacts.

1.3.4 Climate Change

Many of the climate risks and impacts that pose potential threats to populations Bhutan are associated with changes in the hydrological cycle—extreme rainfall events are projected to become more commonplace as a result of climate

[12] NCHM. 2019. *Bhutan Glacier Inventory 2018.*
[13] Jafino, B. A., B. Walsh, J. Rozenberg, and S. Hallegatte. 2020. *Revised Estimates of the Impact of Climate Change on Extreme Poverty by 2030.* World Bank.
[14] ICIMOD. 2016. *Flood Early Warning Systems in Bhutan: A Gendered Perspective.*
[15] WB and ADB Climate Risk Country Profile: Bhutan (2021).

change and translate to flash floods as well as landslides. Similarly, droughts and declining snow fall and glacial loss in the Himalayas can lead to changes in river flow. The latest reports of the IPCC (AR6) use the concepts of "Shared Socioeconomic Pathways" (SSPs) which are closely linked to the previously-used "Representative Concentration Pathways" (RCPs). As per the SSP2 (linked to RCP 4.5) and SSP5 (linked to RCP 8.5) scenarios for Bhutan, it is projected that (i) there will be a rise in annual mean temperature in the range of 1.1°C to 3.2°C between 2021 and 2059, respectively. The country is expected to experience an increase in temperature with a more significant increase projected in the highlands; (ii) annual rainfall will increase between 3 percent and 10 percent between 2021 and 2059, respectively, with an uneven distribution. The projections suggest increasing rainfall during the monsoon (especially in the months June, July and August) while the winter seasons are likely to receive a decrease in rainfall in some parts of the country.

Accelerated melting of glaciers, which act as natural water retention and dispensing mechanisms, can disrupt the hydrological regime of perennial river systems and have a profound effect on water availability and productivity of water-dependent sectors such as agriculture and hydropower, making the population increasingly vulnerable and potentially putting water availability and food security at risk. Several studies have found that South Asia is already a highly water-stressed region.[16] It has low levels of water storage capacity per capita, and groundwater depletion, coupled with declining water availability, increases vulnerability to fluctuations in water flows and changing monsoon patterns. The effects of climate change have the potential to significantly aggravate the situation further.

Given the scale of potential impacts, climate change may derail current development and heavily affect agricultural output. Currently, crops cultivated in Bhutan include rice, maize, wheat, barley, buckwheat, and millet alongside fruit crops. However, given the increasing adverse and unpredictable weather, sustaining or increasing the rate of agricultural production in Bhutan is severely endangered.[17] Droughts in the region have become longer and more severe during the past two decades, thus decreasing the availability of water with a compounding effect on the vulnerability to poverty and food security.[18] There is a need to identify which crops may become unsuitable to farm under current climate projections and, conversely, which crops could provide new opportunities for farmers. Rising temperatures and precipitation could also change transmission patterns for vector borne diseases. Higher temperatures will also affect the northern regions by influencing glacier melt.[19]

Public Health. Changes to the hydrological cycle are not the only possible adverse impact of Climate Change. Outbreaks of vector-borne diseases (dengue and malaria) can occur and some prediction of the likely weather conditions that favor these would help to prepare for them more effectively. Heat health is also an issue; there was a dry period in July in 2022—a break in the monsoon rains—when temperatures rose considerably and it became uncomfortably hot, a situation that possibly should have led to targeted advisories to those undertaking manual work such as in construction. Another important service would be the prediction of events that might lead to infrastructure damage, especially to the water infrastructure, as losing water supply can lead to disease outbreaks.

Changes in the cryosphere, melting of snow from higher temperatures, variability of precipitation, and thawing of permafrost can further trigger

[16] Fung, F., A. Lopez, and M. New. 2011. *Water Availability in +2°C and+4°C Worlds.*

[17] Choggyel, N., and L. Kumar. 2018. "Climate Change and Potential Impacts on Agriculture in Bhutan: A Discussion of Pertinent Issues." *Agriculture and Food Security* 7 (79): 1–13.

[18] Tandlich, R., Angala, H., Vhiriri, E.P., et al., 2018. "Disaster and Health Vulnerability Assessment for the Population of the Kingdom of Bhutan." *Studies in Humanities and Social Sciences* 7 (1).

[19] Climateknowledgeportal.worldbank.org (vulnerability).

glacier lake outbursts. Another aspect of climate change will be the destabilization of large parts of high-altitude mountain environments due to the melting of permafrost and the resulting increase of mass movements, including rock falls and landslides.

1.4 Governance and Management of Hydromet Services in Bhutan

1.4.1 Legal Status in the Government

The National Centre for Hydrology and Meteorology (NCHM) was established in 2016 by the Cabinet as a publicly funded government agency. It is the principal agency responsible for the generation of information and delivery of products and services on weather, climate, cryosphere, and water resources in Bhutan. There are no other sources besides the NCHM to provide meteorological and hydrological forecasts and observations in Bhutan.

The 'Hydro-met Policy of the Kingdom of Bhutan' approved by the Cabinet in 2023, is the main policy framework that defines the responsibilities of the NCHM and provides guidance to standardize hydrometeorological instrumentation and quality management system (QMS), information management, national compliance with international agreements that Bhutan is party to, enhancing research, and engagement with private sector and international entities. The stated objectives of the policy are to strengthen institutional mandate of the NCHM; strengthen hydromet observation network, communication, and infrastructure facilities; strengthen database management and data exchange; enhance effective delivery of hydromet services; harmonize and standardize hydromet instrumentation and data collection; promote understanding of hydromet science through research and development (R&D); promote professional capacity through education and training; enhance partnership with stakeholders; and promote regional and international cooperation.

The Vision of the Hydro-met Policy 2023

Building a nation and society with access to high-quality, actionable weather, climate, and hydrological information, with preparedness and responsiveness to hydrometeorological threats and opportunities in ultimate pursuit of gross national happiness.

1.4.2 Legal Framework

The legal framework that provides the mandate and support to the NCHM is based on the following:

- **The Cabinet on December 11, 2015, during the 92nd Lhyengye Zhungtshog (Cabinet Meeting) approved the establishment of the NCHM** and mandated it to collect and provide authoritative information to the people and development sectors to plan and prepare for, mitigate, and respond to natural and extreme hydromet events.
- **The Water Act 2011** aims to ensure that the water resources of Bhutan are protected, conserved, and managed in an economically efficient and environmentally sustainable manner. The act mandates the earlier Ministry of Economic Affairs which housed the Department of Hydromet Services (DHMS), now NCHM, for collection, analysis, and dissemination of water resources data and monitoring of water flows including the discharge level and sediment for the National Integrated Water Resources Management Plan, planning and design of water resource infrastructure including dams, and GLOF issues.
- **The Climate Change Policy 2020** mandates the NCHM to (a) provide national source of hydrometeorological data and services to meet the needs of the general public, emergency services, and other specialized users and (b) provide hydrometeorological data and information, climate modelling and scenarios, and early warning services.

- **The Disaster Management Act 2013** identifies the NCHM as the hydromet hazard early warning service provider in the country to ensure an early warning system (EWS) for identified hydromet hazards and notify all vulnerable populations and responding agencies of the threatening disaster situation or disaster in the country. Subsequently, in 2019, the National Disaster Management Authority (NDMA) designated the NCHM as the national hydromet hazard early warning service provider in the country.
- **The Civil Aviation Act 2016** retains the authority to direct the development of rules and regulations for aviation meteorological services and delegate a competent entity to provide meteorological services for air navigation. This responsibility has now been transferred to the NCHM which is mandated to provide reliable aviation met services for air navigation in compliance with the International Civil Aviation Organization (ICAO) requirements, other international conventions, and best practices. Civil aviation is regulated and administered by the Bhutan Civil Aviation Authority (BCAA), which came into effect in 2015 to replace the Department of Civil Aviation.

1.4.3 The NCHM Roles, Mandates, and Functions

The **vision** of the NCHM is to be a "Centre of Excellence in Hydrology, Meteorology and Cryosphere Science and Services."

The **mission** of the NCHM is "Monitoring and understanding of hydrology, weather, climate and cryosphere, for timely provision of information and services to protect lives and property and support national needs for ecologically balanced sustainable development."

The **goals** of the NCHM are to:

- Improve result-based decision support service for weather incidents and events that threaten lives and livelihoods;
- Enhance climate services to understand and adapt to climate-related risks;
- Develop capacity to provide integrated and coupled monitoring, detection and forecast services to support assessment and management of water resources and hydrometeorological hazards;
- Build competence to provide sector-relevant information for socioeconomic development, and support development of integrated environmental services to foster healthy communities and ecosystems; and
- Sustain a highly skilled professional workforce equipped with training, tools, and infrastructure to fulfill the mission.

The **mandate** of the NCHM is "Provide scientific and technological services in hydrology, water resources, meteorology, climatology, and cryosphere to ensure the safety and socioeconomic well-being of society and to support national and international needs."

The main **functions** of the NCHM are as follows:

- Establish and operate a national observation network and telemetry system for weather, climate, cryosphere, hydrology, and water resources.
- Maintain a national database (repository) of hydrology, meteorology, cryosphere, and related environmental data and information.
- Provide PWS, climate services, agrometeorology, and climate projection
- Conduct aviation meteorological observation and provide aviation meteorological services
- Provide hydrological forecasting (flow and flood), water resource assessment and inventories

- Assess and map hydrometeorological and GLOF hazards, and provide Early Warning Services
- Study and monitor snow, glaciers, and glacial lakes in the country. Conduct scientific studies on the cryosphere to make an inventory and assess its potential in terms of water resources. Carry out hazard assessment and recommend suitable measures to address risk and hazard associated with this field.
- Promote and conduct research on cryosphere, meteorology (weather and climate), hydrology, and water resources.
- Enhance human resources development and professional capacity in the field of hydrometeorology and cryosphere services.
- Promote and facilitate standardization of hydromet instruments, methods of observation, and recording.
- Establish collaboration and link with relevant national, regional, and international organizations.

1.4.4 Structure of the NCHM

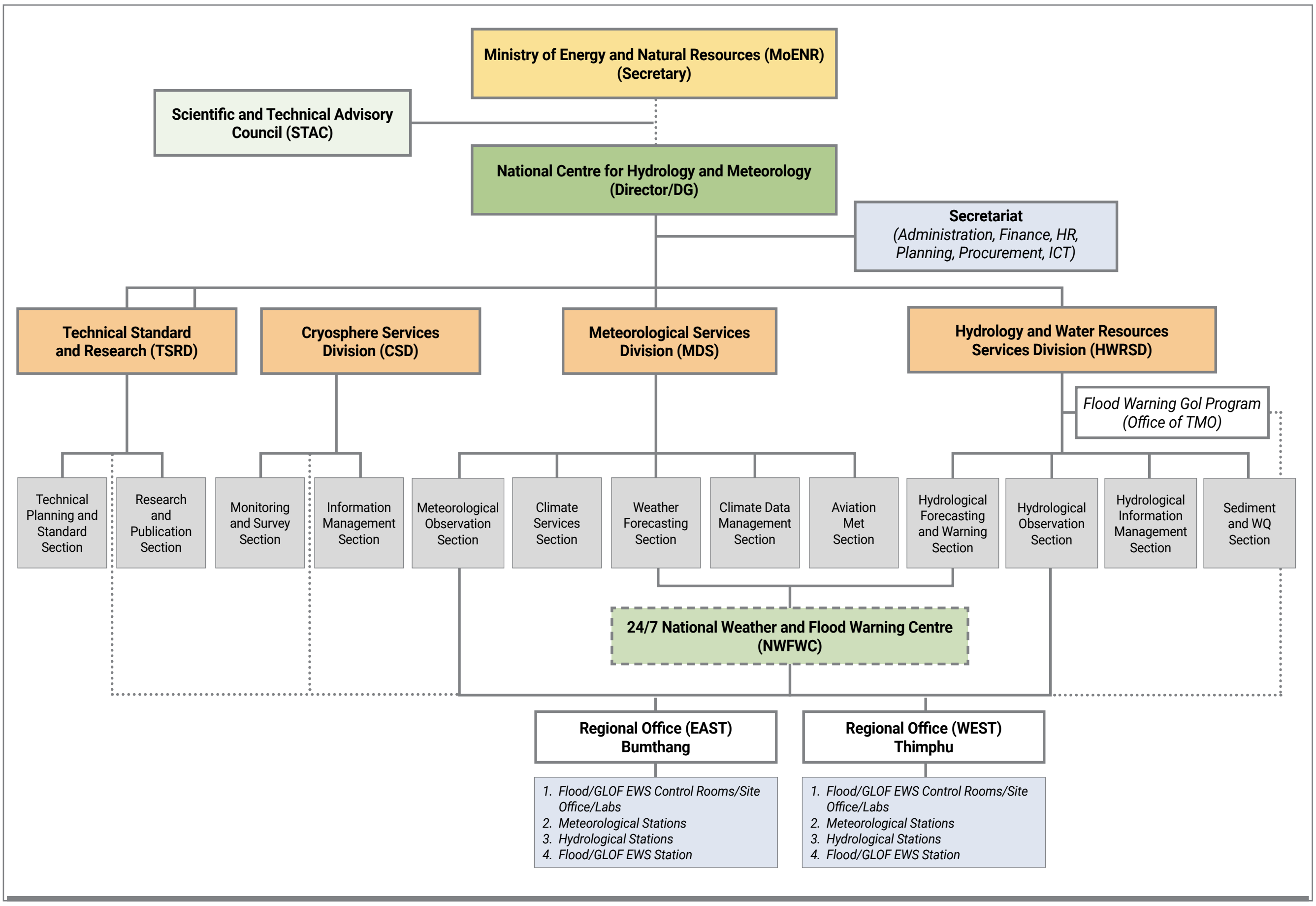
Through the Civil Service Reform Act 2022, the Governing Board was dissolved in December 2022 and the NCHM now has a functional autonomy with the Director overseeing its administration and management. The Director reports to the Secretary, Ministry of Energy and Natural Resources (MoENR), based on relevance and synergies of functions. The oversight on administration, strategic policy, and governance of the center is guided by the Secretary, MoENR. The new organogram of the center is shown in **Figure 6**. The organizational structure of the NCHM accounts for the important divisions and sections common to national hydrological and meteorological service institutions internationally. Quite significantly, it combines meteorological, hydrological, and cryosphere divisions within the same organization, making coordination between forecasting and service delivery easier. This is often not the case in other countries, which makes coordination between meteorology and hydrology challenging. Functions of the secretariat and the four divisions of the NCHM are described in **Annex I**.

The NCHM has its headquarters (HQ) in Thimphu and operates two regional offices. The West Regional Office is within the HQ in Thimphu which looks after all the hydrometeorological network and facilities covering Jaldakha, Ammochhu, Wangchhu, Punatsangchhu, Aiechhu, and Aiechhu (Maokhola) sub-basins. The East Regional Office is at Kurjey, Bumthang, and looks after all the hydrometeorological network and facilities covering the whole Manas River basin.

1.4.5 Staffing

The NCHM has 207 approved posts according to the 12th FYP. The center currently operates with 185 employees. All technical positions are at the HQ where there are also a similar number of nontechnical staff. The field positions are all nontechnical. Most of the technical positions are filled by engineers. There are few university-trained meteorologists, atmospheric scientists, or hydrologists. This is a significant gap because the national hydrological and meteorological service staff have to be trained to cover all basic functions related to weather services, meteorology, atmospheric science, hydrology, and cryosphere. Since the center is responsible for monitoring and operation of national hydrometeorological network stations covering the whole of Bhutan (all national hydrometeorological stations), the majority of staff are under the technician/nontechnical category followed by the professional and management levels. **Annex I** presents the current staffing details of NCHM.

Figure 6. Approved revised organogram of the NCHM (January 2023)

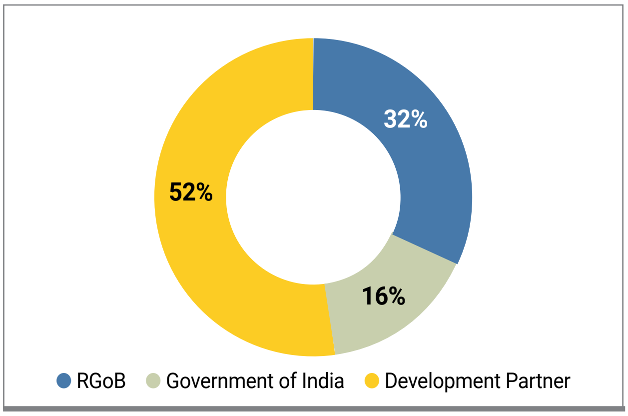


Source: NCHM.
Note: DG = Director-General; TMO = Technical Maintenance Officer.

1.4.6 Budget of the NCHM

Between FY13 and FY21, the NCHM's total annual budget ranged from US$1.3 million to US$4.5 million, of which more than half was funded by donors, followed by the RGOB (32 percent) and GoI (16 percent). The strong dependency on development partner funding was observed to support capital expenditure[20], although in more recent years the capital expenditure is more balanced between the three sources, mainly due to a decrease in capital (project) funding from development partners. However, a degree of resilience in the current budget[21] and the increase over the final three years displayed are noteworthy. This is particularly relevant as the proposed capital investments outlined in Chapter 4 as being necessary for the modernization program will need to be complemented by a significant rise in the current budget if the full benefits of modernization are to the delivered to the Bhutanese citizens. The NCHM has been efficient in utilizing both its own (RGoB) budget resources and those provided by development partners with the expenditure figures reaching 90 percent or more of the available budget.

Figure 7. Sources of NCHM Budget, 2012–2021



[20] Includes operation and maintenance (O&M) of existing works/ equipment and new works
[21] Includes staff salary and allowances

More details are provided in Annex I.

1.4.7 Major Users and Stakeholders of the NCHM

A considerable number of government ministries and departments including those responsible for agriculture and livestock, water resources, disaster management, health, energy, particularly hydropower, tourism, infrastructure, forestry and park services, environment and climate change, and transport are among the main users of hydromet information provided by the NCHM. In addition, the NCHM provides weather/climate and hydrological data and information to private sector entities such as the Druk Green Power Corporation as well as academic researchers and students, foreign institutes, and others based on request. The meteorological, hydrological, and cryosphere information and services required and some of the major users who require the information are as follows:

- Short- and medium-range and seasonal forecasts (agriculture, energy)
- Probabilistic forecasts (all sectors)
- Long-range forecasts/projection (agriculture, health, forestry)
- Impact-based forecasts (all sectors)
- Aviation services to ICAO standards, including the QMS (aviation sector)
- Route forecasts (tourism)
- High-frequency spatially distributed hydrological and climate data (all sectors)
- Climate projection (all sectors)
- GLOFwarning services (all sectors)
- Impact-based flood early warning services (all sectors)
- Snow, avalanche, and mass movement early warning (all sectors)
- Hourly forecasts (transport)
- Icing advisories (transport)

Table 1 provides the list of some of the main stakeholders and partners of the NCHM and their respective requirements for products and services provided by the center.

Table 1. The main stakeholders of the NCHM and their areas of interests

Agency	Information and services required from the NCHM
Department of Water (DoW), MoENR	Precipitation, temperature, and relative humidity short-range forecasts, hydrological data in terms of flow, sediments, and ambient water quality for major rivers, site-specific weather/climate information, and forecasts which actually are representative of that particular locality. Warnings for different kinds of floods and extreme weather events are mostly isolated based on the establishment of weather stations, but there is a need for uniformity in making forecasts and projections throughout the country There is a need for a more dense network of rain and river gauges to provide data for modelling river catchments. Also needed are better statistics for extreme rainfall events which would incorporate the likely impacts of climate change.
Department of Local Governance and Disaster Management (DLGDM)	Extreme weather, floods, GLOF EWS, and flood hazard maps to allow intervention by first responders as well as climate statistics for developing preparedness and strategies and planning.
Department of Public Health, Ministry of Health	Medium-/long-range forecasts to prepare for and prevent climate-sensitive diseases as well as to position medical supplies and equipment at the health facilities in advance, preventing and mitigating the impact of climate-sensitive diseases. Capacity development of health professionals to help them utilize hydromet information more fully is a major requirement.

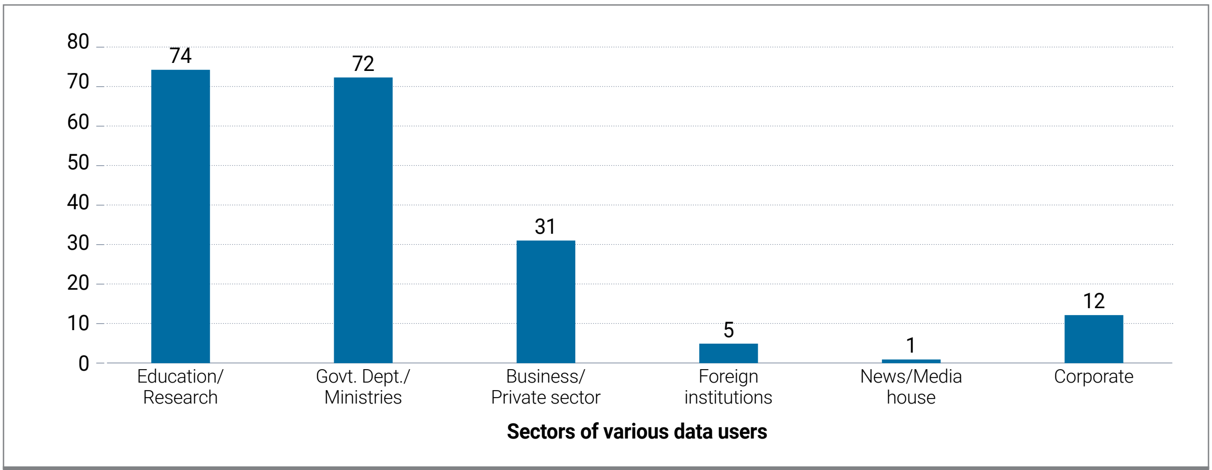
continues

Table 1. The main stakeholders of the NCHM and their areas of interests (cont.)

Agency	Information and services required from the NCHM
Department of Energy (DoE, MoENR) and Druk Green Power Corporation (DGPC)	Long-term and reliable data/information for planning and design, short-term forecasts (24 hours ahead) for daily scheduling market (DSM). Additional information and products required include hydrological data on tributaries (currently all hydrological data are limited to major river basins) to allow hydropower developments of smaller capacity, hourly inflow forecasts for energy forecast production, rainfall with a return period for flood estimation, isohyet maps, extreme flood and rainfall events, and rainfall intensity-duration-frequency (IDF) curves.
Department of Agriculture (DOA), Ministry of Agriculture and Livestock (MoAL)	Hydromet data and information (short- and medium-range weather forecasts, seasonal forecasts, drought monitoring) in support of operations for land preparation, date of sowing, nutrient management, pesticide application, irrigation, and harvesting. There is a need for additional improvements in medium-range forecasting and its integration in the ADSS agromet decision support system (ADSS) of Bhutan. Also, higher-resolution temperature and rainfall data are required for crop modelling.
Department of Livestock (DoL), MoAL	The information received is mainly the general public weather forecasts, and although these are useful for short-term daily operations, they are not helpful for long-term planning. Improvements required include area-specific forecasts and easy access to real-time and time series data for scientists and researchers as well as client-centric weather forecasts formats (text, voice, graphics, and so on).
Department of Air Transport (DoAT), Ministry of Infrastructure and Transport (MoIT)	Aviation meteorological services are required for flight safety and efficiency of flight operations and monitoring aerodrome weather conditions. Meteorological information is required that includes basic data/information such as quasi-nonhydrostatic (QNH), wind direction/speed, altitude, temperature, cloud, and visibility for both ends of the runway. Improvements required include implementation of the ICAO Meteorological Information Exchange Model (IWXXM) and QMS as mandated by ICAO and the Bhutan Civil Aviation Authority.
Department of Forests and Park Services (DoFPS), MoENR	Studying and managing forest ecosystem, forest species/vegetation shift modelling, forest fire hazard modelling, and pest and disease modelling require long-term climate data (although not conducted at the moment). At the moment, forecast and warning information about weather and hydrology is not being used in the forestry sector, but the climate data have been useful in understanding the growth of different forest/vegetation types as per the climate variability for the particular forest management area and helpful in planning harvesting and planting/reforestation activities. An online portal where climate data could be downloaded is highly desirable, and temperature, precipitation, and humidity data in spatial format (raster data) with high resolution would be required for advanced applications of weather and climate data in the forestry sector.

Figure 8 shows the sectors and number of weather/climate data requested in FY2020–2021.

Figure 8. Weather/climate data requested by users in FY2020–2021



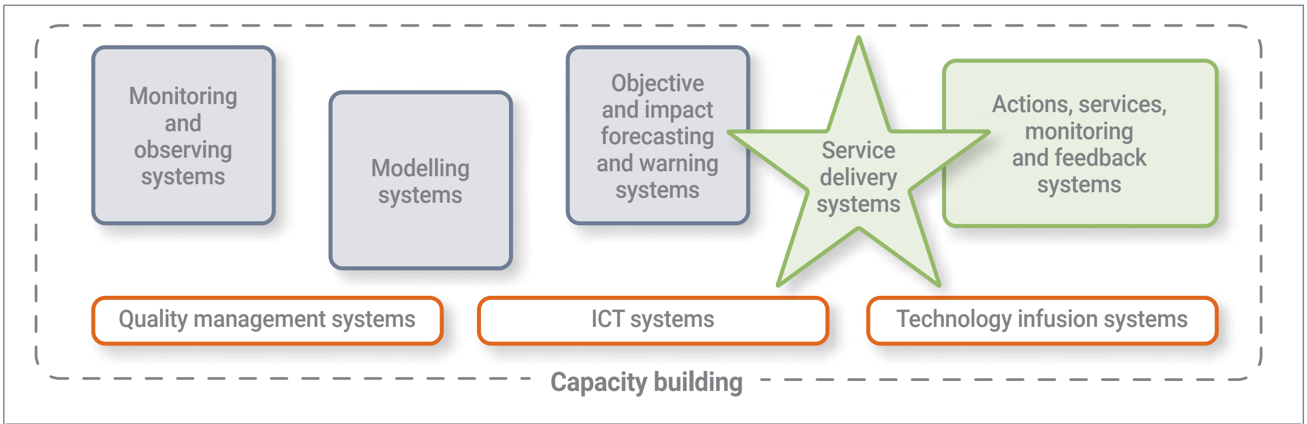
2. Approach to Modernization

Paro International Airport. Photo credit: mtcurado.

2.1 A System-of-Systems Approach

This roadmap uses a system-of-systems approach to arrive at two scenarios for modernizing the NCHM. The purpose of modernizing hydromet services is to reduce the socioeconomic risks of weather, climate, hydrological and cryosphere-related events, and to protect lives and economic/development gains. It will also contribute to ensuring water security for the country by providing reliable information and projections on the country's water resources, seasonally as well as a result of climate change. The modernization proposed in this roadmap intends to help the NCHM fulfill its public tasks by strengthening its institutional and technical capabilities and capacities. The generic illustration of a weather, climate or hydrological 'system of systems' of a typical National Meteorological and Hydrological Service (NMHS) is shown in **Figure 9**. This and the subsystems (**Figure 10**) of each system can be used to analyze the status of any NMHS and to visualize investments required to achieve a particular level of improvement.

Figure 9. Schematic of an NMHS as a system of systems



Source: Rogers et al. 2019.

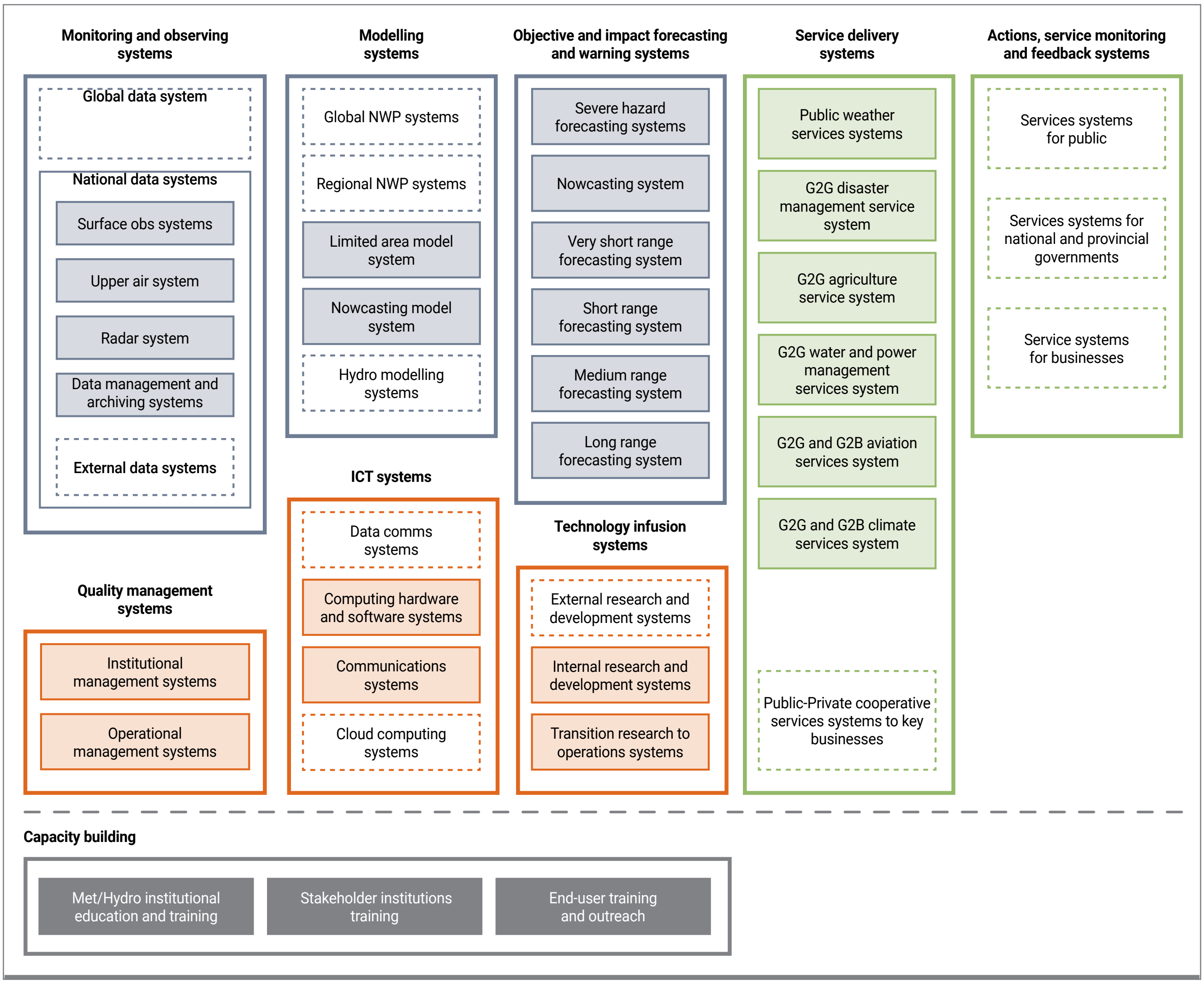
A modernization program for any NMHS should include three components: (a) enhancement of the service delivery system; (b) institutional strengthening and capacity building; and (c) modernization of the observation, ICT, and forecasting infrastructure.[22] This path has been followed in developing this roadmap. The proposed activities aim to strengthen the NCHM's institutional basis, enhance the capacity of staff, technically modernize the operational infrastructure and forecasting facilities, and advance the delivery of hydromet and multi-hazard early warning system (MHEWS) to the population of Bhutan and sectors dependent on weather, climate, and water information. A high-level overview of the major requirements for each of the three components in an NMHS is presented below. This collection of activities will need to be tailored to the actual needs and the existing situation of the NCHM at the time of implementation.

Enhancing Service Delivery:

- Establishing and/or strengthening communication channels and developing stronger relationships with stakeholders and users of hydromet information including gathering feedback, for improving both the use and the usefulness of the hydromet services

[22] Rogers and Tsirkunov 2013.

Figure 10. Subsystems within each system



Source: Rogers and Tsirkunov 2013.
Note: G2G = Government to government; NWP = Numerical weather prediction.

- Developing MHEWS including streamlining the mechanisms for issuing and disseminating early warnings among the main responsible agencies
- Developing impact-based forecasting to facilitate users' anticipatory measures and response capability
- Enhancing communication of information on severe weather and hydrological and cryosphere hazards
- Improving access by vulnerable communities to weather, water, and climate information through multiple dissemination and communication channels and socially relevant modes and communication formats
- Enhancing tailored services to critical weather and climate-dependent economic sectors, including, but not limited to,
  - Agricultural services, including an agriculture advisory service with drought monitoring and allied activities to strengthen the ongoing operational Agromet Advisory Services;
  - Hydrological and cryosphere information services for integrated water resources management; and
  - Services to strengthen resilience in sectors such as energy, transport, health, and urban environment.

Institutional Strengthening and Capacity Building:

- Enhancing the technical and management capabilities and skills of staff of the NCHM, including managing and maintaining modern observing networks; utilizing modern forecasting tools
- Establishing an institutional mechanism between the NCHM, partners, and stakeholders for sharing data and information and for joint product development and dissemination.

Improving Observing Network, ICT Infrastructure, and Forecasting:

- Designing new and rehabilitating (as required) existing observation networks
- Establishing/enhancing data management systems
- Strengthening the ICT infrastructure
- Introducing modern forecasting tools and methodologies, including ensemble prediction systems (EPS) and probabilistic forecasting to produce forecasts with increased accuracy, lead time, and spatial resolution based on end user requirements
- Improving hydrological forecasting including flood modelling
- Establishing/enhancing forecast verification methods
- Establishing routine cryosphere observations, warnings, and forecast for selected sectors (for example, hydropower generation)
- Introducing an impact-based forecasting system.

2.2 The Hydrometeorological Value Chain and Maturity Model

The hydrometeorological value chain and maturity model are used to assess the current and future status of the NCHM through the short- and medium-term modernization programs in Chapters 4 and 5. In meteorological terms, a value chain describes the general relationship between different activities in each system and subsystem, from the making of observations through to the application of forecast and warning services by users. The value chain conveys the important concept of the production of value (which only happens when the meteorological and/or hydrological information is used to make or influence decisions) and is a useful way of exploring the organization and performance of an NMHS. **Figure 11**, adopted from Thorpe and Rogers (2021),[23] provides one interpretation of the meteorological value chain. It has five links: observations, models and analytics, forecasts, tailored services, and integrated services. Each link is the product of science and technology infusion, and each contributes to social and economic benefit.[24]

The Power of Partnership[25] introduced two important elements to the meteorological value chain: the sector balance between public, private, and academic actors, and the maturity level of each link (**Figure 12**).

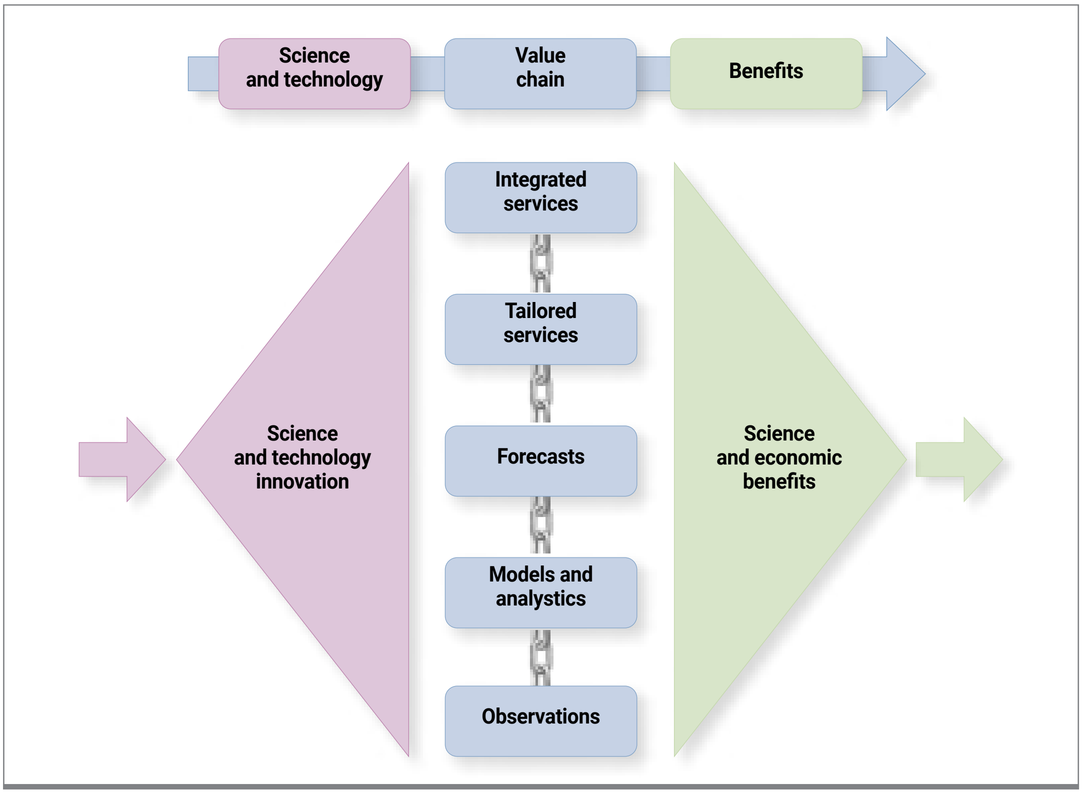
The elements in the Power of Partnership value chain differ from Thorpe and Rogers (2021) primarily in the name rather than substance. Examples of the activities that contribute to each link in the value chain are shown in **Figure 13**.

[23] Thorpe, A., and D. Rogers. 2021. *Creating Value in the Weather Enterprise.* Washington, DC: World Bank.
[24] Rogers, D., V. M. Staudinger, V. Tsirkunov, M. Suwa, and H. Kootval. 2022. *Affordability of National Meteorological and Hydrological Services.* Washington, DC: World Bank.
[25] World Bank. 2019. *The Power of Partnership: Public and Private Engagement in Hydromet Services.* Washington, DC: World Bank.

- ***Observations*** are a foundational element of the value chain. Meteorological, cryosphere, and hydrological observations created as part of an NMHS public task are recognized as high-value datasets and in many countries are provided as open data for anyone to use and reuse.[26] Within the NMHS, these data are integral to the production of higher-value products and services.
- ***Models and analytics*** link includes NWP, whether produced locally or accessed through global and regional production centers, as well as hydrological and hydraulic models well calibrated for the watersheds in which they will be applied.
- ***Forecasts*** link includes the production of basic meteorological and hydrological forecasts and warnings.
- ***Tailored services*** occupy an important link and are nominally made for a single beneficiary or sector—for example, aeronautical meteorological services or hydrological forecasting services.
- ***Integrated services*** link indicates the shift of responsibility for the service to the beneficiary. These services are often coproduced by different entities. *Integrated services* include, for example, impact forecasts and warnings created collectively by disaster management agencies, meteorological services, and hydrological services working together.

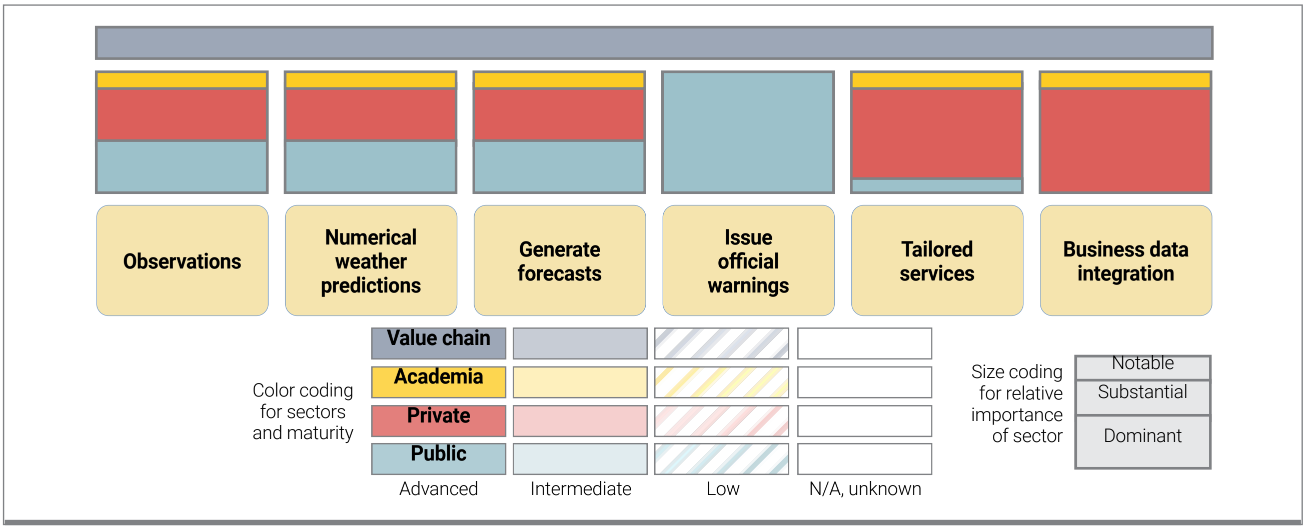
[26] Rogers, David P., and Vladimir V. Tsirkunov. 2021: *Open Data: A Path to Climate Resilience and Economic Development in South Asia?* Washington, DC: World Bank; Rogers, D., V. Tsirkunov, A. Thorpe, A.-M. Bogdanova, M. Suwa, H. Kootval, S. Hodgson, and M. Staudinger. 2021. *The Level Playing Field and the Business of Weather, Water and Climate Services.* Washington, DC: World Bank.

Figure 11. The meteorological value chain, shown in blue, utilizes new knowledge, shown in lilac, to create social and economic benefits shown in green



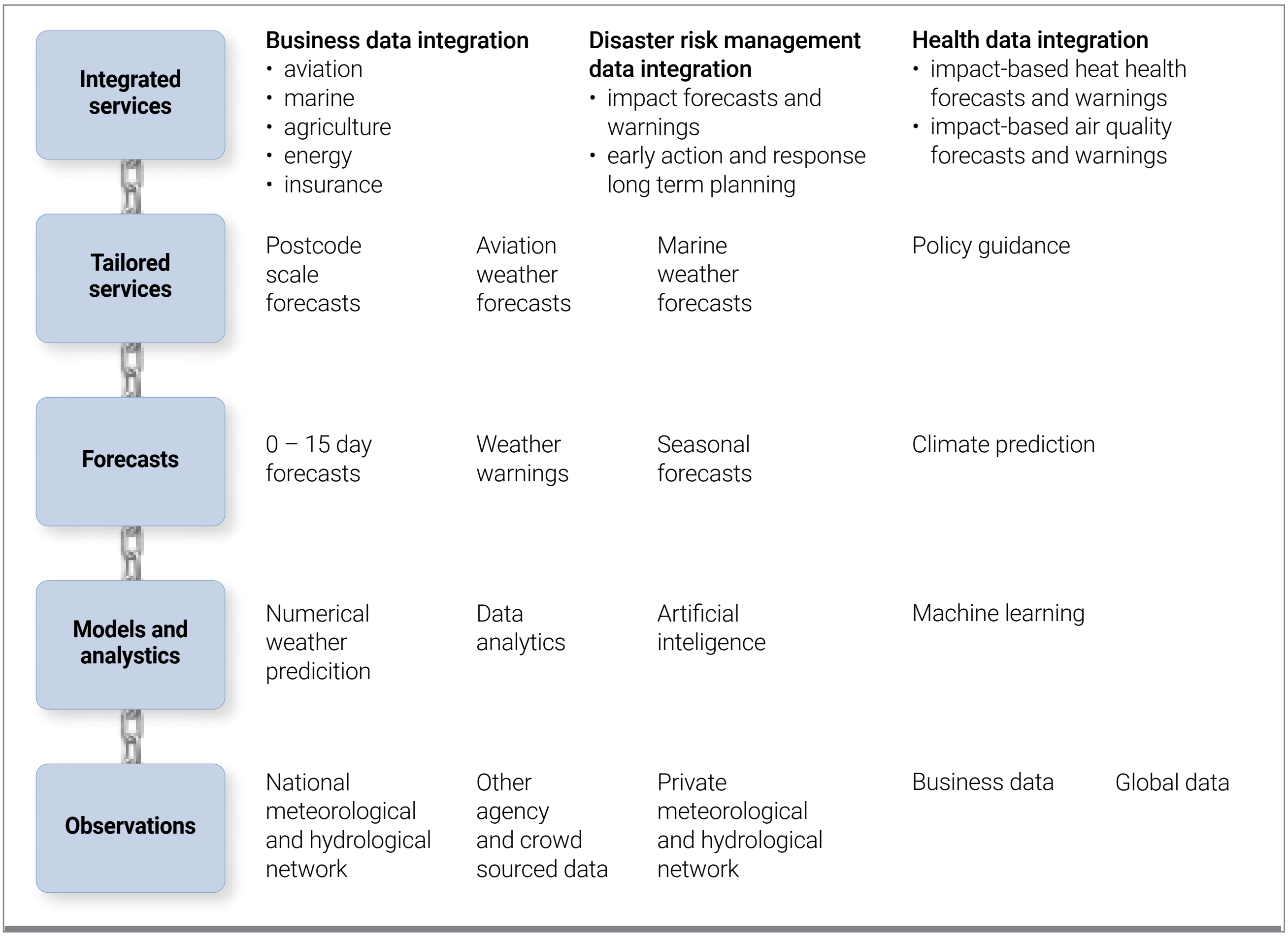
Source: Thorpe and Rogers 2021.

Figure 12. Sector balance and maturity diagram based on hydromet value chain



Source: World Bank 2019.
Note: An advanced value chain is shown in this figure.

Figure 13. Examples of the activities that contribute to each link in the value chain



Source: Thorpe and Rogers 2021.

The notion of maturity, defined in *The Power of Partnership*, is a complementary way of exploring the value chain. By highlighting the level of maturity, it is possible to identify the most significant 'weak links' in the value chain and understand where interventions are likely to be needed and have a positive impact.

3. Current Status of NCHM Services and Infrastructure

Chele La Pass. Photo credit: KiltedArab.

3.1 Observation Systems

The NCHM operates and maintains the national hydromet observation network that includes the following:

- Meteorological station network
- Hydrological station network
- Flood/GLOF EWS
- Flood warning network.

The NCHM maintains metadata records for observation stations.

A careful assessment of not only the current but also the future need for data is required when planning an expansion or reorganization of an observation network, which should consider the requirements of the users and constraints of the operators. The NCHM does carry out a strategic review of the temporal and spatial coverage of observations on a periodic basis to ensure continued optimization of the design of the observing system. Although the observation network follows a plan based on user requirement, the plan is not regularly updated. Regular preventive maintenance procedures for operational observing equipment, to be carried out by trained personnel once the network expansion has been undertaken, will be a major condition for success.

The NCHM has access to global meteorological observational data through the GTS. The subsequent sections describe the status of the national data systems.

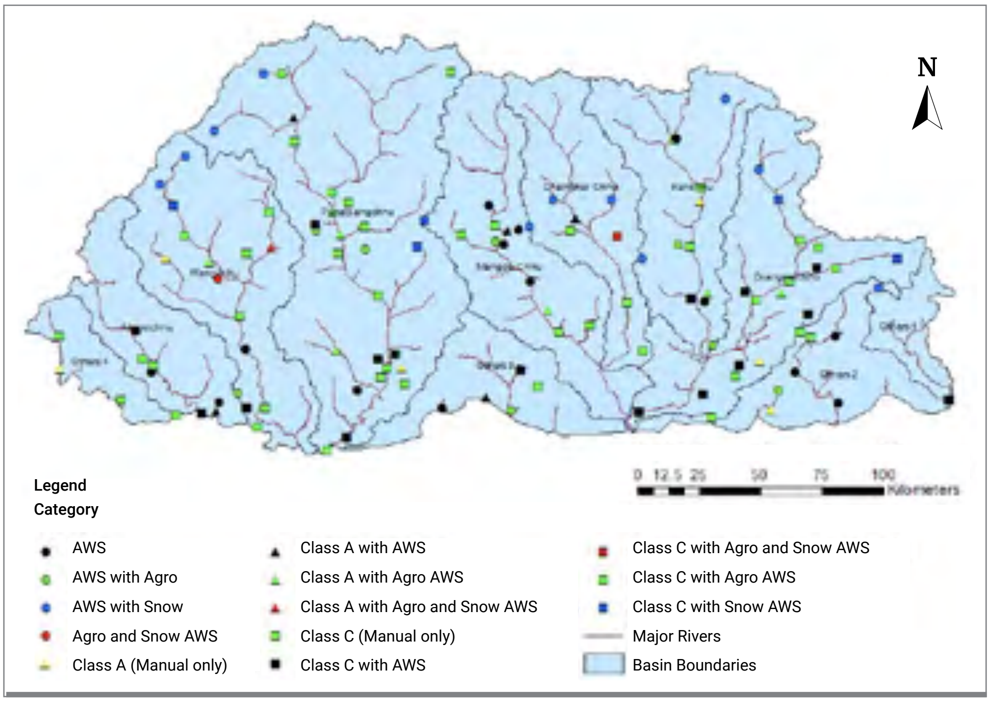
3.1.1 Surface Meteorological Observation Network

The NCHM does not have any meteorological stations that are of synoptic standard and data are not automatically transmitted to the HQ. The meteorological stations network of the NCHM operates a total of **169** stations, comprising **80** automatic weather stations (AWSs), **20** Class A (agromet) stations, **65** Class C (climate) weather stations, and **four** automatic weather observing systems for aviation observations at airports. The weather stations measure temperature, precipitation, relative humidity, wind speed, wind direction (or wind run), solar radiation, and atmospheric pressure. Some of AWSs are co-located with Class A and Class C stations, reducing actual sites of observations to **128** (41 AWSs are co-located with manual sites). The map in **Figure 14** shows all locations with different combinations of manual and automatic stations. Class A stations are manually operated, in which the observers make two readings per day and report them to the HQ daily (by telephone) and monthly (the first week of the following month). Data from these rainfall stations are manually transmitted via postal service once a month and are not necessarily used for hydrological forecasting. The NCHM does not operate a lightning detection network and it does not subscribe to lightning data services from a service provider. There are no global atmospheric watch (GAW) stations operating in Bhutan.

Bhutan's precipitation network faces challenges in adequately representing higher elevations and remote areas. The majority of the stations are located at or below 2,999 meters, and a small percentage of them are at elevations equal to or higher than 3,000 meters. Thus, the higher elevations are under-represented compared with the lower elevations. Gaps in Bhutan's precipitation network are generally in the northern part of the country, which is remote, difficult to access, and at high elevations. This is due to the difficulty in locating, installing, and maintaining stations at high elevations, although they represent a significant area of the country.

> **All 80 AWS installations are prone to frequent interruptions of service mainly due to challenges in communication and network connectivity.** These challenges make identifying alternative communication channels a necessity.

Figure 14. NCHM surface meteorological network



Source: World Bank.

Figure 15. An example of a Class A meteorological station in Punakha

Photo credit: Haleh Kootval.

The NCHM operates four automatic weather observing system (AWOS) stations at airports. These stations measure weather conditions at the airport and are used by commercial pilots to help with decision-making related to flight navigation. The data are shared with the international aviation and meteorological community through an aviation meteorology communication system. AWOS data are used in a similar manner to Class A stations data and are usually included in synoptic analysis and provided to the international community through the GTS.

While the NCHM operates 20 manual agromet stations, there is a need to expand automatic agrometeorological observatories with the capacity to record specialized agromet observations. These stations report data once a day with parameters mostly used for agriculture. For instance, these stations do not report pressure. Among the 20 stations, 8 are co-located with AWSs which measure parameters required for agriculture. However, for improved agromet services, there is a need to expand automatic agrometeorological observatories with the capacity to record specialized agromet observations such as soil moisture and evapotranspiration.

Climate data are collected but not used for near real-time synoptic analysis, nor are they sent to the international meteorological community for

model assimilation. Like Class A stations, Class C stations are manned stations with observations recorded either on a chart or read nominally once every day at the same time (usually in the morning). These stations are considered climate stations, and observations are generally relayed back to the HQ by post. The data are simply collected to document the climate and are available for assessing climate trends. Data collected include minimum and maximum temperatures over the past 24 hours and the daily rainfall, which are entered manually every day. These data are used by various stakeholders for planning. The NCHM undertakes detailed climate analysis, including monthly monitoring and assessing the annual climate conditions.

The NCHM owns and operates an instrument calibration laboratory. The laboratory was recently equipped with temperature and humidity chambers with support from the Japan International Cooperation Agency (JICA).

3.1.2 Surface Hydrological Observation Network

The NCHM is responsible for observing hydrological parameters. It operates multiple networks based on different applications, as described below.

a. **Principal river gauging stations.** There are 18 principal stations, sometimes called primary stations, which are advanced stations equipped with staff gauges, a cableway and winch shed, and an electronic water level recorder and are staffed by full-time gauge and discharge readers who take hourly readings during the monsoon season and two readings a day during the lean season (**Figure 16**). Discharge measurement is taken from the bank—operated cableway using a suspended current meter once a week. Water level data and discharge results, after computation, are sent to the HQ at Thimphu every month for analysis and archival.

Figure 16. Example of a principal hydrological station and current meter in Thimphu

Photo credit: Haleh Kootval.

b. **Secondary river gauging station.** There are **9** of these stations that are intended to be operated only long enough to establish the flow characteristics of their watersheds, relative to those of a watershed gauged by a principal, or primary, hydrologic station. A secondary station consists of a set of staff gauges for water level reading. Discharge measurements are taken by using the traditional float method every day.

c. **Automatic water level stations.** There are 45 automatic stream gauging stations (15 of them colocated at principal river gauging stations) equipped with automatic water level sensors (AWLSs) with telemetry to sense, store, and automatically transmit the data to a central database. The water level sensors are either non-contact (radar sensors) or contact (pressure transducer to sense hydrostatic pressure). The data transmission occurs at 30-minute intervals. In addition, the station is equipped with air temperature, relative humidity sensors, and a precipitation gauge. These stations frequently suffer from transmission issues due to poor mobile network coverage. Although the NCHM carries out maintenance annually, transmission problems continue to persist, which require the NCHM to investigate the real issues and address the root cause. The options of upgrading problematic sites to satellite-based telemetry should be explored.

d. **Automatic river discharge measurement stations.** There are two stream gauging stations equipped with river velocity sensors, recorders, and telemetry systems to transmit the computed discharge data (using the manually keyed cross-sectional area and sensed velocity) to the central database. The data transmission interval is 30 minutes. Apart from these, the NCHM operates one acoustic doppler current profiler (ADCP) for updating rating curves or validation of discharge measurement.

e. GLOF early warning stations. A total of 15 GLOF early warning stations function the same way as AWLSs and send the data to a control room and central database through a satellite (10 through iridium and 5 through Himawari) every 15 mins. These stations are positioned at strategic locations along the river and at the outlet of potentially dangerous lakes for a particular basin to have sufficient lead time to alert the downstream stations and control room of the rising water level. Apart from water level sensors, four stations are also equipped with AWSs. These stations are more than 10 years old and are in normal working condition. However, some stations suffer occasional errors due to freezing of water at the outlet of bubbler pipes, resulting in a sudden spike on readings. The NCHM intends to upgrade these stations by inclusion of seismic sensors and cameras, replacing bubbler with non-contact radars wherever feasible, and shifting from iridium to a different satellite to reduce operating costs. The NCHM also intends to install such systems in other basins.

f. **Suspended sediment sampling stations.** There are 15 stations colocated at principal and secondary stations. Samples are collected once a day by means of a depth integrating sampler using a cableway or handheld samplers. The NCHM operates six labs for analysis of samples.

g. **Spot low flow measurement.** A total of 70 stations are operated during the lean period to measure low flow levels in east-west tributaries, by wading using propeller current meters. The east-west tributaries are a main source for irrigation, drinking water, and development of mini/micro hydropower stations.

h. **Automatic water quality stations.** Four continuous monitoring stations have been installed and operational at Dodeyna and Lungtenphu on Thimchhu and at Gunitsawa and Bondey on Pachhu. These would measure physical water parameters (temperature, turbidity, electrical conductivity, pH value, and so on).

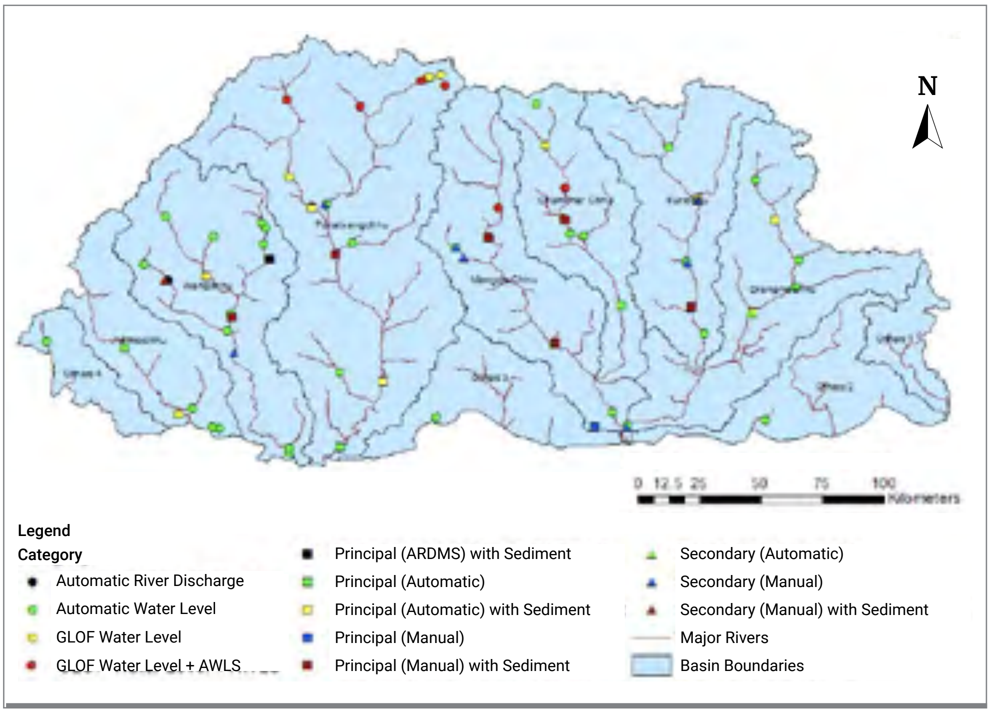
i. **Flood warning stations in collaboration with the GoI.** The GoI and the RGoB collaborate in operating some hydromet stations and sharing data. The GoI provides funds to the RGoB for the operation of **17** hydromet stations within Bhutan that are owned and operated by the NCHM. Data of these stations are shared with the Central Water Commission (CWC) in India for flood forecasting and warning in the part of India that is downstream of Bhutan. The network is a mix of manual and automatic stations using global system for mobile communications (GSM)-based telemetry. Automatic stations often suffer from transmission issues. The network includes

- Eight AWLS sites, out of which only three are in a functional status (Chazam, Wang-due, and Kurizampa;
- Four manual water level gauge sites;
- Three manual rain gauge sites;
- Two automatic rider discharge measurement systems (ARDMS) (one is faulty and one is working but there is a data transmission issue); and
- Two AWSs (both having data transmission issues).

Some of the automatic and GLOF stations are colocated with manual stations, resulting in a smaller number of actual observation sites compared with the total number of stations operated. **Figure 17** shows locations of observation sites belonging to different categories.

There are no groundwater monitoring stations operated by the NCHM, and no ambient water quality is monitored. When the mandate for measuring ambient water quality was transferred to the NCHM in 2022, the center received four kits for water quality testing. However, the NCHM has not yet started water quality testing due to lack of capacity. The ambient water quality monitoring needs to be started after adequate training has been provided to the staff. Handheld automatic water quality instruments may be deployed for in situ measurement of water quality, and the NCHM may start with one automatic sensor for each basin as a pilot and expand the network once enough capacity is built.

Figure 17. Hydrological stations operated by the NCHM



Source: World Bank.

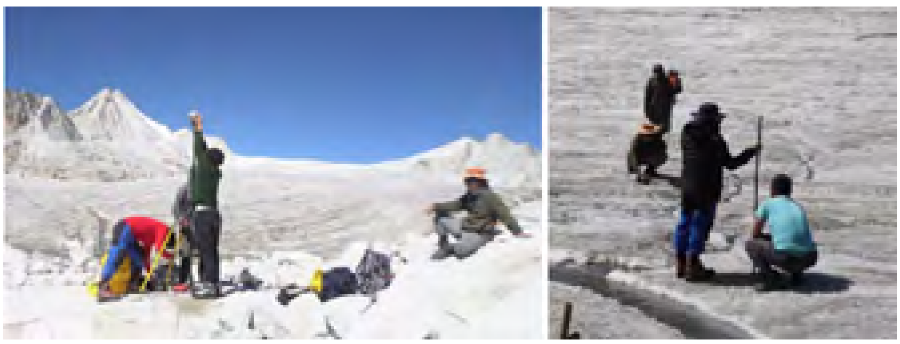
Based on a qualitative analysis, flood warning stations are located mainly along major rivers, and the network is sparse in smaller rivers. Several tributaries have no monitoring, especially at the international border with Tibet in northeastern Bhutan. The NCHM needs to expand the network in ungauged catchments or supplement the monitoring system with modelling for small streams. In addition, rating curves need to be updated at least once every five years and the NCHM may consider deploying two more ADCPs for discharge measurement. The NCHM may also consider deploying automatic sediment monitoring sites upstream of major hydropower stations, which can provide valuable information for operation of turbines and reduce maintenance costs. The GLOF network should be expanded to cover the remaining basins.

3.1.3 Surface Cryosphere Observation Network

Since 2016, the NCHM is responsible for monitoring glaciers and glacial lakes. The Department of Geology and Mines was responsible for monitoring glaciers and glacial lakes in northern Bhutan; this responsibility was transferred to the NCHM in 2016. In 1996, it prepared an inventory of glaciers and glacial lakes in major river basins using maps produced by the Survey of India based on air photographs of 1956 and 1958 and satellite images. At the regional level, the International Centre for Integrated Mountain Development (ICIMOD) has been monitoring decadal shifts in glaciers in the Bhutan Himalayas based on satellite data. Since there is not much long-term data and information on Bhutan glacial regime, the NCHM established two long-term benchmark glaciers in Bhutan for annual monitoring. These are the Gangju La glacier in the headwater of Pho Chu Sub-basin and Thana glacier in the headwater of Chamkhar Chu Sub-basin. In 2021, CSD identified a new benchmark glacier in the headwaters of Thimchu. **Figures 18** and **19** show field work respectively on Gangju La Glacier in the northern border of Bhutan and Thana Glacier in the northcentral part of the Bhutan Himalayas.

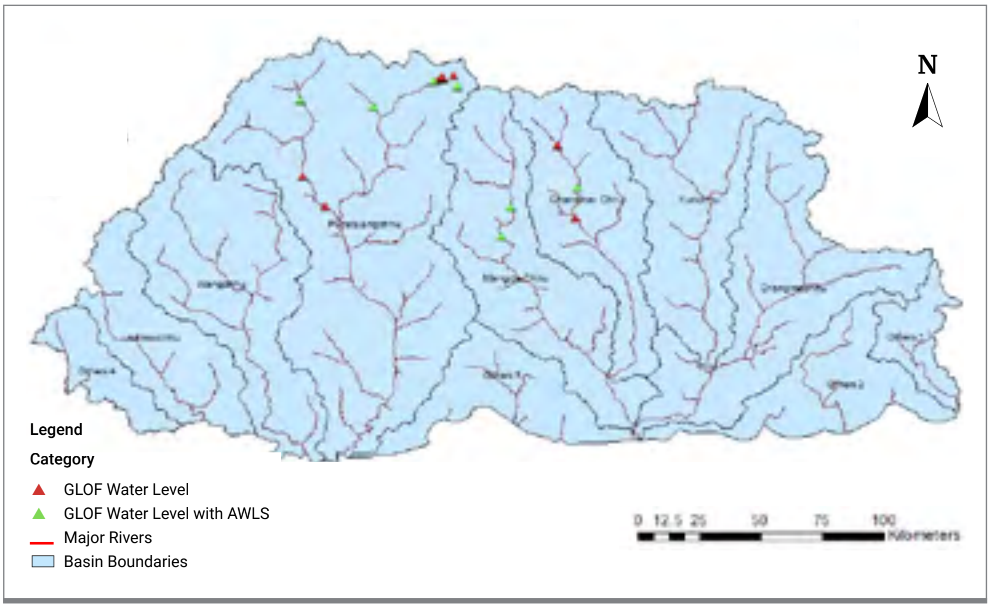
Figure 18. Cryosphere field work by CSD on Gangju La Glacier (2020)

Figure 19. Cryosphere field work at Thana glacier (2020)



There is limited capacity and instrumentation support for cryosphere monitoring. There is no separate network for real time monitoring of the cryosphere. There is no monitoring for snow water equivalent in Bhutan, and it is recommended NCHM to consider installing snow pillows for representative basins, to aid in snowmelt modelling. Cryosphere observations include a GLOF EWS for three basins (**Figure 20**). **Table 2** presents a summary of surface monitoring stations operated by NCHM.

Figure 20. Glacier and GLOF monitoring and early warning systems operated by the NCHM



Source: World Bank.

Table 2. Summary of surface monitoring stations operated by the NCHM

Observation system	NCHM
Surface meteorology stations (Class A)	20
Surface meteorology stations (Class C)	65
AWSs	80
Automatic weather observing systems	4
Principal hydrological stations	18
Secondary hydrological stations	9
Automatic water level stations (AWLSs)	45
Sediment sampling stations	15
Flood warning stations in collaboration with the GoI	17
Automatic GLOF water level stations	15
Automatic GLOF weather stations	5
Fire weather stations	0
Groundwater stations	0
Water quality stations (suspended sediment only)	15
Glacial monitoring stations	5
Snowpack monitoring stations	0
Cryosphere stations	9
Avalanche warning stations	0

Source: NCHM.

3.1.4 Upper Air System

The NCHM does not operate any upper air (radiosonde) stations. An application has been made under the WMO SOFF initiative for funding for an upper-air station. However, the available SOFF funds are not sufficient to cover all of the current applications, and the priorities are so support LDCs and SIDS, so the application from Bhutan for SOFF support may not be successful.

3.1.5 Weather Radar System

The NCHM does not operate any weather radars.

3.1.6 Remote Sensing System

The Cryosphere Services Division uses remote sensing for mapping the extent of glaciers and glacial lakes, mass balance studies, and snow covers. Presently, some of the products that NCHM use are Sentinel satellite imageries, Landsat and Moderate Resolution Imaging Spectroradiometer products. No images from polar-orbiting meteorological satellites are received by the NCHM.

Weather satellite data has the potential to provide information on subjects like precipitation patterns, while other satellites can track changes in river morphologies. However given the available resolution of precipitation data from weather satellites (about 10km by 10km) and the extreme nature of the terrain in Bhutan (narrow, steep valleys; significant local effects contributing to rainfall accumulations), it would be unlikely that satellite data will add much information and understanding in this area. In any case the satellite date would need to be bias corrected using in-situ measurements, so it can only ever be a supplementary source of information. Similarly, the use of satellite data to detect changes in river morphologies is more suited to alluvial plains, but is not so useful in the case of hilly rivers in gorges and boulders in rivers as is the case in Bhutan.

3.1.7 Data Management and Archiving Systems: Data Collection System, Quality Control/ Assurance System, Storage, and Archiving

3.1.7.1 Data Collection System

The NCHM uses HYDATA for quality control of at least hydrological data. The field observer sends the data from the manual stations twice a day (9 a.m. and 3 p.m. Bhutan Standard Time) all seasons except during monsoon. During the monsoon, the observer sends hourly data to headquarters. The observations collected manually from meteorological stations are first entered into a HYDATA database in the HQ at Thimphu and are then entered into Excel spreadsheets for a quality check. The data are later archived in Excel format and in hard copy. HYDATA is an outdated database system and recently a new central database management system known as Central Database Management System (CDMS) has been introduced which is supposed to store all meteorological and hydrological data. Migration from HYDATA to this new system is in progress.

Agromet data are collected and transmitted to the NCHM HQ by telephone. For agromet stations (Class A), data recording is done by NCHM staff in all 20 districts. Field staff transfer data to the HQ daily at 3 p.m. Bhutan Standard Time (9 a.m. UTC) by telephone (maximum and minimum temperature, rainfall, cloud coverage, and relative humidity). The staff record more details, such as wind speed and sunshine hour, but they only communicate to the HQ what is required for the weather forecasts. In addition, data on rainfall, storms, and lightning are conveyed by telephone when a severe weather event occurs. The entire observation sheet is sent to the headquarters at the end of every one or two months, and a field book is maintained at the site. At the headquarters in Thimphu, data are first entered in a register and then used as a guidance to prepare the next day's forecast. These observations are not put into the forecast model. Forecasters refer to the WRF model outputs as well as other products from regional and international centers as guidance to prepare their forecasts. No data from AWS are used for forecast preparation. NCHM needs to work on integrating its own data in its forecast procedures.

In general, real-time data from the AWS is not available in the forecast office and thus no real-time data are used for forecast preparation. The entire observation sheet is sent to the HQ at the end of every one or two months, and a field book is maintained at the site. At the HQ in Thimphu, data are first entered in a register and then used as a guidance to prepare the next day's forecast. These observations are not put into the forecast model. Forecasters refer to the weather research and forecasting (WRF) model outputs as well as other products from regional and international centers as guidance to prepare their forecasts. The NCHM needs to work on integrating its own data in its forecast procedures. In addition, data on rainfall, storms, and lightning are conveyed by telephone when a severe weather event occurs.

For Class C stations, the observers maintain a field book and send the observation sheets to Thimphu every three months which are subsequently stored in an Excel database. The observers are part-time recruits. These data are for the record and can be used for climate data analysis and for monsoon outlooks, cold waves, heat waves, and cyclones. For these manual stations, data loggers and other spare parts are stored in the HQ, where the only quality checks for collected data are carried out. Limited data processing or analysis is done using the data from these manual stations. Observers stationed at the sites conduct minor maintenance. A team of technicians from the field offices and officials from the HQ conduct the annual maintenance. When there are major technical issues, the same teams attend as needed.

For flood warning stations, the hourly water level information is passed on to the principal control centers and subsequently to the HQ via high-frequency radio. This information is then passed on to partners in India (West Bengal and Assam). For automatic stations, data come directly to the server in the HQ through general packet radio service (GPRS) and Global System for Mobile (GSM) communications standards used by short message service (SMS).

For real-time monitoring, multiple systems are in operation (flood warning stations, AWLSs, GLOFs, AWSs, and so on), and all use different servers, different systems, and protocols. NCHM should consider consolidating all real-time systems into one server that feeds into the central data management system. Apart from that, for manual stations, recording data on the register and sending them at the end of the month for digitization results in a time lag between the time of monitoring and data availability. This can be reduced by introducing mobile apps available to the gauge reader personnel, who can enter the data at the time of monitoring and make them available on the server in near real time, making it available for modelling and forecasting applications. This can also reduce efforts devoted to digitization and provide software-based quality control.

3.1.7.2 Quality Control and Data Storage System

While hydromet data have been collected for decades, at present, there is no comprehensive data quality assurance system. Hydromet data have been available since about 1997, and nearly all collected data have been digitized. Some of the climate observations go as far back as 1985. Discontinuous rainfall data dating back to the 1950s are available from a few locations. No quality control was performed on data collected before 2010. A few basic tools for quality checks are used for data collected since 2010. The data quality is controlled manually by the data manager upon reception and archival of the data. For hydrological data, the real-time data from AWLSs are stored in the CDMS. The data from AWLS are shared once the responsible officer checks the quality. Historical data are stored in both digital and paper forms. The data from the manual hydrology stations are stored and quality checked using HYDATA. Plotting of observational data is done manually.

Environmental Management. For managing the pristine environments on Bhutan, access to high-quality data is essential in monitoring climate change and its impacts. A single data repository for weather and other environmental data is ideally needed. Standardization of data formats into more user-friendly formats will also be essential, as is the open sharing of climate data. Publishing and redistributing NCHM data on other websites and in other apps (for example, using the iFrame concept or similar) would also help enormously in extracting the full value to society of this essential data.

3.1.8 O&M of the Existing Observation Network

The NCHM does not have a sufficient number of qualified maintenance technicians to cover the entire observation networks. While the NCHM has a program of regular maintenance and calibration of the observation instruments, there is a need for detailed and proper guidelines for carrying out maintenance and for its scheduling. The Maintenance Plan is not regularly updated and the NCHM does not implement reliability measures based on quality assurance/quality control routines and procedures for observations of weather, climate, and hydrology. The annual maintenance work related to the observing network includes, among others, troubleshooting, replacement of sensors/equipment, calibration of sensors, installation and upgrading of selected hydromet stations, and so on. The NCHM endeavors to keep all operational measuring equipment and sensors in working conditions compliant with international standards. The NCHM does not use the services of a WMO regional instrument center (RIC) or a national standards laboratory/institution due to lack of capacity. **Table 3** shows the number and type of stations where annual maintenance work was carried out during 2019–2022. The maintenance team could not cover the stations located along the southern border due to COVID-19 restrictions and minor maintenance were carried out by the respective field observers. At present, the NCHM has a budget of BTN 10 million (approximately US$125,000) for the O&M of the observation network.

3.2 Modelling, Analytics, and Forecasts

3.2.1 Meteorological Models

3.2.1.1 Global and Regional NWP Systems

The NCHM uses NWP products from global models made available through the WMO Severe Weather Forecasting Programme for South Asia. These include the European Centre for Medium-Range Weather Forecasts (ECMWF), National Oceanic and Atmospheric Administration (NOAA)/ National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), Japan Meteorological Agency (JMA) Global Spectrum Model via GTS, and India's National Center for Medium-Range Weather Forecasting (NCMRWF).In general, the NCHM accesses NWP products that are rather limited be-

Table 3. Annual maintenance work for the hydromet observing network in 2019–2021

S. No.	Station category	Station type	2019–2020 maintenance	2020–2021 maintenance	2021–2022 maintenance
1	GLOF EWS	Automatic	15	15	15
2	Hydrological stations	Manual	19	20	15
3	Hydrological stations	Automatic	42	36	25
4	Meteorological stations	Manual	20	20	20
5	Meteorological stations	Automatic	82	15	15

Source: Annual Report 2021 and NCHM.

cause these models give a global outlook which provides some guidance for preparing forecasts but is not specific to local scenarios. Furthermore, except for products from NCMRWF from which both data and images are received, only images are available from websites of the other agencies which cannot be used for analysis.

3.2.1.2 Limited Area Models

While the NCHM carries out objective verification of the model outputs as well as the public forecasts, no data assimilation or post-processing is performed. The NCHM runs Environmental Modelling System Weather Research and Forecasting (EMSWRF) version 3.4 for daily weather forecasting with a lead time of three days (72 hours). The EMSWRF has been installed and operational since November 2015 with support from the Finnish Meteorological Institute (FMI) under the project of Strengthening Hydromet Services for Bhutan. The EMSWRF is a local area model which runs every six hours for initial conditions of 00, 06, 12, and 18 UTC with a nested domain of 45 vertical levels, with the parent domain and nested domain having horizontal resolution of 15 km and 3 km, respectively (**Figure 21**). The boundary and initial conditions used for the model are from the GFS model, NCEP, NOAA, which is a coupled model (atmosphere, ocean, land/soil, and sea ice) with 64 vertical levels and has a horizontal resolution of 28 km. The WRF data period used for the analysis is from January 2016 to December 2018, with a 12 UTC run.

Figure 21. Nesting domain configuration: 15 km and 3 km domains

3.2.2 Hydrological Models

The NCHM mostly uses the hydrologic engineering center (HEC)-based models to calculate runoff for producing hydrological forecasts. As it is not mandated to carry out any flood mitigation work to prevent flooding, the NCHM does not use hydraulic models for replicating flow, water transport, and distribution processes. The systems available include the following:

a. **Flood decision support system (FDSS).** A FDSS was developed in collaboration with the Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) and the World Bank. The system uses a three-day meteorological forecast generated by RIMES and transforms it into runoff for different sub-basins using the HEC Hydrologic Modelling System (HMS) Model. This runoff is then routed through rivers using lumped routing parameters. The deterministic forecast is available for the next three days for 10 selected locations. The results are also available through a webpage, maintained by the NCHM.

   The automation for downloading forecasts, running the model, and updating the website is carried through the FDSS, which is a custom-built interface and uses scripting for automation of processes. A new system called WIMES is now being introduced as FDSS considering that NCHM is now trained in this system.

   The NCHM has some capacity in running the models but limited capacity to use the DSS interface. The DSS is a basic system that does not use any hydraulic modelling and currently does not incorporate any real-time data for data assimilation. Since the NCHM has ongoing support from RIMES, it should continue to build capacity in DSS and upgrade the system to incorporate real-time monitoring, improved interfaces, scenario analysis and management, dissemination systems through email and SMS, stochastic/ensemble modelling, and expansion to other basins. The major advantage of this system is that it is based on freely available models, providing better sustainability over proprietary software, which requires continuous expenditure for licenses and support from the developer for upgrading the system. There is a need to consider upgrading the DSS platform to freely available off-the-shelf DSS platforms like the HEC RTS, which are updated regularly and provide access to global online resources, such as user forums for troubleshooting and capacity building.

b. **Flood hazard mapping.** The NCHM uses the HEC HMS and HEC River Analysis System (RAS)-based systems to develop flood maps for various return periods based on historical data, which are further used for planning and hazard mapping. The center has enough capacity to use these models.

c. **Although a streamflow prediction tool was developed in collaboration with ICIMOD, this system is not yet calibrated and validated using historical data and can only be used for outlooks and not for quantitative forecasts.** It is a snapshot of a global system, where it uses a 10-day ensemble forecast generated by ECMWF and provides discharge information at any point on the streams. Apart from that, it provides color coding for streams based on the return period of stream flow. There is a need to update the system by validating it using observed data and improving the interface to generate flow for different return periods. Stakeholders like hydropower and road bridge designers often depend on historical flow in small streams for designing various structures. Since long-term data for small streams are often not available, this system, once calibrated against discharge monitoring sites on major rivers, would be a useful tool for such stakeholders.

3.2.3 Meteorological Forecasting and Warning Systems

The NCHM operates a 24/7 forecasting system. It prepares forecasts by making use of observational and model data, including those NWP data available on the GTS/WIS as described below, and the NCHM's own model output available in the SmartMET workstation installed in 2017 with the support of the FMI, under the National Adaptation Programme of Action project funded by the United Nations Development Programme (UNDP). No impact-based forecasts or nowcasts are produced. The forecast schedule is shown in **Table 4**. Examples of weather forecast, summary issued at 4 p.m. daily, and the weekly weather report,

Table 4. Schedule of forecast produced by the Weather Forecasting Section, NCHM

Time	Forecast type and dissemination channel
04:00 hours	24-hour weather update (Email, Website and Facebook) 3-day weather forecast to World Weather Information Service (WWIS) (email)
06:00 hours	1-hour weather forecast for aviation (email)
10:00 hours	3-day weather analysis and report (email, website, and Facebook)
12:00 hours	3-day weather forecast to WWIS (email) 1-hour weather forecast for aviation (email)
16:00 hours	24-hour weather forecast and summary (TV, radio, email, website, Facebook, WhatsApp)
18:00 hours	1-hour weather forecast for aviation (email)
20:00 hours	3-day weather forecast to WWIS (email)
22:00 hours	24-hour weather update (email, website, and Facebook)
Weekly Weather Report	Every Friday

and verification of previous week's temperature and rainfall forecast are shown in **Figures 22, 23, 24,** and **25** respectively. To produce the daily forecasts, the NCHM forecasters use information from a number of sources including India (IMD, Indian Monsoon data Regional output, NCMRWF), SWFP, Japan Meteorological Agency, Korea Meteorological Administration, meteograms from sites neighboring Bhutan, MetGIS (an Australian commercial company), Windy charts produced using ECMWF data, and information from the Thai Meteorological Department. To produce

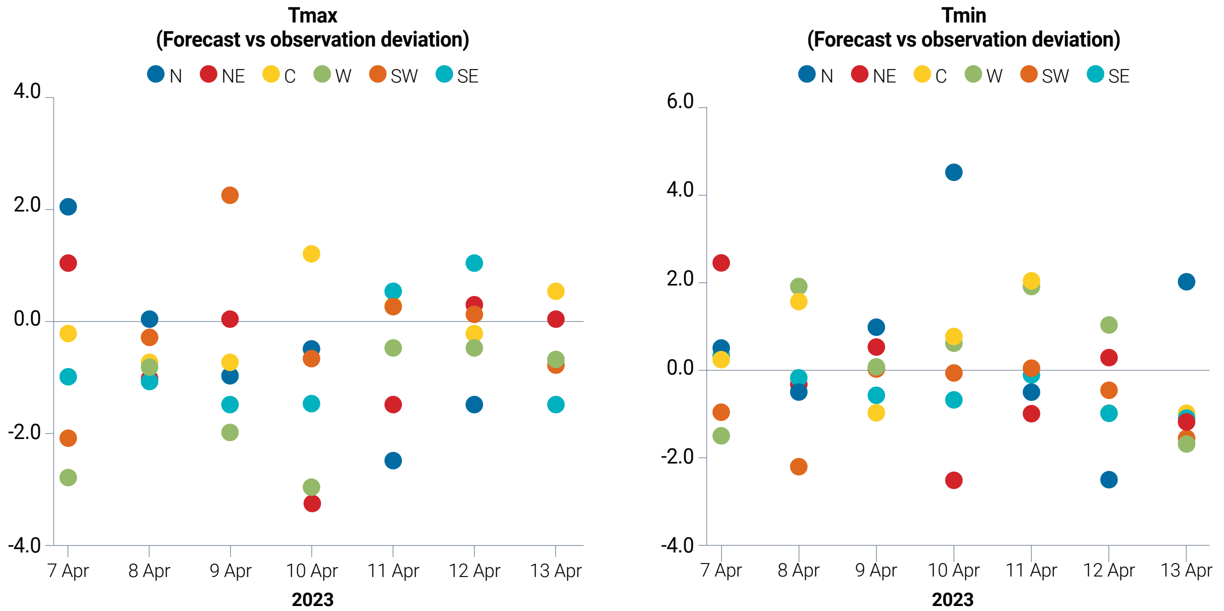
Figure 22. Weather forecast issued at 4 p.m., valid for 24 hours

Northern	North-Eastern		Central	
Gasa	Lhuntse	Yangtse	Trongsa	Bumthang
Partly cloudy with light rain Tmax/min: 19/07	Partly cloudy with light rain Tmax/min: 29/16	Partly cloudy with light rain Tmax/min: 24/09	Partly cloudy with light rain Tmax/min: 23/09	Partly cloudy with light rain Tmax/min: 20/06
Western				
Haa	Paro	Thimphu	Punakha	Wangdue Phodrang
Partly cloudy with light rain and wind gust Tmax/min: 18/06	Partly cloudy with light rain and wind gust Tmax/min: 23/08	Partly cloudy with light rain and wind gust Tmax/min: 23/09	Partly cloudy with light rain Tmax/min: 32/18	Partly cloudy with light rain and wind gust Tmax/min: 30/0176

Figure 23. Weakly weather report

Region	Weather outlook issued	Weather observed
Northern	Partly cloudy to partly cloudy with light rain	Partly cloudy to partly cloudy with light rain
North-Eastern	Partly cloudy to partly cloudy with light rain	Partly cloudy to partly cloudy with light rain
Central	Partly cloudy to partly cloudy with light rain	Partly cloudy to partly cloudy with light rain
Western	Partly cloud	Partly cloudy
South-Western	Partly cloudy to partly cloudy with light rain	Partly cloudy to partly cloudy with light rain
South-Eastern	Partly cloudy to partly cloudy with light rain	Partly cloudy to partly cloudy with light rain

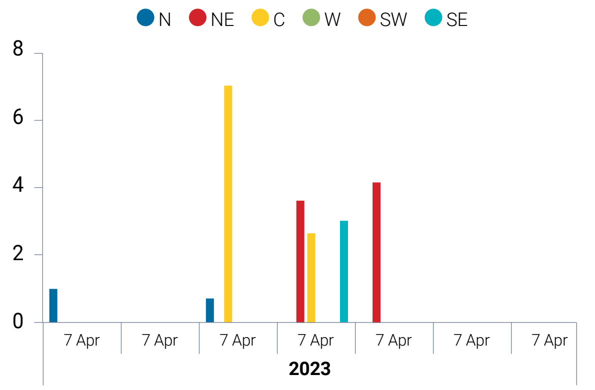
Figure 24. Verification of previous week's temperature forecast



- *Highest forecast temperature was 32.0 °C* for South-Western Phuntsholing on 12th and 13th April, however, the highest temperature observed was 34.0 °C on 11th April in Phuntsholing.
- The highest deviation in maximum temperature was -3.3 (under forecast) in the North-East on 10th April. The best forecasts with 0.0 deviation was in the North (8th and 13th April), and the North-East (9th and 13th April)
- *Lowest forecast temperature was 1.0 °C* for Western Haa on 13th April, but the *lowest temperature observed was -0.5 °C* in Haa on 11th April.
- The highest deviation in minimum temperature was 4.5 (over forecast) on 10th April in the Northern region. The best forecasts (deviation 0.0) was on 9th and 11th April in the South-West.

Figure 25. Verification of previous week's rainfall forecast

- Light rain was forecast for all the regions except for the West.
  24 hr. accumulated rainfall (2023)



- Light rain was forecasted for all the regions except for the Western and South-Western regions.
- Highest rainfall of 15 mm was observed in Zhemgang on 10th April.

three-day temperature forecasts for 20 stations, observation data are combined with WRF and GSM (Japan) model data. To produce rainfall forecasts, model data from Windy charts and the WRF model are used. In addition, Meteoblue (a private company) produces rainfall predictions for 20 cities in Bhutan. The Standard Operating Procedures (SOPs) on Weather Forecasting and Dissemination of Forecast Products and Services guide and determine the daily forecast production operations at the Weather Forecasting Centre of the NCHM.

Extended range prediction (ERP) for Bhutan is prepared with support from IMD. The system uses the CFSv2 coupled model (atmospheric and ocean model) which runs once per week (Wednesday), with 16 ensemble members at a horizontal resolution of around 25 km, and the products are made available the following day (Thursday). The ERP products for Bhutan are generated every Friday. The ERP is produced for two climate variables in Bhutan: rainfall and temperature.

The NCHM has no operational system for seasonal or long-range forecasting. An annual monsoon outlook is prepared using inputs from global producing centers (GPCs). The climate predictability tool (CPT) for downscaling of global seasonal products is used and is discussed in the South Asian Climate Outlook Forum (SASCOF). The final product is a consensus forecast from the SASCOF. The NCHM needs to develop an operational system for seasonal forecasting, for agriculture and for other stakeholders.

Agriculture. Farmers need week-long forecasts (and especially warnings of extreme weather) to help them to gather in crops and keep them safe (for paddy cultivation the rice is often left in the fields to dry, and if untimely rain arrives the crop can be totally lost). Month-long forecasts can help farmers to make choices relating to quick-growing crops. The needs of agriculture suggest that a suitable approach might be to carry out a pilot project, supported by agricultural extension workers, based around bringing more extended forecast information to farmers. Lightning detection is also an important requirement.

As part of its longer-term modernization plans, it is necessary for the NCHM to establish a comprehensive process for operational weather forecasting as is practiced in other well-functioning modern national forecast centers of similar size and complexity. This will include access to the NWP/EPS digital data and products from a range of global centers; the required hardware and software (license) for data handling, NWP post-processing and calibration (model output adjustment to country conditions), assimilation of observational data from the national network, and production of site-specific and impact-based forecasts. Access to uninterrupted broadband internet is essential for moving from deterministic to ensemble prediction systems, which is critical for probabilistic forecasting and estimating the uncertainty in the weather forecasts as well as the likelihood of an extreme event. Necessary tools for the modernization of forecasting process include a forecaster workstation, implementation of real-time data management, forecast process monitoring and verification, NWP post-processing, observation data assimilation, nowcasting, and impact-based forecasting techniques. Training is required both in the use of the tools and interpretation of new products as well as in the overall forecasting process to be supported through SOPs.

The NCHM participates in the WMO SWFP and, as a member of the SASCOF, has access to extensive research and guidance on climate forecasts in the monthly to seasonal range, and already disseminates these to many users. There is also an increasing amount of such guidance freely available from global NWP centers such as the ECMWF. This area of service requirement is likely to grow significantly in the coming years as the skill of the model guidance at these time ranges increases, potentially providing more valuable guidance to many key users. Starting in the summer 2023, for example, ECMWF will provide extended range forecast guidance up to 46 days ahead from an ensemble of 101 members, updated daily with global coverage at a resolution of approximately 36 km.

3.2.4 Hydrological Forecasting and Warning Systems

The NCHM does not provide forecast-based riverine flood warning. The Hydrological Forecasting and Warning Section (HFWS) under

HWRSD produces flood forecasts by viewing the regional systems like the Flash Flood Guidance System (FFGS) and ICIMOD's Stream Flow Forecasting System and issues advisories when high levels in rivers are observed. However, it does not issue forecast-based riverine flood warnings. Water levels, which are observed at varying frequencies across seasons, are relayed to the HQ. The information is placed on a whiteboard and shared throughout the division. The division issues flood advisories based on a routing scheme using water level and discharge data from higher elevation hydrological stations to warn downstream communities of high water.

Figure 26. Thimphu, the capital of Bhutan, is located in a flood-prone valley

The FWS under HWRSD collects and shares data with India for use in monitoring downstream floods. While information from these stations is shared with the HQ in Thimphu, it is not used to provide flood warning within Bhutan in a systematic way.

While flood warnings are currently issued by the NCHM on a detect-and-warn basis, routine forecasts of river levels are not disseminated. Bhutan has a significant hydroelectrical sector; forecasts of water levels in rivers are also of significant interest to other sectors such as agriculture, construction, road engineering, and tourism as well as for day-to-day water resource management. The NCHM cooperates with other relevant regional and global institutions and NMHSs such as RIMES, ICIMOD, and IMD as well as the WMO at the international level to improve its hydrological warnings capability. Although the NCHM contributes to improving the adaptation capacity of water resources systems in a changing climate through some research in hydrology and surface water availability, it does not predict hydrological droughts. Some verification of flood forecasts is performed, but it is not done regularly or systematically.

Flood Control. The issues concerning flood control are much the same concerns as those noted earlier for hydropower. The need is for better statistics for extreme rainfall events, which would incorporate likely climate change impacts on the weather (especially the rainfall) regimes. Inflow forecasts for flood management are needed. A Decision Support System (DSS) for Flooding is required. There are also challenges in regard to water resource management—as much good information as possible is needed.

3.2.5 GLOF Monitoring, Modelling, Forecasting, and Warnings

The NCHM carries out a program of monitoring the snow and glaciers in the territory of Bhutan including glacier mass balance calculation for three benchmark glaciers every year (Thanza glacier in the central-north, Gangjula glacier in the western-north, and Shodug Glacier) and bathymetry surveys of glacial lakes in the Gangkar Puensum region and Lunana region every two years or whenever it is needed.

The NCHM's GLOF EWS is based on flood detection as a result of an outburst. The NCHM carries out a GLOF monitoring program and produces GLOF early warnings along the Punatsangchu and Chamkhar-Mangde basins. There is an SOP for GLOFs in the Punakha-Wangdue valley and HWRSD also monitors, through the flood warning system, a few glacial lakes (Luggye, Thorthormi, Rapstreng, and Baytsho), where the water level is measured with an automatic system as a part of GLOF EWS in the Punakha-Wangdue Valley. The system does not use any models for quantification but relies mostly on measured water levels using automatic instruments and telemetry. The information is received on servers and monitored at flood warning centers/control rooms. If water levels exceed critical limits, the information is transmitted through high-frequency radio and the public is warned through sirens installed at strategic locations near populated areas.

To strengthen the GLOF EWS, it is necessary to continue improving the GIS catalogue and regular surveys of the lakes with outburst potential, by using many sources of information—including high-resolution satellite data and field surveys. Subsequently, an analysis of the occurrence and intra-annual distribution of mudflows and major rock and icefalls should be carried out to determine the location and period of occurrence of such events and their impacts.

3.2.6 Avalanche Risk and Warnings

At present, there is no avalanche warning system at the NCHM. Avalanches pose a serious threat to infrastructure and human lives. Their occurrence is a result of meteorological conditions including precipitation, temperature, building of snow cover over time, and thawing processes as well as terrain and exposure. All these determine the risk for avalanches to occur. An avalanche warning system would determine the degree of risk of avalanches to occur based on models containing essential meteorological variables, the status of snow cover conditions, and possible triggers for an avalanche. Based on infrastructure and human lives at risk, zones for avalanche warning systems need to be established and different levels of risk for avalanches to occur (low risk, intermediate risk, high risk) need to be defined depending on the status of the snowpack and ambient meteorological conditions.

Tourism. Since the beginning of tourism in 1974, Bhutan has targeted high value tourists to minimize the impacts on the environment. There is a need for more extended range / monthly / seasonal forecasts for tourism planning and also warnings of potentially dangerous events for trekking etc. A two-week forecast for making go/no go decisions on treks would be a very helpful development. Better education for those leading and participating in treks to encourage them to pay closer attention to the weather forecasts would also be very useful.

3.2.7 Flash Floods Forecasts

While the NCHM participates in the FFGS, it does not routinely monitor conditions for triggering landslides and mudflows. Flash floods are fast-developing adverse hydrometeorological phenomena, with significant potential danger to the population and economy of Bhutan. The NCHM participates in the FFGS and issues general flash flood warnings by analyzing the global and regional systems and adapting these to national conditions based on actual weather conditions and forecasts. However, the center does not routinely monitor conditions for triggering landslides and mudflows to issue warnings for these phenomena although the FFGS has a well-tested landslide module.

3.3 Services Delivery

3.3.1 Public Weather Services

The Meteorological Services Division (MSD) is responsible for providing PWS, severe weather warnings, meteorological data services, aviation meteorology services, agrometeorology services, and climate change information. The National

Weather and Flood Warning Center (NWFWC), Thimphu, operates on a 24/7 basis and monitors the weather conditions of all the 20 dzongkhags. The daily short-range forecast for the 20 dzongkhags includes a precipitation outlook with maximum and minimum temperature. The NCHM issues three-day weather forecasts once a day via the national television, print media, social media, and the NCHM website (https://www.nchm.gov.bt) and provides three updates via email to the climate-sensitive stakeholders, along with 24-hour city forecasts for a selected location in each district. In addition to these channels, email, SMS, and toll-free telephone are also used to disseminate forecasts upon request. Mobile phones are used to respond to public requests for information, although a mobile application does not exist.

At present, the NCHM does not have the capacity to provide a formal and structured weather warning service. Based on severity of weather, the center issues weather advisories and weather updates as needed. During extreme weather events, information is provided to the media through face-to-face discussions or reports sent by email. However the ambition should be to develop a full Multi-hazard Early Warning System, which would satisfy the Early Warning for All (EW4ALL) initiative called for by the Secretary-General of the United Nations in March 2022.

The NCHM staff also appear on Bhutan Broadcasting Service (BBS) to provide briefings during extreme weather events. The NCHM is setting up its own TV studio through the support of a project by JICA for making video clips to enhance dissemination and reach of EWS. Establishment of a structured weather and flood warning system in Bhutan is a priority.

The NCHM's weather forecasts are deterministic, and currently it does not have the capability to produce probabilistic forecasts. Although no impact-based forecasts are produced, forecasts are written in simple form to help recipients with the interpretation of the weather systems. The NCHM currently runs the WRF model (six runs per day at 00, 6, 12, 18 UTC) that produces forecasts for three days ahead. However, the center needs to work on parameterization schemes and data assimilation for improved forecasting skill. The model is set up as nested with two domains, the inner domain with 3 km and the outer domain with 15 km resolution. The initial conditions are used from the GFS and no observation data are assimilated. Manual verification of outlooks and temperature forecasts are carried out at the end of the year. However, there is no validation and verification system for the WRF model. The NCHM needs to work on providing quantitative precipitation forecasts, rather than just qualitative outlooks. It is questionable whether running its own limited-area model represents a sensible strategy for an organization such as the NCHM or whether the resources would be more effectively used by downscaling and bias-correcting the output from the leading global NWP models over the territory of Bhutan.

The NCHM does not implement the WMO Guidelines for Education and Training of Personnel in Meteorology and Operational Hydrology (WMO-No. 258) requirements for PWS personnel and thus does not meet the appropriate education and competency requirements. Since August 2020, with the support of IMD, the NCHM's WCSD issues medium-range outlook (10 days ahead) and temperature forecasts on a weekly basis which are displayed on the NCHM website. The NCHM contributes operational weather information for eight cities to the WMO's online World Weather Information Service (WWIS). Forecasts are verified daily in a qualitative form against observations. The center does not operate a user satisfaction program through obtaining feedback from users on the usefulness of the forecasts through, for example, opinion surveys and user groups on a regular or systematic basis, although such information is gathered when workshops are organized.

3.3.2 Water Resources and Flood Warning and Flood Forecasting Services

Monitoring and forecasting of the state of rivers, lakes, and river reservoirs are among the main tasks and services of the NCHM. The NCHM has installed and operates the GLOF and rainstorm flood early warning services along the river basins of Punatsangchu, Mangdechu, and Chamkharchu. It has also installed and operates an FDSS[27] for Amochhu and Wangchu basins.

At present, the EWS operates on the basis of detecting and issuing warnings, but the NCHM is planning to integrate flood forecasting with more lead time into the EWS. As part of services provided, the NCHM is also exploring the implementation of impact-based forecasting for weather and floods. The staff are capable of carrying out flow modelling and flood forecasting. Under the UN Early Warning System for All, the NCHM plans to extend the GLOF/rainstorm flood EWS to all river basins.

Other hydrological services provided by the NCHM are (a) historical hydrological data services, (b) flood monitoring, (c) flood advisory, (d) hydrological/flow forecasting, and (e) flood hazard modelling based on the HEC HMS and HEC RAS. The NCHM plans to conduct water resource assessments in the future. Likewise, the NCHM plans to largely enhance the value of flood forecasting services through the adaptation of, and migration toward, impact-based flood forecasting services. The NCHM also intends to explore the suitable global and regional products and best practices to significantly enhance its hydrological forecasting capabilities.

3.3.3 Cryosphere Services

Cryosphere services are relatively new to the NCHM. The Cryosphere Service Division focuses its main activities on monitoring glaciers through mass balance studies on benchmarked glaciers, monitoring glacial lakes for GLOF hazards, preparing and regularly updating inventories of glaciers and glacial lakes, updating the list of potentially dangerous glacial lakes, conducting studies on melt contribution from glaciers to surface runoffs in major river systems, and assessing hazards associated with cryosphere. The center provides data and information generated through the above activities as part of cryosphere services to the general public and line agencies. Currently, due to limited technical expertise, manpower shortages, and financial constraints, services provided by CSD are limited to the abovementioned activities.

3.3.4 Climate Services

The NCHM does not conduct regional climate research or operational climate forecasting due to limited capacity and resources. Seasonal forecasts are issued for the summer and winter monsoons, based on the consensus statement from the SASCOF. The NCHM participates in SASCOFs and since 2016 has been organizing National Climate Outlook Forums (NCOFs) but has not yet established a National Framework for Climate Services (NFCS). The NCHM provides climate information services, including monthly and annual climate monitoring reports, seasonal forecasts, and annual statistical information and analysis of the climate extremes. This information is available on the NCHM website. In addition, as mandated by the Climate Change Policy, the NCHM has been working on the climate projections for Bhutan and monitors climate change and climate variability. However, no regional climate downscaling and regional or subregional climate research is conducted by the center. Similarly, no operational climate forecasting (for example, monthly and seasonal) services exist due to insufficient capacity and resources. Records of the number of users receiving climatological products as well as details of data users, including name and purpose for which data is used, are kept. The NCHM refers to Websites where products from GPCs and regional climate centers for long-range forecasts are displayed but does not have access to

[27] The establishment of the FDSS was supported through the Hydromet Services and Disaster Resilience Regional Project supported by the World Bank.

data itself and the use of these products is limited. The center has digitized almost 90 percent of existing climate records and digitization of the remaining historical records is ongoing.

3.3.5 Agrometeorological Services

The NCHM provides agromet advisories and forecasts services for farmers in collaboration with the DOA under the MoAL. The DOA in collaboration with NCHM operates the ADSS. The NCHM provides three-day quantitative forecasts to generate agromet advisories and agrometeorological information and forecast services for farmers in the form of seven-day outlooks obtained directly from the global/ regional models. The center provides outlooks for both temperature and precipitation, but the farmers need quantitative precipitation forecasts and temperature. The NCHM does not have an operational seven-day forecasting system and relies on what is available from regional centers on the internet. No indexes are provided, and no crop modelling is performed. A drought monitoring and warning system is being implemented in a pilot phase. The NCHM does not operate an EWS for heat waves, cold spells, or frost formation. The DOA is developing a roadmap for agrometeorological services delivery in collaboration with the NCHM.

3.3.6 Aeronautical Meteorological Services

The NCHM is the designated aeronautical meteorological service provider within Bhutan. The Aviation Meteorological Section maintains and operates airport weather stations at all aerodromes of the country, Paro International Airport and three domestic airports (Bumthang, Gelephug, and Yongpula), to provide meteorological information for international and domestic flights as well as for helicopter services.

While international meteorological data and information are required for flight planning and safe, economic, and efficient air navigation, the NCHM's capacity and resources are limited. Although the NCHM provides flight documentation to airlines, it does not issue Terminal Area Forecasts (TAFs) or Significant Meteorological Information (SIGMET) bulletins to airlines and does not receive Operational Aeronautical Meteorological Data (OPMET). The World Area Forecast System (WAFS) products are received on an operational basis by the NCHM, and these provide a basis for issuing flight documentation to international departures. However, there is no capacity to produce low-level Significant Weather charts to support internal flights and helicopter operations, which by nature of the terrain and the frequent challenging weather are already at an elevated risk. Given the challenges with maintaining commercial airline access to Bhutan, a three-day forecast for flight scheduling would be very useful as weather conditions cause the cancellation of many flights. The Aviation Meteorological Section completed the routine (as well as needs-based) maintenance of all the weather observation stations in the airports in 2021.

Aviation Weather Services. Bhutan is a member of the International Civil Aviation Organization (ICAO) which is the regulatory authority for civil aviation worldwide However, NCHM does not currently fulfill the regulatory requirements of ICAO as they apply to the provision of aviation meteorological services. Bringing aviation weather services up to full ICAO-mandated standards would contribute both to increased safety and increased reliability of commercial aviation operations in Bhutan. This is an area of NCHM operations that requires significant strengthening.

There is no cost recovery of aeronautical meteorological services implemented and no QMS for aeronautical meteorological services exists. Consequently, the NCHM is not ISO certified for provision of aeronautical meteorological services. The center does not implement the WMO-No. 258 requirements for aeronautical meteorological personnel by meeting competency or education and training requirements. However, in 2022 a

Figure 27. Paro Airport, the main aviation gateway into Bhutan, has a very challenging approach flight path

Photo credit: Gerald Fleming.

fully qualified meteorologist was posted to Paro Airport with the task of working toward the development of aviation forecast service provision to full ICAO standards. No routine feedback is gathered from aviation users.

3.4 ICT

Although the NCHM transmits observations from remote stations in real time for around 100 stations, it lacks a fully functioning meteorological and hydrological data center which would act as the collection and storage hub for meteorological data and products. The overview of the ICT architecture of the NCHM covers data flow from observing networks to data management, forecast preparation, and dissemination. The forecasts prepared using model guidance are disseminated to the relevant stakeholders through email, social media (for example, Facebook), and the national mass media. The NCHM uses different servers for different types of observational data rather than a central server where all observations reside for processing. There is a need to establish a generic meteorological and hydrological data center, which could comprise a number of different elements, such as servers to receive AWS data, servers to automatically receive synoptic station reports, servers for weather satellite reception and processing and for weather radar reception and processing, an integrated file and message switching system (to handle data communication internally and with the WIS network), a forecast operations database, data visualization systems (for the forecasters to use), a meteorological production system, a data archive, a climate data management system (CDMS), and a high-performance computing (HPC) facility for the running of local-area NWP models (if this is deemed necessary in the absence of a substantial regional computing facility). Similarly, the hydrologists need to be able to collect and view data in real time from the gauges and other measurement devices placed in rivers and streams. In addition to the specialized needs of the NWFWC, such a data center will also include an email server, a shared file server, print servers, and similar equipment that supports normal office working. Appropriate ICT security systems, such as firewalls, will also need to be accommodated.

The NCHM utilizes various visualization platforms such as SmartMet and Himawari satellite, while being connected to the GTS/WIS. The NCHM operates SmartMet (a common visualization operating platform provided through the FMI), the Himawari satellite visualization, and a flood forecasting warning visualization system. The NCHM is connected with the GTS/WIS with Tokyo being the primary Global Information System Centre (GISC) hub, connected at a speed of 8.87 Mbps for download and 13.35 Mbps for upload. Binary Universal Form for the Representation (BUFR) and Synop formats are used for receiving observation data via the GTS/WIS. Data from one observation station are transmitted to the GTS, while the NCHM is in the process of including six more stations in this process. It is also connected to the internet at a speed of 2 Mbps. There is no radio facsimile broadcast in operation at the NCHM.

Due to the presence of multiple networks, the NCHM maintains different telemetry systems for different networks:

a. **A close observation shows that there is a time lag of more than 2 hours between the time of monitoring and when data are available on the system for decision-making/warning, requiring an upgrade of the GLOF network.** The GLOF network operates on satellite systems, with 10 stations on the iridium satellite and the remaining 5 on Himawari. This time can be reduced by upgrading servers and software, as newer technologies/systems have become available since these systems were installed in 2012. There is a need to upgrade these 10 stations in the next five years, as they are already more than 10 years old and have outlived their design life. The remaining five stations, which are relatively new, can be upgraded after 5 years.

b. **AWS and Automatic Weather Logging and Retrieval (AWLR) networks, operated on GSM/GPRS-based communication, suffer frequent failures** due to multiple reasons, including weak signal strength, change in technology by mobile operators, shifting of towers due to mobile operators' commercial reasons, weakened signal strength during heavy rainfall events, and excessive load on the networks during hazardous weather situations as they share the same network with the public, resulting in failure during peak demands. The NCHM has recently carried out some maintenance activities, but a large number of AWLSs and AWSs are still unable to transmit.

Although the NCHM should continue to operate both satellite- and GSM-based telemetry, there is a need to migrate all critical meteorological and hydrological stations used for forecasting, EWS, and modelling to satellite-based telemetry. Satellite-based telemetry offers several advantages including wide coverage, robustness, flexibility, long-distance connectivity, and data accuracy and timeliness. The remaining stations (which are not critical for forecasting and EWS but are important for maintaining national database and ambient environmental parameters) can continue to operate on the GSM network for optimizing the operating cost.

Apart from telemetry systems, there is a need to semi-automate the existing manual monitoring system. In that intervention, the monitoring would still be carried out by gauge readers, but they can use mobile applications to enter data immediately after taking readings. In this way, data can be made available on central servers in near real time, and software-based quality control can be carried out on server or within the app. Alternatively, gauge reader personnel can take a geo-tagged time-stamped photograph of the gauge and upload it to the server through the app, which would act as a validation tool in case of any discrepancy in data during analysis.

3.5 Quality Management Systems

The NCHM does not have a QMS in place to govern its management and technical operations. The NCHM recognizes, however, that the adoption of international data quality standards, methods of observation, communication, and data handling is of the utmost priority. SOPs were developed in 2020 for all the operational activities of the NCHM; these need to be updated to reflect more recent changes in divisional responsibilities.

3.6 Research

No active research is being undertaken aiming at understanding of meteorology, hydrology, and the cryosphere in Bhutan. The NCHM created the TSRD to promote culture of research on hydrometeorology and water resources, climate change impacts, and so on. The NCHM started an annual Bhutan Hydromel Journal to promote research work since 2022. There is a lack of research direction, human resources, technology, and tools required for significant research work.

3.7 Education and Training

Building capacity through training activities and cooperation with other WMO members is indispensable for a modern NMHS such as the NCHM. These activities should be conducted on a regular and continued basis and include access to new skills for new and existing staff. A major challenge for the NCHM, as for many other NMHSs, is to create a professional and technical workforce with access to training opportunities that will enable them to take advantage of rapid advances in many areas of meteorology, particularly advances in information technology (IT), modelling, and forecasting. It is equally important to have a sufficient number of trained technicians for maintenance of equipment such as AWS and AWLS networks. These systems are becoming increasingly sophisticated and maintaining them requires in-depth training for the relevant technical staff. It is critical to provide in-house courses in line with the WMO competency requirements to ensure that all staff become familiar with new meteorological tools and software. In addition, training should also be provided at regional or international training facilities, and twinning with more advanced NMHSs should also be pursued.

At present there is no established mechanism for the training of NCHM staff, nor are there any institutional arrangements, involvement of academic institutions, or a curriculum of topics to be covered. New recruits are given at least a week-long introductory training by the NCHM. NHCM staff are trained in various hydromet applications whenever the financial resources are secured through external sources. There are no GIS specialists in the NCHM, but there are a few engineers and officers who have taken basic and intermediate GIS courses. Most personnel learn the GIS on their own based on their job requirements. The IT system of the NCHM is looked after by only one ICT personnel. It is evident that the NCHM lacks capacity in ICT systems. Aside from acquiring additional ICT staff and procuring hardware and software and additional training, outsourcing of selected IT tasks and applications is an option in the future.

A generic staff training plan has been initiated by RCSC, but the NCHM does not have its own structured training plan for professional, technical, and support staff in place, and there is no regular in-house training program. The NCHM has access to and uses e-learning materials for certain WMO online courses. The NCHM participates in regional forums and training activities including those offered by the WMO and RIMES. As part of its continuous educational programs and refresher courses for technical staff, an annual refresher course is conducted at the NCHM. An annual GLOF awareness program is implemented along the Punatsangchu and Chamkhar-Mangde river basins. By contrast, no training is conducted for mid- and high-level management positions. There are no twinning or attachment arrangements with other NMHSs or organizations, and use of WMO regional training centers (RTCs) is infrequent. In-country training opportunities with universities and other relevant institutions of higher education are not available.

The ongoing trend of emigration adversely affects the NCHM. In terms of progress in capacity building for the NCHM, there were a number of capacity-building measures through knowledge transfer that were implemented for the staff as per the recommendations of Roadmap 2015. However, the issue faced by the center at present is that trained staff have resigned or left on long-term leave, and this seriously affects the service delivery of the center.

Another critical area of capacity development is in the provision of aviation meteorological services. As noted, a young meteorology graduate has recently been posted to Paro Airport with the task of developing aviation forecast services, including the provision of TAFs, TRENDs, SIGMETs, and products such as low-level significant weather charts for domestic and other short-range flights. As the NCHM has no experience whatsoever in this aspect of meteorological service provision and therefore no relevant institutional knowledge, a support/mentoring system from experienced professionals outside Bhutan, perhaps through a twinning arrangement, needs to be put in place.

While no academic courses in meteorology or hydrology are available in Bhutan, the NCHM collaborates with academia. There are no academic courses in meteorology or hydrology available in Bhutan, either at the undergraduate or postgraduate level. Technical collaboration with the Royal University of Bhutan (RUB) has been strengthened in carrying out research related to melt water contribution and development of flood hazard maps. As required laboratory facilities for undertaking such research do not exist in the NCHM, the NCHM carries out this work in collaboration with Sherubtse College under the RUB. Memoranda of understanding have been signed between the NCHM and some of the RUB institutes. As part of this agreement, the NCHM has been receiving intern students from those institutes for practical training.

3.8 Partnerships and Investments

The NCHM benefits from projects implemented by development partners and donors in the form of strengthening the technical and technological capacity of the organization (for example, installation of automatic meteorological stations) and human resources capability (training, seminars, conferences). These include projects implemented through the Green Climate Fund (GCF) and the World Bank.

The NCHM collaborates with RIMES, ICIMOD, and other regional organizations as part of enhancing its capacities and capabilities for improved early warning services and service delivery. The NCHM does not have license agreements with global NWP centers for access to various graphical or digital model products, although the need to have such an agreement, for example, with NCMRWF (India) is recognized. While for the WRF model, freely available data from NOAA are used, products from centers such as ECMWF would be of utmost benefit, especially for providing guidance for long-range forecasting. Another example of engagement with partner organizations is in the health sector where the NCHM has been engaged in health-related studies with the Ministry of Health and the World Health Organization (WHO). An analysis of the economic benefits of enhancements in the capacity and capability of the NCHM was performed in 2014 for a number of sectors in Bhutan by the FMI and the Department of Hydrology and Meteorology, but a similar study has not been repeated since.

The NCHM is a co-chair of the South Asia Hydromet Forum (SAHF). The SAHF, launched in 2018, brings together hydromet experts from all South Asian countries for sharing knowledge, building capacity, and aligning national-level technical assistance with regional engagement. The proposed activities will focus on (a) enhancing the Knowledge Hub (for example, fully operationalize the Forecasters Workbench including knowledge management and integration of regional and global model forecasts, cloud services for the Knowledge Hub, Data Exchange Platform, and allied information exchange/sharing platforms), (b) strengthening regional engagement (for example, Forecasters Forum, Working Group, Executive Council, and SAHF annual meetings established as a part of the SAHF), and (c) building capacity (for example, NWP, impact-based forecasting, observational network, and capacity enhancement). The SAHF is implemented by RIMES and financed by the World Bank, initially with funding support through the European Union South Asia Capacity Building for Disaster Risk Management Program and by the UK Aid, administered by the Global Facility for Disaster Reduction and Recovery. Now, continued support is provided through the World Bank-funded Climate Adaptation and Resilience for South Asia and United Kingdom Foreign, Commonwealth, and Development Office (UKFCDO).

The GoI and NCHM cooperate in the operation of some hydromet stations and sharing of data. The GoI provides funds to the NCHM for the operation of 17 hydromet stations of interest that lie within Bhutan. These stations within Bhutan are owned and operated by the NCHM. Data of these stations are shared with the CWC in India for flood forecasting and warning in the part of India that is downstream of Bhutan. The network is a mix of manual and automatic stations using GSM-based telemetry. In addition, ERP for Bhutan is prepared with support from IMD. The ERP products for Bhutan are generated every Friday. The ERP is produced for two climate variables in Bhutan: rainfall and temperature.

There is strong collaboration with regional institutions such as RIMES and ICIMOD. RIMES has developed an FDSS and an ADSS. The NCHM developed a streamflow prediction tool with ICIMOD, and there have been numerous activities to monitor snow and glaciers in Bhutan in collaboration with ICIMOD.

3.9 Summary: Current Capacity and Maturity of the NCHM

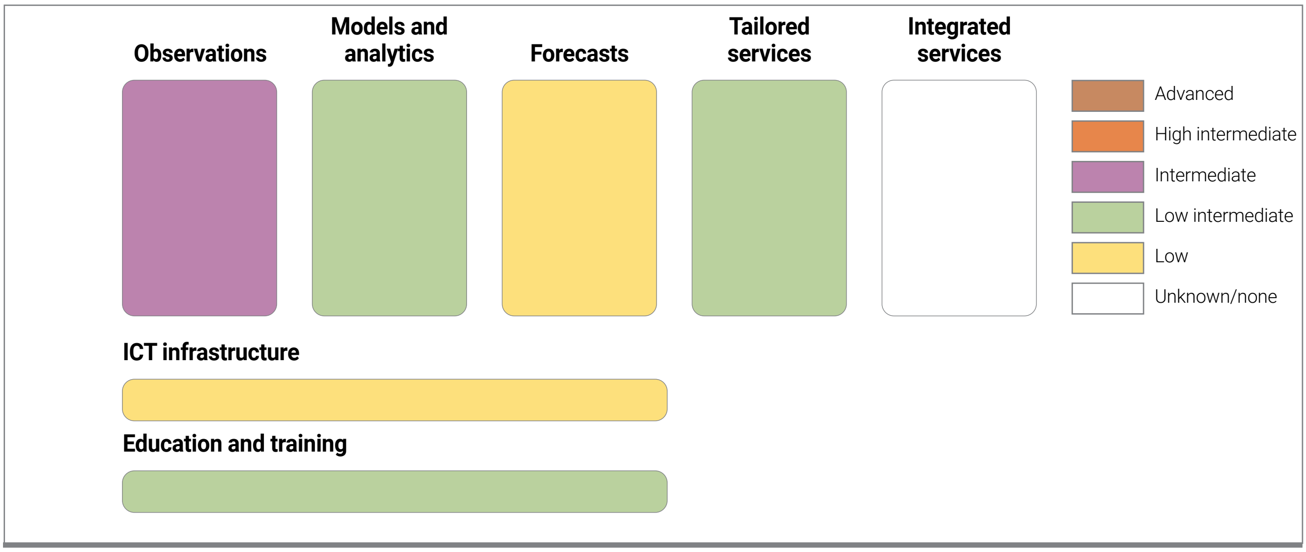
Using the value chain approach (*refer to Chapter 3 for detailed explanation of the value chain model*) and activities in each link of the chain, the existing operational capacities of NCHM are illustrated in **Figure 28**.

The major gaps in the observation network of the NCHM are in the lack of upper air and weather radar coverage. The observation network of the NCHM (*observation link*) comprises 169 meteorological stations, 99 hydrological stations (inclusive of 15 GLOF/rainstorm water level stations, and 17 flood warning stations in collaboration with the GoI), and 15 sediment stations. There is also a need for synoptic stations, more hydrological gauges, glacier and snow observations, and AWSs. An *intermediate* maturity level can be assigned to the *hydrometeorological observation* link.

The *models and analytics* link is at a *low intermediate* maturity level. This is because, although the NCHM has access to model results from ECMWF, NOAA/NCEP(GFS), JMA (GPS), and IMD-NCMRWF and runs EMSWRF version 3.4 for the daily weather forecasting, the local models are crude, the use of model data is basic (for example, no use of EPS), and the relevant staff have little or no training in properly employing model guidance. Although the NCHM performs objective verification of the model outputs, it does not assimilate any of its own observational data into the models and currently there is no post-processing.

The *forecast* link is considered to be *low* on the

Figure 28. Schematic of the NCHM current value chain



maturity level. The NCHM runs a 24/7 weather forecasting operation and produces short-range (6–24 hours) and medium-range (two to six days and monthly) forecasts on a regular basis, with forecasts issued for 7–10 days ahead upon request; produces PWS forecasts up to six days ahead and provides some limited interpretation of the forecasts to users; issues advisories of hazardous weather (but no formal warning system is in place); and performs daily qualitative verification of weather forecasts against observations. However, the actual information issued is broad and general. At present, no impact-based forecasting or nowcasting is performed by the NCHM, and a major gap exists in the provision of aviation forecast services.

There is also low capacity for hydrological forecasting. The center produces flood forecasts and issues flood warnings when high levels in rivers are observed. Water levels, which are observed at varying frequencies across seasons, are relayed to the HQ. While flood advisories are currently issued by the NCHM on a detect-and-warn basis, routine forecasts of river levels are not disseminated.

It is necessary for the NCHM to establish a comprehensive process for operational weather forecasting as is practiced in other well-functioning modern national forecast centers of similar size and complexity. This will include access to the NWP/EPS digital data and products from a range of global centers, the required hardware and software for data handling (license), NWP post-processing and calibration (model output adjustment to country conditions), data assimilation into the forecast models, and production of site-specific forecasts. It will also require significant capacity development and training for the team of PWS weather forecasters, none of whom have any formal training in meteorology. As a member of the SASCOF, the NCHM has access to extensive research and guidance on climate forecasts in the monthly to seasonal range and already disseminates these to many users.

The *tailored services* link is at the low *intermediate* maturity level. The tailored services link in the value chain is used to include any service to which value has been added beyond the forecasts link. This maturity level is justified mainly because the hydrological services are at a more basic level than the meteorological services. The NCHM issues three-day public weather forecasts once a day and 24-hour city forecasts for a selected location in each district. The NWFWC, Thimphu, operates on a 24/7 basis. It issues routine daily weather forecasts through various dissemination channels including radio, television, social media, and the NCHM website. Since August 2020, with the support of IMD, the NCHM issues extended-range forecasts on a weekly basis. Forecasts are verified daily in a qualitative form against observations. Surveys are conducted to assess user satisfaction relating to the usefulness of the forecasts. Seasonal forecasts are issued for the summer and winter monsoons. The NCHM provides weather and climate information to DOA to develop agromet services for farmers. The Aviation Meteorological Section maintains and operates airport weather stations at all aerodromes of the country—Paro International Airport and three domestic airports. The following hydrological services are provided by the NCHM: (a) historical hydrological data services (1990 to present), (b) a warning system for GLOFs and rainstorm floods (warnings are only issued once high water flows are observed), (c) flood monitoring, (d) flood advisory, (e) flood/GLOF hazard mapping and zonation, and (e) hydrological/flow forecasting.

The *integrated services* link is currently not occupied since there is no coproduction of services, even with the relevant government agencies, including the Department of Local Governance, Department of Geology and Mines, and Department of Surface Transport. Collaborations follow the traditional tailored services approach. MHEWSs are missing and need to be established.

The *ICT* link is at a *low* level of maturity for the hydrometeorological component. Although the NCHM uses SmartMET workstation, a common visualization platform, and a data management system, it lacks an integrated meteorological and hydrological data center comprising a number of different elements, such as servers for various purposes, a forecast operations database, a meteorological production system, and a data archive. These components would act as the collection, routing, and storage hub for meteorological data and products. Similarly, the hydrologists will need to be able to collect and view data in real time from the gauges and other measurement devices placed in rivers and streams. The NCHM has been recently connected to the WIS/GTS, with support from JICA, and data from one observation station are transmitted to the GTS, while it is in the process of including six more stations in this process.

The ***education and training* link is at the *low intermediate* level** because while new recruits are given some short introductory training by the NCHM, there is no established mechanism of training NCHM staff, nor are there any institutional arrangements or involvement of academic institutions. The level of formal training for staff in meteorological science is low. However, NHCM staff are trained in various hydromet applications whenever the financial resources are secured through external sources.

Some reflections on the 2015 Roadmap: Many of the recommendations contained in the earlier Roadmap, prepared with support from the World Bank, remain valid. Some of them, such as improving the ICT assets and strengthening the hydrometeorological and climate service provision, are ongoing activities that would apply to almost any National Meteorological and Hydrological Service. NCHM has undergone a number of institutional and structural changes in the last few years, and a national policy for hydromet is also now in place. Other more specific recommendations, such as improving basic weather and hydrological forecasting, improving the meteorological contribution to aviation safety, and developing end-to-end warning services are still very much works-in-progress and have probably not advanced as far as was hoped at the time the earlier Roadmap was completed. The inadequacy of the staffing and the O&M budgets remain as critical challenges.

4. Roadmap for Modernizing and Strengthening NCHM's Services and Systems

Cleaning the riverbed in Paro. Photo credit: nmessana.

There is a growing need among the stakeholders and users in various weather, water, cryosphere, and climate-sensitive economic activities in Bhutan for data, advisories, impact-based forecasts, and information. Frequency and intensity of natural hazards are likely to be exacerbated by the impacts of climate change. These increasing demands for weather and water data will pose challenges as well as provide opportunities for the NCHM to make optimum use of emerging new technologies to play its role in responding to these major challenges.

While monitoring, recording, and providing observational data by the NCHM has been occurring over the past several decades, delivery of advisory services is still relatively new and is an area of importance recognized by the NCHM and is beginning to be developed. During the preparation of this roadmap, gaps in the service provision capabilities of the NCHM were identified. The activities proposed in the roadmap are meant to raise the standards and capabilities of the NCHM for products, services, and service delivery to the highest possible level to discharge its public task to the satisfaction of the users. While endeavoring to provide products of quality, diversity, and coverage to users, the NCHM faces challenges including (a) shortage of a sufficient number of well-trained technical staff; (b) insufficient access to appropriate new technologies, technical assistance, and guidance; (c) keeping pace with the growing demand for its services; (d) unsuitable premises for the conduct of scientific, technical, and operations work; and (e) inadequate funding for sustained O&M of its services and systems.

This roadmap represents the first step in a planned long-term engagement of the RGoB on hydromet for enhancing the current capabilities of the NCHM. The three essential components[28] for a holistic modernization program for any NMHS are (a) enhancing service delivery system; (b) strengthening and building institutional capacity; and (c) modernizing observation, ICT, and forecasting infrastructure. This principle and the hydromet value chain concept guide the activities proposed in the subsequent sections of this roadmap to respond to the challenges highlighted in Chapter 3. They aim to strengthen the institutional capacity of the NCHM, modernize those elements of the infrastructure and facilities that require upgrading, and advance the delivery of hydromet services and MHEWS to the population of Bhutan and weather-dependent sectors.

Achieving this modernization program over a period of 5–10 years in the roadmap requires anticipation and proactive measures to be taken by the NCHM with adequate funding and technical support on several fronts. To start with, it should be acknowledged that while modernization of the NCHM infrastructure and capacity building of its personnel remain the responsibility of the center, the expected increase in hydrometeorological extremes in the future requires an integrated approach by the NCHM and other relevant stakeholders and government agencies. The approach should go beyond modernizing observing and forecasting systems and embrace integrating the services of the NCHM with those provided by other agencies to prepare for anticipatory and early actions in response to extremes in a holistic manner. This is not a trivial task and should be initiated as part of a modernization program; it is also consistent with the aims of the United Nations' 'Early Warning for All' (EW4ALL) initiative which puts forward the ambition of providing meaningful early warning services to all citizens on the globe by 2027. This approach has been introduced using the concept of 'integrated services' in the roadmap, which highlights the key importance of co-design and co-development of service delivery with government entities responsible for disaster management, health, water resources management, and transport, among others.

[28] Rogers and Tsirkunov 2013.

The roadmap offers two approaches, short and medium term, described below in Sections 5.2 and 5.3, for enhancing the capacity of the NCHM with detailed descriptions of each approach, including their respective costs. The short- and medium-term approaches are interdependent and should be conducted in a phased manner to seamlessly build on each other and contribute to the overall goal of the modernization progress. Thus, the medium-term plan assumes the accomplishment of objectives achieved in the short term and builds on them. They contribute to a system capable of producing and delivering (a) timely warnings of extreme and hazardous events and their potential impacts and (b) weather and hydrological including cryosphere information and forecasts for operations and planning in weather, climate, and hydrologically sensitive economic sectors, particularly agriculture, energy, transport, water resources, and disaster risk management.

The two modernization approaches aim to guide the NCHM toward a more systematic basis for setting strategic and forward-looking priorities to improve its service delivery and contribute to the development of the national economy by producing location-specific, well-articulated, and usable information not only on hazards but also on their impacts on target areas and population. These approaches highlight that certain steps can be taken quickly and with rather limited investments and effort to enhance the utility of weather, climate, and hydrology information for users. Examples include training of the NCHM technical staff to access, use, and apply readily available products and guidance from various regional and global centers for improved forecast and warning services and apply remote sensing techniques to improve their forecasting capabilities; streamline forecasting and ICT procedures and practices; and develop robust and reliable means for communicating with users and gathering their feedback. A major consideration is migration from threshold-based forecasts to impact-based forecasts to provide enhanced service value. Other changes may require longer-term and more substantial investments. Examples include enhancing the meteorological and hydrological observation networks, introducing new observation, ICT and forecasting technologies, and capacities for impact-based forecasting.

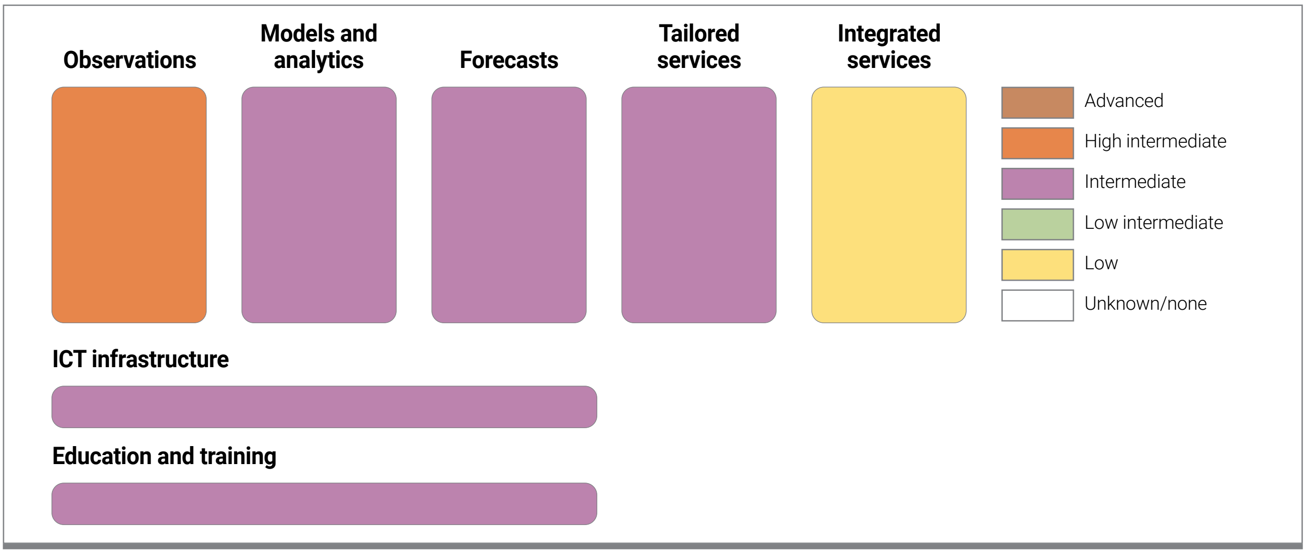
These recommendations are expected to inform the five-year planning cycle of the RGoB. While the roadmap offers a strategic framework to advance the scientific and technical capabilities of the NCHM for the next decade and beyond, the full details of achieving such an ambitious and far-reaching vision (beyond what is described below) will need to be worked out and detailed in an implementation plan once the roadmap has been approved by the NCHM management.

4.1 Short-Term Modernization (2024–2029)

The focus under this time frame would be mainly on strengthening the center's capacity to access and use available tools and technologies, acquiring a certain amount of essential new equipment, and establishing critical infrastructure to enable organizational modernization.

Introduction of significant resources is needed if the required level of modernization in five years is to be achieved. The estimated cost of implementation of modernization over five years is approximately **US$14.9 million.** This includes capital investments in the new NCHM center (U**S$2.8 million**), observation and ICT infrastructure as well as O&M costs (excluding labor costs) of approximately **US$2.2 million** and capacity-building costs of **US$1 million**. Some of this funding resource, typically for capital items of infrastructure, can come through the different development agencies. However, much of it, especially that related to the costs of building the skill of staff members and recruiting a sufficient number of highly skilled professional staff, will need to be borne by the RGoB itself as it requires

Figure 29. Schematic of the NCHM value chain after medium-term modernization intervention



an increase in (present and future) expenditure on salaries and related personnel expenses. Similarly, the government will need to dedicate sufficient resources for the effective O&M of the improved operational infrastructure.

Upon implementation of the short-term modernization priorities, the result of the interventions toward modernization is expected to be in the state of the value chain links as depicted in **Figure 29**, showing higher levels of maturity.

4.1.1 A New HQ Campus for the NCHM

At present, the physical facilities of the NCHM do not, in any sense, support the particular needs of a scientific, technical, and operational organization that is focused on public services that should be underpinned by a strong organizational identity and a visible public presence. The NCHM HQ functions are accommodated in standard office buildings within a government compound close to downtown Thimphu. The operational forecast offices (meteorology and hydrology) are located in an adjacent building (NWFWC) that has significant drawbacks with regard to providing operational spaces; the operations rooms are rather small and are divided by supporting columns, effectively breaking up the working space into even smaller units. There are no laboratory facilities for the maintenance and calibration of equipment, much less the sort of facilities that would be needed for water quality work and sedimentation analysis. There are no specific facilities for accommodating training nor those for hosting meetings and conferences.

An added challenge arises from the need for resilient 24/7 operational services and ensuring that adequate staff are always available to sustain these services. Experiences during the COVID epidemic, in Bhutan and elsewhere, exposed the difficulties of maintaining operations during these interruptions to the normal functioning of society—interruptions that can also be caused by severe weather events or seismic occurrences. These latter are precisely the occasions when fully functioning meteorological and hydrological services are most needed by society to ensure the safety and security of citizens. The clear inference is that a sufficient number of NCHM staff should reside near the operational offices, as the best way to ensure their availability and the resilient provision of essential services.

To enable modernization and proper development of the organization, a new, purpose-built campus is required for the NCHM.[29] This

[29] Bhutan - Technical Guidance Note for Establishment of National Centre for Hydrology and Meteorology Head Quarter, National Weather, and Flood Warning Centre and Scientific Facilities (RGoB and World Bank 2023).

should comprise specific buildings devoted to administration, operational service provision, technical laboratories, educational and meetings spaces, a variety of other support functions, and residential accommodation for sufficient staff that will guarantee resilient services. The campus should also allow for the siting of weather observing equipment, including provision for balloon launches to gather upper air data. It would clearly be impossible to accommodate all these diverse needs on the existing site, and the space required will be such that a suitable site is unlikely to be found near the center of Thimphu.

Multiple benefits will flow from the provision of a well-designed HQ campus for the NCHM. At a technical level, the facilities will support the operation, maintenance, and calibration of equipment that comprises the essential meteorological cryosphere and hydrological observing network of the country. At an ICT level, it will provide a 'nerve center' for the collection of meteorological and hydrological data and its exchange with the global community. At an operational level, it will facilitate the provision of top-quality meteorological and hydrological products and services to the citizens of Bhutan, including the critical warning services. At a scientific level, it will support excellence in meteorology and hydrology through providing opportunities for experts to gather and exchange knowledge; indeed, it could well host a center of excellence in key subjects such as mountain meteorology or glaciology. At a broader level, it will support food security, hydropower, transport, tourism, and other key economic activities through facilitating more extensive and more targeted meteorological and hydrological services. These services will help minimize the vulnerability of the Bhutanese economy to shocks deriving from natural hazards and assist the nation in consolidating its status as a middle-income country.

The cost of the construction of the NCHM offices and related scientific and technical facilities is estimated at US$2.8 million. The planning, design, and development of such a campus will necessarily take a number of years, but it can be staggered, with the key buildings (HQ building, NWFWC, calibration laboratory, sediment and water quality laboratory, store, and equipment maintenance workshop) put in place first and the remaining buildings following later. However, the envisioning and construction of this facility should go hand in hand with the rest of modernization outlined below, with the ambition that, within the decade, the transformation of the NCHM to a full-capacity NMHS will be complete. An indicative preliminary breakdown of the cost is shown in Annex II.

Key activities

Establish NCHM Headquarters, 24/7 National Weather and Flood Warning Centre (NWFWC) and Scientific Facilities that will include:

- Calibration Laboratory, Sediment and Water Quality Laboratory
- Store and Equipment Maintenance Workshop
- Establishment of Aviation offices at domestic and international airports
- Establishment of Hydromet Information Centre and climate lab
- Establishment of training center
- Acquiring vehicles for stations maintenance

The envisioning and construction of this facility should go hand-in-hand with the two time frames for modernization, with the aim to transform NCHM to a full-capacity NMHS within the decade.

4.1.2 Observation

To enhance the effectiveness and reliability of Bhutan's observing network, modernization efforts should prioritize cryosphere observations, synoptic network rehabilitation, and the automation of observations to improve data

quality, frequency, analysis, and forecasting capabilities. Modernization of the observing network in Bhutan should include cryosphere observations with a focus on snow and glaciers and pay attention to the rehabilitation of the existing synoptic network to safeguard compatibility and interoperability between different types of equipment and sensors. Modernization also needs to address the automation of observations with a view to eliminating or greatly reducing data collection and transmission errors, increasing the frequency of available observation data, facilitating analysis, storage, and retrieval of information, introducing nowcasting, and improving very-short-range forecasting.

Any plan to modernize the observing network must also pay close attention to the long-term sustainability of the network, and consider how to overcome the challenges currently experienced. These would include addressing critical assumptions such as that NCHM build sufficient capacity to maintain the stations (engineers, technicians, extended warranty contracts), how the issues with connectivity are to be solved, the types of capacity that will be essential to operate the expanded network, etc.

The *observation* link after a five-year intervention will be at the *high intermediate* maturity level. Observation network design is an ongoing and complex process with the addition of new stations as required and the rehabilitation of existing stations. In making these decisions, many factors have to be considered such as access to stations, reliability, reporting accuracy, costs, O&M requirements, durability, and site specifications. Data management is a key element of an observation network for proper storing, validating, analyzing, and reporting of all data that are being generated and collected on a continuous basis.

The majority of this expansion should take place in the mountainous regions of the country, where there is a great need for increasing the number of stations and capabilities to measure discharge in fully turbulent streams using (fluorescent) mobile tracer techniques. The NCHM plans to upgrade, with assistance from JICA, five AWSs to synoptic stations by adding the required sensors and connecting them to the GTS. In addition, according to the NCHM, to meet national needs, an optimal observing network is required, amounting to five new synoptic stations, five AWSs (including snow pillows) at high altitude, with a view to forecasting avalanches, assessing GLOF risks, and monitoring changes to the contribution of water from high-altitude mountain regions. Likewise, 10 new hydrometric observing sites are required. In addition, one upper air station should be installed in the five-year time frame.

Automation of monitoring, transmission, and reception of data is an urgent need for meteorological, hydrological, and cryosphere networks. It is assumed that all stations will become fully operational and produce reliable data in accordance with established data quality standards. All observations will be transmitted automatically to the central collection center. Digitization of historical records will be continued. Attention has to be paid to interoperability of the new and existing stations with regard to different manufacturers, challenges to the maintenance of instruments, and comparable standards of data quality as well as interoperability in terms of communication services.

The possibility also exists to develop widespread network of "second grade" stations, developed in conjunction with partners and possibly hosted in schools and on the premises of stakeholders. However, this would involve considerable effort by NCHM in both setting up the networks, ensuring that adequate standards in maintenance and calibration are achieved, in curating the resulting dataflows, and in housing the data. Some European Met Services (Norway, Switzerland, UK) have used this technique. This approach has also been applied in Africa through the TAHMO network and the experiences suggest that long-term sustainability of such networks needs to be carefully considered, and the levels of ambition need to be realistic. The production of 3D Printed Automatic Weather Stations (3D-PAWS) has been tested in South Asia and is used widely in other regions as well. These are low-cost stations and could possibly be used to augment the core NCHM station networks.

Key activities

Climate and weather observation network:

- An upgrade of the existing observation network; installation of **one** upper air station, **five** new synoptic stations, **five** new cryosphere observing stations
- Upgradation and standardization of existing **20** Agrometeorological stations (Class A stations)

Aviation observation network:

- Upgrade AWOS at domestic airports
- Install AWOS at international airport
- Integrate AWOS with Centralized Database Management System

Cryosphere monitoring network:

- Install **three** AWS (or other appropriate technology) with capabilities of observing snow water equivalent/ snow depth
- Set up at least one glacier runoff model in a sub basin
- Establish **five** new cryosphere monitoring stations (weather stations, AWS)
- Increase number of benchmark glaciers for long term monitoring from three to **four** glaciers.
- Develop systematic observations of volume changes of selected glacier lakes including bathymetric surveys

Hydrological monitoring network:

- Upgrade from existing GPRS/GSM to satellite-based telemetry for critical AWLS and AWS sites and FWS
- Introduction of **six** manual and handheld automatic water quality monitoring units for ambient water quality monitoring
- Install **five** real-time sediment monitoring systems upstream of major hydropower stations
- Procure **two** ADCPs for regular discharge measurements and update rating curves
- Procure **two** mobile spectrofluorometer instruments for discharge measurement using fluorescent tracers (Uranin) in highly turbulent mountain streams and rivers
- Expand the GLOF EWS for basins where this is required
- Enhance existing GLOF and early warning monitoring network

Calibration of hydromet equipment:

- Install **one** humidity sensor calibrator, one rain gauge calibrator, **one** solar radiation calibrator, sunshine recorder calibrator
- Install **one** current meter calibrator and water level sensor calibrator
- Develop user manuals, check lists and guidelines for data collection, quality management, maintenance and forecasting

4.1.3 Models, Analytics, and Forecasts

An important aspect of strengthening the capacity of the NCHM is to increase the lead time and improve the quality of its forecasts, develop methods for forecasting, especially of the hazardous hydrometeorological phenomena, and establish approaches and methods for assessing the economic benefits of its activities. Modelling, building, and implementing forecasting techniques for the rapid-onset adverse hydrological phenomena (for example, flash floods, mudflows, and GLOFs) are among the major goals of the NCHM.

The ***models and analytics*** link will be at the ***intermediate*** maturity level through enhancing the forecasting procedures and practices to include access to, and use of, other regional and global models, especially the post-processing and calibration of global models to the conditions of Bhutan. Attention will be mainly focused on improving modelling capabilities in water availability assessment, flash floods, mudflows, avalanches, and GLOF risks in these areas as well as in overall impact-based flood forecasting. As part of this effort, developing and sustaining a catalogue of mountain lakes with outburst potential through use of high-resolution satellite imagery and application of GIS tools is a crucial activity at this stage of modernization. This also relates to the mapping of high-impact and risk areas of devastating avalanches.

The *forecasts* link will be further enhanced to the *intermediate* maturity level with improvements and innovations. It will build on current capabilities of forecasters by upgrading the tools for visualization and manipulation of data and products by forecasters, introducing the EPS and the concept of probabilistic forecasting, enhancing the understanding and full use of NWP/EPS data and products for short- to medium-range forecasts, introducing impact-based forecasting techniques, and nowcasting. Forecasting and assessing water availability for the agriculture and energy sectors, GLOFs, flash floods and mudflows, and long-range streamflow are hydrological and cryosphere areas of focus for development and enhancement.

Key activities

Weather and climate forecasting:

- Further access and use other regional and global models; introduce data assimilation, post-processing, and calibration of these models
- Introduce EPS and probabilistic forecasting
- Initiate weather forecast verification
- Introduce impact-based forecasting
- Develop nowcasting systems
- Operationalize medium range forecasting (7-10 days)
- Initiate long range climate forecasting (monthly, seasonal)
- Conduct climate projection and downscaling
- Develop Terminal Aerodrome Forecasts (TAF) and Severe Weather Forecasts (SIGMET) for Aviation
- Initiate Numerical Weather Prediction (NWP) verification system (WRF)
- Operationalize common operating platform (COP-SMART MET)
- Parameterize NWP (WRF)

Hydrological and flood forecasting:

- Develop grid-based forecasting tools for hydrology
- Acquire a forecast visualizations system (or upgrade the existing system)
- Develop sectoral-based forecasts
- Enhance hydrological models for hydrological forecasting
- Initiate hydrological forecast verification
- Develop dynamic riverbed modelling (incorporation of sediment transport)
- Expand flood forecasting and early warning system to other basins (WIMES)

Snow and Glacier modelling:

- Model snow and glacier melt water
- Develop enhanced and quality-controlled datasets on snow and glacier melt and initial modelling of seasonal snow and glacier melt
- Develop glacier mass balance modelling
- Develop glacier lake breach modelling

4.1.4 Services Delivery

The *tailored* services link will reach the *intermediate* maturity level. The services will be enhanced by paying closer attention to the users' needs and their level of satisfaction with services of the NCHM and collecting their feedback. Closer collaboration with DLGDM will be established, for example, in developing/strengthening joint SOPs and exercises. Improved services will be provided to the agriculture and energy sectors. Climate services will be enhanced by producing climate indexes and implementing plans for establishing a National Framework for Climate Services.

Similarly, cryosphere services will be enhanced by the provision of water resource assessments from high-mountain snow and ice fields as well as avalanche and GLOF warnings. It should be fully recognized that tailored services may not be generated by NCHM resources alone but require a knowledge base to be established in close cooperation with institutes of higher learning, the science community, and the public civil service as well as private sector organizations.

The *integrated services* link will be at a *low* maturity level. Following the medium-term modernization stage, the *integrated* services will be initiated in collaboration with DLGDM in the form of impact-based MHEWS and forecasts. Agromet services will be codeveloped with the agriculture sector to include preparing various crop-specific advisories and analytical information. Similarly, the NCHM jointly will start codeveloping hydromet services for the energy sector.

Improvements in *tailored* and *integrated* services should drive choices around the development and use of models. Section 5.3 below provides some guidance on the choices and possible directions in the future use of weather models by NCHM. The choices should always be informed by the possible improvements in services (including integrated and tailored services) that can be facilitated by the scientific and technical improvements under consideration.

Key activities

- Establish/improve user-oriented culture including introduction of user feedback systems
- Develop/strengthen SOPs for service delivery
- Enhance the website of the NCHM
- Enhance weather services provided on social media
- Develop/deepen links with broadcast media
- Develop mobile application for the delivery of products
- Initiate the use of CAP for warnings
- Initiate SMS-based warnings in collaboration with telecom service provider
- Establish cell phone broadcast services for warnings in collaboration with telecom providers
- Establish glacier lake outburst warning services including assessments of glacier lake dam stability
- Further develop GIS-based inventory and time/spatial development of hazardous glacier lakes in Bhutan
- Conduct field surveys to monitor hazardous glacier lakes, including arial visualization and terrestrial observations
- Develop grid-based precipitation and temperature forecast maps
- Acquire ISO certification for aviation
- Develop and implement QMS for the entire NCHM
- Develop manuals for observation methods, instrumentation including their calibration, and maintenance.
- Develop standards for observation, data collection, monitoring, data management and forecasting
- Develop National Framework for Climate Services (NFCS)
- Enhance Agrometeorological Services
- Develop drought monitoring portal
- Develop of climate information system
- Enhance remote data collection using mobile apps

4.1.5 ICT

The ICT link will be at an *intermediate* level of maturity. The ICT link will be further developed with an integrated system for data transfer, quality control, data storage, and management. All data will be in the standard format required for the functioning of an integrated meteorological and hydrological ICT system, allowing the retrieval of data in the format required by all staff and thus covering the requirements for improved data exchange between them. The visualization system, including hardware, software, and training for the forecast and services divisions, will be upgraded for integration of all meteorological, hydrological, and cryosphere observations and model data. Additional dissemination channels for enhanced provision of PWS and hydrological services will be established including mobile platforms and the use of the Common Alerting Protocol (CAP).

While CAP is an excellent tool to disseminate forecast and warning information (and especially warnings) efficiently to key users, improved dissemination of routine information to the general public through broadcast channels, smartphones, text and voice messaging is also crucial. This will entail some improvements in audio and video recording facilities, and also the augmentation of back-end ICT facilities to support improved online platforms for forecast and warning information.

Key activities

- Establish an Integrated File and Message Switching System (IFMSS)
- Acquire software and adaptation of existing software
- Establish a data archive system
- Acquire sufficient numbers of servers, work-stations, and PCs
- Develop a data management system
- Develop intensity duration frequency curves using precipitation data
- Develop mobile apps for transmitting data from manual observation sites
- Enhance ICT systems for Centralized Data Management System
- Install high performing computing system for modelling and forecasting
- Upgrade existing networking components
- Acquire power backup systems, such as UPS and generators
- Upgrade firewall and security systems
- Replace existing old servers

> In neighboring Nepal, the introduction of an Integrated File and Message Switching System and a fully-featured Climate Database Management System (as part of a World Bank modernization project) has facilitated the semi-automated production of a rich selection of daily and seasonal climate reports, focused primarily on temperature and rainfall. These are made freely available on the website of the Department of Hydrology and Meteorology at https://www.dhm.gov.np/climate-services and constitute a very valuable resource for many user sectors in that country.

4.1.6 Education and Training

The *education* and *training* link will be at the *intermediate* maturity level. The education and *training* link will benefit from the introduction of more structured training activities to complement the new techniques, hardware, and software introduced into the NCHM at its medium-term modernization. These will include training of staff at the regional training and research institutions in meteorological and hydrological modelling techniques, impact-based forecasting, implementation and maintenance of the mobile app and CAP, and implementation of MHEWS.

Key activities

- Training in managing and maintaining the rehabilitated and expanded observation networks, including refresher courses for site observers
- Training in instrument calibration
- Training in basic weather forecasting on all time scales
- Training in impact-based forecasting
- Training in nowcasting
- Training in aviation forecasting
- Training in agromet advisory preparation

- Training in satellite meteorology
- Training in GIS and remote sensing application and interpretation of high-resolution satellite data
- Training in climate downscaling and projection
- Training in the database management system
- Advanced training in NWP
- Acquire access to and use of GIS tools for various purposes
- Acquire remote sensing GIS software and analysis tools for snowmelt modelling (specific to cryosphere modelling)
- Training in system administration and networking
- Training in QMS
- Introductory course on cryosphere physics (snow and glaciers) and cryosphere meteorology and hydrology
- Training in instruments and methods of cryosphere observations
- Training in use of satellite observations in cryosphere environments
- Training in theory and practice of fluorescent tracer hydrological observations in cryosphere environments (rivers and glaciers)
- Training in physics and processes of the formation and development of avalanches
- Training in theory and practice of elementary snow and glacier hydrological modelling
- Training in hydrological modelling and flood forecasting
- Training in tracer hydrology to introduce tracer hydrological methods, especially discharge measurements in mountain streams
- Training in the river water quality monitoring
- Training in snow and glacier hydrology, melt modelling, and snow cover mapping
- Training in preparing O&M strategy and annual plans.
- Develop training modules for refresher courses and basic courses on hydromet
- Develop competency framework for hydromet technicians and forecasters

4.1.7 Research and Development

In addition to enhancing the delivery of hydromet services on a daily basis, research and development are vital to advancing the reliability and delivery of hydromet services. This includes developing better models, improving understanding of the impacts of climate change on hydrometeorological patterns, and keeping up to date with advancing technologies and data availabilities, among many others.

Key activities

- Enhance the quality of Hydromet Journal
- Develop research guidelines for hydromet related subjects
- Conduct/organize national, regional and international seminars/conferences
- Conduct research to enhance hydrological modelling capabilities, incorporating advanced techniques and data assimilation methods for improved accuracy in river flow simulations.
- Conduct research to assess the impact of climate change on hydrological patterns, exploring potential shifts in precipitation, temperature, and extreme weather events
- Investigate and implement advanced data assimilation methods for integrating real-time observational data into hydrological and meteorological models, enhancing prediction accuracy
- Establish ongoing capacity-building programs to ensure staff proficiency in the latest research methodologies, modelling techniques, and technological advancements in both hydrology and meteorology
- Conduct research on glacier dynamics, mass balance, and retreat patterns
- Investigate the increased risk of GLOF and availability of water resources from melt contribution

4.1.8 Human Resource Requirements

The modernization plans, as described above, will need to be accompanied by an increase in staffing of the NCHM if the investments are to be fully exploited for the benefits of the citizens of Bhutan and fully sustainable. For example, an increase in the number of synoptic stations will increase the workload for maintenance and calibration activities. Increased exploitation of global and regional NWP models will require highly trained specialist meteorologists who can become expert at this work. Similarly with the greater use of satellite imagery, both for weather prediction and for monitoring of GLOF hazards, specialists in the area of satellite meteorology will be needed. Provision of 24/7 weather forecast and warning services (for both PWS and aviation) will need fully staffed rosters; the same applies to hydrological forecast and warning services and the oversight and maintenance of the ICT operations which underlie and facilitate all operational services. The introduction of upper air observations and weather radars will require specialists in these technologies to be either hired or trained from within the existing staff complement. The estimates of the staffing requirements for 24/7 services underlie the detailed staff number recommendations provided in Annex VII, as summarized below:

- Five extra technicians trained in instrument use, maintenance, and calibration, to support the expansion of the meteorological and hydrological observing network.
- One extra meteorological technician to support the upper air station (assuming that this is an auto-launcher and is located at an existing NCHM site).
- Six new met/hydro (M/H) officers for the operational weather forecast office (to bring the complement of fully trained forecasters in this office up to eight). The existing technical staff working in weather forecasting can either be trained up to full meteorologist level or be redeployed.
- Five new M/H officers for the aviation forecast office (to bring the complement of fully trained forecasters in this office up to six).
- Two new Instrumentation Engineers to support calibration and Instrumentation
- One new M/H technician for the operational flood forecast and warning office (to bring the complement in this office to six).
- Six new ICT-trained technicians to provide 24/7 oversight of the operational ICT systems.
- Three new specialists in NWP modelling, to lead the exploitation and adaptation of global models to Bhutan and engage with regional modelling groups in the development and use of high-resolution modelling capability.
- Two new specialists in climate modelling and downscaling.
- Two new specialists in cryosphere modelling.
- Three new specialists in hydrological modelling and verification.
- One new specialist in the exploitation of satellite data.
- Two new specialists in 'meteorological ICT' to oversee the establishment and maintenance of the IFMSS, data archive, data management system, and so on.
- Two new specialists in web/communications/broadcasting to enhance the delivery of weather products and services online and build stronger links with the TV and radio broadcasters in Bhutan.
- Two new specialists to work in developing and delivering tailored services to important user communities such as disaster management, agriculture, hydropower, and so on.
- One new QMS specialist to develop a QMS for the NCHM, oversee its implementation, and develop and maintain the necessary documentation and records.
- One new training officer who would work with staff to develop individual training plans and who would match training needs with training opportunities to ensure that all NCHM staff

remain up-to-date with their knowledge and expertise.

Training activities are expensive and at present, the provision of training opportunities is heavily dependent on the availability of funds. This roadmap therefore includes suggestions for different approaches to capacity building. Bhutan might be able to make use of the WMO RTC facilities available in India. Regionally organized training events, through bodies such as SAHF and/or RIMES, might be more economical than bespoke courses for NCHM alone. NCHM would most likely benefit from twinning with an advanced NMHS (for example, IMD) by sending its staff, particularly in modelling and forecasting areas, to spend time in such institutions to learn first-hand how a more advanced NMHS functions. Possible increases in the staffing complement, such as have been detailed above, can only come about through increased funding from the RGoB; for this the development of a strong business plan linking increased staffing with increased service provision would be of significant assistance, and this Roadmap provides some of the basis for this.

Annex III presents indicative costs and **Annex IV** presents the timeline for implementation of the proposed interventions for the short-term (5 years) in the NCHM.

4.2 Medium-Term Modernization (2029–2034)

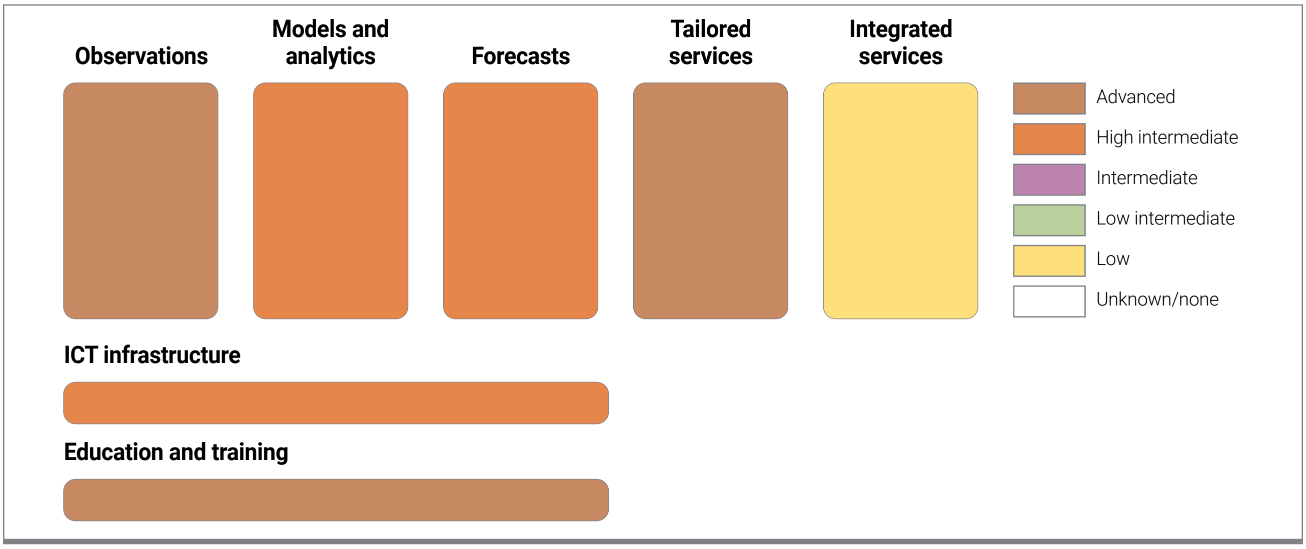
The provision of the best possible products and services requires a more complete modernization program. This forms the medium-term modernization in this roadmap, aiming to bring the NCHM up to the level of a well-functioning, modern NMHS with matching capabilities for providing data, forecasts, and warning services. Under this approach plans are made for a further five-year outlook beyond the government's immediate five-year planning cycle, to be reflected in the preparations for the 14th FYP.

Investments are targeted toward enabling development and acquiring advanced capabilities for the NCHM, as described in the sections below, to provide fit-for-purpose data, forecasts, and warning services for the safety of the public and protection of their livelihoods and enhanced support to the development of Bhutan's economy. This time frame provides the opportunity to develop integrated services in partnership with other national and international institutions and build on the public task to develop closer relationships with the private sector leading to the flourishing of private sector service providers. This modernization plan is expected to cost approximately US$20 million to implement over 10 years. This includes capital investments in the observation and ICT infrastructure, the total O&M costs (excluding labor costs) of approximately US$5.5 million, and capacity-building costs of US$1 million.

The short- and medium-term approaches are interdependent and should be conducted in a phased manner to seamlessly blend and build on each other to contribute to the overall goal of the modernization progress. Thus, the medium-term plan assumes the accomplishment of the majority of objectives in the medium term and builds on them.

Investment in the medium-term will provide the NCHM with a substantial increase in capabilities in forecasting, ICT, and service delivery to meet various user needs, in addition to fully meeting the public task. At this stage, most of the effort is focused on the full utilization of all the new/upgraded systems in observation, modelling, forecasting, and ICT that have been put in place during the medium term of modernization to produce fit-for-purpose services, so the investments proposed for this stage of modernization build on those detailed in Section 5.1. It is expected that a fully developed maintenance program for all hardware and software is in place. Following a 10-year modernization effort, the NCHM is expected to have a value chain whereby all the links are occupied at significantly higher levels on the maturity scale. The value chain after the completion of this period is shown in **Figure 30**.

Figure 30. Schematic of the NCHM value chain after medium-term modernization intervention



4.2.1 Observation

The *observation* link will be at an *advanced* level of maturity with the installation of **two** additional upper air stations, **one** weather radar to cover the Thimphu/Paro regions, 10 synoptic stations, and 10 AWSs, all of which transmit data automatically and are fully integrated and absorbed into a central ICT system. Cryosphere observations of permafrost are carried out at **two** locations. All historical data are digitized. The O&M budget is used for a proper life-cycle management of observation infrastructure and facilities. The investment for observations covers the cost of new observing equipment, tools, instrumentation, software and facilities, supply of spare parts, consumables, vehicles for field visits, fuel, the increased communication costs, power and other operating costs, and quality control/ quality assurance procedures. All the stations are fully functional.

Key activities

Weather and climate observation network:

- Expand the observation network to install **10** synoptic stations, **10** AWSs, two Doppler weather radars, **two** upper air stations

Hydrological monitoring network:

- Procure **two** additional ADCPs for discharge measurement and updating rating curves
- Enhance existing EWS and install additional EWS in other risk prone river basins

Cryosphere monitoring network:

- Provide **two** permafrost monitoring stations

Calibration of hydromet equipment

- Install **one** Wind sensor calibrator and **one** ADCP calibrator

4.2.2 Models, Analytics, and Forecasts

The *models and analytics* link will be at a *high intermediate* level of maturity. At this stage, a modelling group is established which is engaged in continuous R&D and introducing innovations in modelling, with strong links to regional partners in developing, running, and exploiting advanced models. Model post-processing and calibration and data assimilation are now part of the routine operation of the NCHM. In addition, a 30-year reanalysis of the Bhutan climate using a limited-area model would aid the design of infrastructural projects such as roads, bridges, and dams. The data could also be used to drive hydrological models to estimate return periods for flood conditions. In terms of hydrology modelling and forecasting, techniques for medium-term and long-term forecasts (including ensemble approach) are enhanced.

The *forecasts* link will be at the *high intermediate* level and the production of nowcasts, probabilistic forecasts as the basis of impact-based forecasting, and hydrological forecasts are routine.

Key activities

Weather and climate forecasting:

- Mainstream data assimilation, model post-processing, and calibration in the forecasting process
- Conduct routine production of probabilistic forecasts as the basis for impact-based forecasting and nowcasts
- Operationalize long range prediction system (climate forecasts, monthly, seasonal)
- Provide forecasts for wind, heatwave, and droughts

Hydrological and flood forecasting:

- Improve modelling and forecasting capabilities for medium- and long-term streamflow forecasts
- Enhance hydrological and cryosphere models and hydrological and flood forecasting
- Establish regular avalanche risk and warning services in selected areas
- Conduct routine hydrological and weather forecast verification

4.2.3 Services Delivery

The *tailored services* link will be at the *advanced* level at this stage, but further enhancements are still being made. Tailored services are now available to a wide cross-section of user sectors and further improvements are made in the dissemination mechanisms to communities. As part of its PWS, PWS/civil contingency advisers are deployed to provide links with user sectors and especially with DLGDM, to support the necessary preparatory and anticipatory actions to minimize the impact of hazardous hydromet events. Programs are developed and activities are organized to help increase the capacity of users to enable them to extract maximum benefits from data, products, and services provided by the NCHM and raise understanding and awareness among the public, especially in remote and mountainous communities, on weather-related hazards and risks. This work is especially important as impact-based forecasts and warnings become the more commonly used forms of information shared with the public. At this stage, the NCHM uses its own TV studio facilities to broadcast forecasts and prepare content for online platforms. SOPs enable the NCHM to codify how alerts, warnings, and other operational products are issued. The SOPs also enable stakeholders to define their responses to the various levels of alerts and warnings. The ISO certification for aviation services and an organization-wide QMS are maintained.

The *integrated services* link will be further enhanced to an *intermediate* maturity level. Opportunities are explored to develop a new business strategy for more sustainable operations by initiating public-private engagement such as fee-based service provision and outsourcing of certain activities such as modelling, ICT services, and software upgrading. MHEWS and impact-based forecasting intermingle, leading to the development of impact-based MHEWS in close collaboration with DLGDM. Other integrated services are also developed, for example, in agriculture, transport, construction, and health sectors by working closely with these sectors and coproducing services.

Key activities

- Develop services for a wide cross-section of user sectors with enhanced dissemination mechanisms
- Co-develop impact-based MHEWS with DLGDM; develop other integrated services, for example, in the agriculture, transport, construction, and health sectors
- Provide outreach and training support for main stakeholders in, for example, hydrology, DLGDM, and agriculture
- Establish an avalanche warning and prediction service for the general public and specific

users (for example, roads department, tourism services, hydropower companies)

- Revise and update SOPs to codify issuing alerts, warnings, and other operational products
- Maintain ISO 2001:2015 certificate for aviation
- Complete and maintain QMS for the entire NCHM.
- Establish regular assessment of seasonal changes and mid/long-term trends in water resources availability from snow and glacier regions for the scientific community and water resources management including hydropower generation potential
- Make available mass-balance changes and trends of selected glaciers
- Implement Quality Management System for entire NCHM

4.2.4 ICT

The *ICT* link will be at a *high intermediate* level. State-of-the-art ICT and computing facilities (within the technological, human resources, and financial capability of the NCHM) will occupy the ICT link. This includes a centralized data center comprising an IFMSS, a forecaster visualization system to allow forecasters to view all relevant data, a data archive which allows holding of all raw data in the medium term for quality control before the long-term storage of data; a CDMS for long-term storage of quality-controlled weather data; and sufficient number of servers, workstations, and personal computers. The planned move of the NCMH HQ to a separate campus, comprising specially designed buildings to house and support sophisticated ICT equipment, would be an important enabling element in achieving this level of ICT facility improvement. In addition, a service delivery platform and applications are established to disseminate and communicate products and information. A 'one-stop' users' portal for services, enabling easy and user-friendly access to serve all sectors from one location as well as mechanisms for collecting user feedback, is established.

Key activities

Develop a fully integrated ICT system by establishing:

- Forecast visualization system[30]
- Climate Database Management System
- A 'one-stop' users' portal
- Sufficient numbers of high performing servers, workstations, and personal computers (PCs)
- Software licenses
- Backup server in situ and in cloud

4.2.5 Education and Training

The *education and training* link will be at an *advanced* level, further strengthened to allow development of technical capacity and education through a professional training plan for NCHM personnel. On-the-job training of staff to support the implementation and application of upgrades for hydromet components, including issues around effective service delivery, is ongoing in a routine manner. More staff are trained at regional and international training centers. Training in communication is provided routinely to all staff, especially those who interact with the public and with sectoral stakeholders. Continuing professional development of the managerial, scientific, and technical staff of the organization is the norm.

Key activities

- Continuation of capacity-building and developing training programs for technical personnel through on-the-job and classroom training (by developing and using the training facilities of the new NCHM HQ)
- Training at regional and international training and research centers and other institutions—fellowships, attachments, longer-term education (for example, master's and PhD. degrees).

[30] This item was included in the five-year plan. If it has been implemented, then it can be removed from the 10-year plan. Another possible pathway is to provide a relatively simple forecast visualization system under the five-year plan and a more fully featured and advanced system (with production capability) under the 10-year plan.

4.2.6 Research and Development

- Undertake research on urban hydrology to understand the impact of urbanization on local hydrological cycles, storm water management, and flood risk in urban areas
- Explore the use of remote sensing technologies to monitor land cover changes, snowmelt patterns, and soil moisture, contributing to more comprehensive hydrological assessments
- Initiate community-based hydrological monitoring programs, involving local communities in data collection to enhance understanding of regional hydrological dynamics
- Invest in the development of probabilistic forecasting tools for both hydrology and meteorology, providing decision-makers with a range of possible scenarios and associated uncertainties
- Conduct research on flash flood prediction, focusing on developing accurate and timely forecasting models that consider local topography, rainfall patterns, and soil conditions
- Establish ongoing capacity-building programs to ensure staff proficiency in the latest research methodologies, modelling techniques, and technological advancements in both hydrology and meteorology

4.2.7 Human Resource Requirements

- **Four** extra technicians trained in instrument use, maintenance, and calibration, to support the expansion of the meteorological and hydrological observing network
- **Two** extra meteorological technicians to support the additional upper air stations (assuming that this is an auto-launcher and is located at an existing NCHM site)
- **Four** additional specialists to support, maintain, operate, and exploit the proposed weather radar network (two engineers, two meteorologists)
- **Four** additional hydrology technicians to help operate the new ADCP equipment and expand the collection of rating curves and so on
- One specialist technician to manage, maintain, and oversee the proposed permafrost monitoring station
- **Two** extra specialists in meteorological NWP to further improve exploitation of global weather models, deepen engagement with regional modelling initiatives, and conduct a 30-year reanalysis of the climate of Bhutan as a proxy for a detailed climate record
- **Two** extra hydrological modelers to enhance flood forecasting
- **One** additional cryosphere modeler to help develop avalanche risk and warning services
- **One** additional climate modeler to improve seasonal and climate range forecasting
- **Two** extra specialists in meteorological ICT systems—one each to manage and support the forecaster visualization system and the climate database management system
- **One** extra meteorologist or hydrologist focused on service delivery, to broaden and deepen the engagement of the NCHM with user communities
- **One** extra training and development officer, to focus on training, education, and outreach programs for users and for the public.

Annex V presents indicative costs and **Annex VI** presents the timeline for implementation of the proposed interventions for the medium-term (10 years) in the NCHM.

5. Conclusion

Directing traffic in Thimphu. Photo credit: Andrew Peacock.

5.1 Short- and Medium-term Modernization and Beyond

The modernization of hydromet products and services in Bhutan is driven by the needs of various user communities, as outlined in the roadmap. Discussions with NCHM management and stakeholders indicate a need to strengthen meteorological and hydrological information provision. The roadmap aims to enhance NCHM's capabilities by accessing up-to-date technologies and tools. Key improvements include a reliable data management system, diverse forecasting capabilities, integrated ICT systems, and effective service delivery mechanisms. Collaboration with disaster management, agriculture, health, and other sectors is encouraged. The roadmap offers two approaches to enhance NCHM's capabilities with different complexities and resource requirements.

Short-Term (5 years) Modernization (2024–2029)

This modernization approach, aligned with Bhutan's 5-year planning cycle, outlines investments needed to enhance NCHM's capabilities in providing meteorological and hydrological services, especially for disaster management, water resources, hydropower, and agriculture. It prioritizes critical activities such as accessing tools, acquiring essential equipment, and training personnel to improve forecasting expertise. Training focuses on interpreting observations, remote sensing data, numerical weather models, ensemble forecasting, methodologies, and communication techniques. The aim is to establish a solid foundation of meteorological knowledge among staff, addressing current deficiencies, and ensuring effective service delivery.

> The estimated cost of implementation of this approach is **US$14.9 million**. This includes operation and maintenance costs (excluding labor costs) of approximately **US$2.2 million** and capacity building costs of **US$1 million** and also cost of the construction of the scientific facilities of NWFWC of US$2.8 million.

Medium-term (10 years) Modernization (2029–2034)

Under this approach, plans are made for a further 5-year outlook beyond the immediate governmental 5-year planning cycle. Investment is needed to enable the development and acquisition of advanced capabilities for providing fit-for-purpose data, forecasts and warning services for the safety of the public, and for support to the development of Bhutan's economy.

> This modernization plan is expected to cost **US$19.9 million** to implement over 10 years. This includes total operation and maintenance costs (excluding labor costs) of **US$5.5 million** and capacity building costs of **US$1 million.**

Looking ahead: 2034 and beyond

While this roadmap focuses on modernization measures in short and medium term, the NCHM plans to prioritize the following investments from 2034 and beyond, after the successful implementation of the short- and medium-term modernization efforts. The following are areas which will require continuous and ongoing attention and investment if improvements are to be maintained:

- *User Interface platform and data accessibility:* Develop a unified user interface platform to facilitate easy access to meteorological, climate, and hydrological data, fostering engagement with end-users, policymakers, and stakeholders.
- *Climate Services Information System:* Establish and enhance a CSIS that integrates meteorological, climate, and hydrological data, ensuring interoperability and providing a centralized repository for comprehensive information.
- *Observations and Monitoring:* Upgrade and expand observational networks for meteorology and hydrology, incorporating advanced technologies for real-time monitoring and data assimilation.

- *Climate Research and Modelling:* Invest in cutting-edge climate research and modelling, utilizing advanced techniques to enhance understanding and predictability of climate patterns and trends.

- *Early Warning Systems:* Strengthen and expand early warning systems, integrating meteorological, hydrological and Cryosphere data for improved weather and flood forecasting, enhancing resilience against climate-induced disasters.

- *Vulnerability and Impact Assessments:* Conduct regular vulnerability and impact assessments to identify climate-related risks and guide adaptive strategies, ensuring a proactive approach to changing climate conditions.

- *Capacity Building:* Implement capacity-building programs to empower professionals in meteorology, climate science, hydrology and cryosphere, fostering a skilled workforce capable of addressing evolving challenges.

- *Knowledge Management and Public Awareness:* Establish effective knowledge management systems and public awareness campaigns, promoting a better understanding of climate-related issues and encouraging informed decision-making.

- *Cross-sectoral collaboration:* Facilitate cross-sectoral collaboration by integrating climate, meteorological, and hydrological considerations into various sectors, fostering resilience in agriculture, water management, and infrastructure.

- *Climate-Resilient Infrastructure development:* Develop and implement climate-resilient infrastructure development, incorporating meteorological and hydrological insights to ensure infrastructure sustainability in the face of changing climate patterns.

- *Community Engagement:* Engage local communities in climate and weather initiatives, incorporating indigenous knowledge and enhancing community resilience through tailored meteorological and hydrological solutions.

- *Innovation and Technology Integration:* Foster innovation and technology integration, exploring emerging technologies to enhance meteorological and hydrological services, and embracing advancements for continuous improvement.

- *Financial Mechanisms and Resource Mobilization:* Establish sustainable financial mechanisms, including public and private partnerships, to support the implementation of meteorological, climate, and hydrological projects over the 15-year period.

- *Continuous Monitoring and Evaluation:* Implement a robust monitoring and evaluation system to assess the effectiveness of interventions, ensuring adaptive management and continuous improvement throughout the 15-year time frame.

5.2 Public-Private Engagement and Service Provision

The private sector's involvement in the hydrometeorological value chain is limited in Bhutan, although both public and private actors are essential for improving weather and climate services. There is a need, on the one hand, to protect society from the impact of extreme/high-impact meteorological and hydrological events and, on the other, to increase economic activity in a range of weather sensitive sectors. Any effort to further improve weather and climate services must explicitly consider the role of both the public and the private sectors throughout the value chain—from the delivery of observations to the provision of services to end user customers and clients.[31] It is important to explore how both public and private sector actors can engage in the market and how to

[31] Thorpe, A., and D. Rogers. 2021. *Creating Value in the Weather Enterprise.* Washington, DC: World Bank.

ensure that competition is fair and of social and economic benefit to society.32

There is a general understanding that weather, climate, and water information is critical to business development, particularly in the context of climate change and the greater sensitivity of modern economies to environmental factors. While a government department or agency may benefit from participating in a commercial market, there is a risk that attempting to provide commercial services may detract from the core public task, resulting in weaker public services. Care must, therefore, be taken in any effort to balance commercial and public activities within an NMHS.

Sustainable funding is key, and for the immediate future it must come from government sources and development agencies as the current capacity of NCHM to develop alternative income streams through service provision is limited. However, NCHM needs to give serious thought as how to explore opportunities in marketing its products and services as it develops more technical capabilities. Some pilot projects in targeted service provision to specific stakeholders / user communities could be the first step to help NCHM to develop expertise and confidence in this area, and to improve its knowledge about the potential market for hydrometeorological services in Bhutan.

Improvements in the capacity of NCHM would bring with it the possibility of generating high-quality commercially-based services and thus augmenting the core income received from the RGoB. Ideally, an up-to-date economic study would be needed to estimate the potential revenue available for high quality meteorological services provided to key commercial stakeholders. This revenue estimate would then need to be set against the costs of providing and delivering such services (extra staff, high-level training, technology) to assess whether there would be a solid business case for investing in this approach.

At present, private hydrometeorological service providers do not operate in Bhutan. Cooperative activities between the NCHM and the private sector are also either nonexistent or are exceptions, for example, in the hydropower generation sector. One possibility to explore would be a joint venture between NCHM and hydropower companies to explore the potential of small tributaries through the establishment of localized rainfall and river gauging networks. This may change in the future with the increasing development of the economy and potential growth of the private sector engaged in hydrometeorology. In such a future environment, the primary role of the NCHM would be to focus on providing public services while operating within a regulatory framework with respect to any overlapping with the operations of the private sector. It is perhaps fair to assume that the NCHM is expected to continue as the principal public service provider for the foreseeable future.

Through strengthening Public-Private Engagement, NCHM can engage with potential partners in the hydromet space (for example, equipment and service providers) that can potentially help in the dissemination and implementation of the main findings and recommendations of this roadmap.

5.3 Innovation

Advances in scientific and technical innovations have been a cornerstone of the evolution of meteorology and hydrology over the past decades and these will continue into the future with exciting and promising developments to produce ever more relevant, useful, and usable tools for decision-making by individuals and the society as a whole. Some of the key innovations in meteorology and hydrology such as the application of artificial intelligence (AI), ever more powerful ensemble forecasting models, climate reanalysis, and data assimilation are described below in general and with specific application to Bhutan.

[32] World Bank. 2019. *The Power of Partnership: Public and Private Engagement in Hydromet Services.* Washington, DC: World Bank.

AI, deep learning (DL), and machine learning (ML) techniques will enable all NMHSs, including those in developing countries, to access a range of products that will enhance forecasting techniques. The use of these techniques is a rapidly growing aspect of weather modelling and involves creating large member forecast ensembles, potentially extending the number of ensembles and downscaling both global and regional models to provide highly localized forecasts of rain and other critical weather parameters.

The size and resolution of operational ensemble forecasts are constrained by computational resources, particularly in developing countries. ML techniques can be used to oversample numerical weather prediction distributions, enabling more accurate representation of extreme weather events (the so-called tails of the distribution), for example, high rainfall, at relatively low computation cost.

ML tools can generate more specific impact maps using location data in real time enabling more targeted risk communication. This will overcome the difficulties with current practice of issuing warnings which often cover a large geographical area when, in practice, the area affected is likely to be much smaller. This will also allow sending resources, like emergency workers and supplies, to places to be affected by the hazard.

ML techniques can also be applied to data on weather impacts which when combined with the ensemble predictions provide point-specific and sector-specific highly localized probabilistic forecasts of weather impacts. In addition, ML techniques can be applied to human behavior to create realistic decision support systems which can target specific needs of individual communities and businesses and provide personalized actionable forecasts and warnings.

By including ML generative forecasts that utilize all existing local data in addition to numerical weather predictions, warnings can be issued earlier. This is particularly important for nowcasts of severe weather. Similarly, ML can provide timely warnings related to human activities rather than only considering the meteorological event. For example, ensuring that messages are received before rush hour or before schools and workplaces open.

One of the challenges faced by users of meteorological services in Bhutan is that the climate record is sparse and rather short in duration. The orography of Bhutan is extreme, which makes it difficult to construct a comprehensive and consistent record of the evolution of weather over the country, because of the relative lack of observations and because the observations from a given location may not be representative of nearby areas. Local observations could be extended using ML techniques to create fields, which in turn can be used for bias correction of the ensemble and rapidly update the forecast cycle to create 0–6-hour hyperlocal predictions.

Climate reanalysis technique could be used to construct a useful climatological record for Bhutan. This uses the analysis schemes that are part of modern NWP models coupled with all available historical weather data to create a series of weather analyses over the target area from some chosen date in the past up to recently. The global ERA-5 reanalysis dataset has been created by ECMWF, with a horizontal resolution of about 31 km and extending from 1940 to almost the present day. The data would be too coarse to provide useful climatological information for Bhutan, but they do provide a baseline record of the climate over the past eight decades. Climate reanalysis techniques provide a means to overcome the short, and patchy, climate record for Bhutan are an alternative source of estimates of extreme weather etc.

It would be possible to create a much higher-resolution reanalysis dataset for a specific limited domain which could act as a proxy for a climatological record based only on surface observations. For example, the 'MÉRA' dataset33 was created for Ireland by Met Éireann. This dataset can be used to provide estimates of extreme values of wind, rain, and temperature and other parameters of interest to users at any particular point within the model domain. The meteorological data can also be used to drive flood modelling for river catchments, helping to generate an understanding of the possible extreme events and their annual likelihood.

Creating these reanalyses takes a lot of computer time and power and could best be carried out in an academic environment or at an advanced weather modelling center. In the case of Bhutan, it is likely that an Indian institution would be best placed to carry out this type of work. An ML model based on the ERA-5 dataset from ECMWF would suffer from the coarse resolution for the extreme orography of Bhutan. Using ML models in the context of Bhutan, therefore, would necessitate developing a high-resolution climate dataset (similar to the MÉRA dataset) which might then be used to train the ML-based model. A considerable amount of research work would be required to arrive at this point.

The major drawback of the limited-area WRF model run by the NCHM is lack of assimilation of local data into the model initialization and post-processing schemes to provide bias correction or calibration. This is also a deterministic model, providing only one possible evolution of weather conditions. There is a strong move away from deterministic models and toward ensembles where a model is run multiple times and probabilities of weather events can be derived from the output.

[33] MÉRA = Met Éireann Reanalysis. Whelan, E., E. Gleeson, and J. Hanley. 2018. "An Evaluation of MÉRA, a High-Resolution Mesoscale Regional Reanalysis." *J. Appl. Meteor. Climatol.* 57: 2179–2196, https://doi.org/10.1175/JAMC-D-17-0354.1. (The MÉRA dataset covers 35 years from 1981 and creates a high-resolution (2.5 km) regional climate reanalysis dataset at 3-hour time intervals over the 35-year period.)

Currently, ECMWF is running a global 100-member ensemble every six hours with a horizontal resolution of 9 km and using world-leading (4Dvar) data assimilation techniques. The output from this ensemble is far superior to almost all the limited-area modelling that is run in the developing countries, so it makes no sense to compete with it in any way. The long-term plans for ECMWF are for the model resolution to be improved to 5 km and eventually to 1 km or 2 km over the coming decade, as more high-powered computers become available.

The question for smaller NMHS such as the NCHM, therefore, is how best to benefit from this exceptional capability provided by the global models. One approach is to directly calibrate and downscale the output from the global ensembles to local scales (calibration would lean heavily on the output of local or regional reanalysis schemes). It is possible that ML would have a role to play in this process. Another is to run impact-based models which would take the weather forecast data and transform them into information of value to users. An example might be a model which would convert rainfall amounts into river flows and thus predict available capacity for hydroelectric generation. Other examples might combine forecast data for rainfall, temperature, and sunshine to produce indexes of crop growth or similar.

One drawback of these extremely high-resolution global ensembles is that the data volume which they produce is enormous. Therefore, schemes such as those described in the preceding paragraph would need to be implemented at the supercomputer site where the model is run, so that only the locally focused output would need to be transmitted back to the relevant NMHS. This 'bringing the application to the data' is a common challenge in all big-data contexts.

This section strongly suggests the overall migration over time toward the use of superior ECMWF product. However, in the short term NCHM will not lose anything in learning the basics of NWP such as verification and parametrization, since WRF already is used, and to abandon this work precipitously would not confer any benefits. The roadmap stresses that human and financial resources should not be invested in developing new Limited Area Models; this is rather different than making the best use of what NCHM already has in the short to medium term.

The implications for the NCHM would be, in the longer term, to move its focus away from developing local-area NWP modelling and instead focus on schemes to bias-correct, calibrate, and downscale global model data and train some of their scientists in AI/ML techniques. It will also be important to develop a climate reanalysis dataset. Costs for these activities, including capacity building, have been included in the estimates in Annexes III and V.

5.4 An Inclusive Approach to Modernization

Inclusion is paramount in providing hydromet services, since the access and use of information and the ability to understand the information and messages and make appropriate decisions vary widely. Vulnerability to high-impact and severe weather and coping capacities vary due to criteria such as the socioeconomic standing, gender, age, and physical and mental disabilities. It is recognized that women play a key role in protecting family and assets from hazards during extreme and high-impact hydrometeorological events, when men are often working away from home. It is also known that men and women have different needs and capabilities for accessing information and responding to warnings. It is therefore essential to be responsive to gender-based and socioeconomic considerations in formulating and communicating warnings for multiple hazards. Also, in building community capacities to receive and be able to take early action in response to warnings, differences in vulnerabilities and capacities are key considerations. Studies conducted in Bhutan[34] have identified that due to the prevailing gender-based disparities that are discriminatory toward women, their receipt and access of information related to disaster and climate risk, technical support, and extension services are not equitable.

It is vital to ensure that the modernization of the NCHM takes an approach that is inclusive of gender aspects[35] and vulnerable groups (such as those suffering from physical or mental disabilities), as the impacts of forecasts and warning services lie in their ability to reach the people, sectors, and businesses that are most at risk, and in the capacity of people to take protective actions in good time. Warning messages, for example, should be communicated in ways that enable those with vision or hearing impairment to receive them.

The implementation of this roadmap must reflect this approach, acknowledging the roles and capacities of different groups and maximizing their involvement. This would not only provide opportunities for them to participate but also ensure that the process benefits from their key knowledge (including traditional and cultural) and experience. This is aligned with achieving objectives and targets of several national policies and strategies in Bhutan such as national FYPs, Climate Change Policy, Disaster Management Act, National Environmental Protection Act, and National Gender Equality Policy.

For gender-responsive and socially inclusive hydromet services, there are three essential areas to consider:

a. Livelihoods and economic production in the climate-sensitive sectors

[34] RGoB, National Commission for Women and Children, Gender, and Climate Change in Bhutan, with a focus on Nationally Determined Contribution Priority Areas: Agriculture, Energy, and Waste, 2020.
Analysis of Disaster Risk Management and Gender Nexus in Bhutan (Draft- Assessment conducted for the World Bank)
[35] Gender-based disadvantages and discriminatory practices that mostly affect women.

b. Vulnerabilities of varying community groups to impacts of hydrometeorological hazards and coping capacities

c. Impact-based services and warning systems, tailoring services to user needs.

This should be done by collecting information via various tools, such as surveys and focus groups, to inform the design of hydrometeorological information services, particularly warnings, such that they include these different needs for anticipatory action and promote coherence of response. In addition, Bhutan needs to strengthen the availability of gender- and age-disaggregated data to understand the severity of the impact of disasters on different gender identities. Country-wide specific analysis on how different gender and vulnerable groups receive, interpret, and respond to alerts is also needed.

Provision of gender-transformative high-impact weather and early warning services means addressing the root causes and structures that lead to gendered impacts. Different from a superficial headcount, this requires proactively designing and redesigning practices to reduce inequalities to meet all people's needs. Similar consideration should be given to the inclusion of vulnerable groups. Disaster risks for people with different abilities and disabilities are greater and they face more danger during any hazard, yet common warning alerts and response measures are not always adequate for them. An inclusive approach in impact-based and early warning services design and implementation would improve outcomes for vulnerable people and create accessible products that also benefit others in their communities. A transformative gender-responsive and socially inclusive methodology examines who is most at risk; who has access to the information required for generating early warnings; how and to which population groups early warnings are issued; whether preparedness and response measures are adequate to respond to alerts; and which groups should contribute to disaster preparedness, response, and recovery.[36] These considerations need to be an integral part of the implementation of this roadmap.

The following provisions under the 'service delivery' component of this roadmap enable strengthening the existing actions, and initiating new actions, to address the range of gender and social inclusion aspects related to hydromet information and services:

- Address communication channels, strengthening relationships with stakeholders and users including gathering feedback *(enables two-way communication).*
- Develop impact-based forecasting to facilitate users' anticipatory measures and response capability *(enables consideration of variations in vulnerability and capacity of community groups).*
- Enhance communication of information in a needs-based manner through multiple dissemination and communication channels and socially relevant modes and communication formats *(enables consideration of the challenges of non/semi-literate, disabled/differently abled).*
- Enhance tailored services to critical weather-dependent economic sectors *(enables consideration of the weather-related constraints of the livelihoods of the marginalized within the economic sectors).*
- Establish communication links with user groups, private sector entities, related government departments, and institutions of higher learning as well as create links with international partners in the region *(such as ICIMOD) and beyond.*

Lastly, a complementary aspect is the employment of women and persons of marginalized groups in technical as well as administrative functions in production and delivery of services. Equal

[36] Globally, the connection between EWS and the rights of vulnerable groups stems from interaction of the Sendai Framework, Beijing Declaration, and the Platform for Action and the Convention on Human Rights of People with Disabilities.

opportunities should also be made available to men, women, and other groups for contribution with their experience and knowledge and for participation in training and capacity-building programs.

5.5 Stakeholders Engagement and Dissemination

Because meteorology and hydrology are of such key importance to social and economic activity in Bhutan, it is imperative that NCHM keeps in close contact with many elements of society to ensure that its work is both fully exploited and properly appreciated.

- NCHM routinely engages with key stakeholders through workshops and similar. Key stakeholders include government ministries and departments, commercial entities, tourism representatives, community organizations and NGOs. Every opportunity, both formal and informal, should be used to foster awareness on hydromet challenges and to disseminate the recommendations of the roadmap.

- NCHM might consider community outreach through workshops and educational programs to raise awareness at the grassroot level about the benefits of hydromet services.

- Regional/International collaboration: At the regional level NCHM should aim to deepen collaboration and work with neighboring countries which are already contributing to the different components of the hydromet value chain. The South Asia Hydromet Forum (SAHF), of which Bhutan is an active member, represents a platform to advance the ambitions articulated in this roadmap and to foster data and knowledge sharing.

Annexes

Gasa lake. Photo credit: Dechen Tshering.

ANNEX I
Organizational Structure, Staffing, and Budget of the NCHM

A.1 Organizational Structure

Secretariat

The Secretariat is the top-level organizational and administrative unit of the NCHM. The main function of the Secretariat is the management of the NCHM and its divisions and is responsible for Finance, Human Resource Management, Procurement, Stores, and Administration. It provides the overall policy and administrative direction and leadership, facilitating the mobilization of funds, managing the regional and international relations, and monitoring and evaluating programs/plans as per the government procedures.

Technical Standard and Research Division

The TSRD is mandated to coordinate research and publications, calibration of instruments, standardization of hydrometeorological data, and related observations.

Functions

- Develop and establish operational policies, guidelines, and other relevant standards pertaining to hydrometeorological instruments, observations, and statistics.
- Develop and promote national standards for methods, procedures, techniques, and practices in hydrology, meteorology, and operational hydrology in coordination with relevant regulatory agencies and technical regulations, guidelines, and manuals of the World Meteorological Organization (WMO) and ICAO.
- Develop technical manuals for operational hydrology, meteorology, and cryosphere observations.
- Develop a competency framework and training manuals for operational hydrology, meteorology, and cryosphere in coordination with other divisions.
- Carry out calibrations of hydromet instruments and equipment.
- Coordinate and conduct research improvements to existing standards, technical manuals, and guidelines.
- Coordinate research on new science and technologies with technical divisions and external agencies.
- Provide research clearance on the field of hydrology, meteorology, and cryosphere sciences.
- Provide technical sanction for works and procurement of goods and services.
- Publication of research journals, technical manuals, and related reports.
- Compliance monitoring of standards and quality assurance for observation and data collection in the field of hydrology, meteorology, and cryosphere.

Cryosphere Services Division

CSD is mandated to monitor, carry out research and produce inventories on cryosphere (snow, glaciers, glacier lakes), and perform hazard assessments to generate science-based information for understanding climate change, mitigation and adaptation planning, and cryosphere hazards such as avalanches and GOLFs. Cryosphere observation stations are looked after by the Weather and Climate Services Division (WCSD) technicians. Currently, CSD carries out field observations by trained technicians, engineers, and geologists on three benchmark glaciers and other glacial lakes. Hazard assessments and hazard mapping are carried out by HWRSD. The flood/GLOF hazard assessment is carried out by HWRSD while the GLOF modelling is done by CSD.

Functions

- Prepare plans and programs related to cryosphere (snow, glaciers, glacier lakes, permafrost) monitoring in Bhutan Himalaya.
- Conduct time series monitoring of glaciers and glacial lakes.
- Maintain inventory and national cryosphere database (Cryosphere Information Hub).
- Assess hazards and risks of glaciers and glacier lakes and threat of GLOFs including mapping and melt contribution from glaciers and snow to river runoff.
- Provide information on snowpack development and snow properties for the establishment of an avalanche warning system.
- In cooperation with other departments, assess hazards and risks of cryosphere-related mass movements (as a result of thawing of permafrost).
- Research and publish scientific papers on cryosphere and related studies.
- Coordinate with national agencies related to snow and glacier monitoring and data collection.
- Foster collaboration with regional and international institutions/agencies involved in the field of cryosphere research and data sharing through the center.
- Provide professional and technical services to the center/other agencies on conceptual and methodological aspects of cryosphere monitoring and related studies.

Meteorological Services Division

The MSD is mandated to observe and provide PWS, severe weather warnings, climate data management and services, long-range forecasting, climate change information and services, agrometeorology, and aviation meteorological services. The total staff of the division is 57, with 23 of these working in the HQ.

Functions

- Operate the national meteorological observation network.
- Provide PWS.
- Monitor extreme weather events and issue warnings/bulletins/advisories.
- Operate and maintain the national climate database management system.
- Conduct climate modelling, downscaling, and climate change projections.
- Provide climate services including agrometeorological services.
- Prepare and provide short-, medium-, extended-range and seasonal forecasts.
- Conduct research and development in the field of weather and climate change.
- Serve as the aviation meteorological service provider within Bhutan.
- Undertake education, training, and awareness programs on weather and climate.

Hydrology and Water Resources Services Division

HWRSD is mandated for water resources assessment, hydrological observation, forecasting, hydrological data management, dissemination of hydrological data and information, and the issue of early warning services related to floods and GLOFs. This is the largest division with more than one hundred staff members, the majority of whom are stationed at the observing sites across Bhutan.

Functions

- Install, operate, and maintain of national hydrological and flood observation networks including sediment and ambient water quality.
- Operate flood/GLOF EWSs.
- Provide hydrological forecast, issue flood/GLOF advisories, and early warning services.
- Operate the National Hydrological Database Management System.
- Carry out national water resource assessment and maintain river information system.
- Carry out R&D in the field of hydrological science.
- Carry out flood/GLOF hazard assessment and mapping.
- Provide hydrological data and information.
- Provide ambient water quality data and information.
- Conduct education, training, and awareness programs on operational hydrology.
- Under the guidance of CSD, conduct education, training, and awareness programs on GLOF EWS, snow properties, and avalanches.

A.2 Staffing

Table A.1 shows the staff strength in divisions under the NCHM.

Table A.1. NCHM approved and existing staff strength and distribution

Division/Secretariat	Approved by RCSC	Existing	Gap	Remarks
Secretariat	12	9	-3	
TSRD	7	5	-2	
CSD	8	7	-1	
MSD	57	50	-7	
HWRSD	114	105	-22	
Drivers and ESP	9	9	0	
Total	**207**	**185**	**-22**	**Regular approved 198 and 9 by standard**

Source: NCHM.

Table A.2. Staff numbers (existing) by division and by location

Location/Function	Secretariat	TSRD	CSD	MSD	HWRSD	Total
Director/Chiefs	1	1	1	1	1	5
HQ – for 9 to 5 work	8	2	6	12	15	50
NWFWC shift work				7	5	12
Airports				13 (7 Paro, 2 Bumthang, 2 Gelephu, 2 Yongphula)		13
Laboratories		2			3	5
Drivers and sweepers	9					9
Other locations				17	68	78
HWRSD-GoI Program					13	13
Total	**18**	**5**	**7**	**50**	**105**	**185**

Source: NCHM.

Table A.3. Staff mapping, Secretariat, NCHM

Organizational structure		Staffing patterns			
Division	**Section**	**Position**	**Approved post**	**Existing staff**	**Gaps**
Office of Director	Office of Director	Director	1	1	0
		Personal assistant	1	1	0
Secretariat Services	Secretariat	Program officer	1	0	-1
	Human Resources Services	HR officer	1	1	0
		Admin assistant/HR assistant	2	2	0
	Procurement Services	Procurement officer	1	1	0
		Store assistant	1	1	0
		ICT officer	1	0	-1
		ICT assistant	1	1	0
	Finance Services	Finance officer	1	0	-1
		Account assistant	1	1	0
	Pool Staff	Driver	8	8	0
		Sweeper	1	1	0
Total			**21**	**18**	**-3**

Table A.4. Staff mapping TSRD, NCHM

Organizational structure		Staffing patterns			
Division	Section	Position	Approved post	Existing staff	Gaps
Technical Standards and Research Division	TSRD	Chief M/H officer	1	1	0
	Technical Planning and Standard Section (including calibration)	M/H officer	2	1	-1
		M/H technician	2	1	-1
	Research and Publication Section	M/H officer	2	2	0
Total			**7**	**5**	**-2**

Table A.5. Staff mapping CSD, NCHM

Organizational structure		Staffing patterns			
Division	Section	Position	Approved post	Existing staff	Gaps
CSD	CSD)	Specialist/chief M/H officer	1	1	0
	Monitoring and Survey Section	M/H officer	5	4	-1
	Cryosphere Information Management Section	M/H officer	1	1	0
		M/H technician	1	1	0
Total			**8**	**7**	**-1**

Table A.6. Staff mapping MSD, NCHM

Organizational structure		Staffing patterns			
Division	Section	Position title	Approved Post	Existing staff	Gaps
MSD	Weather Forecasting	Chief M/H officer	1	1	0
		M/H officer	3	3	0
		M/H technician	7	4	-3
	Climate Data Management	Statistical officer	1	1	0
		M/H technician	3	3	0
	Climate Services	M/H officer	5	3	-2
		M/H technician	1	1	0
	Meteorological Observation	M/H officer	2	1	-1
		M/H technician	1	1	0
		M/H officer	2	1	-1
	Aviation Meteorology	M/H technician	11	11	0
	East Regional Stations	M/H technician	9	9	0
	West Regional Stations	M/H technician	11	11	0
Total			**57**	**50**	**-7**

Table A.7. Staff mapping HWRSD, NCHM

Organizational Structure		Staffing Patterns			
Division	Section	Position Title	Approved Post	Existing staff	Gaps
HWRSD	HWRSD	Specialist/Chief M/H Officer	1	1	0
	Forecasting and Warning	M/H technician	5	5	0
	Hydrological Data Management	M/H officer	2	1	-1
		Statistical officer	1	1	0
		M/H technician	2	2	0
	Sediment and Water Quality Monitoring	Principal engineer	1	1	0
		Lab assistant	2	2	0
	Hydrological Observation	M/H officer	4	4	0
		Assistant engineer	1	1	0
		M/H technician	1	1	0
	Office of the TMO (GoI)	Engineer	1	1	0
		Admin Assistant	1	1	0
		M/H technician	2	2	0
		Assistant engineer	1	1	0
		M/H technician	1	1	0
	Eastern Region (9 dzongkhags)	M/H officer	1	1	0
		M/H technician	54	36	-18
	Western Region (11 dzongkhags)	M/H technician	33	30	-3
Total			**114**	**92**	**-22**
OVERALL TOTAL HWRSD (Including 13 ESP/GSP under FWS-GoI)				105	

Table A.8. Existing staff capacity by professional category

Division/Secretariat	Engineers/Meteorologists/ Hydrologists	Technicians/Nontechnical	Admin support
Secretariat	1		17
TSRD	3	2	
CSD	6	1	
MSD	11	39	
HWRSD	10	81	1
HWRSD-GoI Program			13 (ESP/GSP)
Total	**31**	**123**	**31**

A.3 Budget

The total NCHM budget allocations (RGoB and Donors) for 2012–2021 and the expenditure for FY2012–2021 are shown in **Tables A.9** and **A.10**, respectively.

Table A.9. NCHM total budget allocation for FY2012–2021 (US$, millions)

Funding source	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
RGoB									
Current	0.516	0.576	0.550	0.6	0.44	0.6	0.6	0.8	1.4
Capital	0.2	0.174	0.378	0.2	0.11	0.23	0.1	0.3	0.4
Total	**0.716**	**0.750**	**0.928**	**0.8**	**0.55**	**0.83**	**0.7**	**1.1**	**1.8**
Development partners and donors									
Current	0.0	0.0	0.0	0.03	0.04	0.03	0.02	0.02	0.013
Capital	0.237	0.571	1.426	2.4	3.4	1.7	2.7	0.38	0.64
Total	**0.237**	**0.571**	**1.426**	**2.43**	**3.44**	**1.73**	**2.72**	**0.4**	**0.653**
GoI (flood warning activity)									
Current	0.230	0.233	0.222	0.0	0.23	0.3	0.3	0.23	0.2
Capital	0.112	0.149	0.227	0.0	0.3	0.5	0.4	0.23	0.3
Total	**0.342**	**0.382**	**0.449**	**0.0**	**0.53**	**0.8**	**0.7**	**0.46**	**0.5**
Grand Total	**1.295**	**1.703**	**2.803**	**3.23**	**4.52**	**3.36**	**4.12**	**1.96**	**2.953**

Figure A.1 depicts the total budget of the NCHM over the past nine years, with **Figures A.2** and **A.3** respectively showing the same budget broken down into current and capital expenditure. Figure A.3 clearly shows the strong dependency on development partner funding to support capital expenditure, although in more recent years the capital expenditure is more balanced between the three sources, mainly due to a decrease in capital (project) funding from development partners.

Figure A.1. NCHM total budget—past nine years

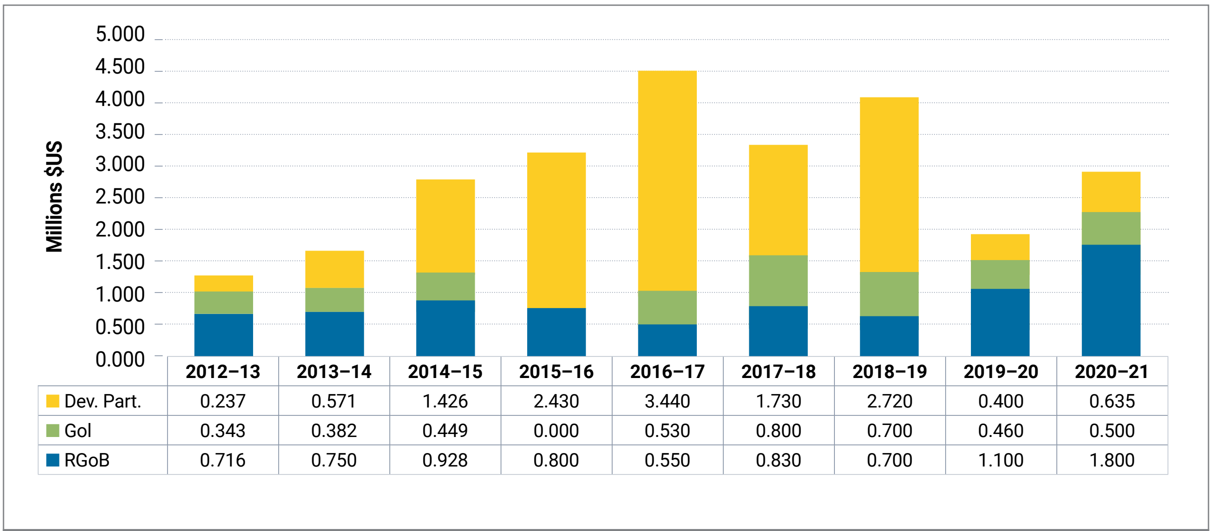
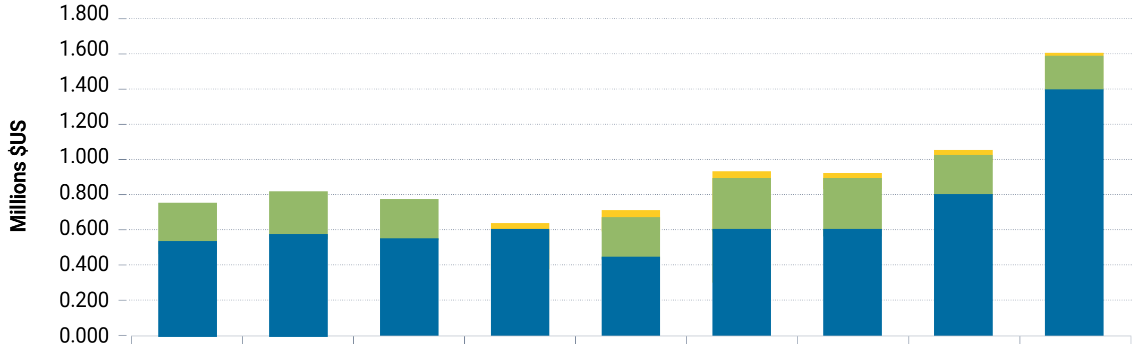


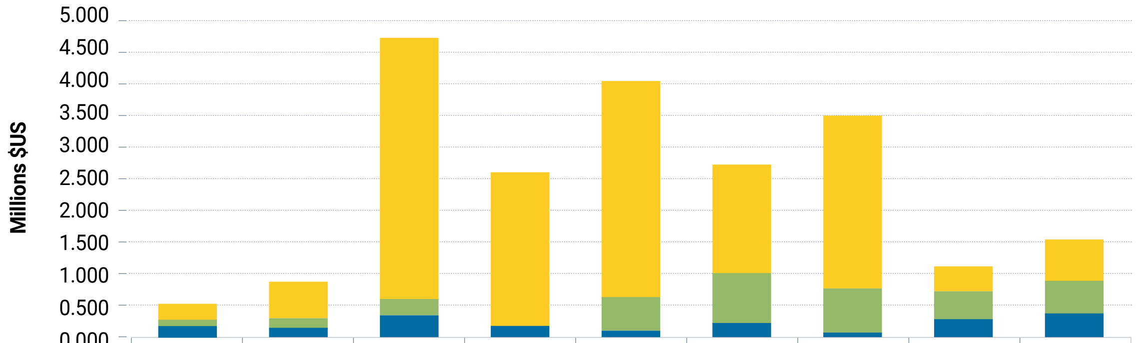
Figure A.2. NCHM current budget—past nine years



	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
Dev. Part.	0.000	0.000	0.000	0.030	0.040	0.030	0.020	0.020	0.013
GoI	0.230	0.233	0.222	0.000	0.230	0.300	0.300	0.230	0.200
RGoB	0.516	0.576	0.550	0.600	0.440	0.600	0.600	0.800	1.400

Figure A.2, however, indicates a degree of resilience in the current budget, and the increase over the final three years displayed is noteworthy. This is particularly relevant as the proposed capital investments outlined in Chapter 4 as being necessary for the modernization program will need to be complemented by a significant rise in the current budget if the full benefits of modernization are to the delivered to the Bhutanese citizens.

Figure A.3. NCHM capital budget—past nine years



	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
Dev. Part.	0.237	0.571	4.126	2.400	3.400	1.700	2.700	0.380	0.640
GoI	0.112	0.149	0.227	0.000	0.530	0.800	0.700	0.460	0.500
RGoB	0.200	0.174	0.378	0.200	0.110	0.230	0.100	0.300	0.400

Table A.10 and **Figure A.4** clearly show how the NCHM has been efficient in utilizing both its own (RGoB) budget resources and those provided by development partners. In almost all instances, the expenditure figures reach 90 percent or more of the available budget.

Figure A.5 provides a percentage breakdown of the total budget spending over the nine years from FY13 to FY21 between the three sources of funding. The figures are clearly skewed by the significant capital expenditure from development partner funding from 2014 to 2019.

Table A.10. NCHM total expenditure summary for 2012–2021 (US$, millions)

Funding source	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
RGoB									
Total approved budget	0.716	0.75	0.928	0.8	0.55	0.83	0.7	1.1	1.8
Total expenditure	0.68	0.7	0.84	0.72	0.51	0.79	0.63	0.96	1.6
% Utilized	94.97	93.33	90.51	90.00	92.72	95.18	90.00	87.27	88.88
Development partners and donors									
Total approved budget	0.237	0.571	1.426	2.43	3.44	1.73	2.72	0.4	0.653
Total expenditure	0.231	0.566	1.4	2.35	3.42	1.71	2.6	0.38	0.63
% Utilized	97.46	99.12	98.17	96.70	99.41	98.84	95.58	95.00	96.47

Figure A.4. Percentage expenditure of annual budget

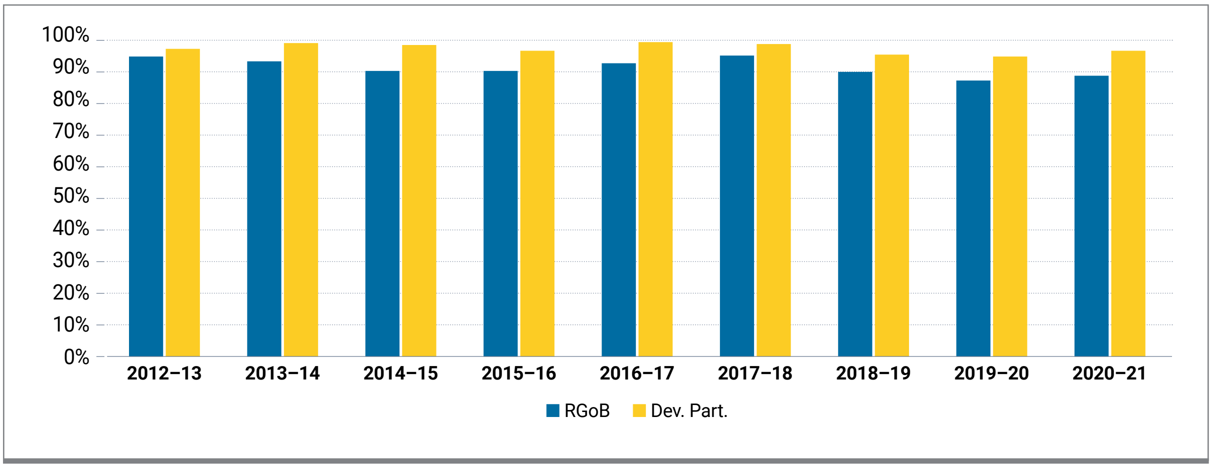
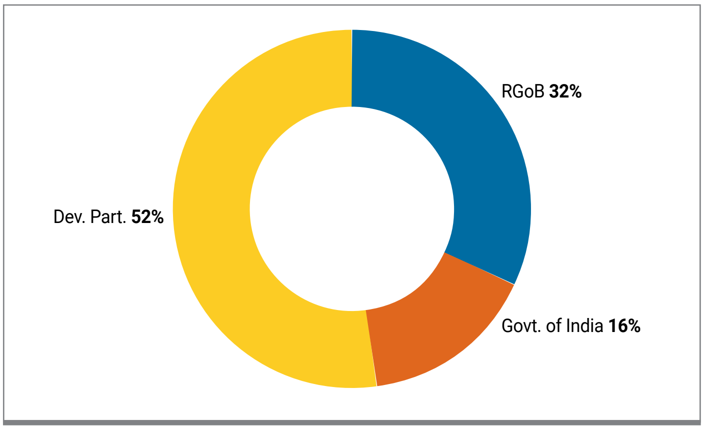


Figure A.5. Percentage of sources for total budget, 2012–13 to 2020–21



ANNEX II
Breakdown of the Estimated Cost of the New NCHM Campus

S. No.	Building type	No. of buildings	Plinth area (m^2)	No. of floors	Total plinth area (m^2)	Plinth area rate (BTN)	Plinth height (m)	Cost of building (BTN)
1	Main office building	1	410.14	2	820.276	7,084	3.5	40,675,846.29
2	Conference	1	134.22	1	134.22	7,084	3.5	3,327,850.68
4	Office canteen	1	134.22	1	134.22	7,084	3.5	3,327,850.68
5	Sediment lab and water quality analysis lab	1	175.25	1	175.245	7,084	3.5	4,345,024.53
6	Instrumentation and calibration lab	1	175.25	1	175.245	7,084	3.5	4,345,024.53
7	Central store and instrument maintenance workshop	1	206.82	1	206.82	7,084	3.5	5,127,895.08
8	24/7 staff quarters	1	120.00	2	240	7,084	3.5	11,901,120.00
9	Hostel	1	120.00	2	240	7,084	3.5	11,901,120.00
10	Establishment of hydromet garden	1	Lumpsum					10,000,000.00
11	Compound fencing	1	Lumpsum					5,000,000.00
12	External water supply and storage tank	1	Lumpsum					5,000,000.00
13	Site development and parking	1	Lumpsum					10,000,000.00
14	Construction of approach road	1	Lumpsum					84,607,900.00
15	Solar field 20 KVA	1	Lumpsum					13,680,128.00
							SUB TOTAL (A)	**213,239,759.79**
16	Occupational health and safety (OHS) cost	2.78% of above sum on (A)						5,928,065.32
17	Cost of Environmental Management Plan	5% Pre, during and operational phase on (A)						10,661,987.99
							GRAND TOTAL (BTN)	**229,829,813.10**
							Equivalent in US$ million Exchange rate used as of December 20, 2022: US$1 = BTN 84	**US$2.8m**

ANNEX III
Indicative Costs of the Proposed Short-Term Modernization

Activity	Quantity	Unit purchase/ upgrade cost (US$)	Total purchase/ upgrade cost (US$)	Annual O&M cost per site[37] (US$)	Total annual O&M cost (US$)	Total O&M cost over 3 years[38] (US$)
Construction of NCHM campus and scientific facilities	**n.a.**	**n.a.**	**2.800,000**			
Observations						
1. Upgrading critical observing stations with satellite telemetry	50	5000	250,000	500	25,000	75,000
2. Establishing new synoptic stations (including civil works and provision of services)	5	100,000	500,000	4,000[39]	20,000	60,000
3. Upper air station	1	750,000	750,000	140,000[40]	140,000	420,000
4. Developing new GLOF warning systems for 3 basins	3	1,200,000	3,600,000	120,000	360,000	1,080,000
5. Developing new cryosphere stations	5	100,000	500,000	5,000	25,000	75,000
6. ADCP	2	35,000	70,000	3,500	7,000	21,000
7. Automatic water quality equipment	6	6000	36,000	600	3,600	10,800
8. Automatic sediment monitoring sites	5	20,000	100,000	2,000	10,000	30,000
9. Mobile spectrofluorometer instruments for discharge measurement in highly turbulent mountain streams and rivers and corresponding robust laptop for direct field data evaluation	2	5,000	10,000	1,000	2,000	6,000
Total costs of observation infrastructure including specialized training	**Capital (US$5,816,000) + 3-year O&M (US$1,777,800) = US$7,593,800**					

Activity	Quantity	Unit purchase/ upgrade cost (US$)	Total purchase/ upgrade cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost over 3 years (US$)
ICT						
1. IFMSS	1	200,000	200,000	30,000	30,000	90,000
2. Training costs		100,000				
3. Data archive	1	210,000	210,000	25,000	25,000	75,000
4. Training costs over 5 years		60,000				
5. Workstations and PCs (including for cryosphere)	1 lot	300,000	300,000	30,000	30,000	90,000
6. Servers	5	10,000	50,000	1000	5,000	15,000
7. Remote sensing and GIS software for Cryosphere	1	45,000	45,000			
8. General GIS software license	1	4,000	4,000			12,000[41]

37 All O&M costs are exclusive of labor costs.
38 Assuming that spare parts and maintenance will be provided by suppliers for one full year following the start of operation of all equipment and taking into account that procurement and installation of equipment will take approximately one year, the indicated O&M budget will cover three full years of operations.
39 O&M costs for high-altitude observing stations and cryosphere observations could be high. Current costs for glacier monitoring expeditions would be a reasonable guide.
40 The O&M costs refer to cost of balloons, sondes, tether, parachute, and gas. Based on the global basic observation network (GBON) requirements, two manual launches per day are assumed (total 730 per year), with 100 percent performance (uptime) and a cost of US$190 per launch.
41 This figure assumes that the license has to be renewed every year.

Annex III: Indicative Costs of the Proposed Short-Term Modernization (cont.)

Activity	Quantity	Unit purchase/ upgrade cost (US$)	Total purchase/ upgrade cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost over 3 years (US$)
9. Acquisition of software and adaptation of existing software[42]	1	100,000				
Total costs of ICT including specialized training	**Capital (US$909,000) + training (US$160,000) + 3-year O&M (US$282,000) = US$1,351,000**					
Modelling and forecasting						
1. Developing probabilistic forecasting, impact-based forecasting (with disaster risk management), nowcasting, and sectoral based forecasting	1		700,000			
2. Monthly and seasonal forecasting and climate projection and downscaling						
3. Hydrological modelling and forecasting						
4. Dynamic riverbed modelling						
5. Glacial melt modelling						
6. Visualization system including hardware and software and software maintenance of support and license fee per year	1	300,000	300,000	30,000	30,000	90,000
7. Training costs spread over 5 years		100,000				
Total cost of modelling and forecasting including specialized training	**Capital cost (US$1,000,000) + training (US$100,000) + 3-year O&M (US$90,000) = US$1,190,000**					
Training						
Capacity-building and training program (on-the-job training, training at RTCs and other institutions) on various targeted areas listed above (Section 5.1.5)	5	200,000	1,000,000			
Total cost of training	**US$1,000,000 (over 5 years)**					
Service Delivery						
1. Establishing/improving user feedback including developing SOPs			50,000			
2. Building media profile and brand	1		100,000			
3. Developing mobile application for delivery of products	1		150,000			
4. Communication training for NCHM forecasters and other key staff	1		100,000			
5. ISO 2001: 2015 certification for aviation	1		300,000[43]		4,000	12,000[44]
6. Developing QMS for the entire NCHM	1		200,000[45]		1,000	5,000
7. Initiating the use of CAP	1		50,000			

[42] This figure can vary from minimal cost for stand-alone shareware software packages (such as shareware hydrology, meteorology software packages) to several hundred thousand dollars for integrated IT systems including the database system, depending on what IT requires. That must be established in a separate IT design concept. The proposed figure is an approximation.

[43] This figure is an approximate estimate since the majority of the cost is that of the full-time staff assigned to the task and the cost of consultant to be engaged to initiate the process.

[44] ISO accreditation is normally on a three-year cycle and costs approximately US$12,000 per cycle.

[45] As for aviation, the majority of the cost is that of the full-time staff assigned to the task and the cost of consultant to be engaged to initiate the process.

Annex III: Indicative Costs of the Proposed Short-Term Modernization (cont.)

Activity	Quantity	Unit purchase/ upgrade cost (US$)	Total purchase/ upgrade cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost over 3 years (US$)
8. Establishing cell phone broadcast services for warnings	NCHM to get an approximate quote from a local telecom provider					
Total cost of capacity building for improved service delivery	**Capital cost (US$950,000) + recurring cost (US$17,000) = US$967,000**					

Overall costs for short-term modernization	
Total capital cost of the new NCHM center	**US$2,800,000**
Total capital costs of equipment and facilities including specialized training	**US$8,935,000**
Total costs of training	**US$1,000,000**
Annual O&M costs	US$717,600
Total O&M costs (3 years @ US$717,600/annum)	**US$2,166,800**

Total cost of implementing	**US$8,935,000 + US$1,000,000 + US$2,166,800 + US$2,800,000 = US$14,901,800**

ANNEX IV
Timeline of Activities for Short-Term Modernization (2024-2029)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Infrastrucutre					
2	Calibration laboratory, sediment and water qyality laboratory	☐	☑	☑	☑	☐
3	Store snd equipment mainetnance workshop	☑	☑	☑	☑	☐
4	Establishment of aviation offices at domestic and international airports	☐	☑	☑	☐	☐
5	Establishment of hydromet information center and climate lab	☐	☑	☑	☑	☐
6	Acquiring vehicles for station maintenance	☐	☑	☑	☐	☐
	Information Technology (ICT)					
1	Establishing an Integrated File and Message Switching System (IFMSS)	☐	☑	☑	☐	☐
2	Acquisition of software and adaptation of existimng software	☐	☑	☐	☐	☐
3	Establishing a Data Archive System	☐	☑	☐	☐	☐
4	Acquiring sufficient numbers of servers, workstations, and PCs	☐	☑	☑	☑	☐
5	Developing a Data Management System	☐	☑	☑	☑	☐
6	Acquiring access to and use of GIS tools for various purposes	☐	☑	☑	☐	☐
7	Remote sensing GIS software and analysis tools for snow melt modelling (specific to cryosphere modelling)	☐	☑	☑	☐	☐
8	Development of intensity duration frequency curves using precipitation data	☐	☐	☑	☐	☐
9	Developing mobile apps for transmitting data from manual observation sites	☑	☑	☐	☐	☐
10	Enhancement of ICT systems for Centralized Data Management System	☑	☑	☑	☐	☐
11	Installation of high performing computing system for modelling and forecasting	☐	☑	☑	☑	☐
12	Upgradation of existing networking components	☐	☑	☑	☑	☑
13	Acquiring power back up systems, such as UPS and generators	☑	☑	☐	☐	☐
14	Upgradation of firewall and security systems	☑	☑	☑	☑	☑
15	Replacement of existing old servers	☐	☑	☑	☐	☐
	Observation Networks					
A	**Climate and weather observation network**					
1	An upgrade of the existing observation network; installation of 1 upper air station and 5 new synoptic stations	☑	☑	☐	☐	☐
2	Upgradation and standardization of existing 20 Agrometeorological stations (Class A stations)	☑	☑	☑	☐	☐
B	**Aviation observation network**	☐	☐	☐	☐	☐
1	Upgradation of AWOS at domestic airports	☑	☑	☑	☐	☐
2	Installation of AWOS at international airports	☐	☐	☐	☐	☐
3	Integration of AWOS with Centralised Database Management System	☐	☑	☑	☐	☐
C	**Cryosphere monitoring network**	☐	☐	☐	☐	☐
1	3AWS (or appropriate technology) with capabilitie of observing snow water equivalent/snow depth and set up at least one glacier runoff odel in a sub basin	☑	☑	☐	☐	☐
2	Establishing 5 new cryosphere stations	☐	☐	☐	☑	☐

Annex IV: Timeline of Activities for Short-Term Modernization (2024-2029) (cont.)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Observation Networks (cont)					
C	**Cryosphere monitoring network (cont.)**					
3	Developing systematic observation of volime changes of selected glacier lakes including bathymetric surveys	☑	☑	☑	☑	☑
D	**Hydrological monitoring network**	☐	☐	☐	☐	☐
1	Upgrading from existing GPRS/GSM to satellite-based telemetry for critical AWLS and AWS sites and FWS	☐	☑	☑	☑	☐
2	Introduction of 6 handheld automatic water quality monitoring units for ambient water quality monitoring	☑	☑	☐	☐	☐
3	Installation o 5 real time sediment monitoring systems upstream of major hydropower stations	☐	☑	☑	☑	☐
4	2 ADCP for regulart discharge management and updating of rating curves	☐	☑	☑	☐	☐
5	2 mobile spectrofluorometer instruments for discharge measurement using fluorescent tracers (Uranin) in highly turbulent mountain streams and rivers	☐	☑	☑	☐	☐
6	Expansion of the GLOF early warning system for basins as per requirement	☐	☑	☑	☑	☑
7	Enhancement of existing GLOF and early warning monitoring network	☐	☑	☑	☑	☑
E	**Callibration of hydrometequipment**	☐	☐	☐	☐	☐
1	Installation of 1 humidity sensor calibrator, 1 rain gauge calibrator, 1 solar radiation calibrator, sunshine recorder calibrator	☐	☑	☑	☐	☐
2	Installation of 1 current meter calibrator and water level sensor claibrator	☐	☐	☐	☑	☐
3	Development of user manuals, check lists and guidelines for data collection, quality management, maintenance and forecasting	☑	☑	☑	☑	☑

	Modelling and Forecasting Investment					
A	**Weather and climate forecasting**	☐	☐	☐	☐	☐
1	Further accessing and using other regional and global models; introducing data assimilation, post-processing and calibration of these models	☐	☐	☑	☑	☐
2	Introducing EPS and probabilistic forecasting	☐	☑	☑	☐	☐
3	Introducing impact-based forecasting	☐	☐	☑	☑	☑
4	Developing nowcasting systems	☐	☐	☑	☑	☐
5	Operationalize medium range forecasting (7-10 DAYS)	☑	☑	☑	☐	☐
6	Initiating long range climate forecasting (monthly, seasonal)	☑	☑	☑	☑	☑
7	Climate projection and downscaling	☑	☐	☐	☐	☑
8	Development of Terminal Aerodrome Forecasts (TAF) and Severe Weather Forecasts (SIGMET) for Aviation	☐	☐	☑	☑	☐
9	Initiation of Numerical Weather Prediction (NWP) verification system (WRF)	☑	☑	☑	☐	☐
10	Operationaliztion of common operating platform (COP-SMART MET)	☑	☑	☑	☑	☑
11	Parameterization of NWP (WRF)	☐	☐	☑	☑	☐
B	**Hydrological and flood forecasting**	☐	☐	☐	☐	☐
1	Developing grid-based forecasting tools for hydrology	☐	☑	☑	☑	☐
2	Acquiring a forecast visualisations systems (or upgrade the existing system)	☑	☑	☑	☐	☐
3	Developing secotral based forecasts	☑	☑	☑	☑	☑

Annex IV: Timeline of Activities for Short-Term Modernization (2024-2029) (cont.)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Modelling and forecasting investment (cont.)					
B	**Hydrological and flood forecasting (cont.)**					
4	Enhancing hydrological models for hydrological forecasting	☐	☑	☑	☑	☐
5	Initiating hydrological and weather forecast verification	☐	☑	☑	☑	☐
6	Dynamic riverbed modelling (incorporation of sediment transport)	☐	☐	☑	☑	☑
7	Expansion of flood forecasting and early warning system to other basins (WIMES)	☐	☑	☑	☑	☑
C	**Snow and glacier modelling**	☐	☐	☐	☐	☐
1	Modelling snow and glacier melt water	☐	☐	☑	☑	☐
2	Developing enhanced and quality-contolled data sets on snow and glacier melt and initial modelling of seasonal snow and glacier melt	☐	☐	☑	☑	☐
3	Glacier mass balance modelling	☐	☐	☐	☑	☑
4	Glacier lake breach modelling	☑	☑	☐	☐	☐

	Services Delivery Investment					
1	Establishing/improving user-oriented culture including introduction of user feedback systems	☑	☑	☑	☑	☑
2	Developing/strengthening Standard Operating Procedures (SOP) and guidelines for service delivery	☑	☑	☑	☑	☑
3	Enhancing the website of NCHM	☑	☑	☐	☐	☐
4	Enhancing weather services provided on social media	☑	☑	☑	☑	☑
5	Enhancing forecast accuracy for 3 days forecast to more than 65%	☐	☐	☐	☑	☑
6	Developing/deepening links with broadcast media	☑	☑	☑	☐	☐
7	Developing mobile application for the delivery of products	☑	☑	☑	☐	☐
8	Initiating the use of CAP for warnings	☐	☐	☑	☑	☐
9	Initiating SMS based warnings in collaboration with telecom service provider	☐	☐	☐	☑	☑
10	Establishing cell phone broadcast services for warnings in collaboration with telecom provider	☐	☐	☐	☑	☑
11	Establishing Glcier Lake Outburst warning service including assessments of glacier lake dam stability	☑	☑	☐	☐	☐
12	Further development of GIS based inventory and time/spatial development of hazardous glacier lake in Bhutan	☐	☑	☑	☐	☐
13	Field surveys to monitor hazardous glacier lakes, including arial visualisation and terrestrial observations	☐	☑	☐	☑	☐
14	Developing Grid-based precipitation and temperature forecast maps	☐	☐	☑	☑	☐
15	Acquiring ISO certification for aviation	☐	☐	☐	☐	☑
16	Developing and implementation of QMS for Aviation Meteorology	☐	☐	☑	☑	☐
17	Developing manuals for observation methods, instrumentation including their calibration and maintenance	☑	☑	☑	☑	☑
18	Develop standards for observation, data collection, monitoring, data management and forecasting	☑	☑	☑	☑	☑
19	Development of National Framework for Climate Services (NFCS)	☐	☑	☑	☑	☐
20	Enhancement of Agrometeorological Services	☑	☑	☑	☐	☐
21	Development of drought monitoring prortal	☐	☑	☑	☐	☐
22	Development of climate information systems	☐	☑	☑	☐	☐
23	Enhancement of remote data collection using mobile apps	☑	☑	☑	☐	☐

Annex IV: Timeline of Activities for Short-Term Modernization (2024-2029) (cont.)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Capacity Building Investment					
1	Traning in managing and maintaining the rehabilitated and expanded observation networks, including refresher courses for the site observers	☑	☑	☑	☑	☑
2	Traning in instrument calibartion	☑	☑	☑	☑	☑
3	Traning in basic weather forecasting on all time scales	☑	☑	☐	☐	☐
4	Traning in impact-based forecasting	☐	☑	☑	☑	☐
5	Traning in nowcasting	☑	☑	☐	☐	☐
6	Traning in aviation forecating	☑	☑	☑	☐	☐
7	Traning in agromet advisory preparation	☑	☑	☐	☐	☐
8	Traning in GIS and remote sensing application	☑	☑	☑	☐	☐
9	Traning in climate downscaling and projection	☐	☑	☑	☑	☐
10	Traning in database management system	☑	☑	☑	☐	☐
11	Advanced training in numerical weather prediction	☐	☑	☑	☑	☐
12	Training in application of GIS tools	☑	☑	☐	☐	☐
13	Training in systems adminitration and networking	☐	☑	☑	☑	☐
14	Training in QMS	☐	☑	☑	☑	☐
15	Introductory course on cryosphere physics (snow and glaciers) and cryosphere, meteorology and hydrology	☑	☑	☐	☐	☐
16	Training in instruments and methods of cryosphere observations	☑	☑	☐	☐	☐
17	Training in use of satellite observations in crysophere environments	☑	☑	☐	☐	☐
18	Training in theory and practice of fluorescent tracer hydrological observations in cryosphere environments (rivers and glaciers)	☑	☑	☐	☐	☐
19	Training in physics and processes of the formation and development of avalanches	☐	☐	☑	☐	☐
20	Training in theory and practice of elementary snow and glacier hydrological modelling	☑	☑	☐	☐	☐
21	Training in hydrological modelling and flood forecasting	☐	☑	☑	☐	☐
22	Training in tracer hydrology to introduce tracer hydrological methods especially discharge measurements in mountain streams	☐	☑	☑	☐	☐
23	Training in the river water quality monitoring	☑	☑	☐	☐	☐
24	Training in snow and glacier hydrology, melt modelling and snow cover mapping	☑	☑	☐	☐	☐
25	Training in preparing O&M strategy and annual plans	☑	☑	☑	☐	☐
26	Development of training modules for refresher courses, basic hydromet courses	☑	☐	☐	☐	☐
27	Development of competency framework for hydromet technicians and forecasters	☑	☑	☐	☐	☐

	Research and Development					
1	Enhancement of Hydromet Journal	☑	☑	☐	☐	☐
2	Development of research guidelines	☑	☑	☐	☐	☐
3	Conduct/organize national, regional and international seminars/ conferences	☐	☑	☑	☑	☑
4	Conduct research to enhance hydrological modelling capabilities, incorporating advanced techniques and data simulation methods for improved accuracy in river flow simulations	☐	☐	☑	☐	☐
5	Conduct research to assess the impact of climate change on hydrological patterns, exploring potential shifts in precipitation, temperature, and extreme weather events	☑	☑	☐	☐	☐

Annex IV: Timeline of Activities for Short-Term Modernization (2024-2029) (cont.)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Research and Development (cont.)					
6	Investigate and implement advanced data assimilation methods for integrating real-time observational data into hydrological and meteorological models, enhancing prediction accuracy	☐	☐	☐	☑	☑
7	Establish ongoing capacity-building programs to ensure staff proficiency in the latest methodologies, modelling techniques, and technological advancements in both hydrology and meteorology	☐	☑	☑	☐	☐
8	Conduct research on glacier and mass balance, retreat patterns	☑	☑	☑	☑	☑
9	Investigating the incresead risk of GLOF and availability of water resources from melt contibution	☑	☑	☑	☑	☑

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Human Resource requirements to support short-term modernization					
1	Five extra technicians trained in instrument use, maintenance and calibration, to support the expansion of the meteorological and hydrological observing network	☑	☑	☐	☐	☐
2	Two extra meteorological technicians to support the upper-air station (assuming that this is an auto-launcher and is located at an existing NCHM site	☑	☐	☐	☐	☐
3	Six new Met/Hydro officers for the operational weather forecast office (to bring the complement of fully trained forecasters in this office up to eight). The existing technical staff working in wheather forecasting can either be trained up to full meteorologist level or be re-deployed	☑	☑	☑	☐	☐
4	New Met/Hydro officers for the aviation forecast office (to bring the complement of fully trend forecasters in this office up to six)	☐	☑	☑	☑	☐
5	Two new instrumentation engineers to support calibration and instrumentation	☐	☑	☑	☑	☐
6	One new Met/Hydro technician for the operational flood forecast and warning office (to bring the complement in this office to six)	☑	☑	☐	☐	☐
7	Six new ICT-trained technicians to provide 24/7 oversight of the operational ICT systems	☐	☑	☑	☑	☐
8	Three new specialists in NWP modelling, to lead the exploitation and adaptation of global models to Bhutan and to engage with the regional modelling groups in the development and use of high resolution modelling capability	☐	☑	☑	☑	☐
9	Two new specialists in climate modelling and downscaling	☐	☑	☑	☐	☐
10	Two new specialists and cryosphere modelling	☑	☑	☑	☐	☐
11	Three new specialists in hydrological modelling and verification	☐	☑	☑	☑	☐
12	One new specialist in the exploitation of satellite data	☐	☐	☑	☐	☐
13	Two new specialists in "Meteorological ICT" to oversee the establishment and maintenance of the IFMSS, Data Archive, Data Management Systems, etc.	☐	☐	☑	☑	☐
14	Two new specialists in Webb/communications/broadcasting to enhance the delivery of weather products and services online and to build stronger links with the TV and radio broadcasters of Bhutan	☐	☐	☑	☑	☐
15	Two new specialists to work in the developing and delivering tailored services to important user communities such as disaster management, agriculture, hydropower, etc.	☐	☐	☑	☑	☐
16	One new QMS specialist to develop quality management system for in NCHM, oversee its implementation and develop and maintain the necessary documentation and records	☐	☐	☐	☑	☐
17	One new training officer who would work with staff to develop individual training plans, and who would match training needs with training opportunities to ensure that all NCHM staff remain up-to-date with their knowledge and expertise	☐	☐	☑	☐	☐

ANNEX V
Indicative Costs of the Proposed Medium-Term Modernization

Activity	Quantity	Unit purchase cost (US$)	Total purchase cost (US$)	Annual O&M cost per site (US$)[46]	Total annual O&M cost (US$)	Total O&M cost for 8 years[47] (US$)
Observations						
1. Synoptic stations (additional to current, including civil works and support such as power supply)	10	100,000	1,000,000	4,000	40,000	320,000
2. AWSs (including civil works and support such as power supply)	10	75,000	750,000	4,000	40,000	320,000
3. Two Doppler weather radars (one for eastern Bhutan) including civil works and infrastructure (tower, generator, UPS, and so on)	2	3,000,000	6,000,000	50,000	100,000	800,000
4. Upper air station including civil works	2	500,000	1,000,000	124,100	248,200[48]	2,233,800[49]
5. ADCP	2	35,000	70,000	3,500	7,000	56,000
6. Permafrost monitoring stations	2	100,000	200,000	5,000[50]	10,000	100,000
7. Vehicles for field visits, tools to support field operations, maintenance and inspections, spare parts, consumables, fuel	5	20,000	100,000	2,000	10,000	80,000
Total costs of observation infrastructure including specialized training	**Capital (US$9,120,000) + 8-year O&M (US$3,909,800) = US$13,029,800**					

Modelling and forecasting	
1. Continuous improvement of the weather forecasting processes, including mainstreaming of data assimilation, model post-processing, and calibration in the forecasting process 2. Producing routine nowcasts and probabilistic forecasts as the basis of impact-based forecasting (including software as required) 3. Continuous improvement of hydrological and cryosphere modelling and flood forecasting capabilities 4. Enhancing climate forecasting capabilities (monthly, seasonal) 5. Routine hydrological and weather forecast verification 6. Reanalysis of the Bhutan climate using a limited-area model	1,000,000
Total cost of modelling and forecasting	**Capital cost (US$1,000,000)**

46 All O&M costs are exclusive of labor costs.

47 Assuming that spare parts and maintenance will be provided by suppliers for one full year following the start of operation of all equipment, and taking into account that procurement and installation of equipment will take approximately one year, the indicated O&M budget will cover eight full years of operations. It is recognized that this timescale extends beyond the 5-10 year time frame of the medium-term modernization, but it is important to reflect it full here as it will eventually fall back on the recipient institution and thus it needs to be emphasized.

48 The O&M cost refers to cost of balloons, sondes, tether, parachute, and gas. Based on the GBON requirements, two manual launches per day are assumed (total 730 per year), with 100 percent performance (uptime) and a cost of US$170 per launch.

49 The O&M costs for upper air station is calculated for nine years, assuming that procurement and installation of equipment and civil works will take approximately one year.

50 Annual visits will be expensive given the terrain.

Annex V: Indicative Costs of the Proposed Medium-Term Modernization

Activity	Quantity	Unit purchase cost (US$)	Total purchase cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost for 8 years (US$)
ICT (an integrated ICT system)						
1. Forecaster visualization system	1	300,000	300,000	30,000	30,000	240,000
2. Climate database management system	1	750,000	750,000	75,000	75,000	600,000
3. A 'one-stop' users' portal services	1	150,000	150,000	15,000	15,000	120,000
4. Workstations and PCs	1 lot (10+30)	8,000 + 2,000	140,000	14,000	14,000	112,000
5. Backup server for all data	1	20,000	20,000	2,000	2,000	16,000
6. Backup on cloud (subscription)	1				5,000	50,000[51]
7. HPC for downscaling and other post-processing as well as possibly running climate models	1	1,000,000	1,000,000	50,000	50,000	400,000
Total cost of ICT	**Capital cost (US$2,360,000) + 8-year O&M (US$1,538,000) = US$3,898,000**					

Activity	Quantity	Unit purchase cost (US$)	Total purchase cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost for 8 years (US$)
Services delivery						
1. Services for a wide user cross-section with enhanced dissemination mechanisms, including establishing regular avalanche risk and warning services in selected areas	1		300,000			
2. Codeveloping integrated services with DLGDM and other sectors (for example, agriculture, health)	1		400,000			
3. Outreach and training support for main stakeholders (for example, hydrology, DLGDM, agriculture)	1		200,000			
4. Revising and updating SOPs for issuing warnings and other operational products	1		50,000			
5. Maintaining the ISO 2001: 2015 (or upgrading) certification for aviation	1				4,000	40,00052
6. Completing and maintaining QMS for the entire NCHM	1				1,000	10,000
Total cost of service delivery	**Capital cost (US$950,000) + recurring cost (US$50,000) = US$1,000,000**					

Activity	Quantity	Unit purchase cost (US$)	Total purchase cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost for 8 years (US$)
Training						
On-the-job training, training at NCHM HQ new training facilities, RTCs, and other institutions, fellowships, attachments, higher degrees	5 years worth of training spread over 10 years	200,000	1,000,000			
Total cost of training	**Capital cost (US$1,000,000)**					

51 Subscription is for the entire 10 years.
52 ISO accreditation is normally on a three-year cycle and costs approximately US$36,000 per cycle.

Annex V: Indicative Costs of the Proposed Medium-Term Modernization

Activity	Quantity	Unit purchase cost (US$)	Total purchase cost (US$)	Annual O&M cost per site (US$)	Total annual O&M cost (US$)	Total O&M cost for 8 years (US$)
Overall costs for medium-term modernization						
Total capital costs of equipment and facilities						**US$13,430,000**
Total capacity-building costs for 5 years (spread over 10 years)						**US$1,000,000**
Total annual O&M costs						**US$651,200**
Total O&M over 10 years						**US$5,497,800**
Total cost of implementing over 10 years	**US$13,430,000 + US$1,000,000 + US$5,497,800 = US$19,927,800**					

ANNEX VI
Timeline of Activities for Medium-Term Modernization (2029-2034)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Observation Networks Investment					
A	**Climate and weather observation network**					
1	Additional expansion of the observation network to install 10 Synoptic stations, 10 AWS, 2 Doppler Weather Radar, 2 upper air stations	☐	☐	☐	☑	☑
B	**Hydrological monitoring network**	☑	☐	☐	☐	☐
1	Procurement of two additional ADCP for discharge measurement and updating rating curves	☑	☑	☐	☐	☐
2	Enhancement of existing EWS and installation in other risk prone river basins	☑	☑	☑	☑	☐
	Modelling and Forecasting Investment					
A	**Weather and climate forecasting**					
1	Mainstreaming data assimilation, model post-processing and calibration in the forecasting process	☐	☑	☐	☐	☐
2	Routine production of probabilistic forecasts as the basis for impact-based forecasting, and now-casts Re-analysis of the Bhutan climate (e.g., 30 years) using a limited-area model	☐	☐	☑	☐	☐
3	Operationalization of long range prediction system (climate forecasts, monthly, seasonal)	☐	☑	☐	☐	☐
4	Provision of forecasts for wind, heatwave, and droughts	☐	☑	☐	☐	☐
B	**Hydrological and flood forecasting**	☐	☐	☐	☐	☐
1	Improving modelling and forecasting capabilities for medium- and long-term stream flow forecasts	☑	☑	☑	☑	☐
2	Enhancing hydrological and cryosphere models and flood forecasting	☑	☑	☑	☐	☐
3	Establishing regular avalanche risk and warning services in selected areas	☐	☐	☐	☑	☑
4	Routine hydrological and weather forecast verification	☑	☑	☑	☑	☑
	ICT Investment					
1	Developing a fully integrated ICT system by establishing Forecast Visualization System	☑	☑	☑	☐	☐
2	Enhancement of Climate Database Management System	☑	☑	☐	☐	☐
3	A "one-stop" users' portal	☐	☑	☑	☐	☐
4	Sufficient numbers of servers, workstations, and PCs	☐	☐	☑	☑	☐
5	Software licenses	☐	☐	☐	☐	☐
6	Back-up server in situ and in cloud	☐	☐	☑	☑	☐
7	Installation of high performing computers and workstations	☐	☑	☐	☑	☐
	Services Delivery Investments					
1	Services for a wide cross section of user sectors with enhanced dissemination mechanisms	☑	☑	☑	☐	☐
2	Co-developing Impact-based Multi-Hazard Early Warning Systems (MHEWS), developing other integrated services, for example in agriculture and health sectors	☑	☑	☐	☐	☐
3	Outreach and training support for main stakeholders in, for example, hydrology, DLGDM, and agriculture	☐	☑	☑	☐	☐

Annex VI: Timeline of Activities for Medium-Term Modernization (2029-2034)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
	Services Delivery Investments (cont.)					
4	Establishment of an avalanche warning and prediction service for the general public and specific users (e.g., roads department, tourism services, hydro power companies)	☐	☐	☐	☑	☑
5	Revising and updating SOPs to codify alerts, warnings, and other operational products	☑	☑	☐	☐	☐
6	Maintaining ISO 2001:2015 certificate for aviation	☐	☑	☑	☐	☐
7	Completion of and maintaining QMS for entire NCHM	☑	☑	☐	☐	☐
8	Establishment of regular assessment of seasonal changes and mid-, long-term trends in water resources availability from snow and glacier regions for the scientific community and water resources management including hydro power generation potential	☑	☑	☐	☐	☐
9	Making available mass-balance changes and trends of selected glaciers	☑	☑	☑	☑	☐
10	Implementation of Quality management System for entire NCHM	☐	☑	☑	☐	☐
	Research and development					
1	Undertake research on urban hydrology to understand the impact of urbanization on local hydrological cycles, storm water management, and flood risk in urban areas	☑	☑	☐	☐	☐
2	Explore the use of remote sensing technologies to monitor land cover changes, snow melt patterns, and soil moisture, contributing to more comprehensive hydrological assessments	☑	☐	☐	☐	☐
3	Initiate community-based hydrological monitoring programs, involving local communities in data collection to enhance understanding of regional hydrological dynamics	☐	☑	☐	☐	☐
4	Invest in the development of probabilistic forecasting tools for both hydrology and meteorology, providing decision-makers with a range of possible scenarios and associated uncertainties	☑	☑	☐	☐	☐
5	Conduct research on flash flood prediction, focusing on developing accurate and timely forecasting models that consider local topography, rainfall patterns and soil conditions	☐	☐	☑	☑	☐
6	Establish ongoing capacity-building programs to ensure staff proficiency in the latest research methodologies, modelling techniques, and technological advancements in both hydrology and meteorology	☐	☑	☑	☐	☐
	Human resources requirements to support medium-term modernization					
1	Four extra technicians trained in instrument use, maintenance and calibration, to support the expansion of the meteorological and hydrological observing network	☑	☐	☐	☐	☐
2	Two extra meteorological technicians to support the additional Upper-Air stations (assuming that this is an auto-launcher and is located at an existing NCHM site)	☐	☑	☐	☐	☐
3	Four additional specialists to support, maintain, operate, and exploit the proposed weather radar network (two engineers, two meteorologists)	☐	☑	☑	☐	☐
4	Four additional hydrology technicians to help operate the new ADCP equipment and expand the collection of rating curves, etc.	☐	☑	☐	☐	☐
5	One specialist to manage, maintain, and oversee the proposed permafrost monitoring station	☐	☐	☐	☑	☐

Annex VI: Timeline of Activities for Medium-Term Modernization (2029-2034)

SI	Activities	Year 1	Year 2	Year 3	Year 4	Year 5
Human resources requirements to support medium-term modernization (cont.)						
6	Two extra specialists in meteorological NWP to further improve exploitation of global weather models, to deepen engagement with regional modelling initiatives, and to conduct a 30-year reanalysis of the climate of Bhutan as a proxy for a detailed climate record	☐	☐	☐	☑	☐
7	Two extra hydrological modelers to enhance flood forecasting	☐	☐	☑	☐	☐
8	One additional cryosphere modeler to help develop avalanche risk and warning services	☐	☐	☑	☐	☐
9	One additional climate modeler to improve seasonal and climate-range forecasting	☐	☐	☑	☐	☐
10	Two extra specialist in meteorological ICT systems, one each to manage and support the Forecaster Visualization System and the Climate Database Management System	☐	☐	☐	☑	☐
11	One extra meteorologist or hydrologist focused on Service Delivery, to broaden and deepen the engagement of NCHM with user communities	☐	☐	☐	☑	☐
12	One extra training and development officer, to focus on training, education and outreach programs for users and for the public	☐	☐	☐	☐	☑

ANNEX VII
Summary of Staffing Requirements for Modernization

For Bhutan, the following staff[53] complements are proposed for the operational positions:

- **ICT.** For one person to be continuously available on a 24/7 basis, **six qualified and trained ICT technicians are required**.
- **General forecasting.** A typical arrangement for staffing a general forecasting position is to have 24/7 cover, augmented by an additional eight-hour shift each day, to help deal with the greater demand for forecast services during the daylight hours. Thus, **the staff complement should be eight forecasters**: six to provide for the 24/7 cover plus an additional two to allow eight extra rostered hours per day (although in practice all eight would work on an agreed 24/7 roster sequence, sharing the night shifts and so on equally between them).
- **Aviation forecasting.** For full adherence to ICAO regulations, there should be an aviation forecaster on duty at all times, to issue and keep under review TAFs, warnings, and so on a continuous basis. This means that a complement of six forecasters is needed to cover the aviation forecast desk on a 24/7 basis. If general forecasting and aviation forecasting are located in one office, it may be possible to effect some saving of staff numbers across both disciplines, for example, by having one forecaster (typically on night shift) keeping the aviation TAFs and warnings under review while primarily focused on PWS.
- **Hydrology forecast and warning services.** It is vital that a 24/7 watch is maintained for flash flood risks caused by GLOFs and similar events. Therefore, six qualified and trained hydrology officers are required to provide this uninterrupted service.

These estimates of the staffing requirements for 24/7 services underlie the detailed staff number recommendations in this annex. While these staffing requirements may seem ambitious, many of them may be achievable through the training and redeployment of existing staff. For example, the proposal to provide 24/7 staffing of the general forecast office by fully qualified meteorologists would free up the technical staff currently undertaking forecast duties to be retrained or redeployed into other roles. In overall terms, the staff numbers in the NCHM may not increase much, but there is a significant need for more highly skilled staff, particularly for specialist staff in areas such as NWP modelling, satellite meteorology, ICT (particularly meteorological ICT systems), communications, and service delivery.

[53] Typically, a public servant will work about 200 days per year, at an average of 7.2 working hours per day or a total of 1,440 working hours per year. Dividing 1,440 by 365 gives a figure just less than 4 hours per day, which is effectively the average number of rostered hours per day that one person can deliver when working on a seven-day roster. A roster requiring 24/7 coverage therefore needs six persons to provide complete cover (noting that this does not include provision for long periods of absence due to maternity leave, study leave, and so on). This is known as the staffing factor.

Work area/activity	Short term		Medium term	
	Prof.	Tech.	Prof.	Tech.
Observations				
Use, maintenance, and calibration of instruments		5		4
Upper air station		1		2
Weather radar network			4	
Hydrology observations				4
Permafrost station				1
24/7 operations				
Operational forecasting	6			
Aviation forecasting	5			
Hydrological forecast and warnings		1		
Operational ICT management		6		
Modelling and forecasting				
NWP modelling	3		2	
Climate modelling and downscaling	2		1	
Cryosphere modelling	2		1	
Hydrological modelling and verification	3		2	
Use and exploitation of satellite data	1			
ICT systems				
Meteorological ICT systems	2		2	
Service delivery				
Web/communications/broadcasting	2		1	
Development of tailored service delivery	2		1	
QMS specialist	1			
Capacity development				
Training officer	1		1	
Total	**30**	**13**	**15**	**11**

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