Flood Management Plan for Haa Dzongkhag

June 2025

Strengthening Risk Information for Disaster Resilience in Bhutan (RIR) Project

INFRASTRUCTURE PLANNING AND FLOOD ADAPTATION DIVISION
DEPARTMENT OF HUMAN SETTLEMENT
MINISTRY OF INFRASTRUCTURE AND TRANSPORT
ROYAL GOVERNMENT OF BHUTAN

IPFAD
Towards sustainable growth

CIF CLIMATE INVESTMENT FUNDS
THE WORLD BANK IBRD • IDA | WORLD BANK GROUP
GFDRR Global Facility for Disaster Reduction and Recovery

Acknowledgements

The Infrastructure Planning and Flood Adaptation Division (IPFAD) under the Department of Human Settlement, Ministry of Infrastructure and Transport, would like to extend its sincere gratitude to the World Bank for financing this study through the Project ‘Strengthening Risk Information for Disaster Resilience in Bhutan (RIR) project’.

IFPAD would also like to express its appreciation to the Dzongkhag Administration of Haa for their kind assistance in initiating and supporting the study. The office also gratefully acknowledges the valuable suggestions, close coordination, and sincere cooperation of the local governments, particularly the Gups, Mangmis, and Tshogpas of Bji, Katsho, Uesu, and Samar Gewog Administrations.

Our heartfelt appreciation goes to the Hydrology and Water Resources Services Division of the National Center for Hydrology and Meteorology (NCHM) for their generous support in providing essential data and information that contributed significantly to this study.

Lastly, we would like to thank the Department of Disaster Management, the Project Management Unit for RIR for their active engagement and timely feedback throughout various stages of the study, which greatly enriched the quality and relevance of the outcomes.

Table of Contents

Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

Bhutan is among the countries that are most vulnerable to climate change within the Asia-Pacific region due to its vulnerable mountainous terrain and volatile ecosystems. The country is exposed to multiple hazards, in particular Glacial Lake Outburst Floods (GLOF) resulting from glacial melting, flash floods, landslides, windstorms, forest fires, localized changes in rainfall patterns, and increasing droughts during the dry season. Climate change is projected significantly to magnify the intensity and frequency of such natural hazards, as has already been evidenced by the Glacial Lake Outburst Flood (GLOF) of Lugge Tsho in 1994, the high-intensity cyclone Aila in May 2009, which caused substantial damages and more recently in July 2016, whereby the rivers and streams in Southern Bhutan washed away houses, farmland and affected numerous public infrastructures.

Flash floods are among the most common climate-induced hazards in Bhutan. The monsoon season with incessant rainfall increases the river flow, which runs down the steep terrain with high velocity and creates flooding downstream. People have lost their lives, properties, and agricultural products during such a disaster, leaving them to start their lives from scratch. Vehicles get stranded, and school students are unable to attend their classes as the roads and bridges get washed away. Streams in the country have also led to flash floods and caused enormous impacts on the livelihood. Therefore, the Infrastructure Planning and Flood Adaptation Division (IPFAD), in its endeavor to combat the flooding hazard in all the Dzongkhags, initiated a comprehensive flood management plan for Haa Dzongkhag in the year 2021.

Like in most parts of the country, rivers and streams in Haa Dzongkhag also flow through the settlement, infrastructure, and agricultural areas. Although smaller streams flow through the villages, the discharge increases hugely during the peak monsoon time, affecting the people and their properties. Hence, there is a need to conduct proper studies of the rivers and the streams in the Dzongkhag, with particular emphasis on their flooding nature, to place the appropriate measures.

1.2. Rationale

Bhutan is highly vulnerable to recurrent and seasonal natural hazards, including flash floods, Glacial Lake Outburst Floods (GLOFs), earthquakes, windstorms, and hailstorms. Among these, flash floods, localized, high-volume floods occurring over short durations, are the most frequent. The increasing impacts of climate change have further intensified these seasonal hazards, with the country experiencing more extreme weather events in recent years.

Urban areas in Bhutan face growing risks of urban flooding, primarily due to inadequate drainage planning and limited hydrometeorological data. Much of the country's infrastructure is concentrated along river basins that are highly susceptible to flooding, particularly riverine flooding triggered by intense monsoon rainfall and glacial melt.

To address these challenges, the Multi-Hazard Risk Decision Support System component of the *Strengthening Risk Information for Disaster Resilience in Bhutan (RIR)* Project, with financial assistance from the World Bank, is supporting a flood hazard and risk study for Haa District and the subsequent preparation of a Flood Management Plan (FMP). The FMP, whose groundwork started in 2021 with the commencement of the project, will inform the future rehabilitation and upgrading of existing physical infrastructure, to be financed by other development partners.

While this project focuses solely on preparing the FMP and strengthening institutional capacity among government agencies, it also takes into account the potential downstream and environmental risks associated with flood management. The FMP will not propose new flood protection structures that exceed the original scheme, nor will it alter or expand the nature, scope, or extent of existing interventions in a way that would constitute an entirely new or different project.

1.3. Objective

The main objective of the study is to prepare a sustainable and climate-resilient flood management plan for Haa Dzongkhag.

The specific objectives are:

- To assess the flood threat to the settlements and prepare the flood management plan;
- To assess the environment and social risk of flood hazard areas; and
- To provide appropriate recommendations and rehabilitation measures to be adopted.

1.4. Study Approach

A standardized flood assessment methodology was adopted for this study, as illustrated in Figure 1. The data collection phase involved gathering information from various sources, including hydrometeorological data, land use maps, and global datasets such as SRTM Digital Elevation Models (DEM) and soil data.

Statistical analyses of the hydrological data were carried out to determine discharge values corresponding to different return periods. A hydrological model was developed using the Soil and Water Assessment Tool (SWAT), and its outputs were used as inputs for the hydrodynamic model constructed with HEC-RAS software. The resulting flood hazard maps were generated, analyzed, and accordingly concluded.

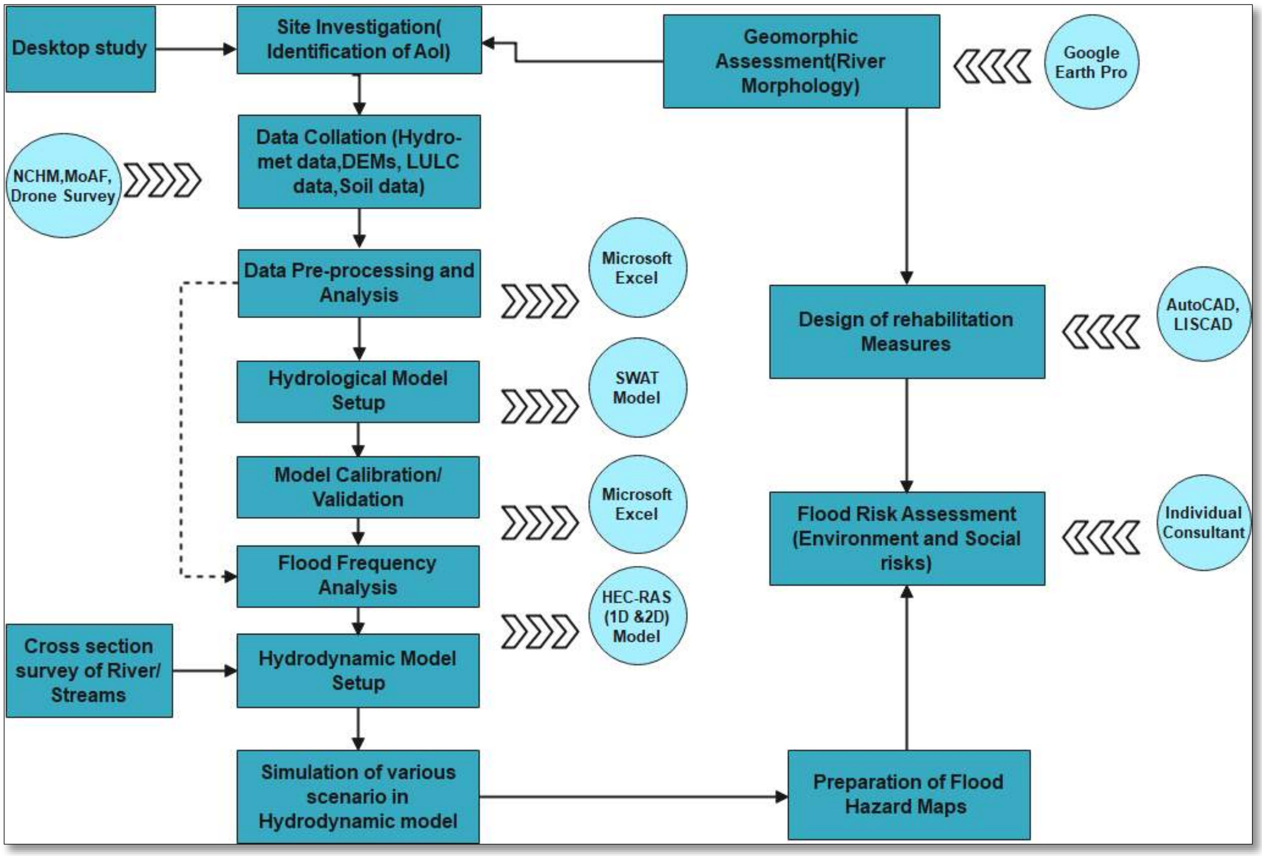


Figure 1: Overall study methodology

1.5. Study Limitations

- Weather data inside the river basin is limited both in terms of the number of stations and data duration, which is the main input for hydrological modeling for a catchment. Only one weather station was available for Haa.
- Available rainfall data is summarized daily, whereas sub-daily rainfall data is essential for the assessment of flood hazard for small-steep slope basins.
- Discharge data is available for only one station for the entire catchment area.
- No water level or historical flood extent map is available for the calibration of the hydrodynamic and flood model.
- Unavailability of damage assessment data;

2. Description of Study Area

2.1. Study Location

The study area includes one major river and fourteen streams assessed against potential flood threats as shown in Figure 1.

Figure 1: Study Area

Haa District is located in the western part of Bhutan, bordering the Indian state of Sikkim. For the purpose of the Flood Management Plan (FMP), four gewogs (blocks) in the district have been identified for assessment, as critical rivers and their tributaries flow through these areas. These rivers ultimately drain into the Brahmaputra River in India, making the river system transboundary in nature. Haa is home to several significant Buddhist temples and ecologically important areas such as the Jigme Khesar Strict Nature Reserve.

Bji Gewog is one of the largest among the six gewogs in Haa Dzongkhag, encompassing 23 villages and 278 households. Covering a total area of 802.2 sq. km, it shares its northern border with the Tibet Autonomous Region of China and its southern border with Katsho Gewog. The gewog lies within the pure alpine region, with elevations ranging from 2,750 to 3,300 meters above sea level.

The climate is characterized by cold, dry winters and wet, warm summers. Winter temperatures can drop as low as -7°C, with snowfall occurring multiple times from late October through April. Most of the population are nomadic yak herders, and livestock remains the primary source of income, contributing to the relative economic well-being of the community. Almost all villages are now accessible via well-connected farm roads.

Katsho Gewog is situated at an elevation between 2,850 and 3,100 meters above sea level, approximately 1 km from Haa town. It comprises five chiwogs: Wangtsa, Bali (Bali & Mombitshokha), Yatam (Yatam & Kargoen), Ingo (Ingo & Pharakha), and Kajana-Drading (including Kajana, Gangkha, Naktshang, and Nam River). The gewog has 289 households with a population of 1,875 and is the smallest among the six gewogs, covering just 42.8 sq. km.

The livelihood of the residents largely depends on dairy products from cattle and yaks. Traditional nomadic practices migrating to higher altitudes in summer and descending during winter are still prevalent. Livestock rearing is integral to their way of life. Although barley, buckwheat, and wheat are cultivated, apples, potatoes, peas, and other vegetables are now the main cash crops grown for both income and personal consumption.

Katsho Gewog is well-served by public facilities, including education, healthcare, and RNR extension services. Residents enjoy good access to both gewog and dzongkhag-level amenities. The gewog also houses six religious sites, including Wangtsa Lhakhang, Bali Lhakhang, Katsho Goenpa, Lungkha Lhakhang, Jung nay Drag, and Dradhing Lhakhang.

Eesu Gewog covers an area of approximately 67.7 sq. km and consists of around 243 households with a total population of 1,752. The primary sources of income are potato cultivation and livestock farming. The gewog is also home to several historically significant lhakhangs (temples), reflecting its cultural importance.

Gakiling Gewog is located in the southern part of Haa Dzongkhag and is separated from the rest of the district by Tergola (Door to Hidden Treasure) and Chelala pass. It spans an area of 192.22 sq. km, with an estimated population of 1,124. The elevation ranges from 1,000 to 2,750 meters above sea level, transitioning from broad-leaved forests in the lower altitudes to mixed coniferous vegetation in the north. Livestock farming is the primary livelihood activity, supplemented by the cultivation of cardamom, which serves as a major source of cash income.

(*Source: Haa Dzongkhag Administration*)

2.2. Topography

The altitude at Haa ranges from 1000 to 5600m above sea level, as shown in Figure 2, which is a massive climb in elevation, and as one travels to Haa from Thimphu or Paro, they can experience the steady ascent across the mountains.

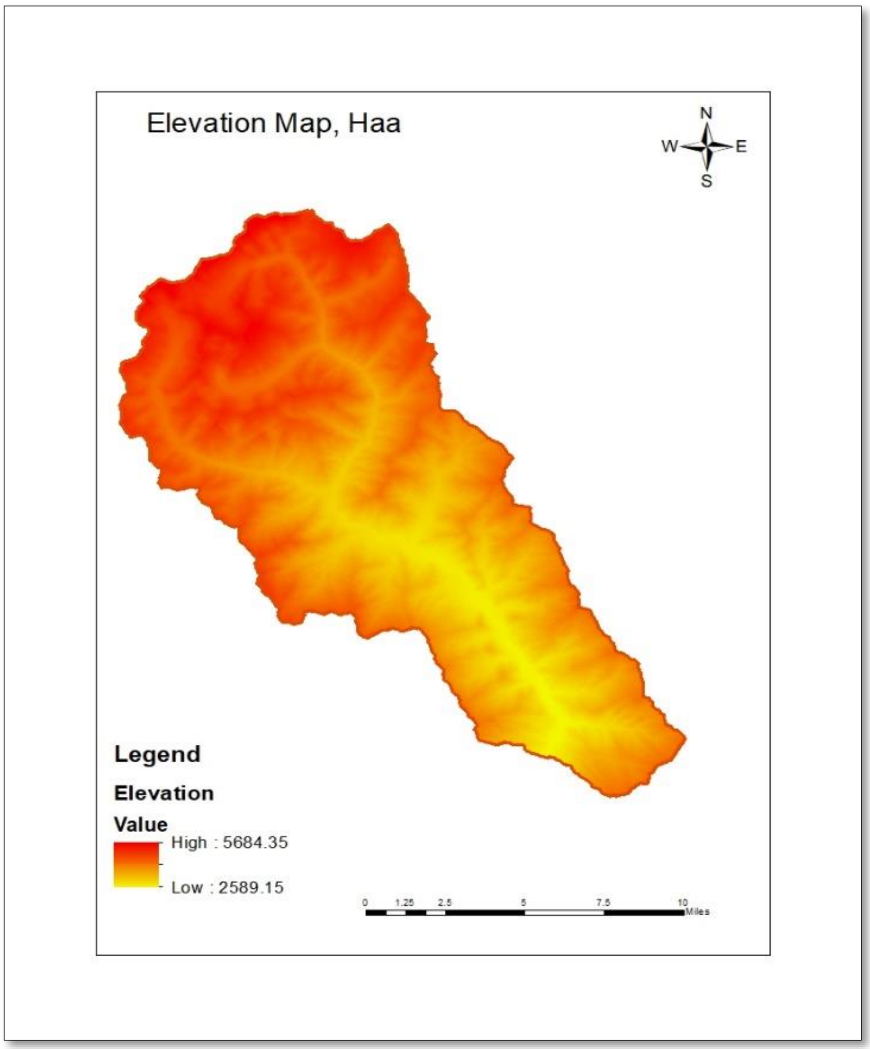


Figure 2: Elevation Map, Haa

2.3. Geology

The geology of the study area comprises various formations with differing potentials for groundwater availability, influenced by their porosity, permeability, and hydro-geomorphological characteristics. Bhutan’s geological landscape has been shaped by intense tectonic activity resulting from the collision between the Indian and Eurasian continental plates, the closure of the Tethys Ocean, and the subsequent uplift of the Himalayas. Although this continental collision occurred approximately 50–40 million years ago, the primary phase of uplift began around 25–20 million years ago.

Contrary to expectations given Bhutan's mountainous terrain, bare rock surfaces are relatively limited. Much of the land is covered with drift materials. At higher altitudes, glacial and periglacial deposits comprising mixtures of stones and sand are widespread. In the lower altitudes, slopes are typically covered by colluvium, a combination of soil and stones deposited through slow creep, minor landslides, and slumps. In certain areas, especially in the southern regions, larger and more frequent landslip deposits are evident. Figure 4 presents the geological composition of the Haa District.

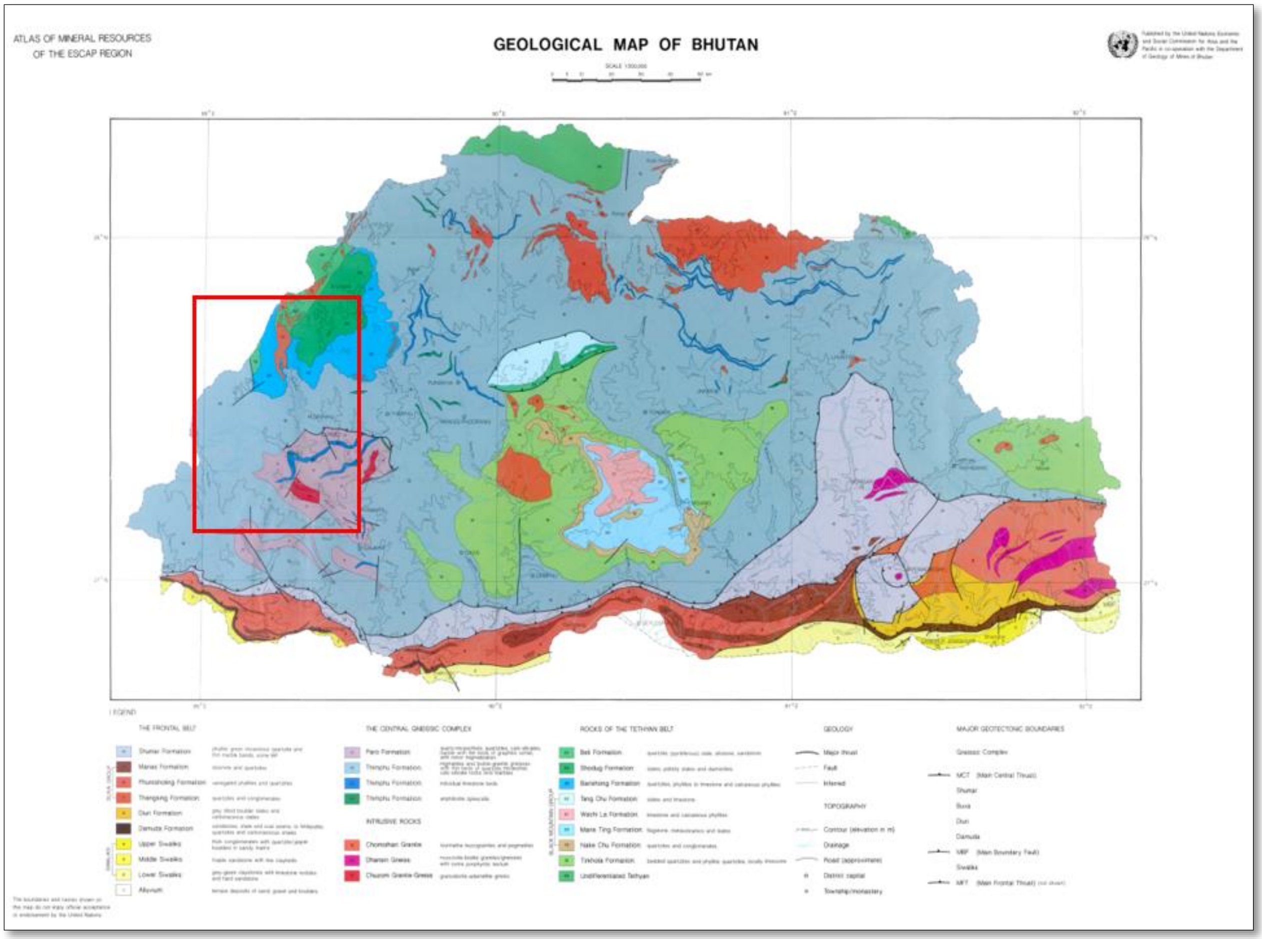


Figure 3: Geological Composition, Haa

2.4. Weather and Climate

Weather patterns in Bhutan vary significantly across its compact geography, largely influenced by altitude. The northern regions, where mountains rise to elevations of over 7,000 meters, experience alpine conditions similar to the snow-covered peaks of the greater Himalayas. In contrast, the southern lowlands, with elevations as low as 100 meters, experience hot and humid summers and cooler winters. The country typically receives heavy rainfall during the monsoon season.

Despite the contrasting freeze-thaw cycles and temperate conditions, Bhutan’s climate can be categorized into four distinct seasons:

- Spring (March, April, and May)
- Summer (June, July, and August)
- Autumn (September, October, and November)
- Winter (December, January, and February)

Broadly classifying, the dry period, particularly in the northern parts of the country, including the study area, extends from October to April, while the wet period spans from May to September.

Weather and climatic characteristics of the study region are assessed based on an analysis of temperature and rainfall data from selected meteorological stations. These analyses are detailed in the following sections.

2.4.1 Temperature

According to the *Bhutan Climate State* report by the National Center for Hydrology and Meteorology (NCHM), meteorological stations such as Sipsu, Phuentsholing, Bhur, Tangmachu, Punakha, and Bajo recorded higher annual average maximum and minimum temperatures. In contrast, stations located in **Haa**, Gasa, Paro, and Chamkhar reported lower annual average temperatures for both maximum and minimum values. Figure 5 illustrates the spatial distribution of the annual average maximum (top) and minimum (bottom) temperatures for the year 2021.

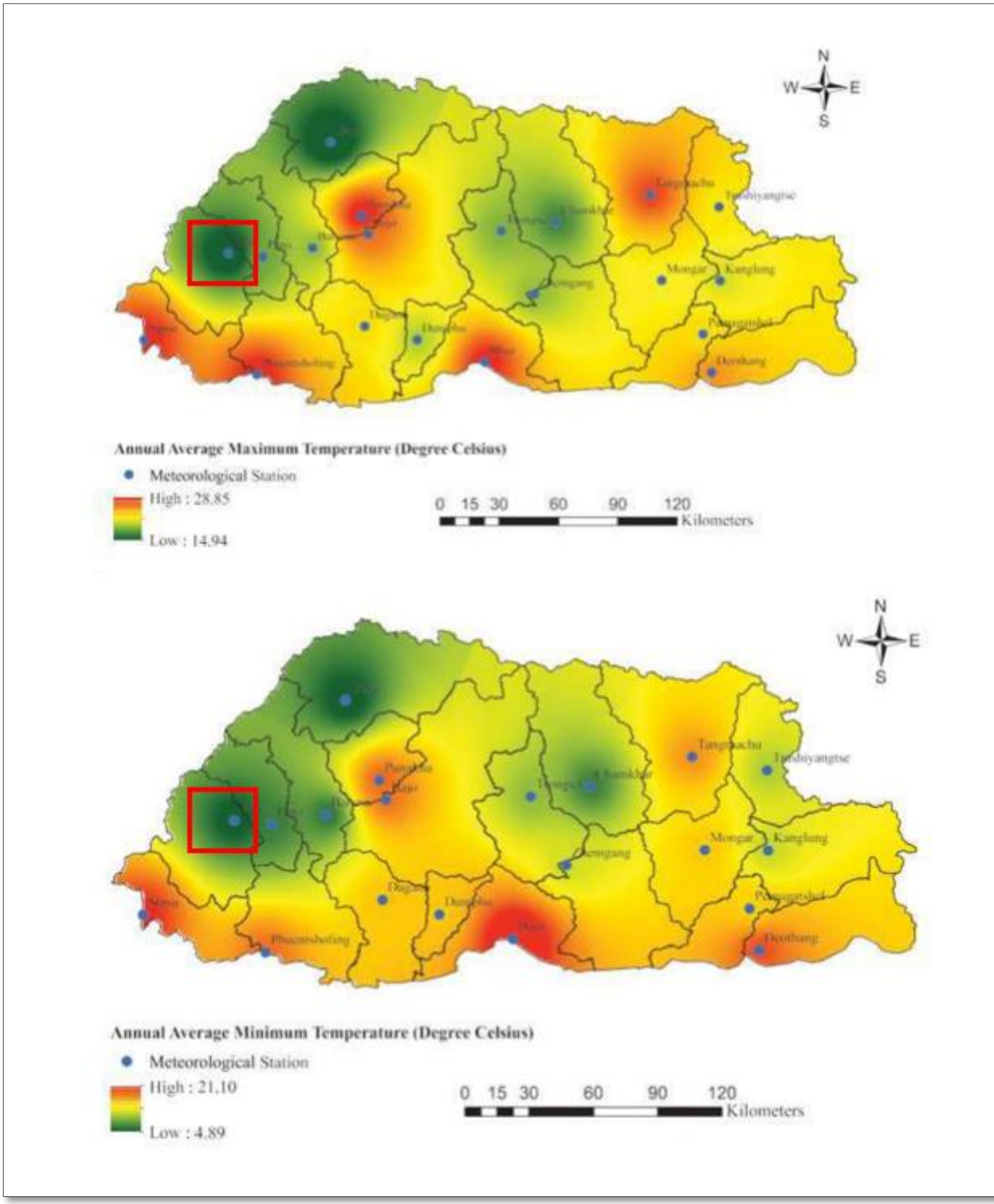


Figure 4: AA Max / Min temperature, Haa

2.4.2 Rainfall

The annual accumulated rainfall for the Namgyeling station located in Haa was analyzed and concluded as shown in Figure 5.

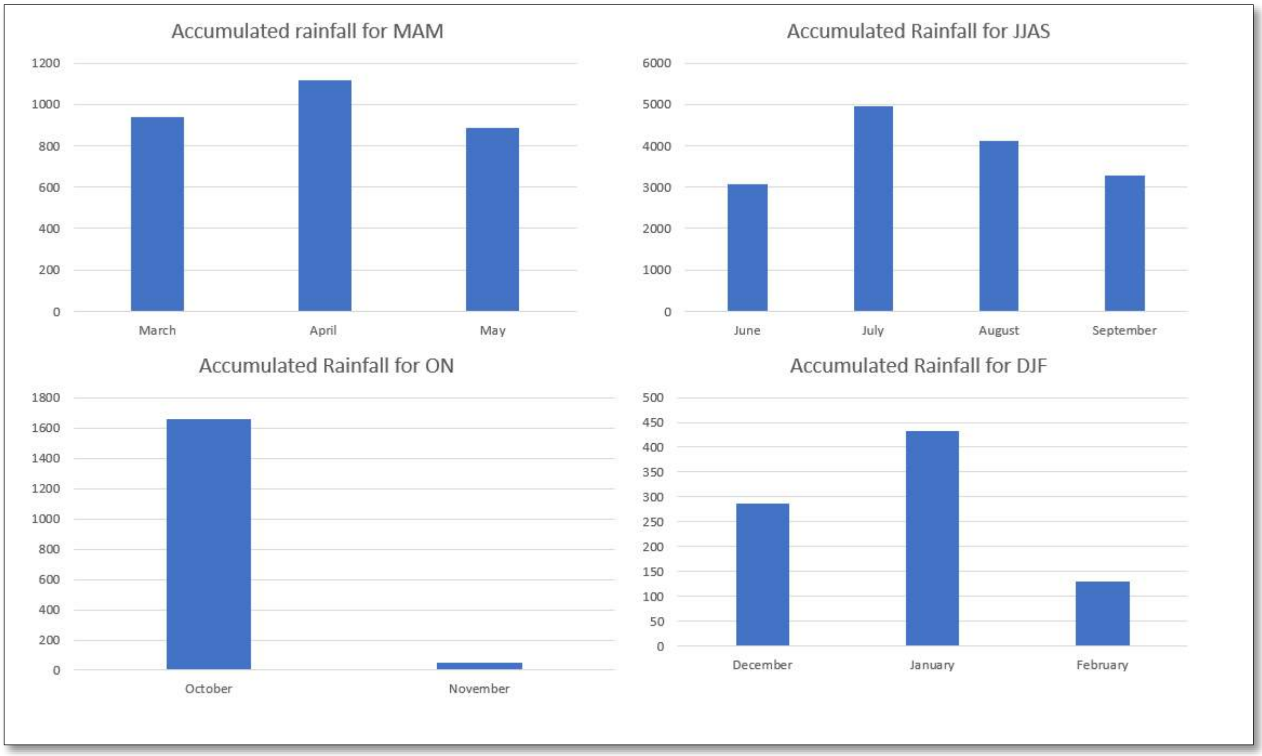


Figure 5: Accumulated Rainfall (Seasonal)

2.5. Hydrology

2.5.1. River

The Haachu (river) is one of the major tributaries within the Wangchu basin, with a reach length of approximately 150 km and a catchment area of 398.62 km². It flows through Bji Gewog in the north, passes through Katsho and Uesu Gewogs in the central region, and continues downstream into Samar Gewog in the south. The main town of Haa and several major settlements are situated along the banks of the Haa Chu.

In 2021, a flooding incident occurred near Pharikha in Katsho Gewog. The flood was attributed to a bridge construction intended to connect Katsho with Bji, which constricted the river's flow during the peak season. This resulted in the washing away of roads and the inundation of nearby settlements. Numerous river training structures have been implemented along the Haachu to mitigate such events. Prominent examples include gabion revetments near Yangthang village and AB mattresses installed along the Haa town stretch.

2.5.2. Streams

Around fourteen (14) tributaries had their outlet in Haachu, located in all the gewogs. The details of the streams are tabulated in Table 1.

Table 1: Stream Network descriptions

Sl. No	Stream Name	Gewog	Catchment area (km2)	Average Flow (m3/s) (May-June)	Structures	Flooding record
1	Yakchu	Bji	19.37	2.54	Gabion walls	2009, near the Yakchu bridge
2	Chukap	Bji	0.63	0.37	Gabion walls	Nil
3	Chunap	Bji	0.069	0.32	Gabion walls	Nil
4	Talungchu	Bji	29.11	0.99	Gabion walls	Nil
5	Bali	Katsho	10.78	0.39	Gabion walls	2020, Flower Exhibition space.
6	Atam	Katsho	9.27	0.29	Gabion walls	2020, Flower Exhibition space.
7	Wangtsa	Katsho	6.17	0.14	Gabion walls, storm drains	Cross drainage overflowing near the Dantak truck parking.
8	Janaphuchu	Katsho	1.17	0.04	Nil	Nil
9	Bangayna	Uesu	4.28	0.14	Gabion wall, RRM	
10	Dungchu	Uesu	6.13	0.15	Gabion wall, Hume pipe, culverts	Nil

11	Tshelenphu chu	Uesu	8.31	0.055		Nil
12	Tshaphelch u	Uesu	9.58	0.20	Nil	Nil
13	Kanaphuchu	Uesu	17.62	0.48	Gabion walls	Nil
14	Zakeychu	Uesu	1.64	2.54	RCC drains	Nil

2.6. Land Use

The land use land cover map 2016 in Figure 6 has been prepared by the Department of Forest and Parks in a study. As per the map, the northern parts of Haa are covered in meadows, while the center sees a mixed conifer and fir. The southern parts are mostly covered by broadleaf.

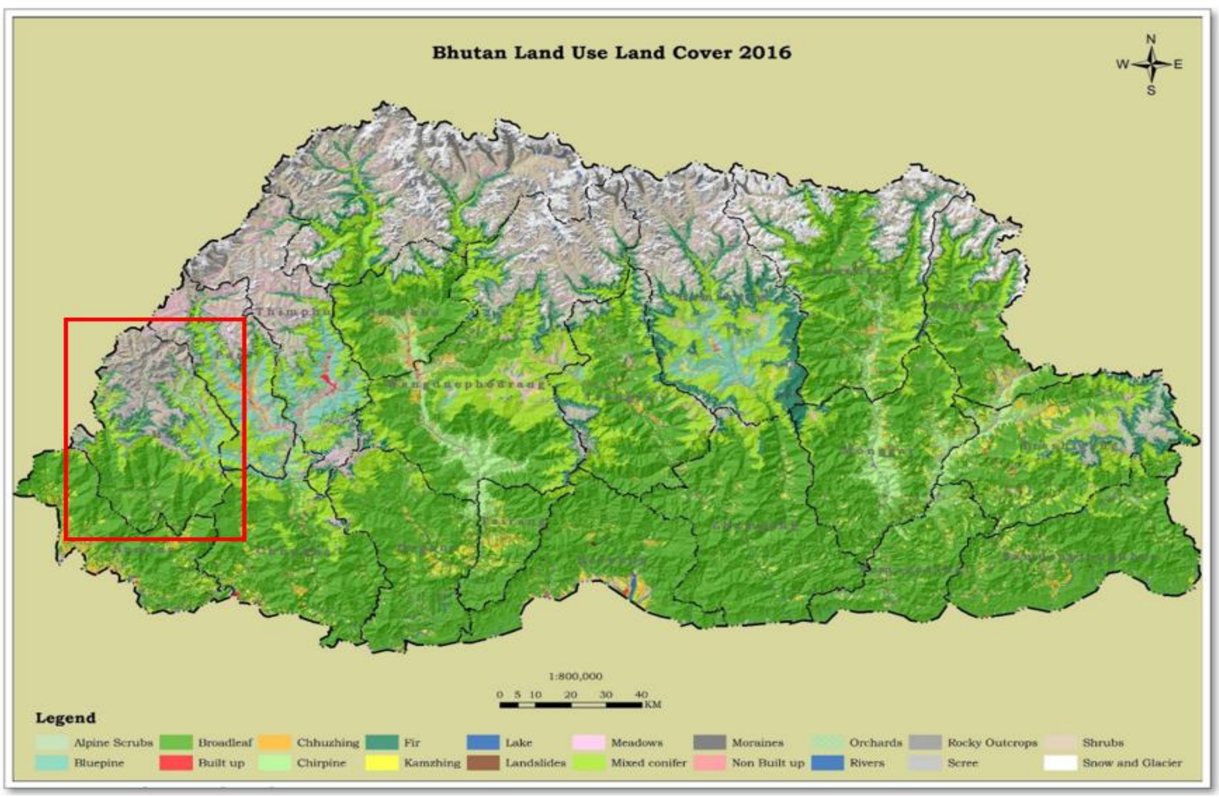


Figure 6: Land Use Map, Haa

2.7. Soil Condition

The terrain of the study area consists of steep, long, and complex southern slopes and consists of monsoon climate and steep gradients, which result in unfavorable conditions for undisturbed soil formation. Soil profiles of the study area resemble those of the overall soil characteristics of Bhutan. Types of soils are different from the High Himalayas to the southern foothills which result in polygenetic soil profiles across the country. Only about 8% of the country is cultivated because high altitudes, harsh climate, and steep slopes limit cropping. The soil type of Bhutan varies along different altitudes. The main soils up to about 3,000m in the inner valleys are moderately weathered and leached and have bright subsoil colors with dark topsoils. According to FAO/ UNESCO, about 27% fall under either Cambisols (mid-altitude) or Fluvisols (southern belts), 45% soils are Acrisols (on steep slopes), and the remaining 21% soils are Lithosols on steep slopes. Some non-volcanic andosols are present in a few pockets across the country. The chemical properties of soil change mainly with the biophysical setting and the land use pattern. The pH value soil lies within the low to medium range. The status of organic matter content in the soil is moderate. The ratio of Carbon and Nitrogen in the soil varies between 11 to 14.1, which is typical for the agricultural soils. The Phosphorus and Potassium content is low in most soils. The cation exchange capacity for most of the soils is also low. Variation in soil nutrient status changes with the variation of land use and agro-ecological zones. The dry-land soils mostly have higher soil nutrients than the wetland soils. Again, warm temperate and dry subtropical soils have the most favorable soil nutrient status, while humid and wet subtropical soils have low nutrient status.

3. Problems and Issues

3.1. Flash Flood

Over the past year, catastrophic rain events characterized as once-in-100-year or even more frequent events have flooded Bhutan, sweeping in billions of dollars of property damage and deaths along with the flash flood. These extreme weather events are forcing many communities to confront what could signal a new climate change normal. Bhutan saw several significant water-induced disasters in the last 10 years. Three significant events stand out: the 2009 Cyclone Aila-induced floods, the 2015 Lemthang Lake outburst flood, and the 2016 Southern Bhutan monsoon floods. These disasters not only resulted in the loss of several human lives, but also displaced people and wiped out homes. They caused damage to major public infrastructures, including roads and bridges. It leads climate scientists to believe that today's 100-year flood might be tomorrow's 70-year flood because of climate change.

Flash floods are typically associated with short, high-intensity rainstorms. As such, they are characterized by short response times and have the potential to severely impact and damage communities in different climatic settings all over the world. Despite their scientific and social importance, the fundamental processes triggering a flash-flood response are poorly understood. This contribution aims to provide a review of the hydrological mechanisms driving hill slope runoff response to intense rainfall and to characterize runoff response from selected extreme flash floods in Bhutan.

A flash flood can be characterized by a rapid stream rise with depths of water that can reach well above the banks of the creek. Flash flood damage and most fatalities tend to occur in areas immediately adjacent to a stream or arroyo. Additionally, heavy rain falling on steep terrain can weaken soil and cause mudslides, damaging homes, roads, and property. Flash floods can be produced when slow-moving or multiple thunderstorms occur over the same area. When storms move faster, flash flooding is less likely since the rain is distributed over a broader area. Occasionally, floating debris or ice can accumulate at a natural or man-made obstruction and restrict the flow of water. Water held back by the ice jam or debris dam can cause flooding upstream. Subsequent flash flooding can occur downstream if the obstruction should suddenly release.

Bhutan's vulnerability to water-induced disasters is well known. Historically, rivers and streams have overflown their banks, causing destruction. Glacial lakes have burst because of dam ruptures. Bhutan's sloppy and mountainous terrain makes for natural surface runoff, and the rivers, running through deep gorges and ravines, receive vast volumes of surface runoff during the monsoon. All these set up a perfect backdrop for water-induced disasters like flash floods. Against this backdrop, it is imperative to investigate the underlying causes of floods. The causes of floods can be broadly divided into several categories like the amount, timing, and duration of rainfall over a catchment or watershed area, an increase in surface run-off following a rain event and a decrease in watercarrying capacity of natural drainage network within the watershed to accommodate the surface run-off, and a reduction in land elevations in floodplain in comparison to riverbed and sea level. But flash floods possess different characteristics than usual monsoon flooding, which can occur within a few minutes or hours of excessive rainfall, a dam or levee failure, or a sudden release of water held by an ice jam. Flash floods can roll boulders, tear out trees, destroy buildings and bridges, and scour out new channels. Rapidly rising water can reach heights of 30 feet or more.

Warming trends and melting glaciers pose severe threats to the nation and its inhabitants. Research reveals that temperatures increase more dramatically in mountain areas, which translates into faster glacier retreat and more Glacial Lake Outburst Floods (GLOFs). Further, monsoon variability is now an established fact for Bhutan. Putting global warming in the broader perspective, the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) estimates that by 2100, South Asian countries, including Bhutan, will experience an increase in average temperatures, with increases in daily minimum and maximum temperatures, mostly taking place at higher altitudes. A 5% decrease in rainfall is expected during the dry season, and an 11% increase during the wet season is expected in the long term. As a result, Bhutan will experience more extreme weather events with increased frequency. The ADB identifies flood risk, and particularly flooding from torrential downpours and GLOFs (of 2,794 glacial lakes in the country, 22 are potentially dangerous), as one of the critical climate threats for Bhutan. Extreme flood events such as the one in 2016 could become more frequent and severe, putting homes, businesses, and public infrastructure at higher risk.

3.2. Problems and Issues for River/Streams within the Study Region

Talung Chu

The Chundu Armed Force School, located near Talung chu in Bji Gewog, as shown in Figure 7, was identified as one of the flood risk-prone areas. The Girls' Hostel with a capacity of more than 57 students lies in the vicinity of Talung chu at an approximate distance of 50 metres with no or less difference in stream bed elevation and the hostel ground level.

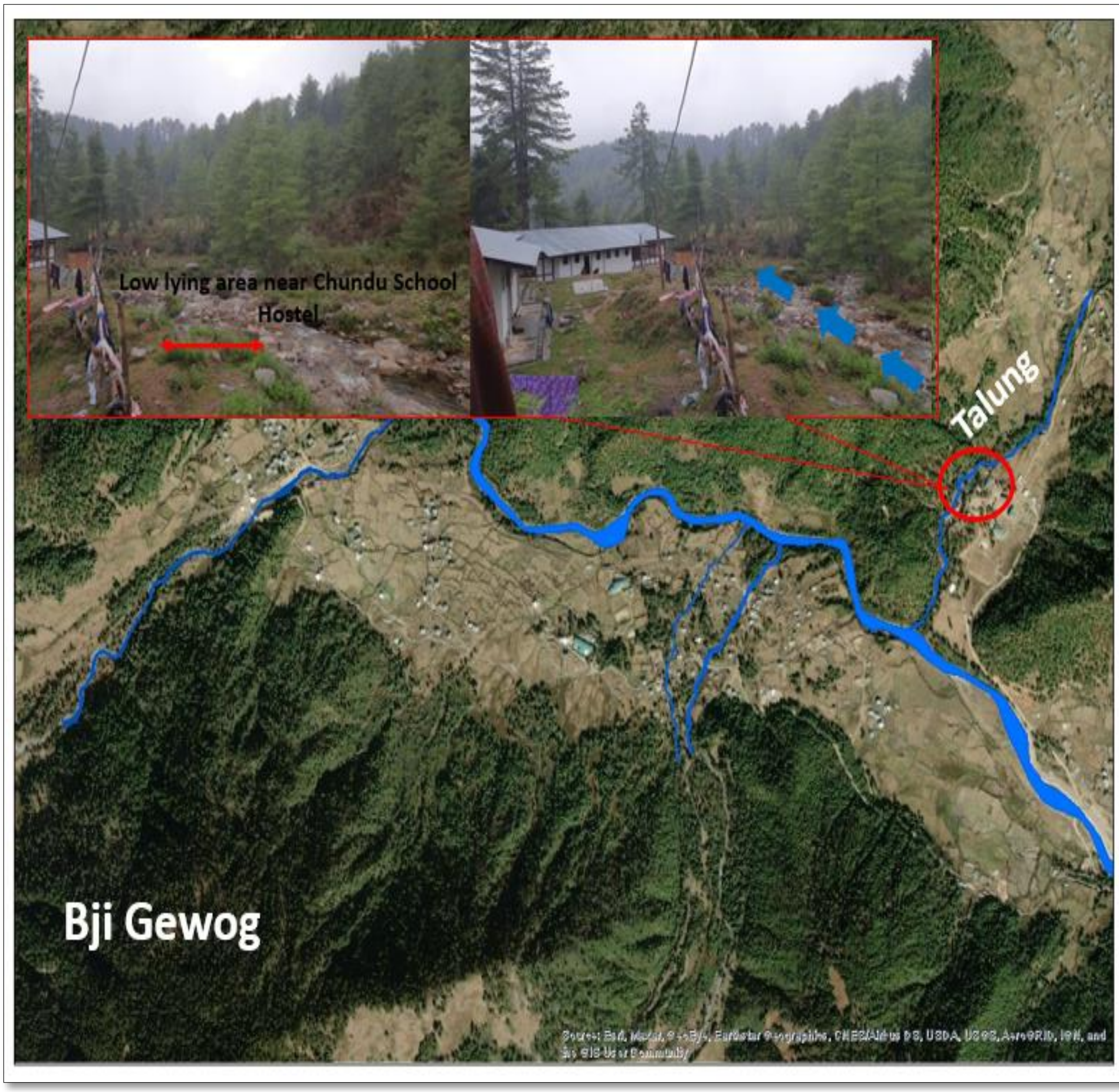


Figure 7: Critical Area along Talungchu

Wangtsa Chu

Three streams were assessed for potential flood risk in Katsho, based on site investigation. Wangtsa chu indicated some critical locations in its flow path. The flow path has been restricted to a drain size at the crossing near the Dantak truck parking. Thereafter, the natural channel is converted to a storm drainage as shown in Figure 8.

Figure 8: Critical Area along Wangtsa

Zakeychu Chu

The RCC drain along Zakeychu was observed to be critical as it obstructed the flow path near the settlement with no defined flow path as shown in Figure 9

Figure 9: Critical Area along Zakeychu

Haachu

Phareykha near Katsho school recorded flooding in the year 2021 near the new bridge construction, as shown in Figure 10. Due to the flooding, the bridge and the road that would connect Katsho with Bji gewog were left incomplete. Figure 11 shows the inundation of the 2021 flood.

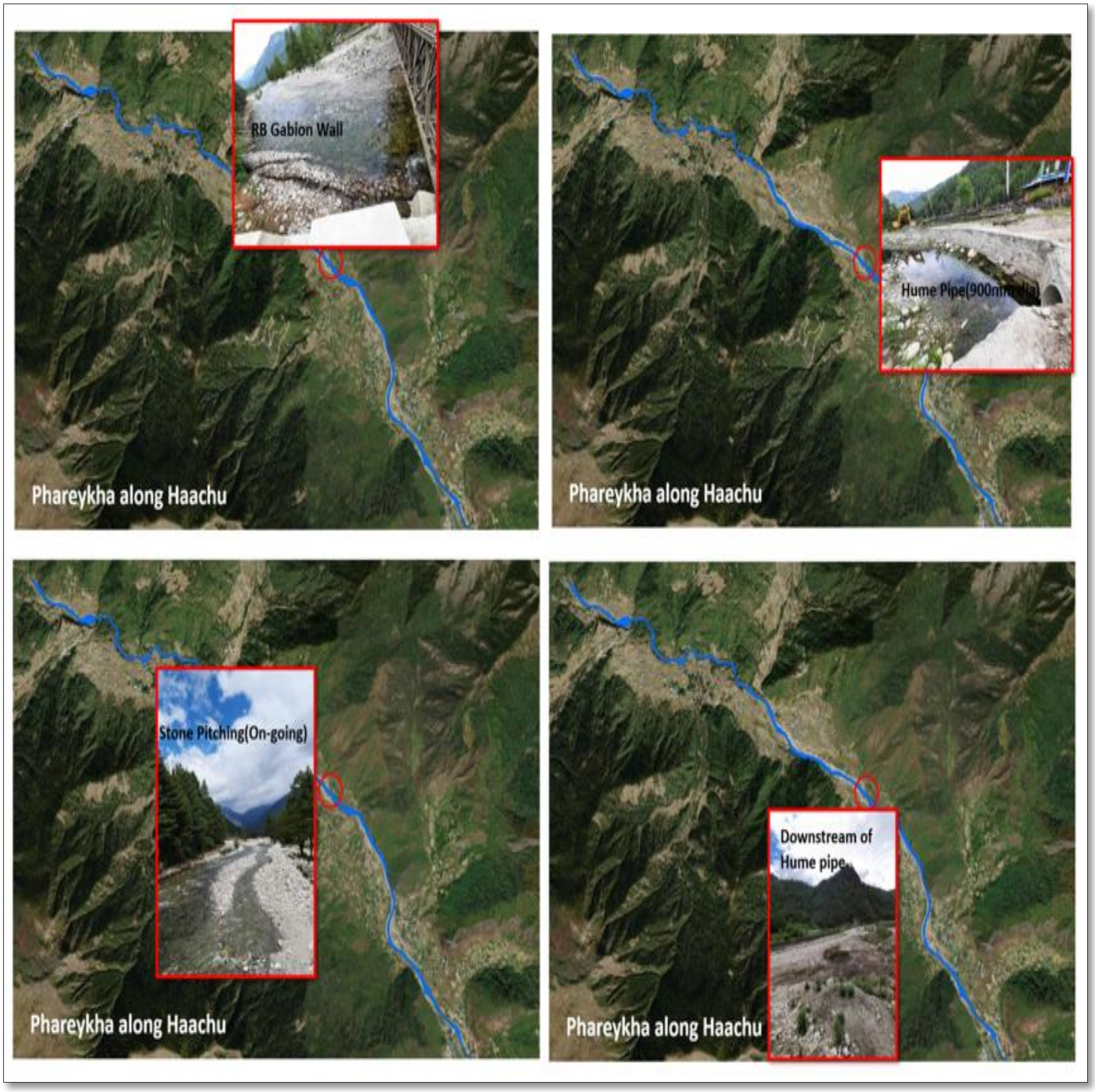


Figure 10: Critical Area along Haachu, near Phareykha Bridge

Figure 11: Flood record at Phareykha, 2021

The location of the new workshop downstream of the helipad is observed to be critical due to its low-lying nature, as seen in Figure 13 below.

Figure 12: New workshop area located along Haachu

4. Data Preparation

4.1. Hydrological and Meteorological Data

There is 1 meteorological station installed in the study area available with the recorded data. And there is a flow measurement station at Haachu at 565 msl. The location of hydro-met stations is shown in Figure 13.

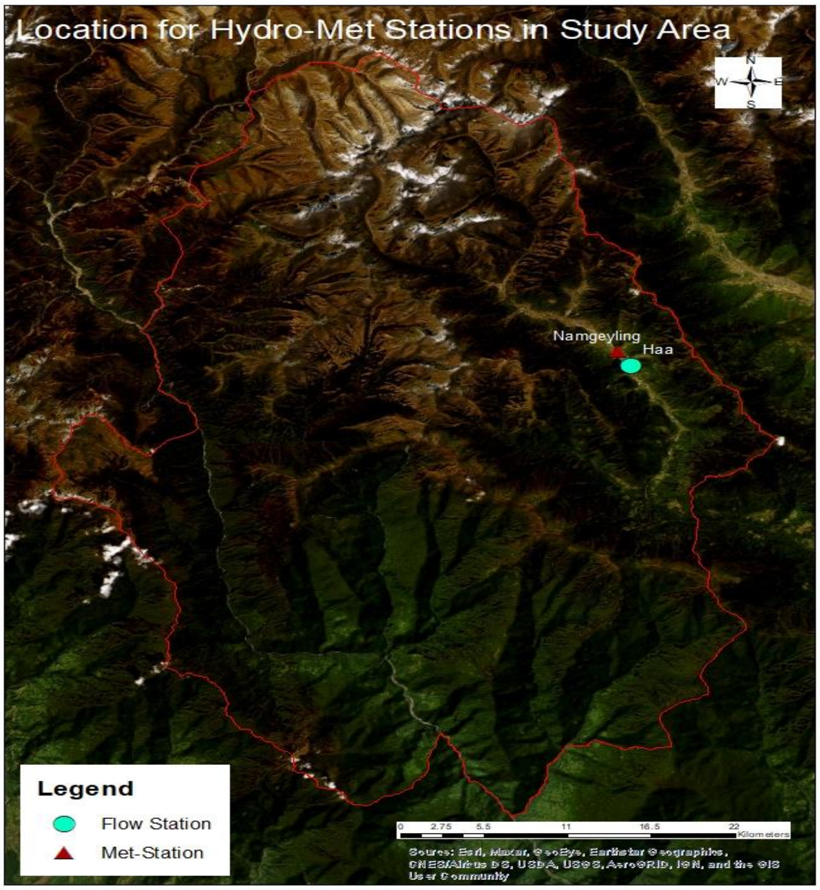


Figure 13: Hydro-Met station location map

All the data have a temporal scale of daily data intervals, and the data availability varies from each station. Precipitation data and daily maximum and minimum temperature data were collected from the National Centre for Hydrology and Meteorology (NCHM), Bhutan, for Namgayeling station and daily flow data at Haachu station. The available data is detailed below in Table 2.

Table 2: Elevation data, Haa

Sl.No	Station name	Elevation (m)	Temporal data available
1	Namgayling	2720	1996-2021
2	Haachu	2700	2000-2021

4.2. Scientific Data

The following Table 3 is the list of globally and locally available scientific data that were used in the study:

Table 3: List of data used for the study

Item	Data Source	Original Cell-size	Model
River cross-section Data along Haachu and critical tributaries.	Collected from the site by IFPAD, DHS, MoIT	N/A	HEC-RAS Hydrodynamic Model and design of the structure
Longitudinal Profile of Haachu and tributaries.	Collected from the site by IFPAD, DHS, MoIT	N/A	HEC-RAS Hydrodynamic Model and design of rehabilitation structures
Spot Height at some stretches of Haachu.	Collected from the site by IFPAD, DHS, MoIT	N/A	Design of rehabilitation structures
DEM	USGS, EarthExplorer	30 m resolution	SWAT Hydrological Model
DEM	NLCS, RIR project	1 m resolution	HEC-RAS Model
DEM	USGS, Earth Explorer	10 m resolution	HEC-RAS Model

Land use	GLCC (USGS, EarthExplorer)	100m grid square	Hydrological model
Bhutan Land Cover Map	Ministry of Agriculture and Forest (MoAF)	Year 2016 data	SWAT Hydrological Model
Soil data	FAO	1 KM resolution	Hydrological model

4.3. River cross-section survey

The field survey was carried out using GNSS RTK and achieved the accuracy within (+-) 10cm, incorporating the SOP of the division, which guides the river cross-section survey. The survey data was then processed and edited using LISCAD and used ArcGIS software for mapping. The survey map is as shown in Figure 14.

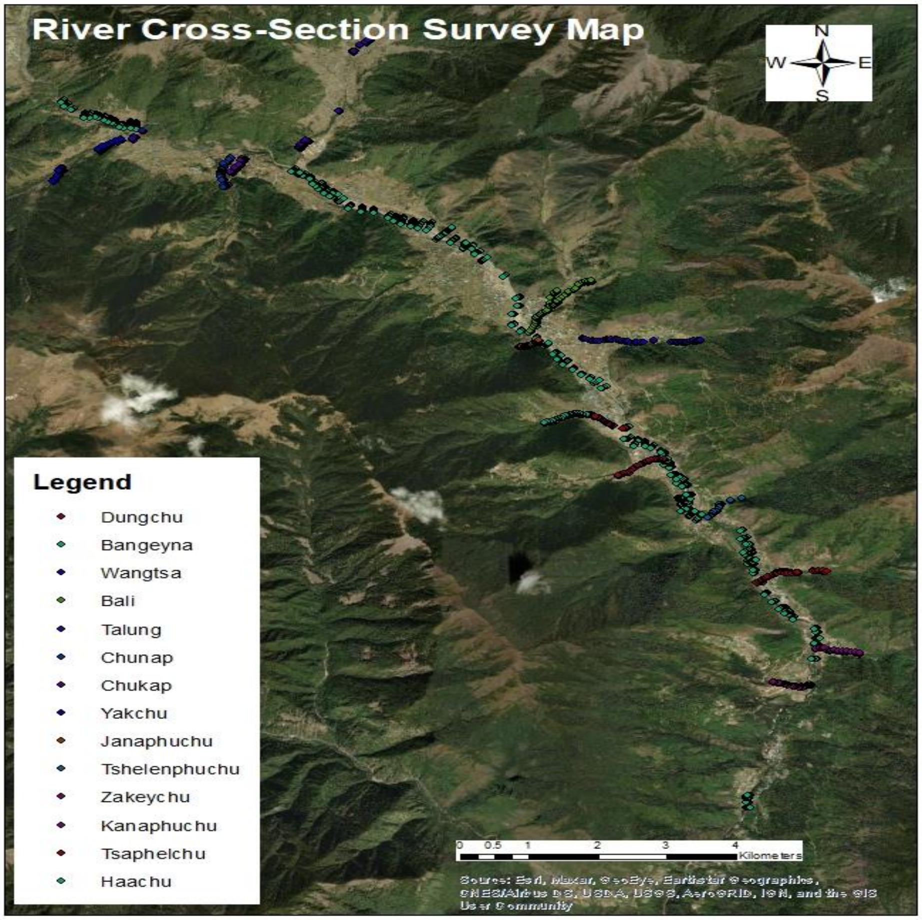


Figure 14: Cross-Section Survey Map

Details of the Survey are as follows;

- Instrument used: GNSS RTK, StoneX
- Types of survey: Geodetic Survey
- Datum: Bhutan National Grid, DRUKREF03
- Projection: Transverse Mercator
- False Easting: 250000.0
- Latitude of Origin: 0.0
- False Northing: 0.0
- Linear Unit: Meter (1.0)
- Central Meridian: 90.0
- Scale Factor: 1.0

5. Hydrological Model

The study has a hydrological station in the watershed area, and the meteorological stations are located in the nearby watershed areas. A hydrological model using the SWAT model was set up with the available meteorological stations, and simulated discharges were analyzed. All the available DEMs for the area were analyzed, and the most suitable DEM was finalized for the model.

5.1. Land Use Land Cover (LULC)

The Land Use Land Cover Map for Bhutan (2016) is used in all the basins. To recognize land use classes by SWAT, SWAT land-use codes are assigned to similar land use in the Bhutan land use map. Figure 15 below shows the different land-use classes in the Haachu catchment.

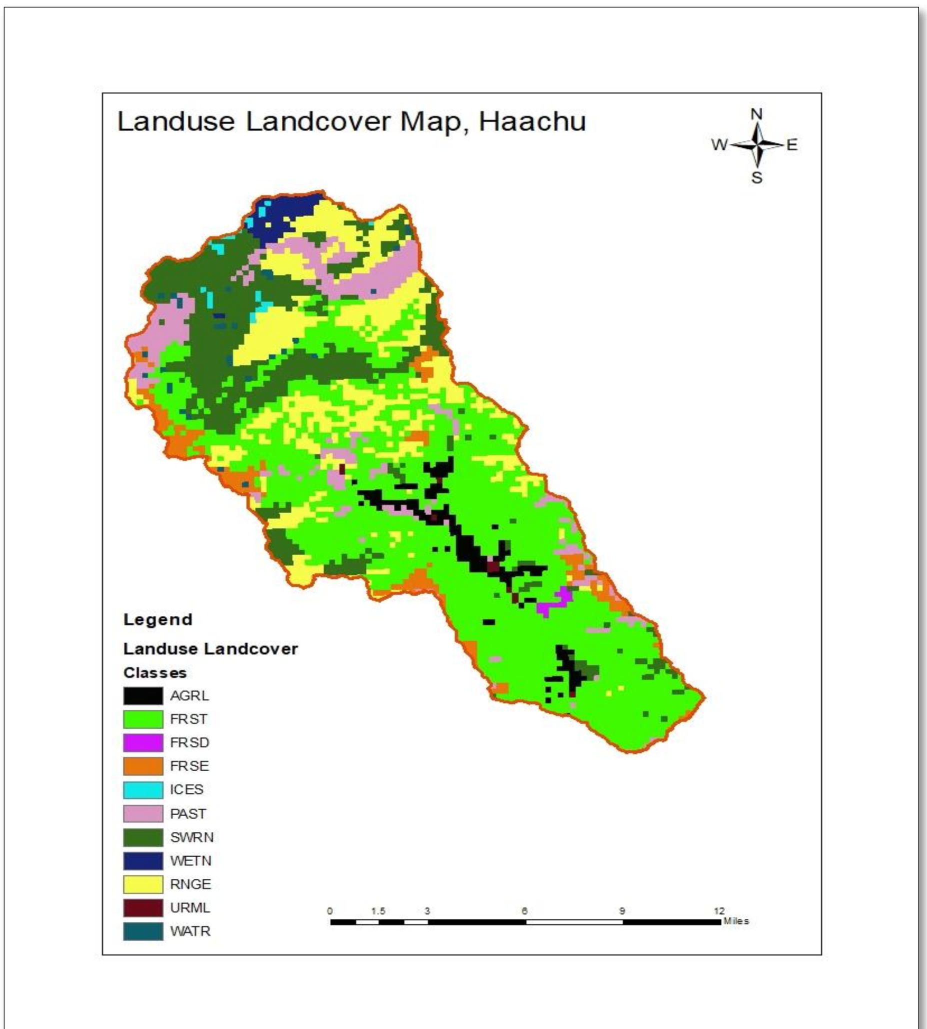


Figure 15: LULC Map, SWAT generated

5.2. Model Data Preparation

5.2.1 Digital Elevation Model

The project area had a 1m DEM prepared, but it was not used as the DEM does not capture the whole drainage basin, see figure 17. Therefore, ALOS 10M Digital Elevation Model (DEM) was used to represent the topography of the study area, and it is projected to coordinate the system (WGS 1984 UTM Zone 46N) in a GIS environment. Figure 16 shows the Digital Elevation Model used in this study.

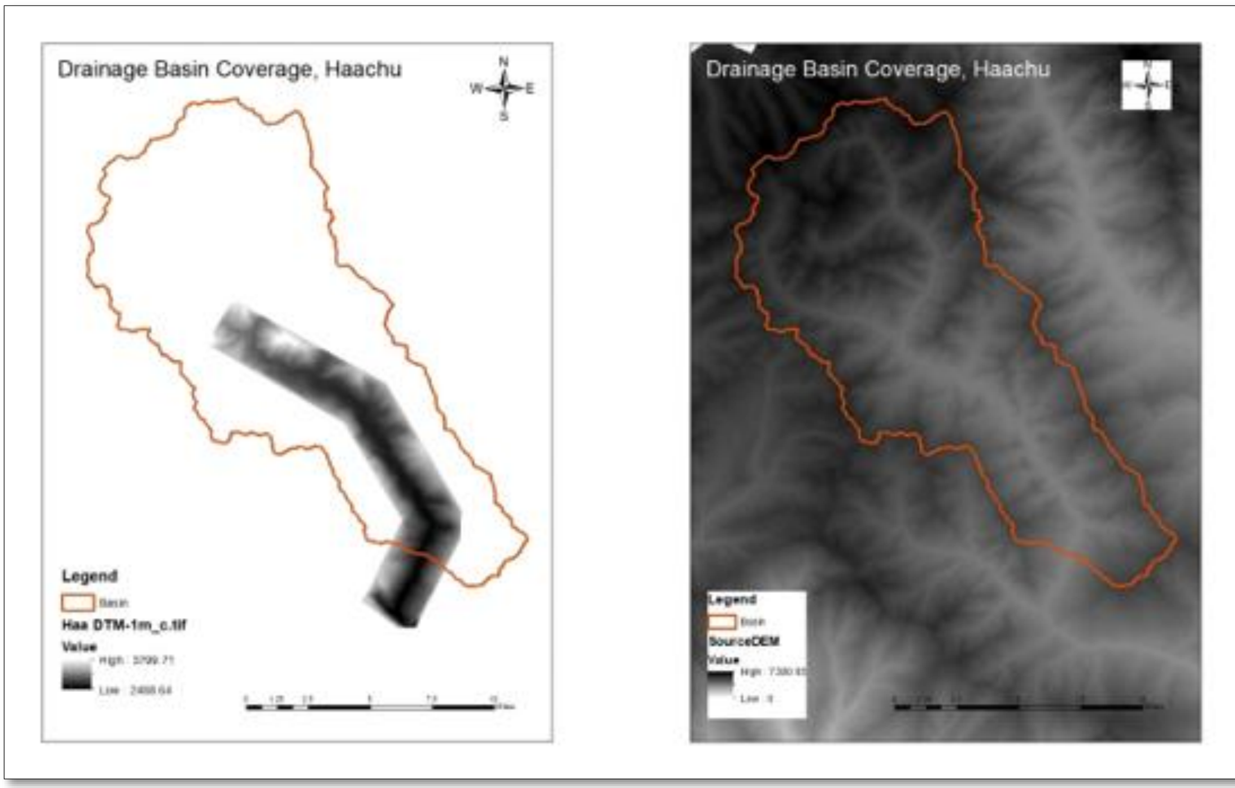


Figure 16: DEMs used for SWAT

5.2.2 Soil Data

The soil map was obtained mainly from the World Soil Database developed by the Food and Agriculture Organization of the United Nations (FAO-UN), and the soil database from the FAO was used to represent soils and their associated properties in the SWAT model. The soil type in the study area is loamy in texture with little variation in the percentage of silt, sand, and clay as shown in Figure 17.

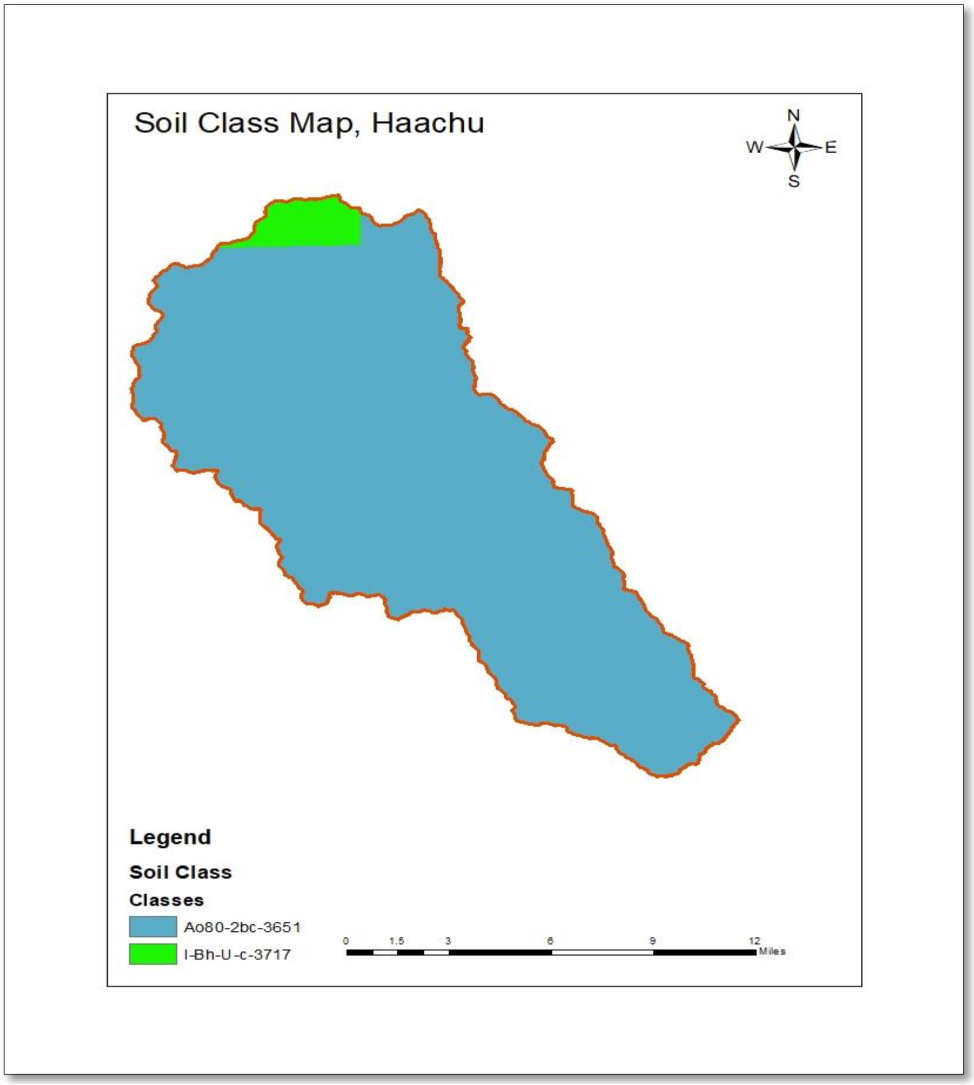


Figure 17: Soil Class Map, SWAT generated

5.3. SWAT Model Setup

The SWAT hydrological model was built in a GIS environment, and the software used was Arc-SWAT 2012 in ArcGIS version 10.4. Five sequential steps have been followed to set up the SWAT model, which are watershed delineation, HRU definition, weather data definition, edit SWAT inputs, and simulation. A detailed description of each of the steps has been articulated in Figure 18.

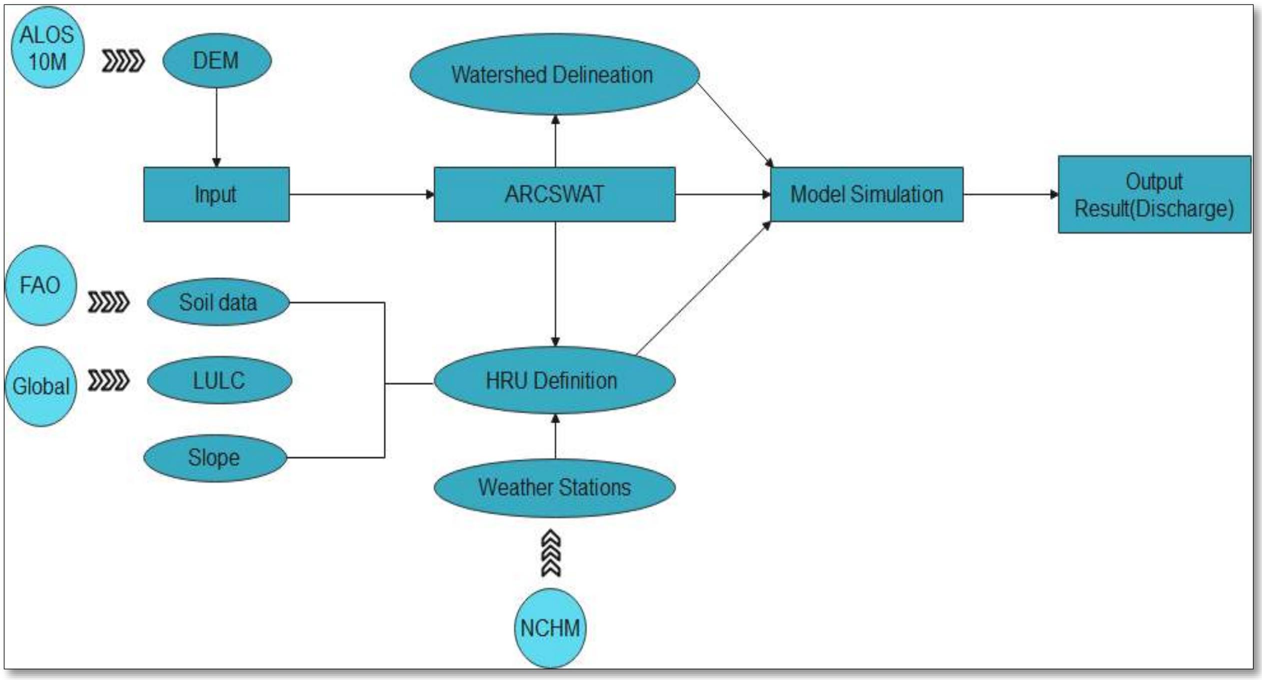


Figure 18: SWAT Model Flow chart

Watershed delineation and Sub-basin discretization

Watershed delineation is the first step towards the model setup in SWAT. The required tiles of the ALOS DEM of resolution 10x10m were used in creating a mosaic in the ArcGIS environment, which was subsequently projected to WGS 1984 UTM Zone 46N and clipped before loading it into the "DEM Raster" tab in the watershed delineator toolbar in ArcSWAT. The outlet of the basin was chosen, and then the watershed was delineated. The number of sub-basin divisions is strongly related to simulating sediments and nutrients in the SWAT model (Jha et al., 2004). Hence, 11 sub-basins for Haachu were created and resulting in an average Watershed area of 398.6 sq. km for Haachu watershed as shown in Figure 19. A large number of sub-basin divisions helps in representing the spatial variation of the variables such as precipitation, temperature, soil type, slope, and land use. After sub-basin delineation, sub-basin parameters like minimum and maximum elevation, longest flow path, and watershed area were also calculated.

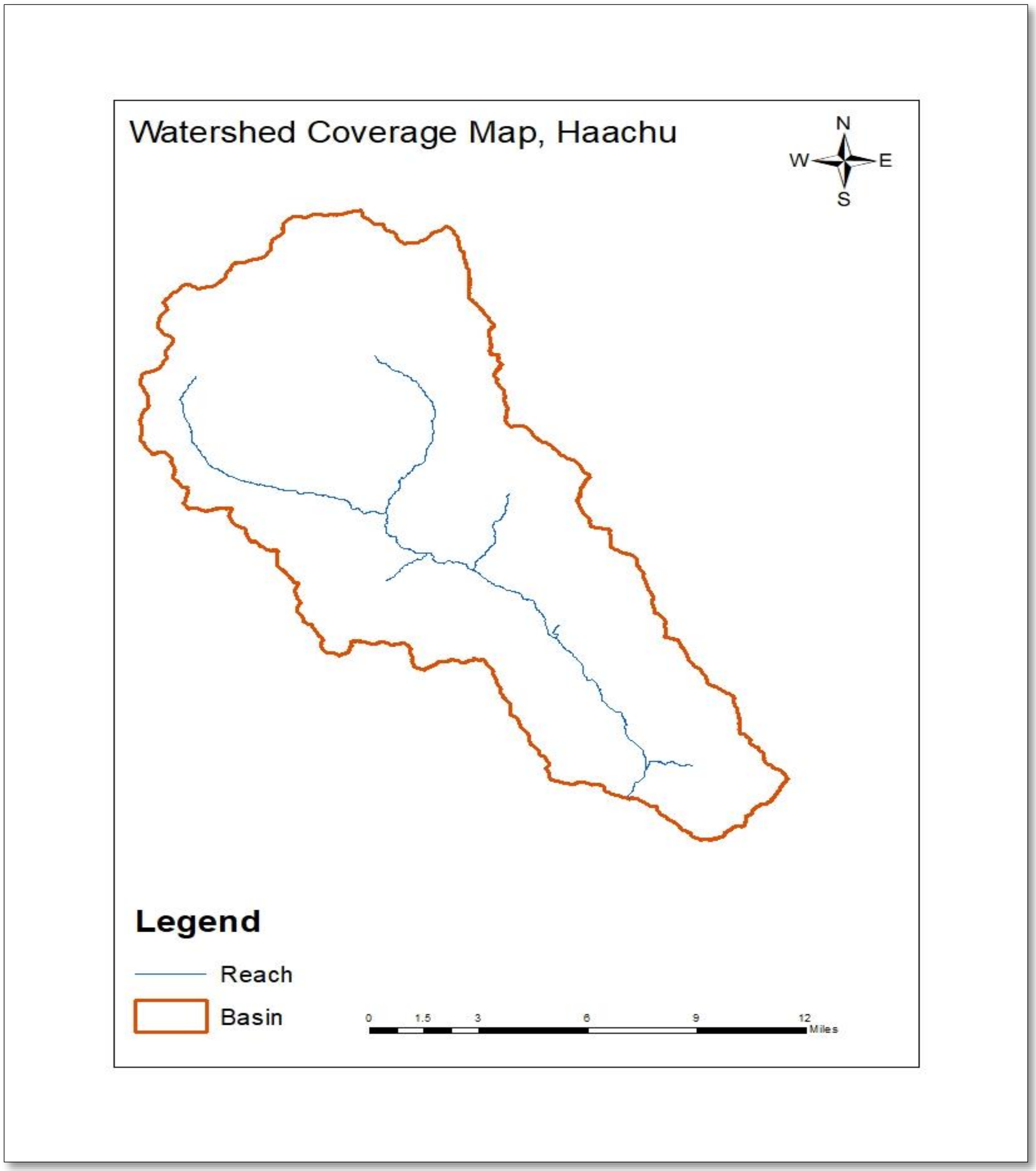


Figure 19: watershed delineation, SWAT generated

SWAT model: HRU Definition

The sub-basins were further divided into Hydrologic Response Units (HRUs). HRU is a unique combination of soil type, land use, and slope, which are the smallest units in SWAT where the calculation of the water balance, sediments, and nutrients takes place. The Bhutan Land-use and Land Cover Map of the year 2011, the Food and Agriculture Organization (FAO) soil data, and user-defined slope range are used to create the Hydrologic Response Unit (HRU).

To proceed with the HRU definition, the projected land use map and soil map were overlaid in the watershed. The land use classes of Land-use Bhutan had to be reclassified to the nearest matching land use category of the SWAT database. This was carried out by making a simple land use lookup table. The soil types and their corresponding parameters were also updated in the *user soil* database of the SWAT model. Next, the basin was divided into three slope categories with the criteria given by the FAO. Areas with slope 0-40% represented the undulating lands, 40 – 70% represented steep lands, and >70% represented mountain areas as shown in Figure 20.

Then the HRU(s) were defined based on land use, soil, and slope of the basin. While defining the HRU(s), the threshold of 10%, 10%, and 10% was applied on land use, soil, and slope, respectively.

Regular monitoring of water quality within the watershed is not carried out as such monitoring data are not available for the study area.

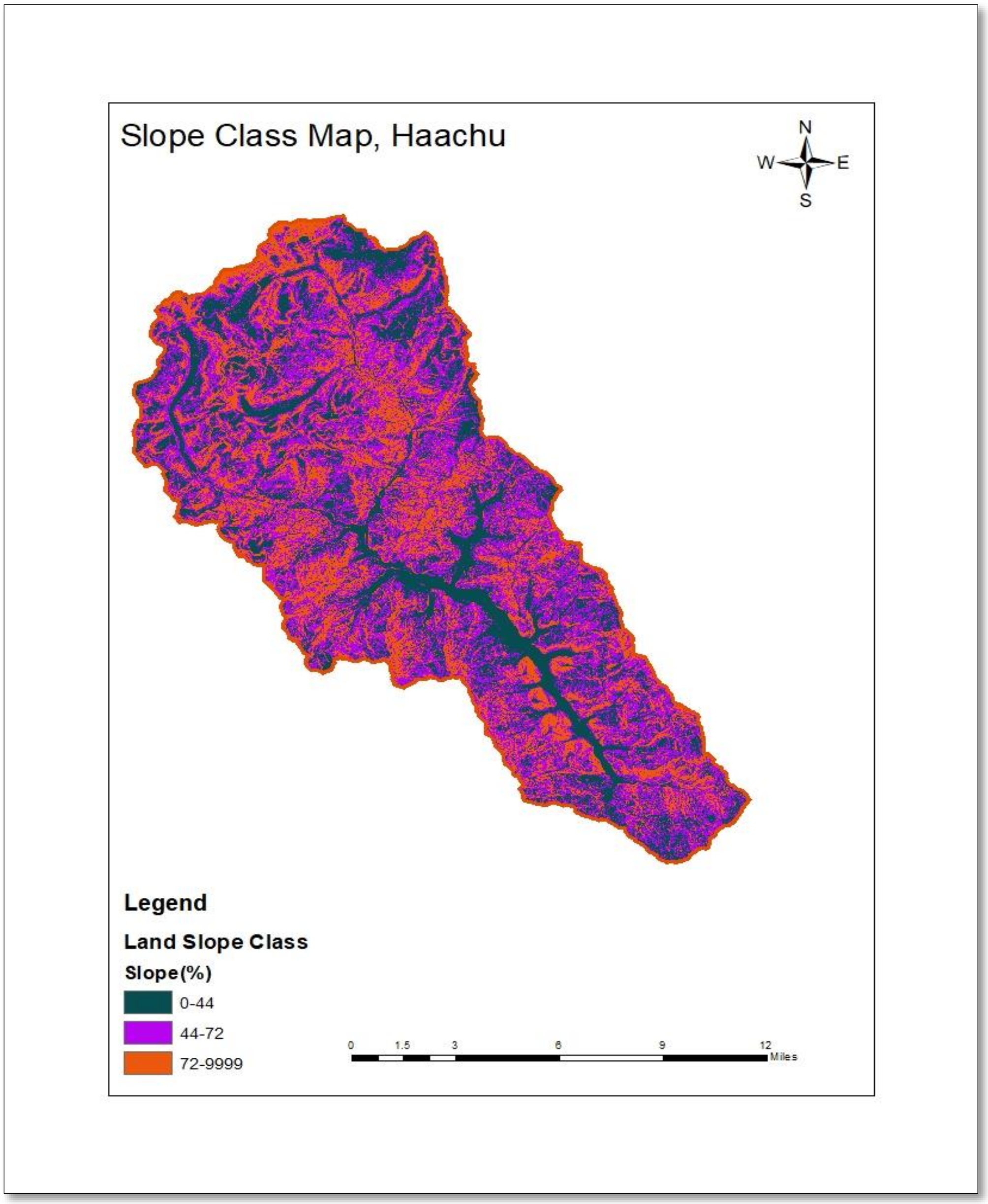


Figure 20: Slope Class, SWAT generated

SWAT model: Weather Data

After the HRU definition, the weather data of two stations were loaded into the model in the weather stations tab. SWAT requires various weather data, such as rainfall, temperature, relative humidity, solar radiation, and wind data for rainfall-runoff simulation. In this case, only daily rainfall data and daily maximum and minimum temperature data were entered in the model. As only the two variables were provided for the model, in the subsequent steps for the calculation of evapotranspiration, the Hargreaves method was chosen for the simulation.

SWAT model: Input modification

Orographic precipitation is a significant phenomenon in the Haachu basin. To account for orographic effects on precipitation, each sub-basin was divided into three elevation bands. The flow accumulation, sublimation, and melting of snow processes are simulated separately for each elevation band. To adjust the precipitation, the elevation of the recording station or the weather station is compared to the elevation specified for the elevation band. The defined elevation bands for each sub-basin of the Haachu Basin, including the fraction of the sub-basin area within the elevation bands, are given in Table 4.

Table 4: Elevation band for Haachu sub catchments

Sub-Basin	Area (Sq.km)	Elevation at the center of band			Fraction of sub-basin		
		1	2	3	1	2	3
1	132.12024	3436	4315	5194	0.2147	0.6717	0.1136
2	72.016863	3445	4341	5236	0.2734	0.6854	0.0412
3	8.748337	3105	3574	4043	0.6854	0.2723	0.0423
4	15.974552	3041	3554	4067	0.4754	0.3589	0.1657
5	29.160446	3016	3480	3944	0.228	0.5007	0.2713
6	17.806082	3167	3760	4353	0.2307	0.4524	0.3169
7	18.915416	2914	3327	3740	0.65	0.2932	0.0568
8	20.743033	2951	3440	3929	0.2689	0.5117	0.2194
9	52.792691	2862	3374	3885	0.3978	0.4379	0.1643
10	18.262334	2850	3338	3826	0.2147	0.366	0.4193
11	12.083586	2822	3288	3754	0.4112	0.3826	0.2062

SWAT model: Model Simulation

The model was run from 1996 to 2017. The first three years (1996-1999) were kept as a model warm-up period. The SWAT model was run at a daily time step.

SWAT model: Model Output

The Simulated discharges for Haachu from the SWAT Model were assessed, and the yearly maximum discharge from the model was calibrated as explained in the following paragraph.

SWAT Model Calibration

The discharge data available from Haachu flow station covers the period from 2000-2021. The calibration was tried using SWAT Calibration Helper v1.0 Microsoft Excel Worksheet developed by Shrestha P.K. (2016), shown in Figure 21.

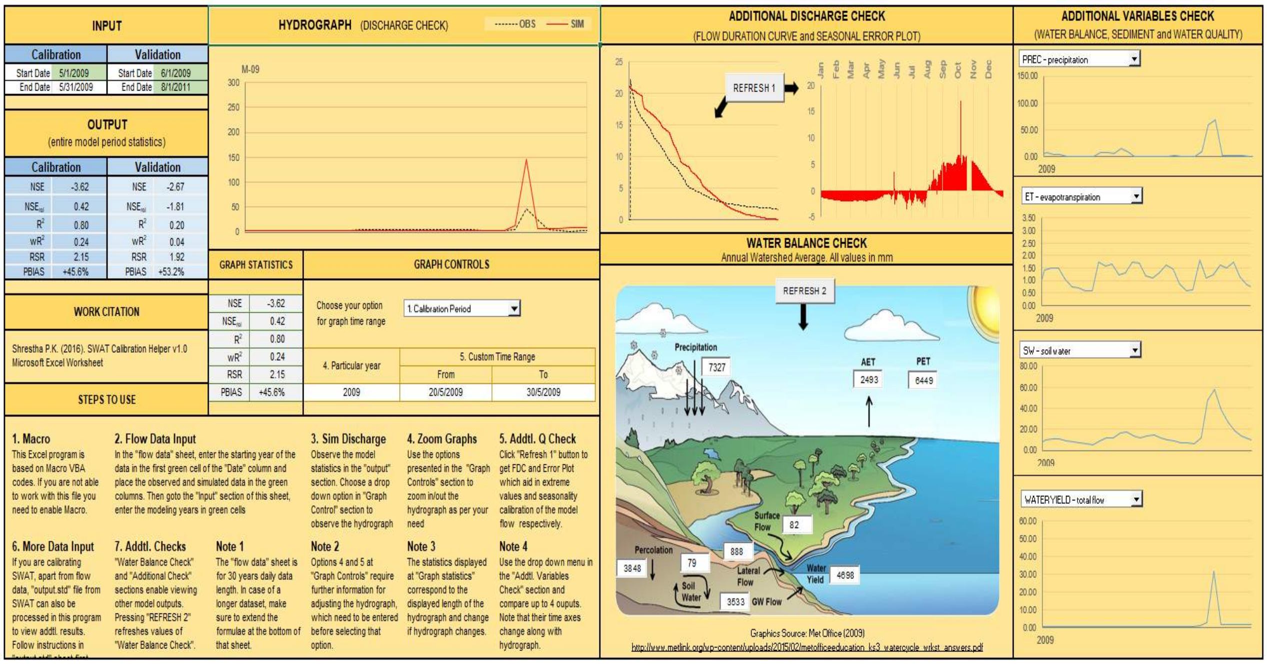


Figure 21: SWAT Calibration Helper v1.0

The calibration is assessed considering the performance of the model during the high-discharge seasons. As for performance criteria, the Nash–Sutcliffe model efficiency coefficient (NSE)10 and Percent bias (PBIAS) have been applied. The NSE value can range from any negative value to a maximum of 1.0. Higher NSE means a better match between the modelled and observed time series. The PBIAS represents the percentage bias between the modelled and observed discharges, with low-magnitude values indicating accurate model simulation. Positive PBIAS indicates overestimation, and negative PBIAS indicates underestimation. The figure given below shows the performance indicators for event-based discharges.

PBIAS (%)	NSE	Performance
0 a 10	0.75 a 1	Very good
10 a 15	0.65 a 0.75	Good
15 a 25	0.50 a 0.65	Fair
>25	<0.50	Inadequate

5.4. Frequency Analysis of Rainfall Data

Hydrologic systems are sometimes impacted by extreme events, such as severe storms, floods, and droughts. The magnitude of an extreme event is inversely related to its frequency of occurrence, with very severe events occurring less frequently than more moderate events. The objective of frequency analysis of hydrologic data is to relate the magnitude of extreme events to their frequency of occurrence through the use of probability distributions.

As per the report on the Analysis of Historical Climate and Climate Change Projection by the National Center for Hydrology and Meteorology (NCHM), the study indicated an increase in temperature and rainfall for Bhutan under future climate scenarios, Representative Concentration Pathways 4.5 and 8.5. Under the RCP4.5 scenarios, the annual rainfall over Bhutan indicates an increase of about 10%-30% in summer (JJAS) rainfall between 5% -15 %. And under the RCP 8.5 scenario, the mean annual rainfall indicates an increase of about 10% - 20% during 2021-2050, and with more than a 30% increase all over Bhutan towards the end of the century.

Considering the maximum percentage increase as 20%, the 100-year return period hydrograph was increased by 20% and the hydrodynamic models were simulated to map the climate change scenario.

5.4.1. Gumbel distribution

Gumbel is an Extreme Value distribution (EV Type I) (Emil Julius Gumbel, 1941) used to analyse the extreme maximum or minimum of a number of samples of a distribution. The parameters for the distribution are as follows. The mean (μ) and the standard deviation (σ) of the annual maximum time series is computed along with values of ‘a’ and ‘c’ which is given by Eqn 1 and Eqn 2.

$$a = \sqrt{\frac{6\sigma^2}{\pi^2}} = 0.7797\sigma \qquad \text{Equation 1}$$

$$c = \mu - 0.5772a \qquad \text{Equation 2}$$

And for each return period of (T), the standard variate is computed using Eqn.3 and the return period discharge is computed using Eqn.4.

$$Y_T = -\ln\left[-\ln\left(1-\frac{1}{T}\right)\right]$$ Equation 3

$$Q_T = c + Y_T a$$ Equation 4

5.4.2. Log Pearson III distribution

The Log Pearson III (Pearson, 1895) was the second statistical technique used to fit the flood frequency for Haachu. The distribution is computed by a general equation, Equation 5. The annual peak discharge data were ranked from largest to smallest, and the $\log_{10}$ value for each data was computed.

$$\log_{10} Q_T = K_T \sigma + \mu$$ Equation 5

Where Mean, $\mu = \frac{1}{n}\sum_{i=1}^{n}(\log_{10}(x_i))$

Standard deviation, $\sigma = \frac{1}{n-1}\sum_{i=1}^{n}(\log_{10}(x_i) - \mu)^2$

Probability of occurrence, $P_T = \frac{1}{T}$

Intermediate variable w for each return period, $w_T = \left[\ln\left(\frac{1}{P_T^2}\right)\right]^{\frac{1}{2}}$ *for* $(0 < P_T \leq 0.5)$

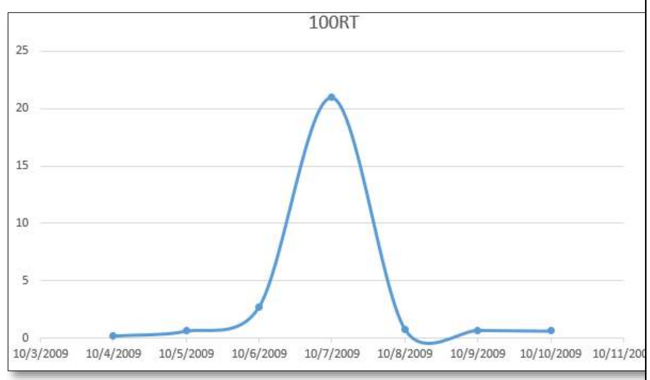
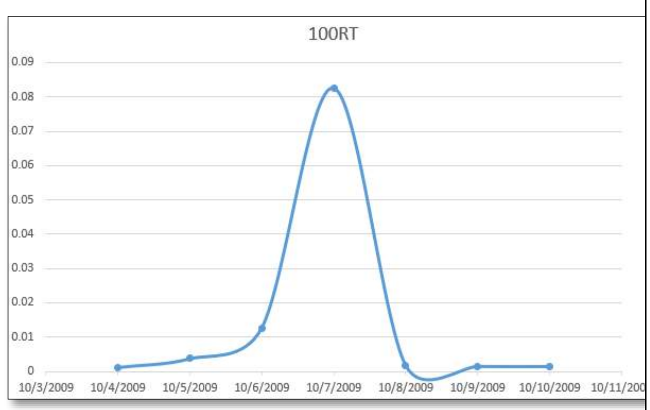
Frequency factor $K_T = Z_T + (Z^2{}_T - 1)k + \frac{1}{3}(Z^3{}_T - 6Z_T)k^2 - (Z^2 - 1)k^3 + Z_T k^3 + Z_T k^4 + \frac{1}{3}k^5$

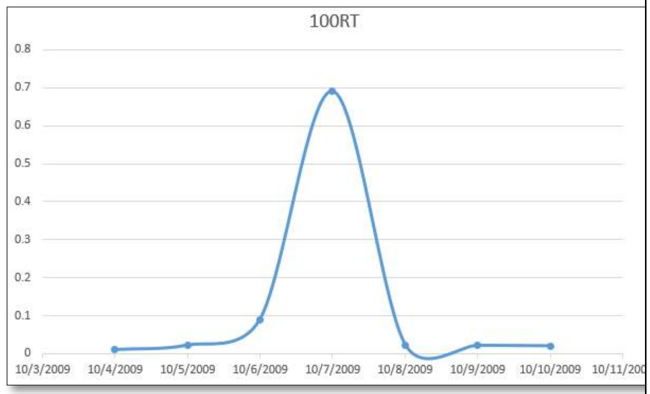
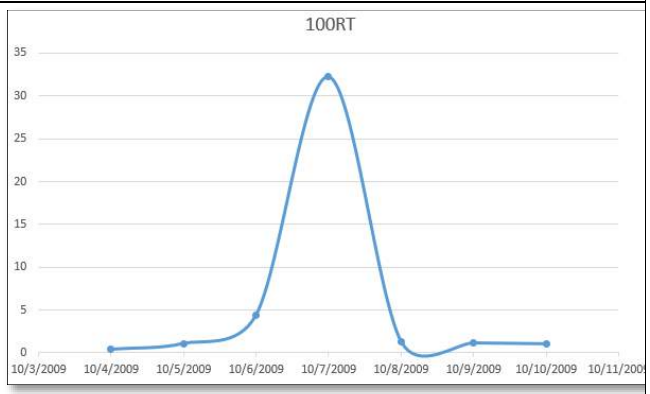
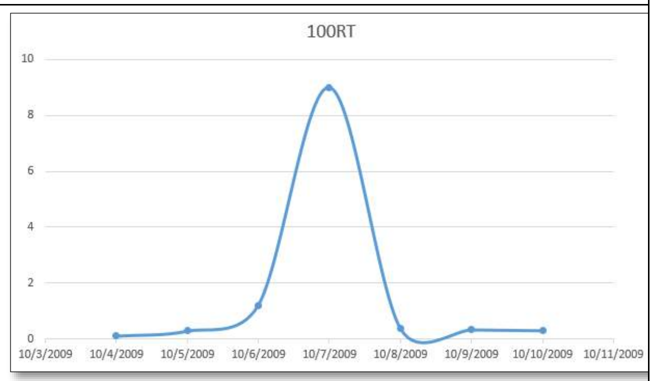
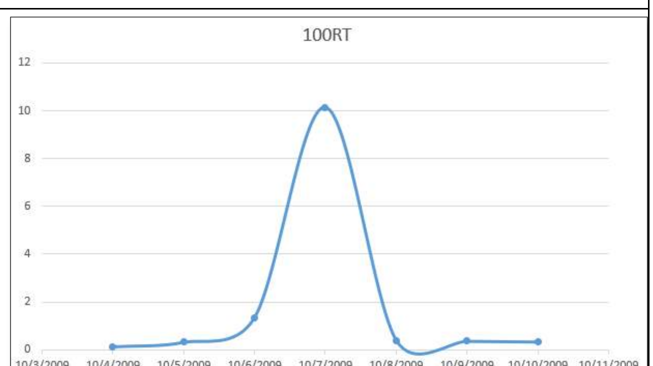
$$k = \frac{C_s}{6};\quad C_s = \frac{n\sum_{i=1}^{n}(\log_{10}(x_i) - \mu)^3}{(n-1)(n-2)\sigma^3}$$

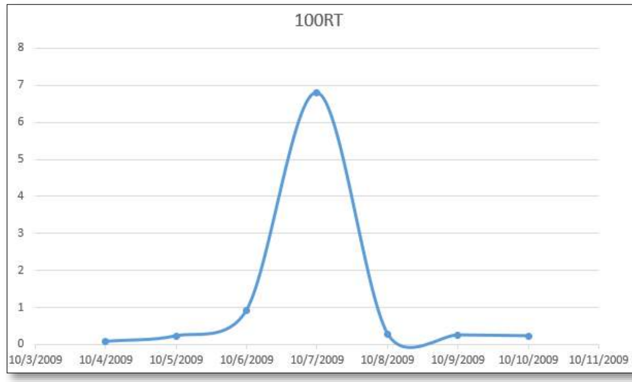
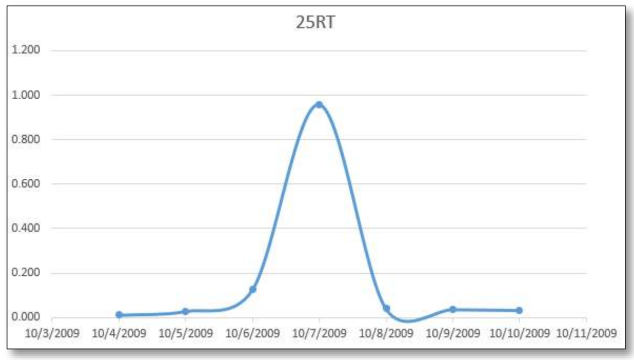
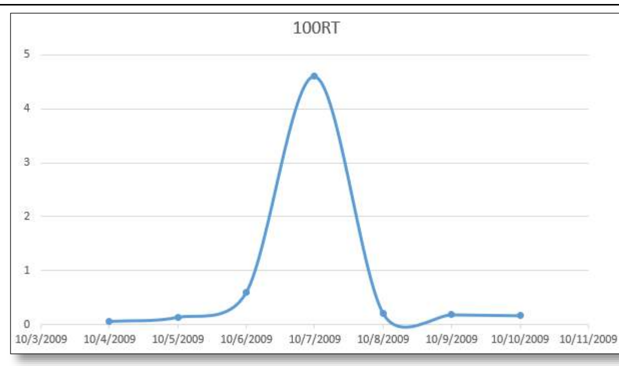
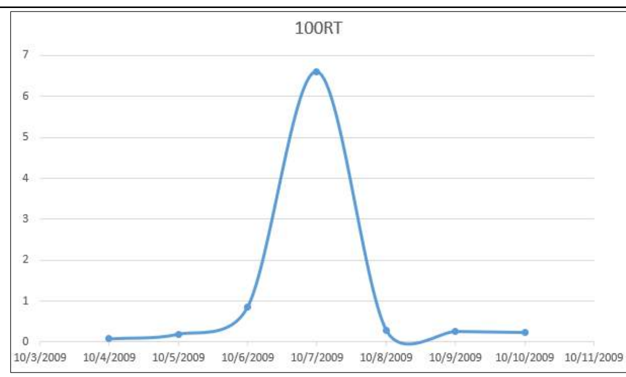
$$Z_T = w - \frac{2.515517 + 0.0802853w + 0.010328w^2}{1 + 1.432788w + 0.189269w^2 + 0.001308w^3}$$

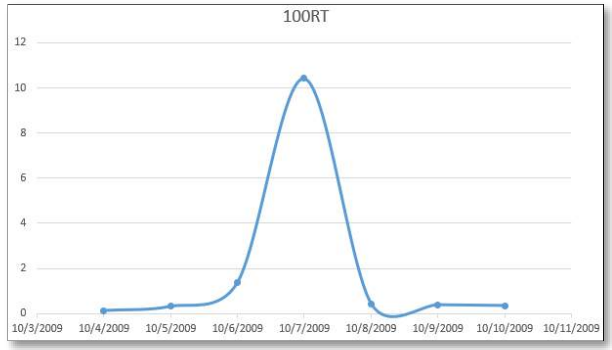
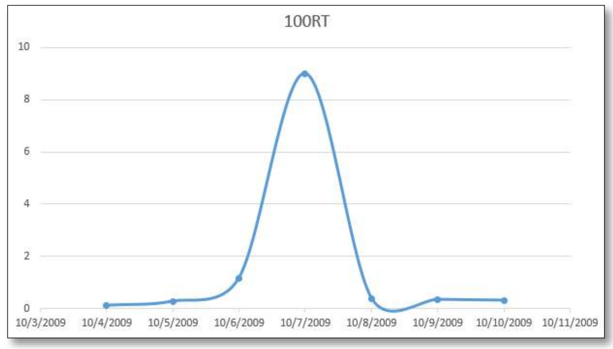
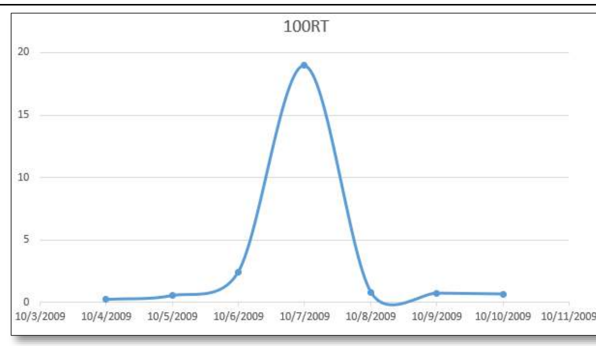
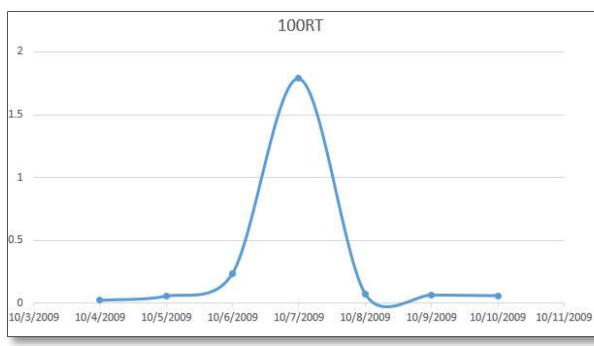
The hydrographs for individual streams and the river are tabulated in the following Table 5.

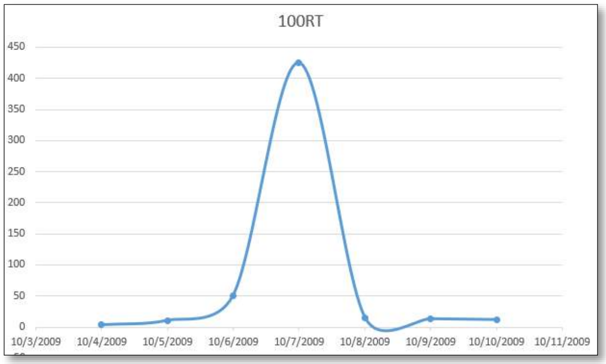
Table 5: Hydrographs for individual streams and river

Stream/ River	**Return Period**	**Return Period Discharge (Peak Method) in m³/s-Climate Change Scenario**	
Yakchu	100	21	
Chunap		0.0826	

Chukap	0.6903	
Talungchu	32.2573	
Bali	0.6903	
Atam	10.1313	

Wangtsa	6.8077	
Janaphuchu	1.27	
Bangayna	4.6062	
Dungchu	6.6042	

Tshaphelchu	10.4225	
Tsalenphuchu	9	
Kanaphuchu	18.9954	
Zakeychu	1.7964	

Haachu		424.55	

6. Hydrodynamic Model Development

The hydrodynamic model for the main river and the streams was developed, and a suitable 1D or 2D model was chosen for each area, as per data availability and results from the models. The following flowchart in Figure 22 shows the methodology adopted for developing HEC-RAS hydrodynamic models.

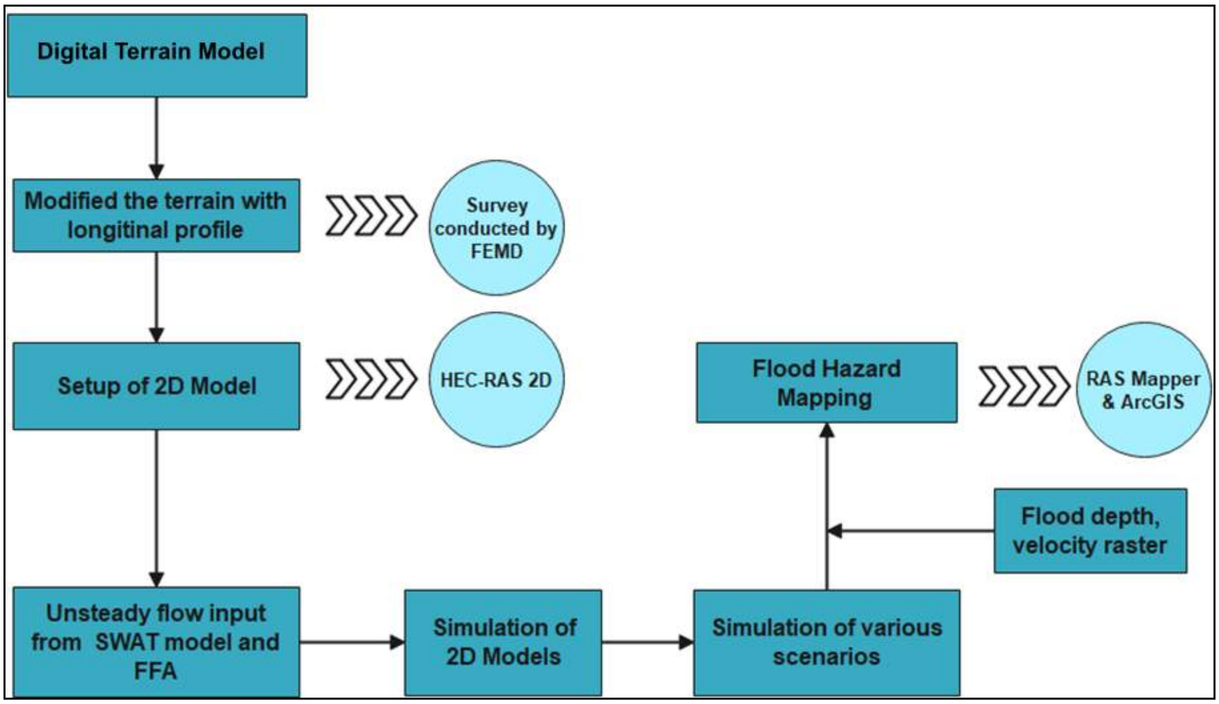


Figure 22: Methodology adopted for developing the 2D Hydrodynamic Model

6.1. Selection of Hydrodynamic Model

Two-Dimensional models predict higher resolution flow characteristics as compared to 1D: velocity, shear stress, stream power. Unsteady models in 2D are faster to build, easier to stabilize, and also account for inertia and eddies.

Therefore, 2D hydrodynamic models were deemed a better fit for the current application, and so, 2D models were developed for Haachhu and its tributaries in assessing its flooding hazards and risks.

6.2. Setup of 2D HEC-RAS Model

6.2.1. Creation of Geometry

The 10m resolution ALOS DEM was used in this study. The channel geometry was modified as per the cross-section survey data collected during the site assessment by the FEMD team. The new modified terrain has been shown in Figure 23. The 2D flow area for Haa catchment has been shown in Figure 24.

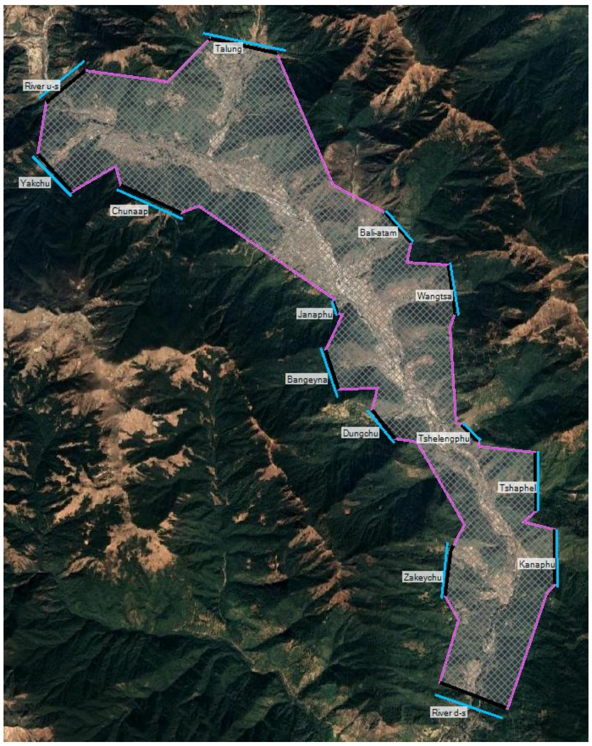


Figure 23:2D Flow Area of Haachu and Tributaries

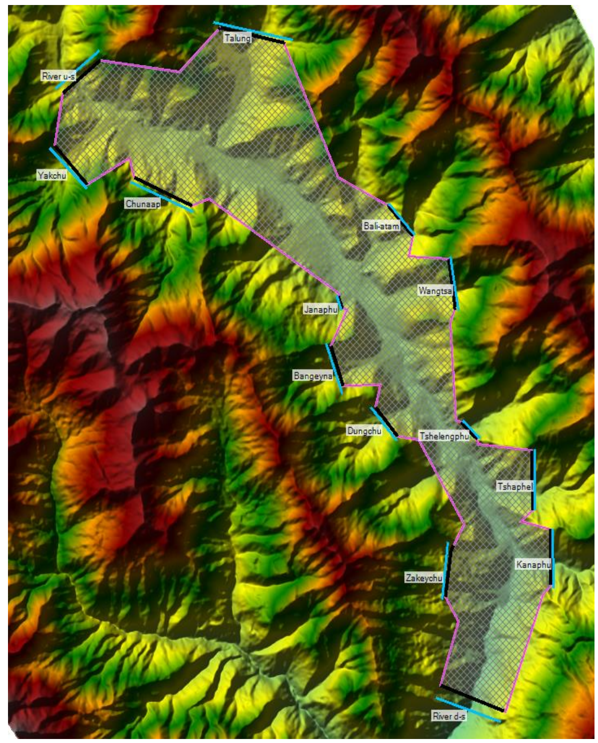


Figure 24: ALOS DEM terrain for the study area

Figure 25 shows the overall 2D flow Area of the study area, including the river and streams. The detail of which is tabulated in Table 6.

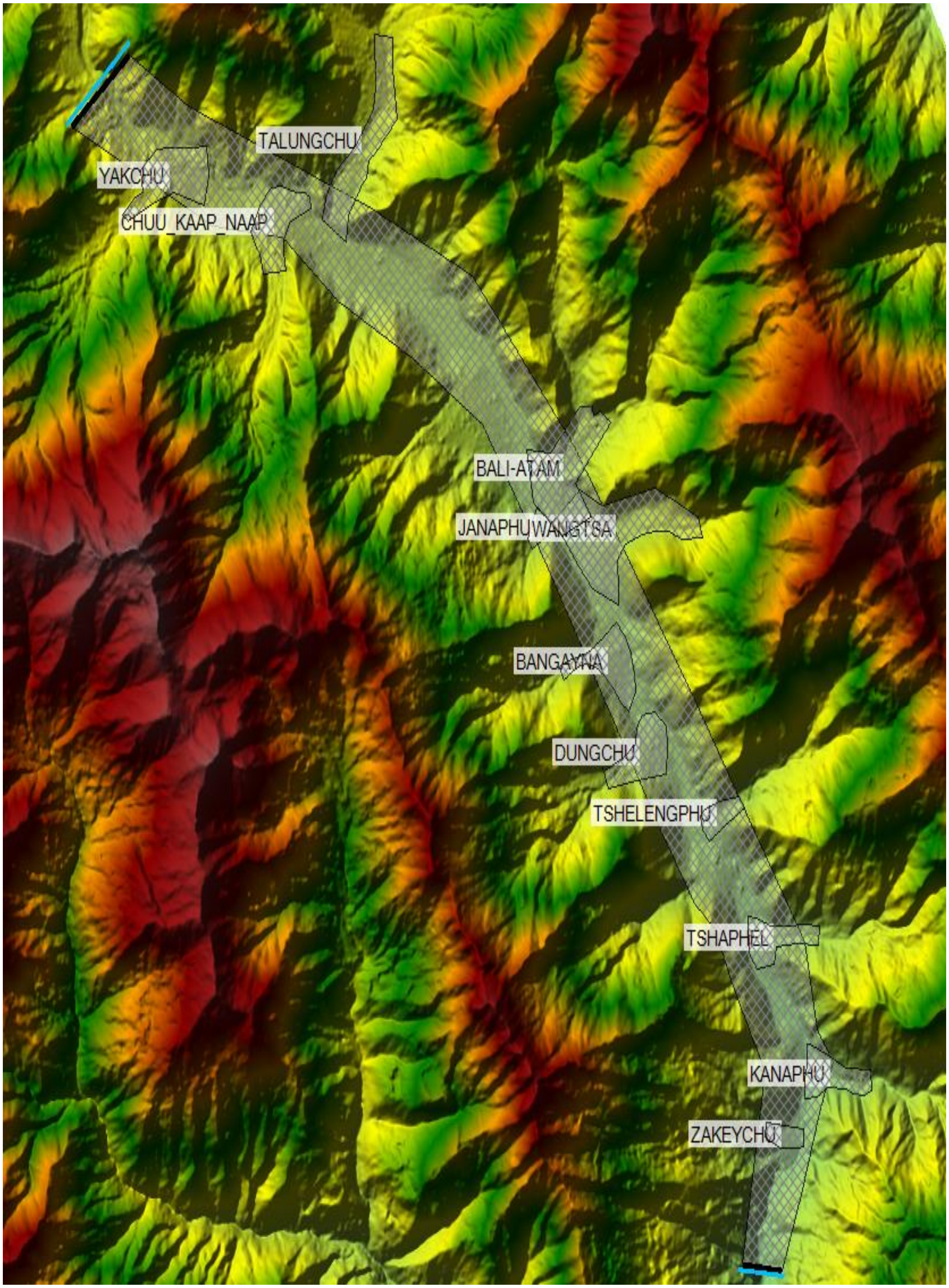
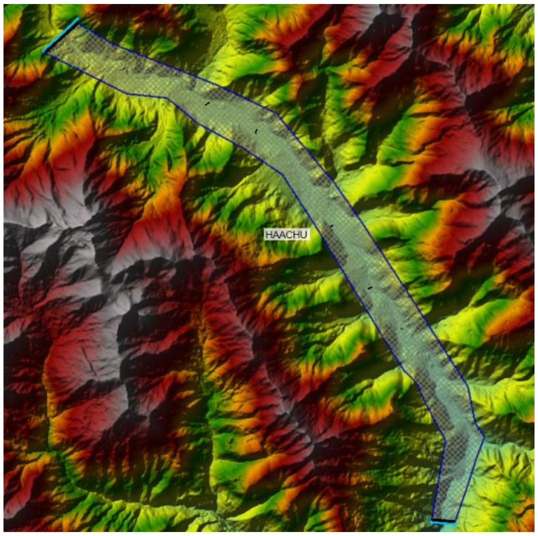
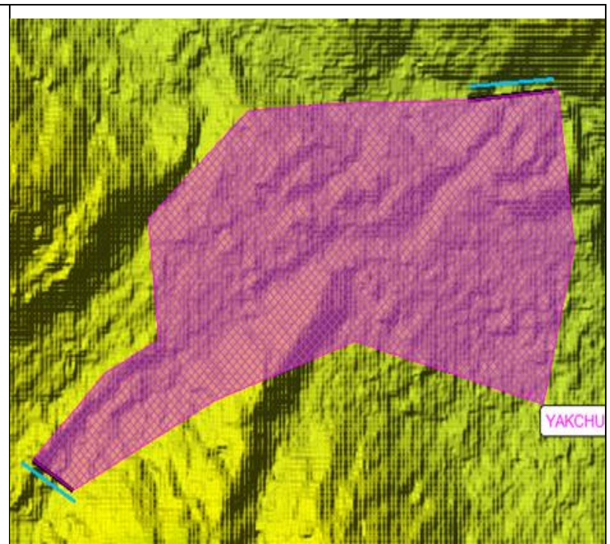
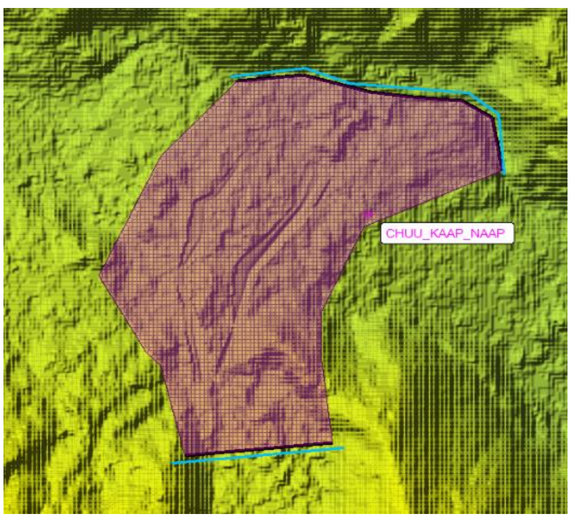
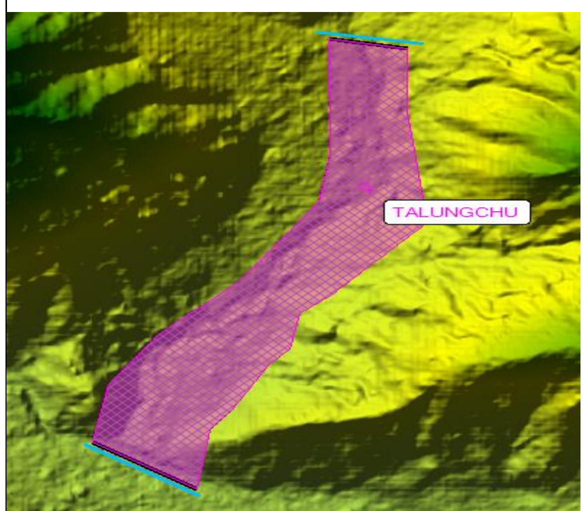
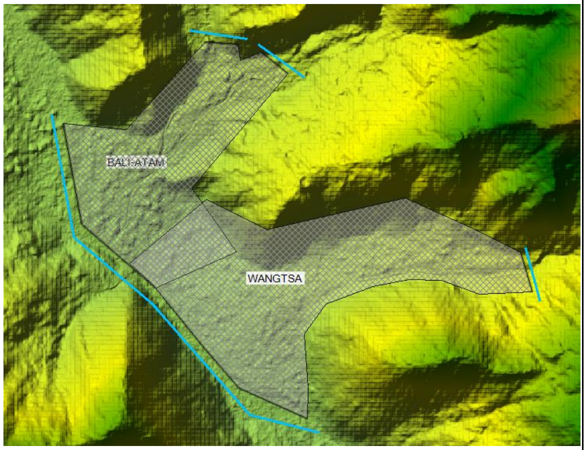


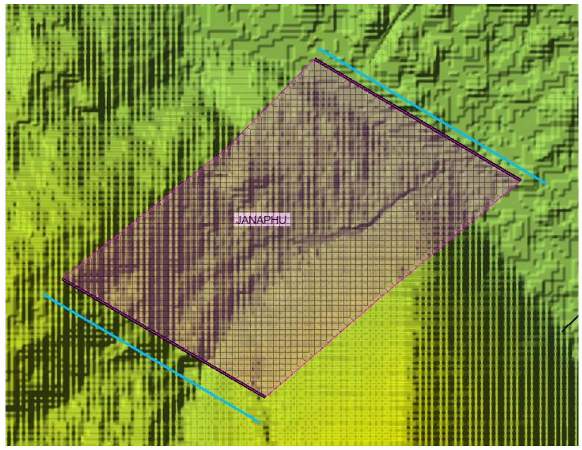
Figure 25:2D Flow Area of Haa Chhu and Tributaries

Table 6: 2D Flow area for the river and streams

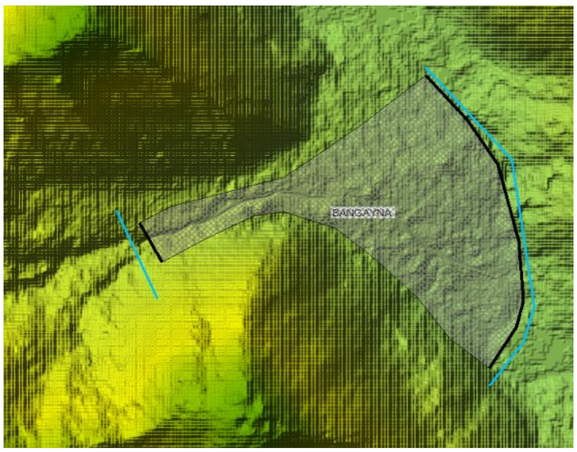
 *2D flow area for Haa River*	 *2D flow area for Yakchhu stream*
 *2D flow area for Chu Kaap and Chu Naap streams*	 *2D flow area for Talung chhu stream*



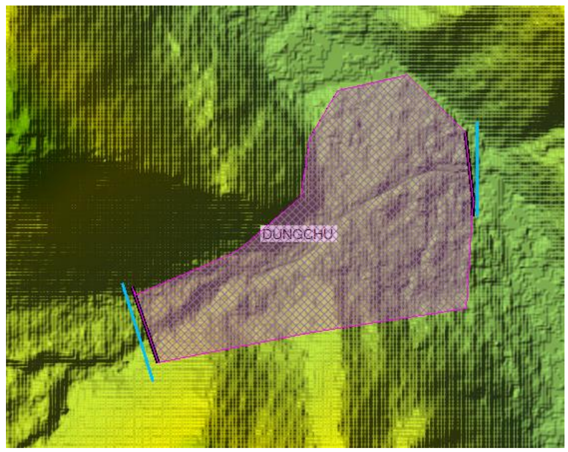
2D flow area for Bali-Atam and Wangtsa streams



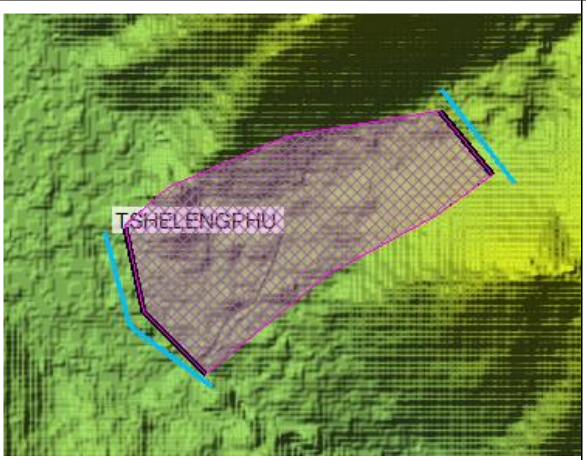
2D flow area for Janaphuchhu stream



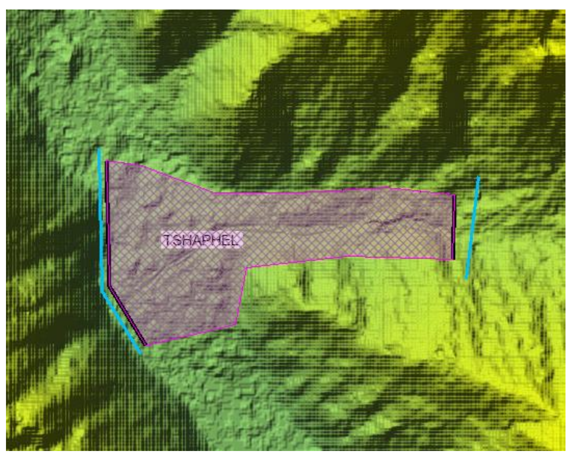
2D flow area for Bangayna stream



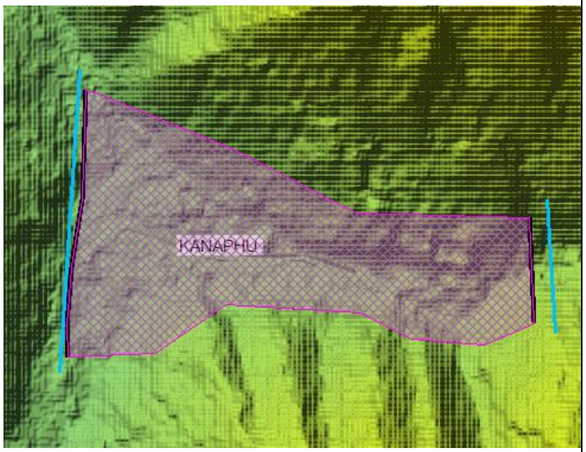
2D flow area for Dungchhu stream



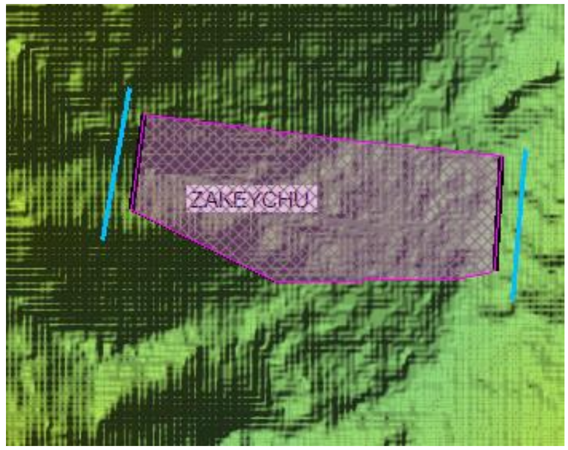
2D flow area for Tshelengphu stream



2D flow area for Tshaphel stream



2D flow area for Kanaphuchhu stream



2D flow area for Zakeychhu stream

The difference in the elevations of the original DEM vs. the modified terrain can be seen as represented with different colors (the red line the terrain CS and green is surveyed CS) Figure 26 and Figure 27 show that the surveyed cross section is generally lower than the DEM where the red line represents the base DEM (i.e. the terrain CS) and the black line represents the surveyed CS.

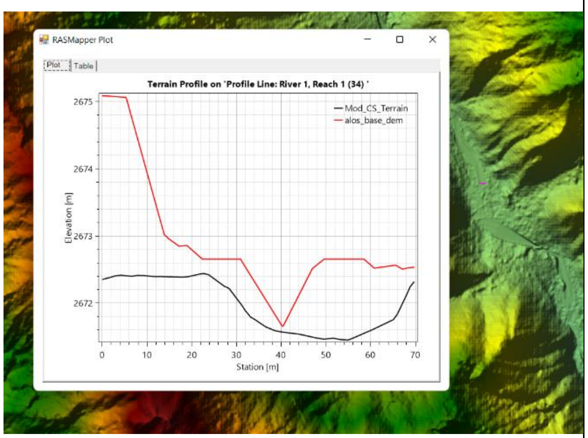


Figure 26: Profile difference in the ALOS DEM and the modified terrain at C/S 34

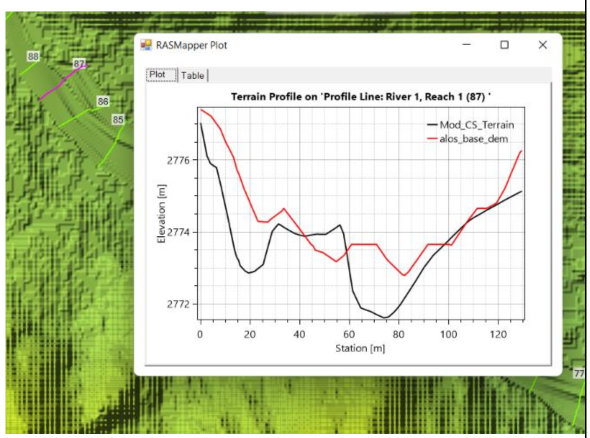


Figure 27: Profile difference in the ALOS DEM and the modified terrain at C/S 87

6.2.2. Preparation of boundary conditions

The flow hydrograph generated by flood frequency analysis of the data from the gauging stations in the catchment area was used as the upstream boundary condition. The hydrographs for a 100-year return period in two different scenarios (business as usual vs. climate change scenario) for the Haa River and its tributaries are shown in Figure 28. Normal depth was used as the downstream boundary condition, which is the slope values tabulated in Table 7.

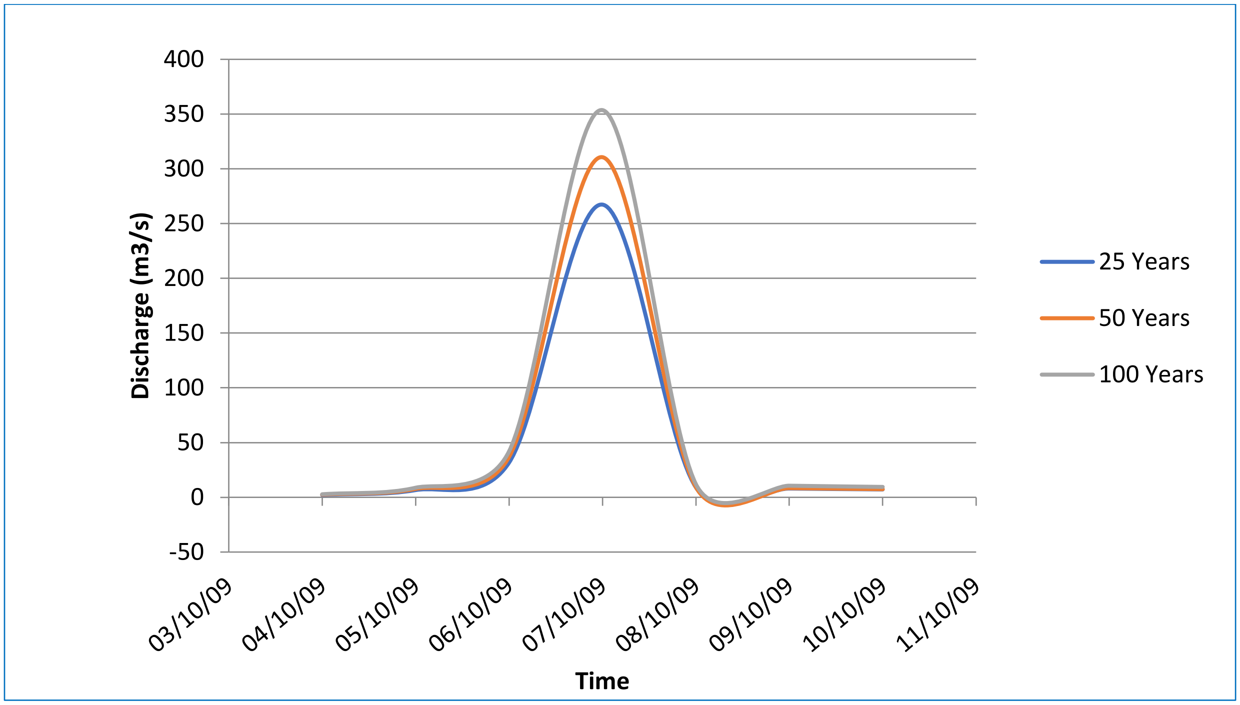


Figure 28: Hydrographs for the Haa River for different return periods.

The Normal Depth (S) was used as an input for the downstream boundary condition for all the models. The normal depth used for each river/stream is detailed in Table 7.

Table 7: Downstream boundary conditions used for the models

Sl.no	River/Stream Name	Normal Depth (S)
1	Haa River	0.015
2	Yakchhu stream	0.127
3	ChhuKaap/ ChhuNaap streams	0.129
4	Talungchhu stream	0.0895

5	Bali-Atam stream	0.108
6	Wangtsa stream	0.135
7	Janaphuchhu stream	0.203
8	Bangeyna stream	0.156
9	Dungchhu stream	0.132
10	Tshelengphu stream	0.142
11	Tshaphel stream	0.109
12	Kanaphuchhu stream	0.092
13	Zakeychhu stream	0.170

6.2.3. Sensitivity Analysis and Model Simulation

HEC-RAS can perform two-dimensional unsteady flow routing with either the Shallow Water Equations (SWE) or the Diffusion Wave Equations (DWE). DWE is the default equation in HEC-RAS, and since it is more appropriate for our terrain and forgiving numerically than the SWE, DWE was used to achieve a numerically stable and accurate result.

In 2D models, assigning mesh cell size (ΔX) and computational time step (ΔT) is important in achieving accurate answers with 2D flow areas. The computational time step is a function of the cell size and the velocity of the flow moving through those cells as defined below:

$$\Delta T \leq \frac{2\Delta X}{V} \ (with\ C = 1.0)$$

Where:

C=Courant Number

V=Flood wave velocity (wave celerity)(m/s)

ΔT=Computational time step (s)

ΔX=Average cell size (m)

The hydrodynamic models were simulated by changing the computation interval from 1 minute and reducing it to 3 seconds. And at the same time, varying the mesh cell size. The computation interval was identified as the most sensitive parameter in the hydrodynamic models. The size of the cell had no drastic change in the result and nor with the Manning's coefficient n-value when varied by +20% and -20%. The 2D area for the Haachhu catchment was computed at a 10m mesh size with a Manning's roughness coefficient (n) of 0.035. A trial-and-error method was used to test various computational time steps to arrive at the largest time step that stabilized the model and produced accurate results. When the computational time was too large, the hydrograph peak was missed at some of the cross sections, which caused the model to become unstable. And too small a computational time step can also cause a stable model to become unstable. The breach locations identified in the model were assessed and verified through site visits.

The hydrodynamic models were simulated for unsteady flow with a 100-year return period for both the main river and the tributary streams, for which the flood hazard maps produced are detailed in the following chapter.

7. Flood Hazard Maps

The 2D hydrodynamic model for Haachu River and its tributary streams was simulated for a 100-year return period with a 20% increase to factor in the climate change. The climate change scenario was generated by adjusting the rainfall as per RCP 4.5 with a climate change factor of 28% increase, as detailed in the Flood frequency analysis.

The Flood hazard has been exhibited in the form of depth maps and velocity maps, as shown in Figure 29– 43. The ALOS DEM modified with cross-section data was utilized for the streams.

This is because the DEM fails to account for gorges and the cross sections of the streams, resulting in the omission of breach points and inundation areas.

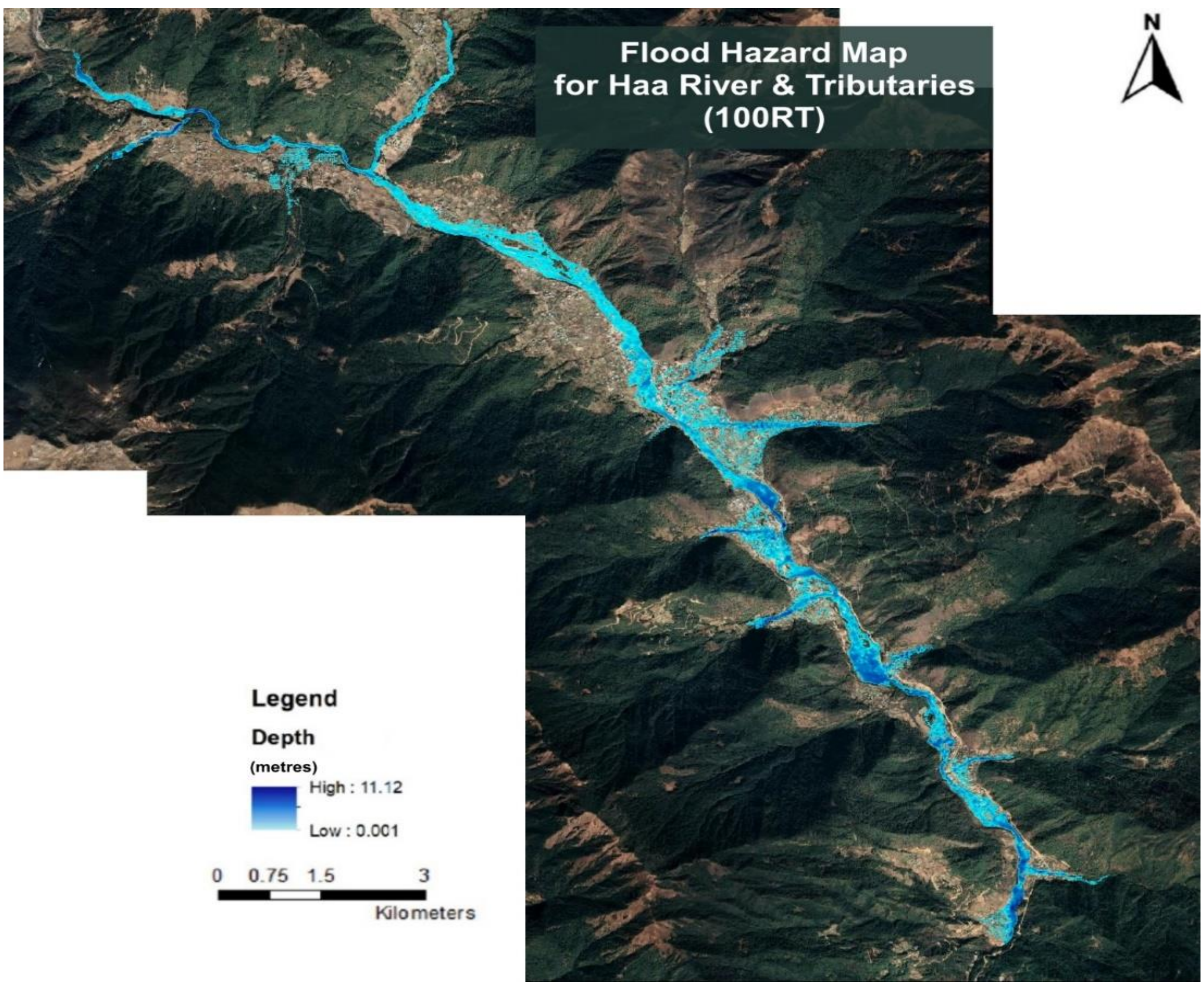


Figure 29: Flood Hazard Map for Haa River and Tributaries for 100 years RT

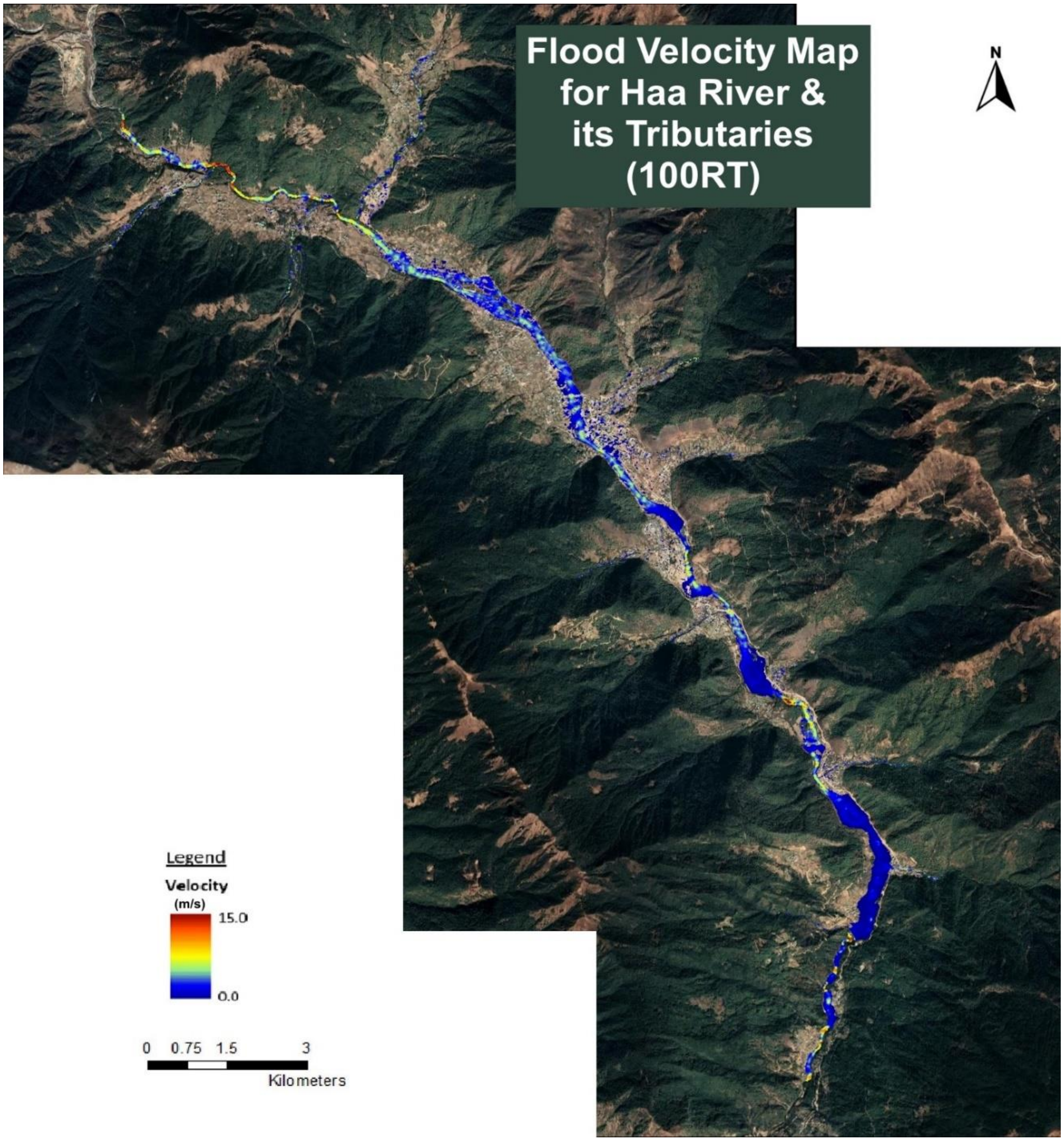


Figure 30: Flood Velocity Map for Haa River and Tributaries for 100 years RT

The flood hazard maps for each stream have been detailed in the figures that follow.

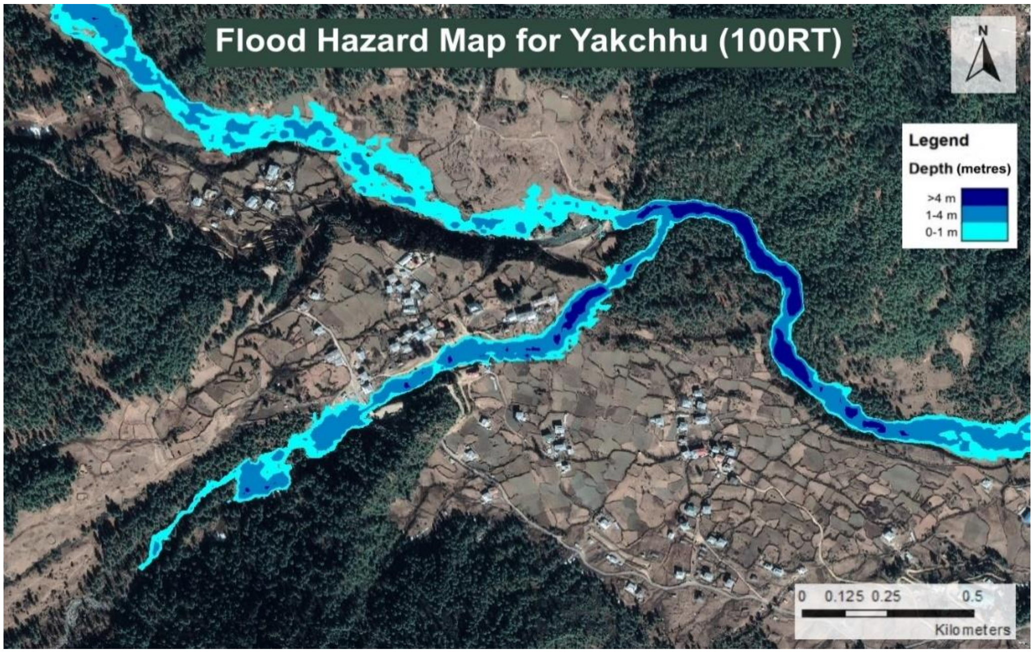


Figure 31: Flood Depth Map for Yakchu Stream

Figure 32:Flood Depth Map for Chukap and Chunap Streams

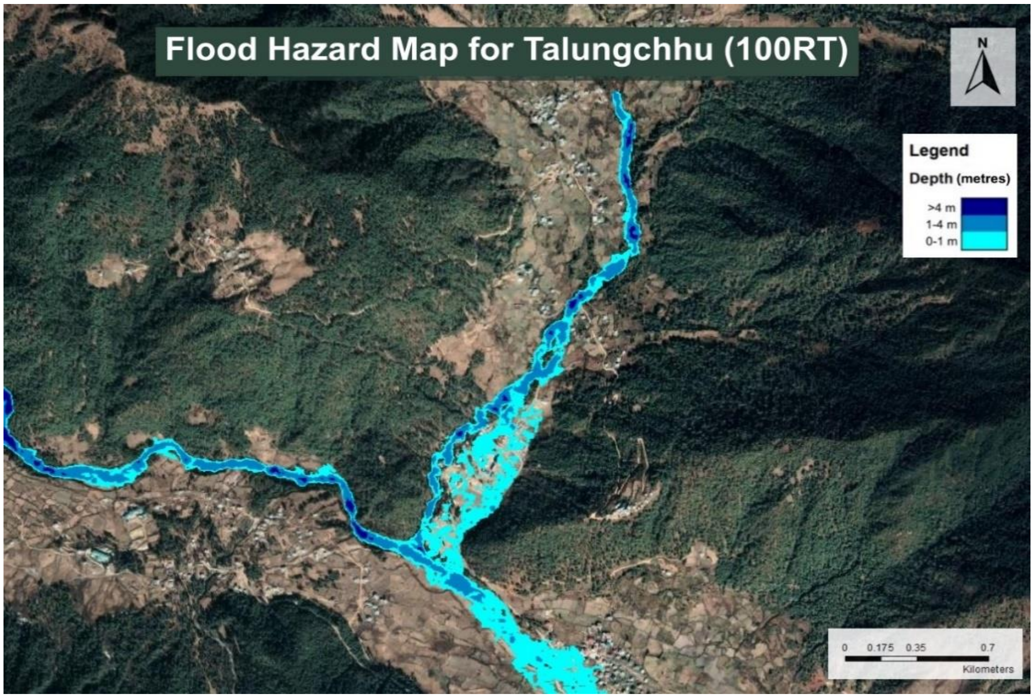


Figure 33:Flood Depth Map for Talungchhu Stream

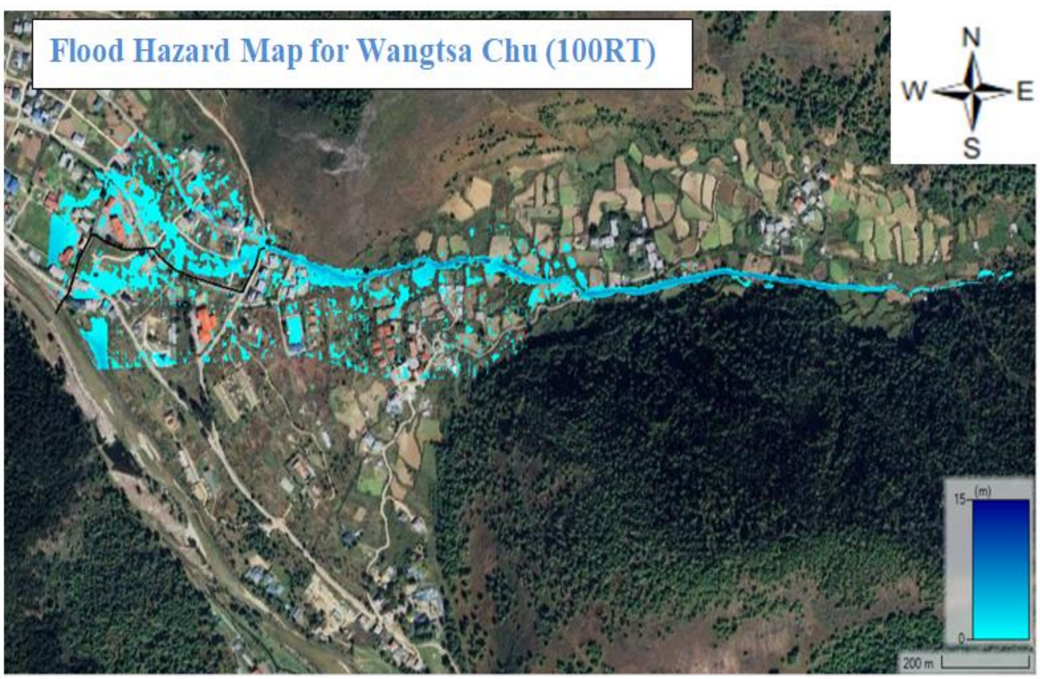


Figure 34: Flood Depth Map for Wangtsa Stream

Figure 35: Flood Depth Map for Bali Atam Stream

Figure 36: Flood Depth Map for Janaphuchhu Stream

Figure 37: Flood Depth map for Bangeyna Stream

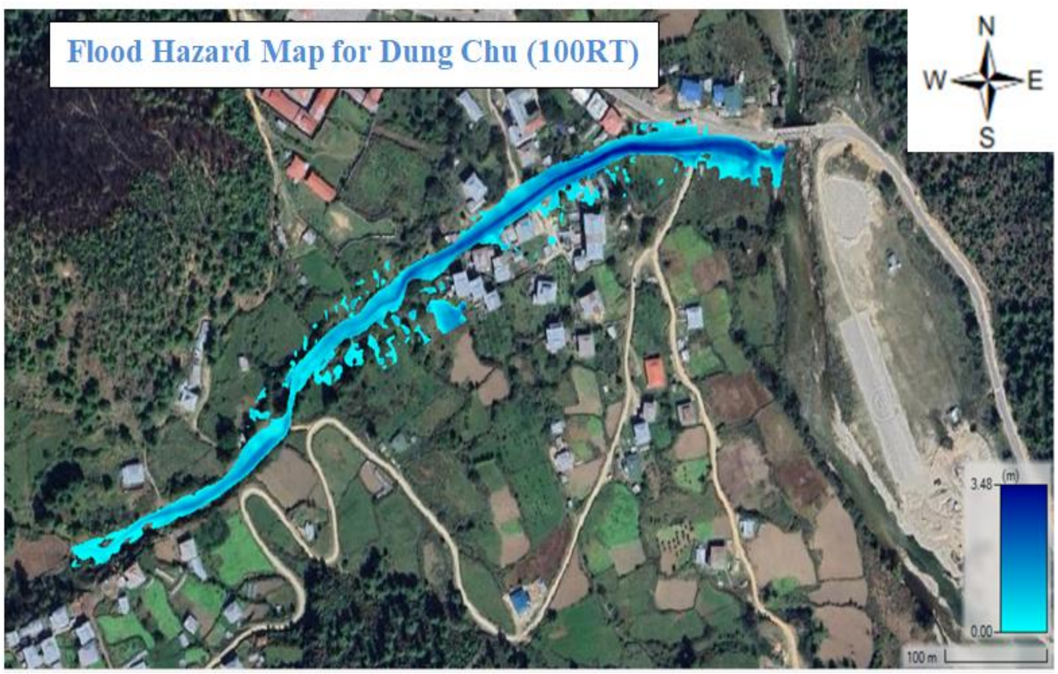


Figure 38: Flood Depth Map for Dung Chu Stream

Figure 39: Flood Depth *Map* for Tshelengphuchhu Stream

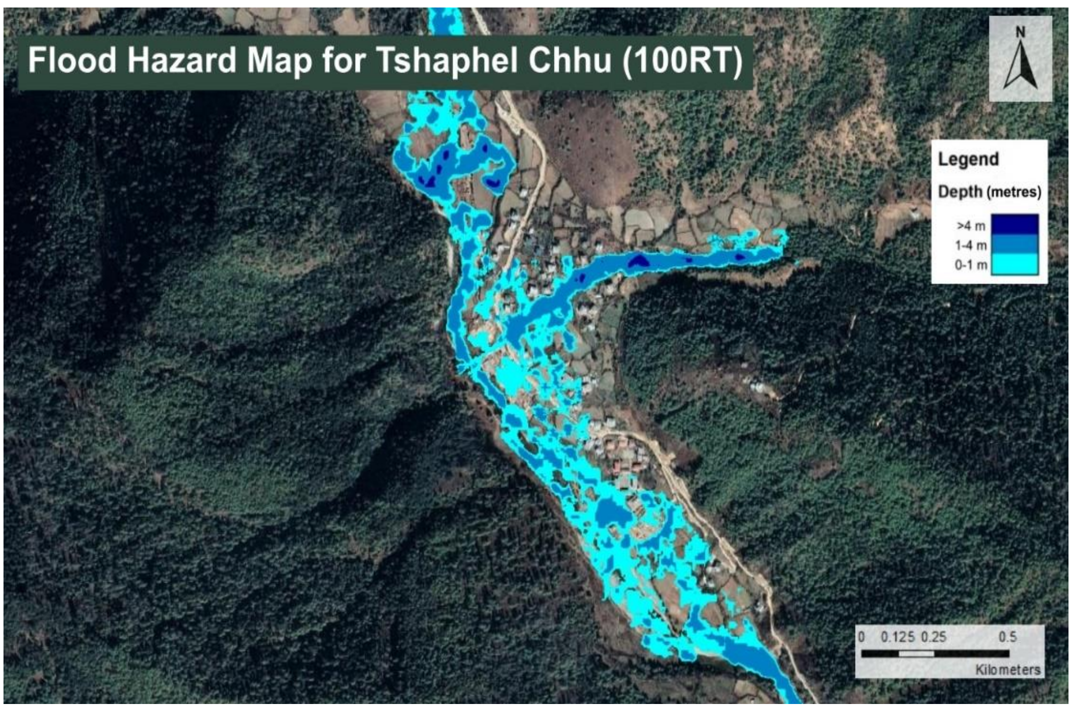


Figure 40: Flood Depth Map for Tshaphel Stream

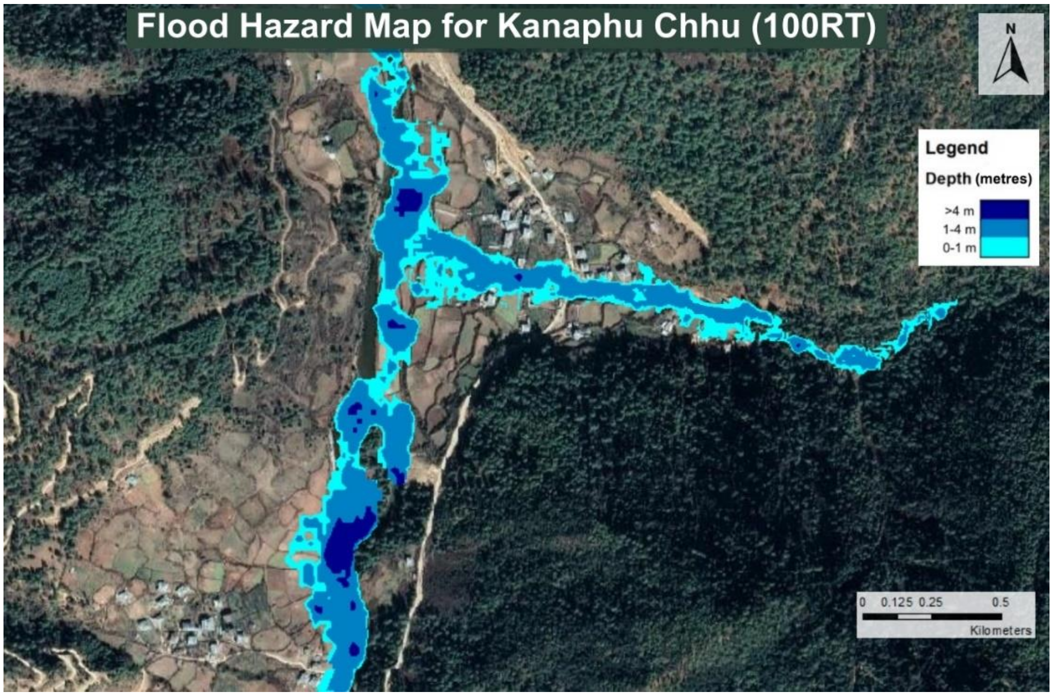


Figure 41: Flood Depth Map for Kanaphuchhu Stream

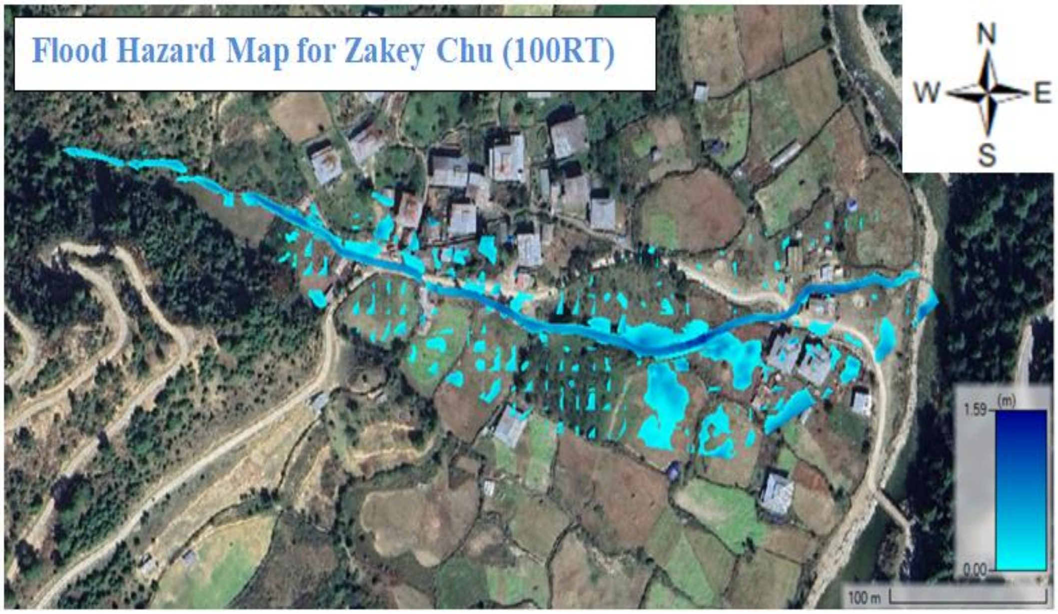


Figure 42: Flood Depth Map for Zakeychu Stream

8. Rapid Flood Risk Assessment

8.1. Data Inventory

Table 8: Data Inventory

Item	Data Source	Original Cell-size	Model
Settlement/Household data	Collected from DHS, MoIT	N/A	Risk assessment
Depth data	Generated from the HEC-RAS model	N/A	Hazard Maps

8.2. Methodology

The household data is overlaid with the depth modeled from HEC-RAS, and the physical vulnerable factors such as the structural building types and the distance from the river/stream were assessed. The details have been populated in Figures 44-Figure 46.

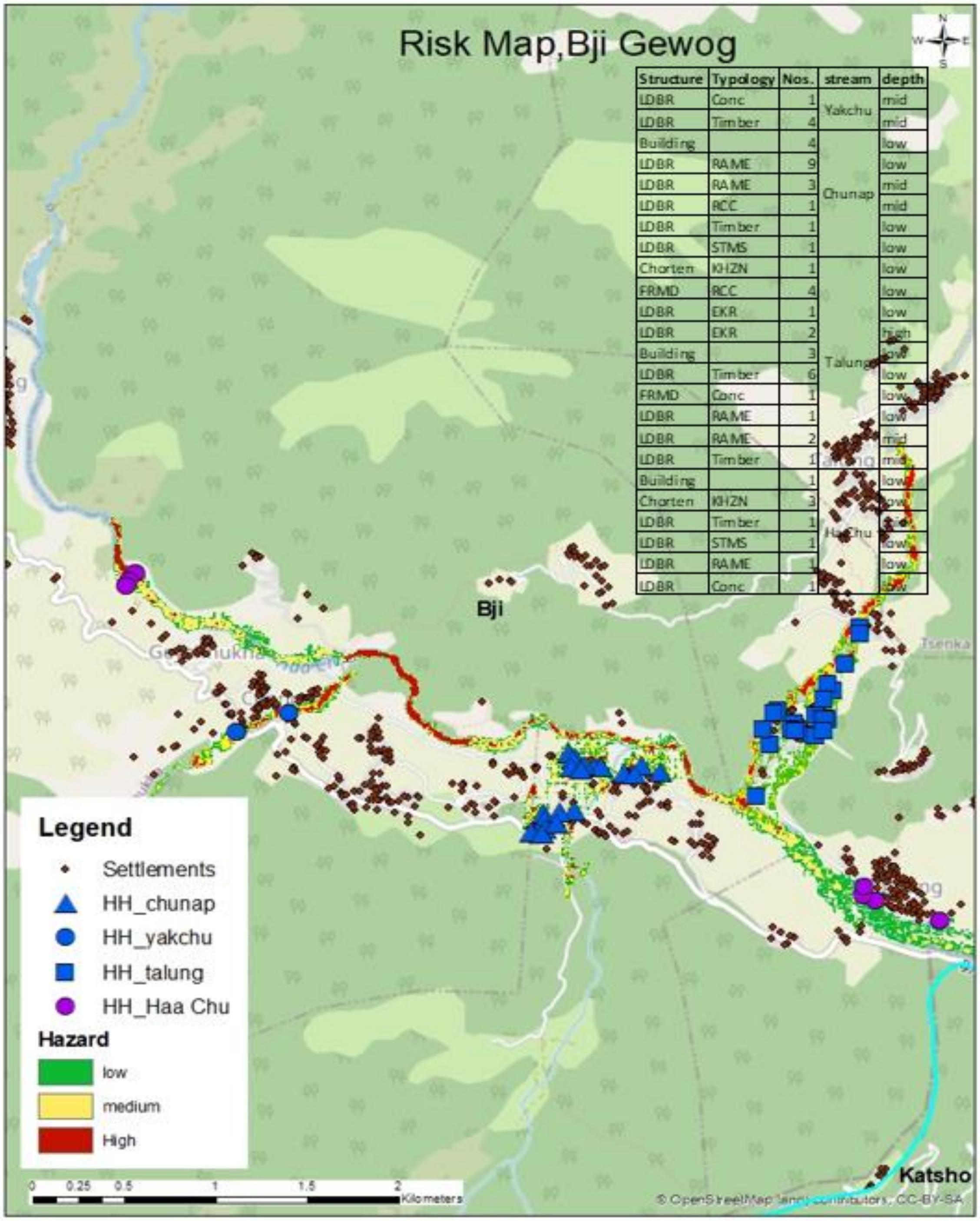
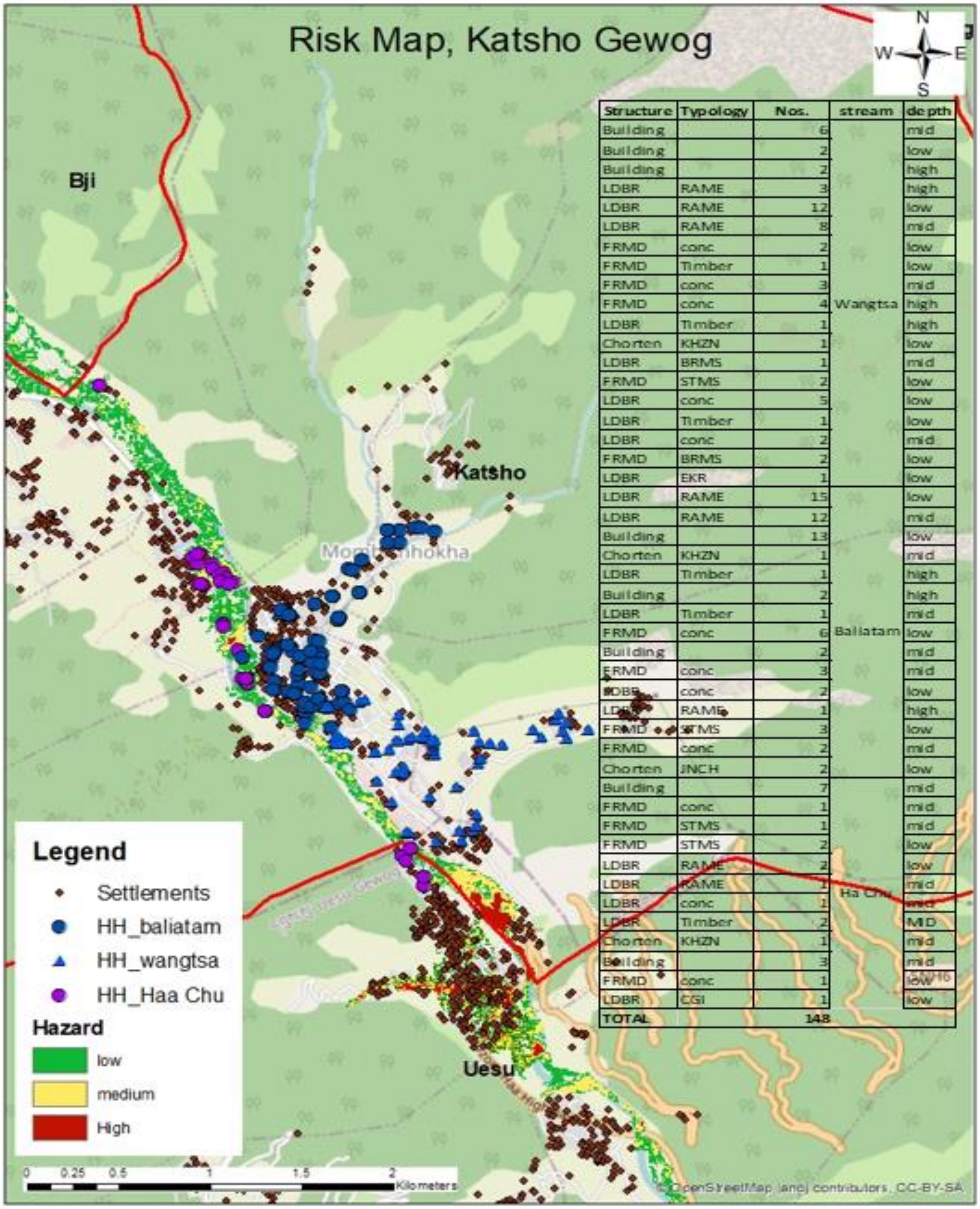
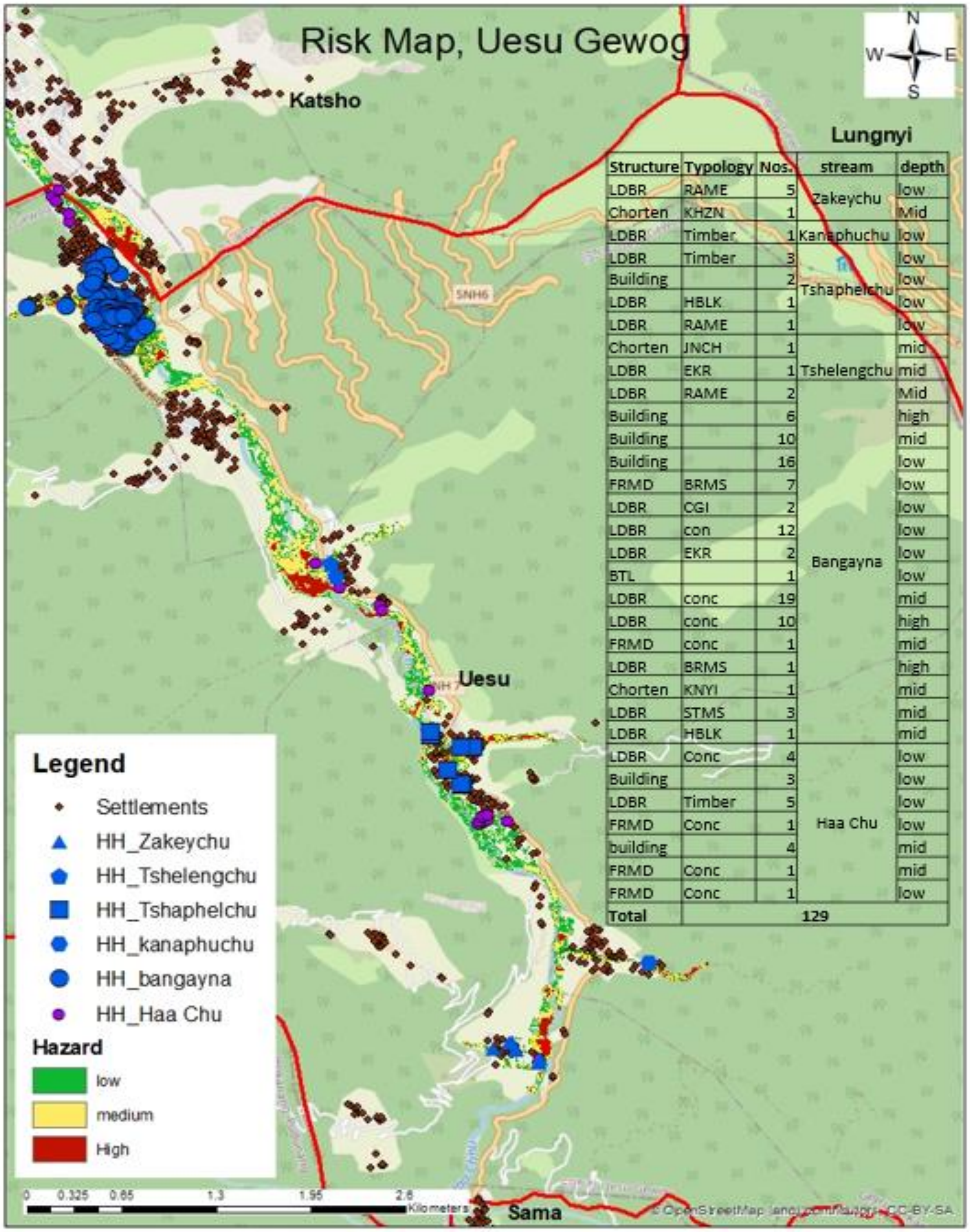


Figure 43: Structural Vulnerability in Bji Gewog



Structure	Typology	Nos.	stream	depth
Building		6	Wangtsa	mid
Building		2		low
Building		2		high
LDBR	RAME	3		high
LDBR	RAME	12		low
LDBR	RAME	8		mid
FRMD	conc	2		low
FRMD	Timber	1		low
FRMD	conc	3		mid
FRMD	conc	4		high
LDBR	Timber	1		high
Chorten	KHZN	1		low
LDBR	BRMS	1		mid
FRMD	STMS	2		low
LDBR	conc	5		low
LDBR	Timber	1		low
LDBR	conc	2		mid
FRMD	BRMS	2		low
LDBR	EKR	1		low
LDBR	RAME	15	Baliatam	low
LDBR	RAME	12		mid
Building		13		low
Chorten	KHZN	1		mid
LDBR	Timber	1		high
Building		2		high
LDBR	Timber	1		mid
FRMD	conc	6		low
Building		2		mid
FRMD	conc	3		mid
LDBR	conc	2		low
LDBR	RAME	1		high
FRMD	STMS	3		low
FRMD	conc	2		mid
Chorten	JNCH	2		low
Building		7	Ha Chu	mid
FRMD	conc	1		mid
FRMD	STMS	1		mid
FRMD	STMS	2		low
LDBR	RAME	2		low
LDBR	RAME	1		mid
LDBR	conc	1		[illegible]
LDBR	Timber	2		MID
Chorten	KHZN	1		mid
Building		3		mid
FRMD	conc	1		low
LDBR	CGI	1		low
TOTAL		148		

Figure 44: Structural Vulnerability in Katsho Gewog



Structure	Typology	Nos.	stream	depth
LDBR	RAME	5	Zakeychu	low
Chorten	KHZN	1		Mid
LDBR	Timber	1	Kanaphuchu	low
LDBR	Timber	3	Tshaphelchu	low
Building		2		low
LDBR	HBLK	1		low
LDBR	RAME	1		low
Chorten	JNCH	1	Tshelengchu	mid
LDBR	EKR	1		mid
LDBR	RAME	2	Bangayna	Mid
Building		6		high
Building		10		mid
Building		16		low
FRMD	BRMS	7		low
LDBR	CGI	2		low
LDBR	con	12		low
LDBR	EKR	2		low
BTL		1		low
LDBR	conc	19		mid
LDBR	conc	10		high
FRMD	conc	1		mid
LDBR	BRMS	1		high
Chorten	KNYI	1		mid
LDBR	STMS	3		mid
LDBR	HBLK	1		mid
LDBR	Conc	4	Haa Chu	low
Building		3		low
LDBR	Timber	5		low
FRMD	Conc	1		low
building		4		mid
FRMD	Conc	1		mid
FRMD	Conc	1		low
Total		129		

Figure 45: Structural Vulnerability in Uesu Gewog

9. Interventions

As per the flood hazard map prepared through hydrodynamic modelling, breach points were identified along critical stream and river. For that matter, the following interventions are proposed, considering the economic and safety factors.

9.1. Design Parameters

The intervention structures along the Areas of Mitigation Interest (AoMI) are designed with a 100-year return period discharge, and the parameters are detailed below.

1. Design discharge = 424.55 m^3/s
2. Silt factor=2.48
3. Mean scour depth =2.6 m
4. Max Scour depth = 3.9 m
5. Length of the apron = 3.0 m
6. Height of the structures = 3 m

Channel parameters: Parameters for the critical stretch along Haachu and Talung streams are as follows:

Table 9: Channel Parameters

	Average Flow Path (m)	**Average Left Bank Height (m)**	**Free Board (m)**
River (Haachu)	39.422-45.90	0.271-0.606	0.5
Streams (Talung)	10.80	0.409	0.5

9.2. Design review based on social risk assessment

The Infrastructure Planning and Flood Adaptation Division under the Department of Human Settlement, in collaboration with the Environmental and Social (ES) expert for the RIR project, organized public consultations in individual gewogs under the Haa Dzongkhag Administration. These consultations were part of the broader Social and Environmental Risk Assessment for the RIR project, under which the preparation of the Haa Flood Management Plan (FMP) is one of the key deliverables. A separate ES document for the project, including the Haa FMP, has been prepared.

However, the Haa Flood Management Plan only focuses on the public consultations related to the design. During the consultations, the draft rehabilitation proposal under the FMP was presented to local leaders and community members for their feedback and endorsement. During the consultation, the draft rehabilitation proposal of the FMP was presented to the Local leaders and the public for their feedback and endorsement. While the draft rehabilitation proposal of the FMP was accepted, there was some feedback on the areas identified as critical and the types of rehabilitation measures.

The Department conducted the review in terms of a) area criticality and b) design review of the rehabilitation measures. The list of the areas from the respective pubic consultations at the gewogs is populated in the following tables.

Location	**River/Stream/ channel bank**	**Structure observatio n**	**Rehabilitation measures**	**Type of Rehabilitatio n**	**Length (m)**
Downstrea m of Sawmill, Bji	ChuNap, LB	Gabion mesh has worn out	Gabion wall	Vertical rehabilitation	57
Near the wooden bridge, Bji	Chukap, LB	Gabion mesh has worn out	Gabion wall	Vertical rehabilitation	30
Near the wooden bridge, Bji	Chukap, RB	Gabion mesh has worn out	Gabion wall	Vertical rehabilitation	30
Chundu School hostel, Bji	Talungchu, LB	Scouring at the gabion wall base.	Gabion wall	Longitudinal rehabilitation	140
Talungchu & Haachu junction, Bji	Haachu, RB	Gabion wall damaged	Gabion revetment/ riprap	Longitudinal upgrade	650
Pharikha, Katsho	Haachu, LB	Collapsed gabion wall	Gabion Revetment	Longitudinal upgrade	984
Pharikha, Katsho	Haachu, RB	Collapsed Gabion Wall	Gabion wall	Longitudinal rehabilitation	797

Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), LB	Base scour & collapsed gabion wall	Gabion stepped wall/bed armor	Vertical rehabilitation	268
Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), RB	Base scour & collapsed gabion wall	Gabion stepped wall/ bed armor	Vertical rehabilitation	274
Helipad, Uesu	Haachu, LB	Collapsed Gabion wall & spurs	Gabion wall	Longitudinal upgrade	284
Below Helipad, Uesu	Haachu, LB	Base scour of the Gabion wall	Gabion wall	Vertical rehabilitation	268
Below Helipad, Uesu	Haachu, RB	Base scour of the gabion wall	Gabion wall with Hume pipe	Vertical rehabilitation	238
Workshop, Uesu	Haachu, LB	Stone pitching washed away	Gabion stepped wall	Longitudinal upgrade	624
Workshop, Uesu	Haachu, RB	Gabion Wall base scour & rupture of basket	Gabion stepped wall	Longitudinal upgrade	99
NRDCL Depot, Uesu	Haachu, LB	Gabion wall bulged & seepage in boulder pitching	Gabion stepped wall	Longitudinal upgrade	140
Tshaphel School, Uesu	Haachu, LB	Collapsed gabion walls	Gabion stepped wall	Vertical upgrade	135

Tshaphel Agriculture fields, Uesu	Haachu, LB	Gabion wall washed away	Gabion Revetement	Longitudinal upgrade	359
Tshaphel Agriculture field, Uesu	Haachu, RB	Collapsed Gabion Wall	Gabion wall	Longitudinal rehabilitation	115

Terminology:

1. *Vertical rehabilitation:* Increased height of the existing structure to mitigate the inundation of the river/streams. E.g., In chunap (stream name), the existing structure height is about 1m of gabion wall, which has collapsed. The rehabilitation works include increasing the gabion wall height to accommodate the stream flow to mitigate inundation.
2. *Longitudinal rehabilitation:* To reinforce the lateral structural strength of the existing structures along the river/streams. E.g., Integration of two existing structures along the same longitudinal profile.
3. *Upgradation:* Existing structure type upgrade. E.g., Short-term/Intermediate interventions such as stone/boulder pitching and riprap structures to be upgraded to a stepped gabion wall. This addresses the seepage problems of the existing structure. Similarly, existing damaged gabion walls are to be upgraded to gabion revetment/ gabion spurs on the same existing longitudinal profile.
4. *LB:* Left Bank.
5. *RB;* Right Bank.

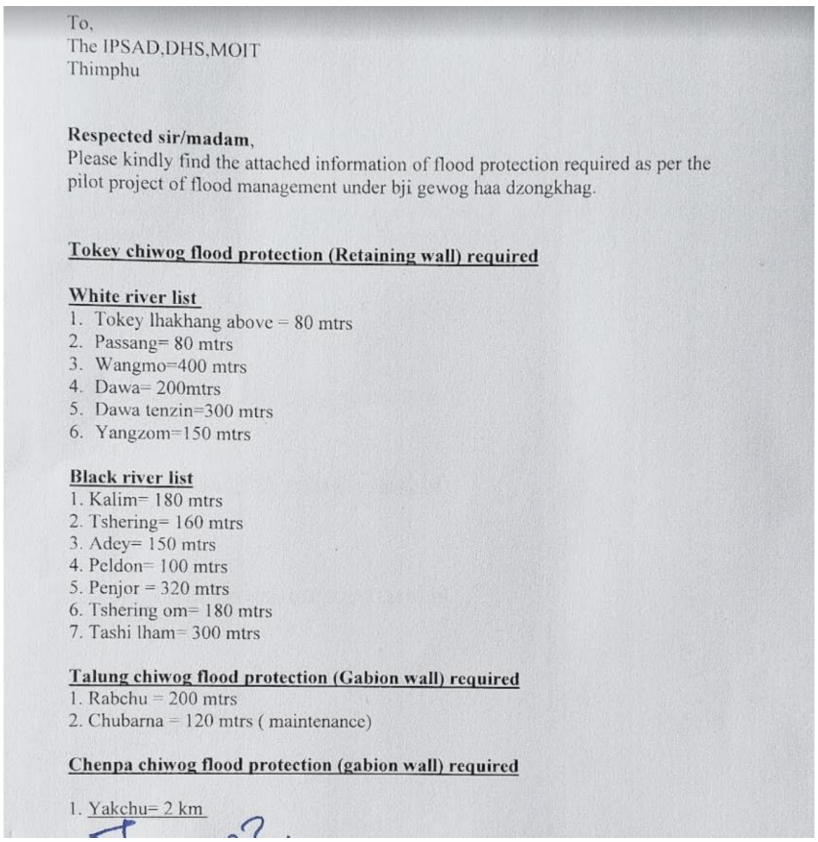
9.2.1. Critical area review

Bji Gewog

Table 10: List from public consultation

Sl. No.	**Within FMP/Review**	**Beyond FMP /Assessment request**	**Others (Landslides/blockage issues)**	**Remarks**
1	Chuba, upstream of Talung	Rabchu	Chalumpa, chu, Yetshentsa	validation
2	Chu kap	Haachu and Talung Junction, Right bank of	Baychu	Detailed assessment

		Haachu upstream of Yangthang.		done, validation from the flood model.
3	Chu Nap		Yaba and beebji	Detailed assessment done, validation from the flood model.



To,
The IPSAD,DHS,MOIT
Thimphu

Respected sir/madam,
Please kindly find the attached information of flood protection required as per the pilot project of flood management under bji gewog haa dzongkhag.

Tokey chiwog flood protection (Retaining wall) required

White river list
1. Tokey lhakhang above = 80 mtrs
2. Passang= 80 mtrs
3. Wangmo=400 mtrs
4. Dawa= 200mtrs
5. Dawa tenzin=300 mtrs
6. Yangzom=150 mtrs

Black river list
1. Kalim= 180 mtrs
2. Tshering= 160 mtrs
3. Adey= 150 mtrs
4. Peldon= 100 mtrs
5. Penjor = 320 mtrs
6. Tshering om= 180 mtrs
7. Tashi lham= 300 mtrs

Talung chiwog flood protection (Gabion wall) required
1. Rabchu = 200 mtrs
2. Chubarna = 120 mtrs (maintenance)

Chenpa chiwog flood protection (gabion wall) required

1. Yakchu= 2 km

Figure 46: List forwarded by Gewog

The critical stream areas **(not as per individual person)** were reviewed and revalidated according to the technical aspects of the assessment.

Figure 47: Chu Nap Downstream

Figure 48: Chukap downstream

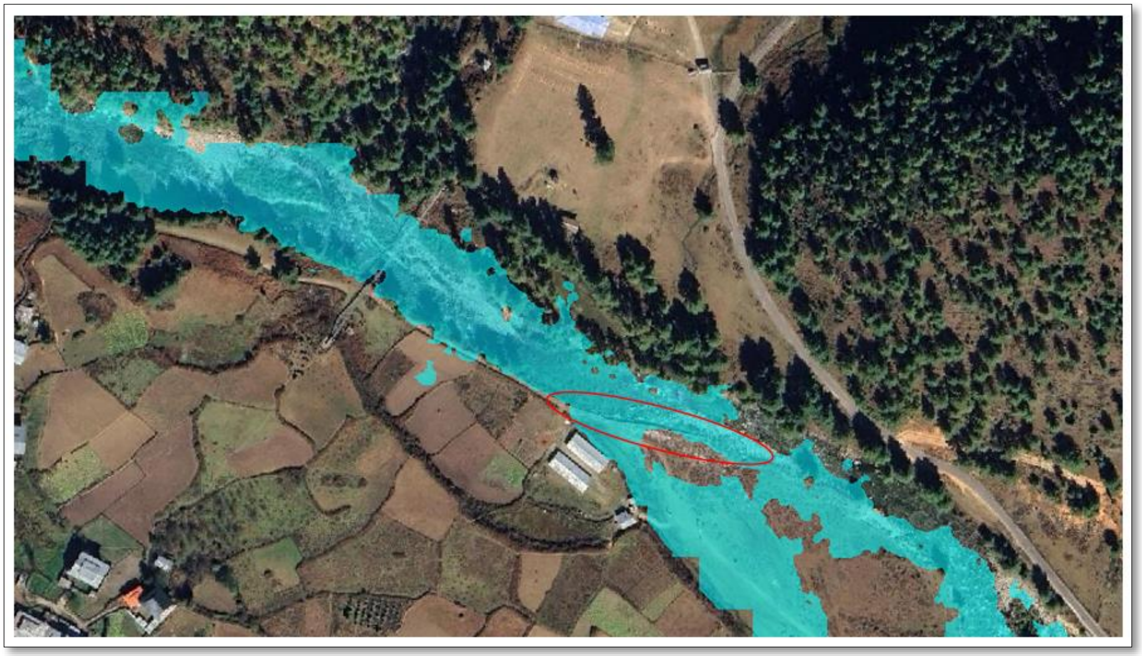


Figure 49: Talung Upstream

Figure 50: Talung and Haachu Junctio***n***

Katsho Geog

Table 11: List from public consultation

Sl. No.	**Within FMP/Review**	**Beyond FMP/Assessment request**	**Others (Landslides/blockage issues)**	**Remarks**
1	Bali	Wangtsa (Hume pipe upstream and Culvert downstream at road cross drainage)		Site validation for ES purpose
2	Atam	Kajena (watershed and drainage)		Site validation for ES purpose
3	Lhayulkha chu	Pharikha, right bank near the sawmill.		Site validation for ES purpose
4	Ingoo (RCC drains and watershed)			Site validation for ES purpose

Figure 51: ingoo RCC drains

Figure 52: Lhayulkha chu, Town

Uesu

Table 12: As per the list from public consultation

SL.No	FMP review	Beyond project scope	Storm and other Issues	Remarks
1	Tshaphel chu, Haachu alignment of the existing Gabion wall (Bridge Agriculture project)	Tsaphel Rongchu new proposal	Tshaphelchu Hume pipe issue near bridge area.	Site Validation
2	Tshaphel school, Haachu rehabilitation review			Site validation
3	Milk processing unit stream. Tsulalkha chu) (review)			
4	Haachu archery ground (Kana Area diverging)			Site validation
5	Haachu below Menlamchenmo area (agricultural area) Rehabilitation of existing	Baytsho chu (Beyond project scope) but assessment-based.		Backed up Flood model
6	Dungchu right bank (Agriculture Land)			
7	Opposite to the workshop Site (Agricultural lands)			
8		Haachu (near gewog office)		Road issues

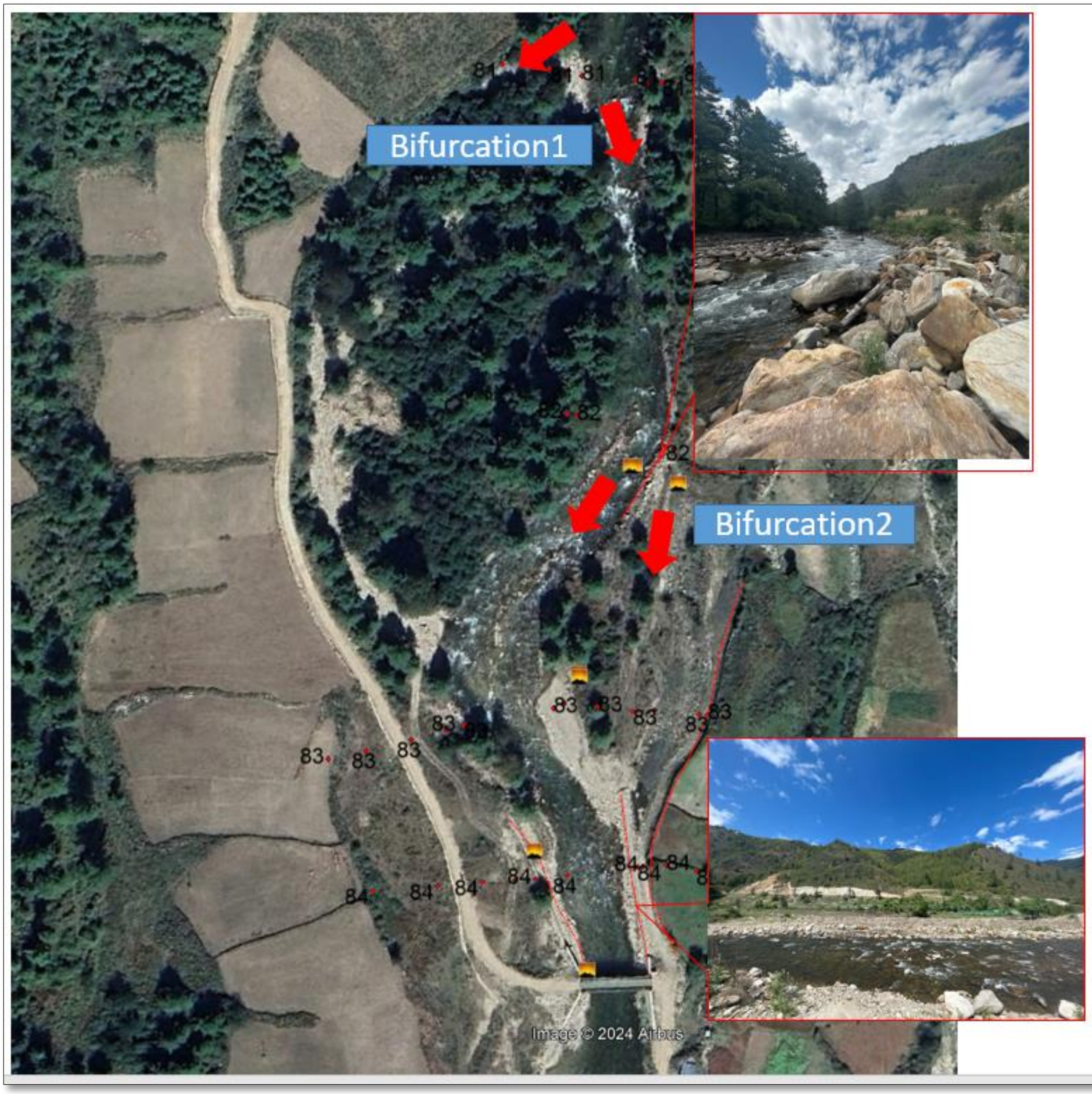


Figure 53: NRDCL depot

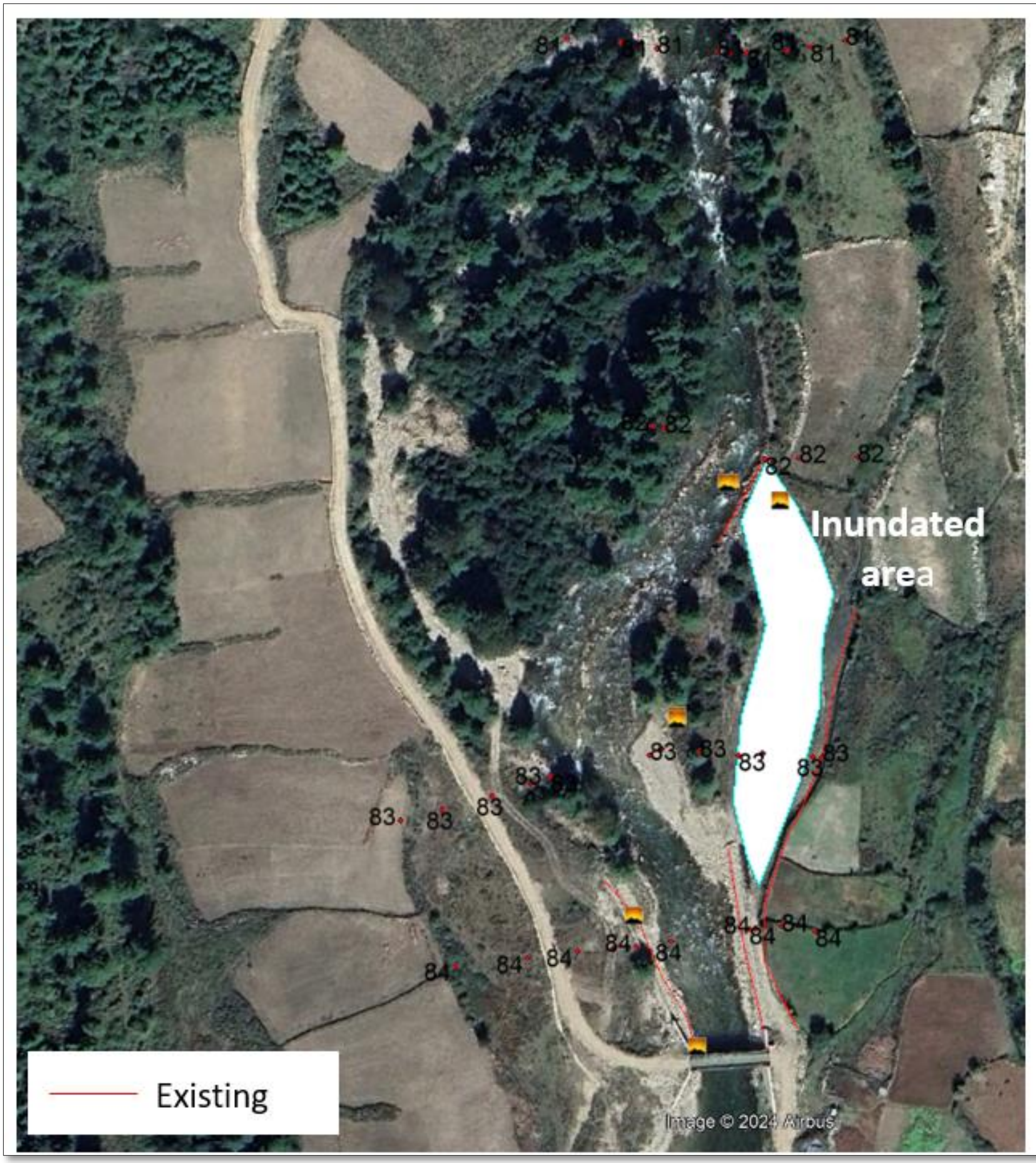


Figure 54: Above the NRDCL depot, the inundation area

Figure 55: Behind Tshaphel school compound

9.2.2. Design Type review

The type of intervention for the critical areas is dependent on the foundation stability, the availability of space, and the river dynamics. Based on these factors, three rehabilitation measures are proposed:

a. Stream level: Step Gabion Wall/ Gabion Wall
b. River level: Step Gabion Wall/Gabion Wall/Gabion revetment

The reviewed outcomes are summarized under Tables 13-Table 14 for respective Gewogs.

Bji Gewog

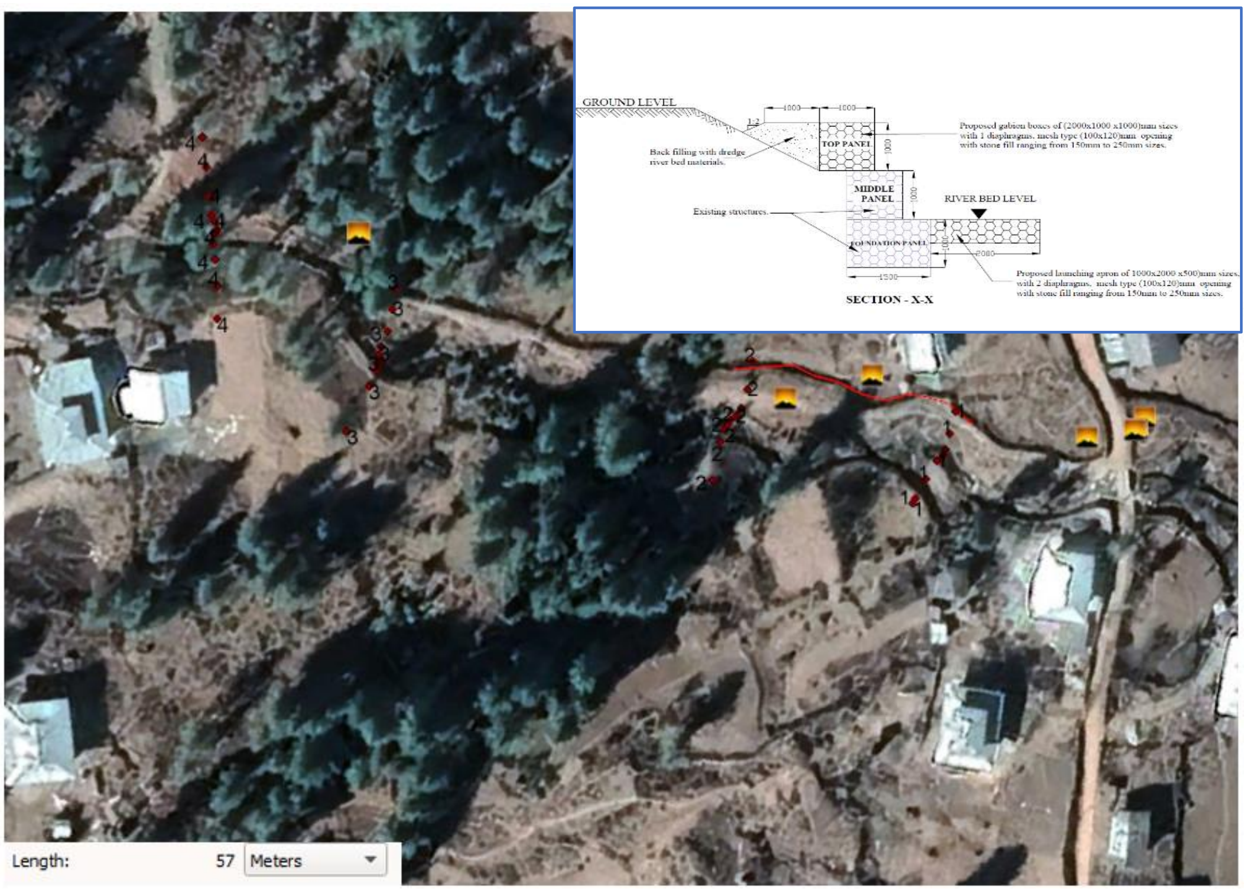


Figure 56: chunap

Figure 57: Chukap

Figure 58: Talungchu

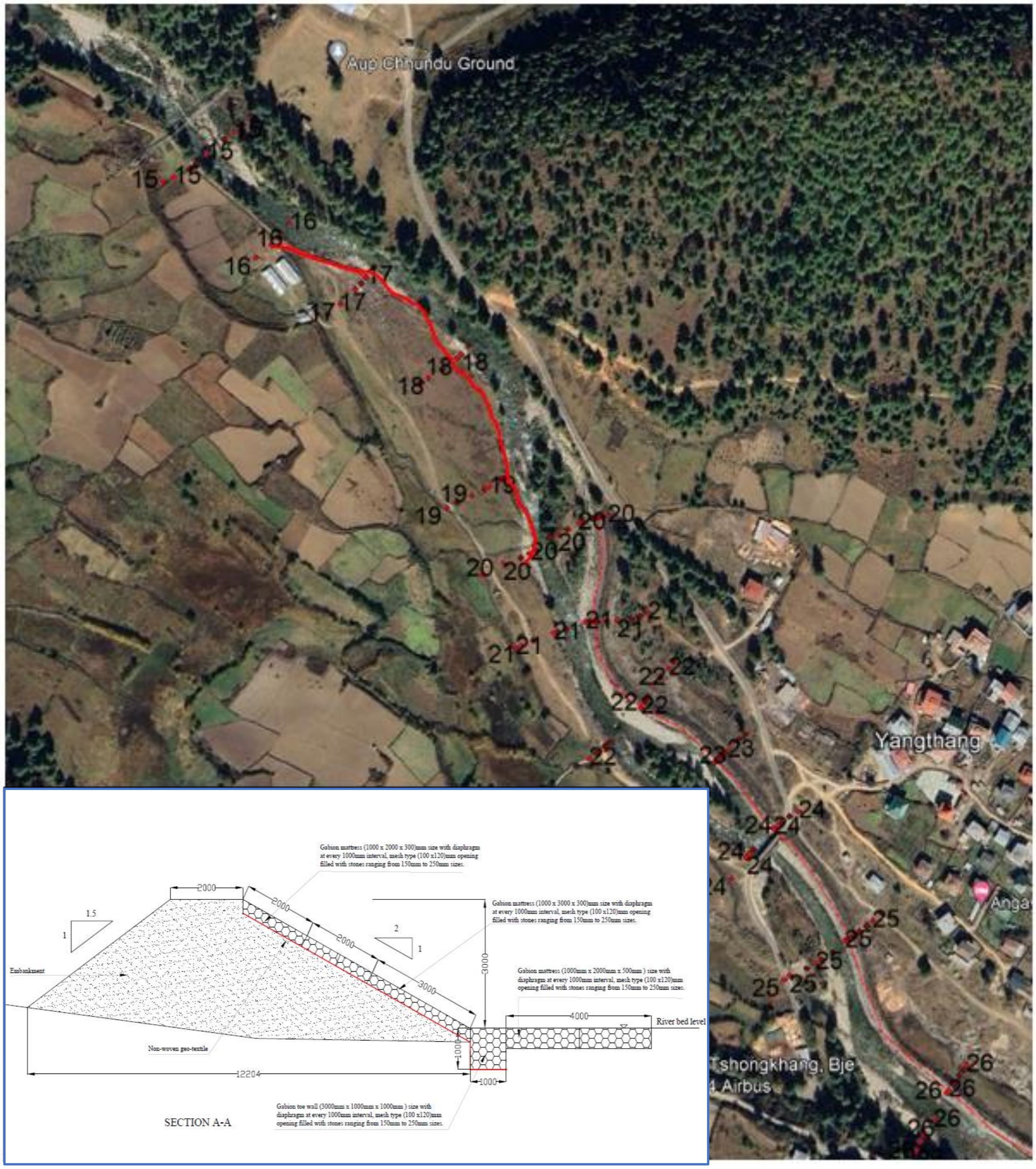


Figure 59: Right bank of Yangthang (Talung junction)

Table 13: Bji review outcome

Category	**Resolution**
Within FMP/Review	The Talung upstream existing structure had a few scouring and ruptures of the gabion mesh. Since the damage is minimal, the technical team will assess the financial analysis to determine the CBR and the feasibility. The existing structures downstream of Chu Nap and Chu Kap had a major collapse of the Gabion wall; hence, rehabilitation measures will be proposed in these stretches. The existing gabion wall at the Junction of Talungchu and Haachu, as per the flood model, is insufficient; hence, the structure will be upgraded.
Beyond FMP/Assessment request	Rabchu as listed from the consultation is beyond the scope of the FMP, hence it is stock taken for future assessment, taking into account the priority/work in hand of the Department.

Katsho Gewog

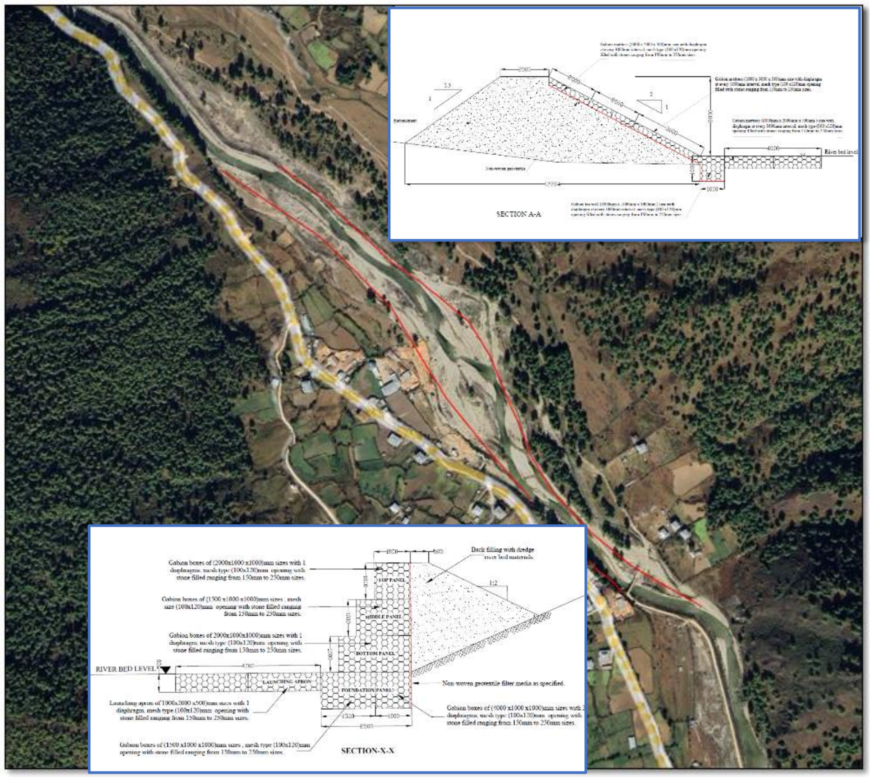


Figure 60: Pharikha

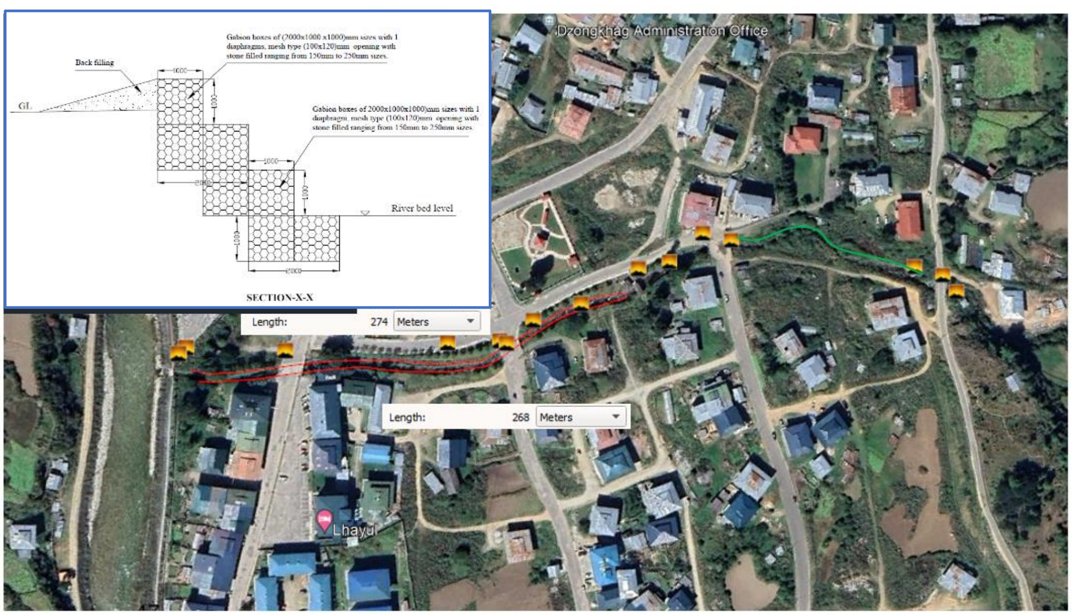


Figure 61: Lhayulkha chu

Table 14: Katsho review outcome

Category	Resolution
Within FMP/Review	As per the Bali and Atam structure assessment carried out, the existing structures are functional. The existing structures along Lhayulkha chu were seen as damaged during the revalidation, and since it was expressed as development priority of the Dzongkhag, considering the investment plans, these structures will be upgraded/rehabilitated. The ingoo RCC drains were found functional, less critical for rehabilitation as of now, under the RIR project. Moreover, the concerns are mostly on the watershed management issues.
Beyond FMP/Assessment request	Wangtsa culvert, cross drainage/hume pipe issues are more related to infrastructure planning issues. Hence, it will be Recommended under the O&M component of the FMP. As for the Kabjena and Pharikha right bank (Sawmill area), it is beyond project scope will hence be stock taken for future activities depending on the priority of the Department.

Uesu Gewog

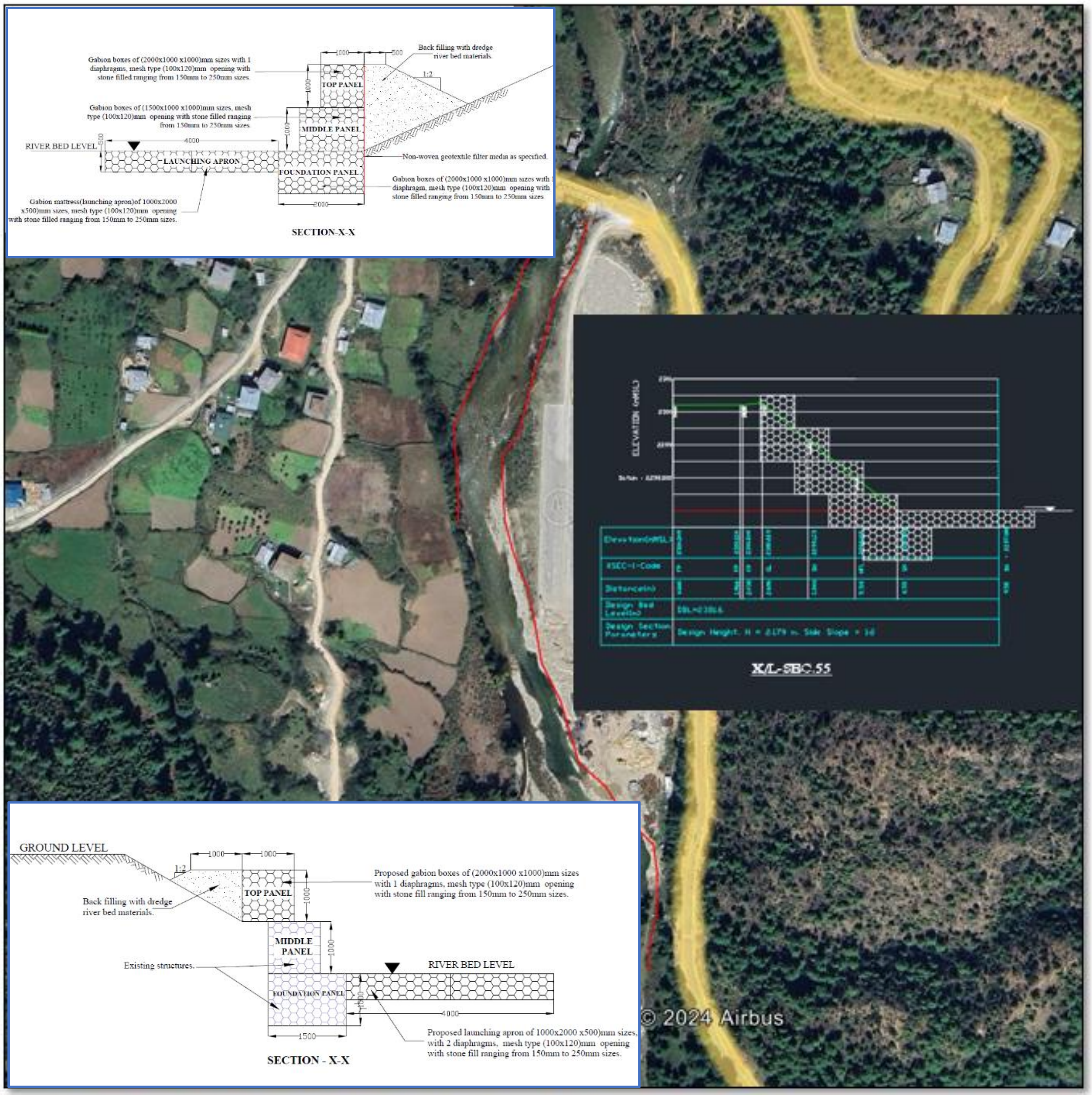


Figure 62: Helipad area

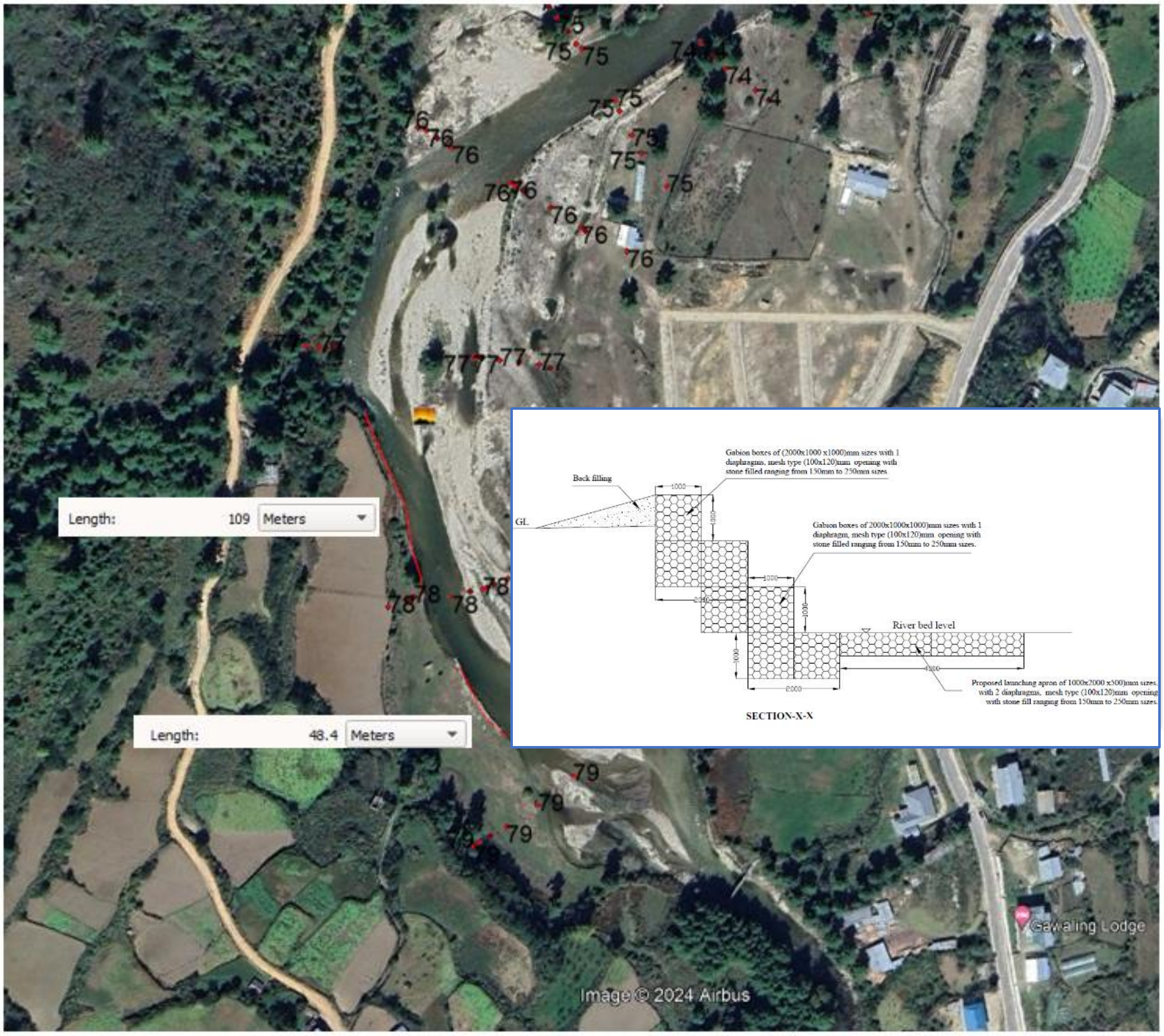


Figure 63: Workshop site

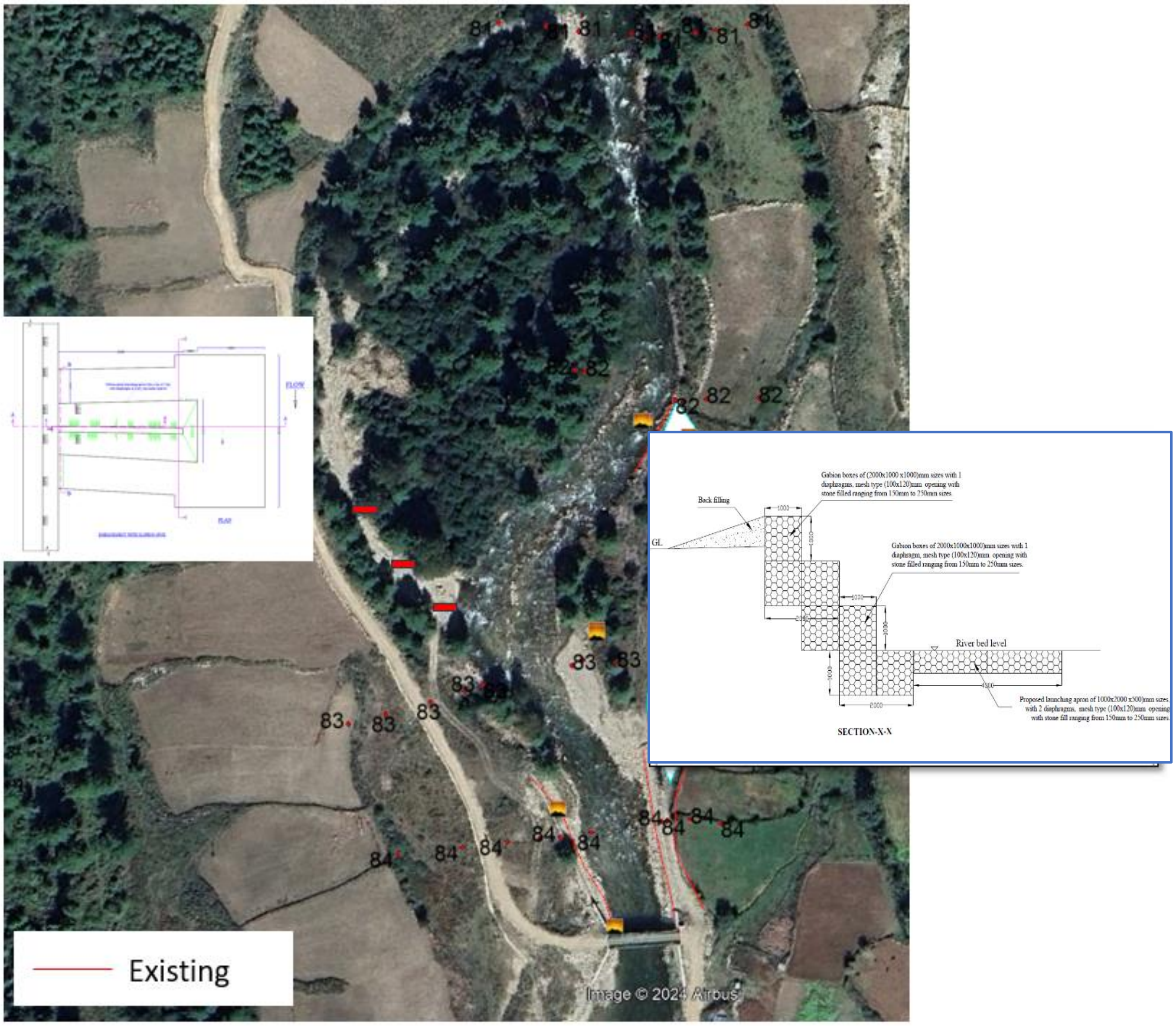


Figure 64: NRDCL depot area

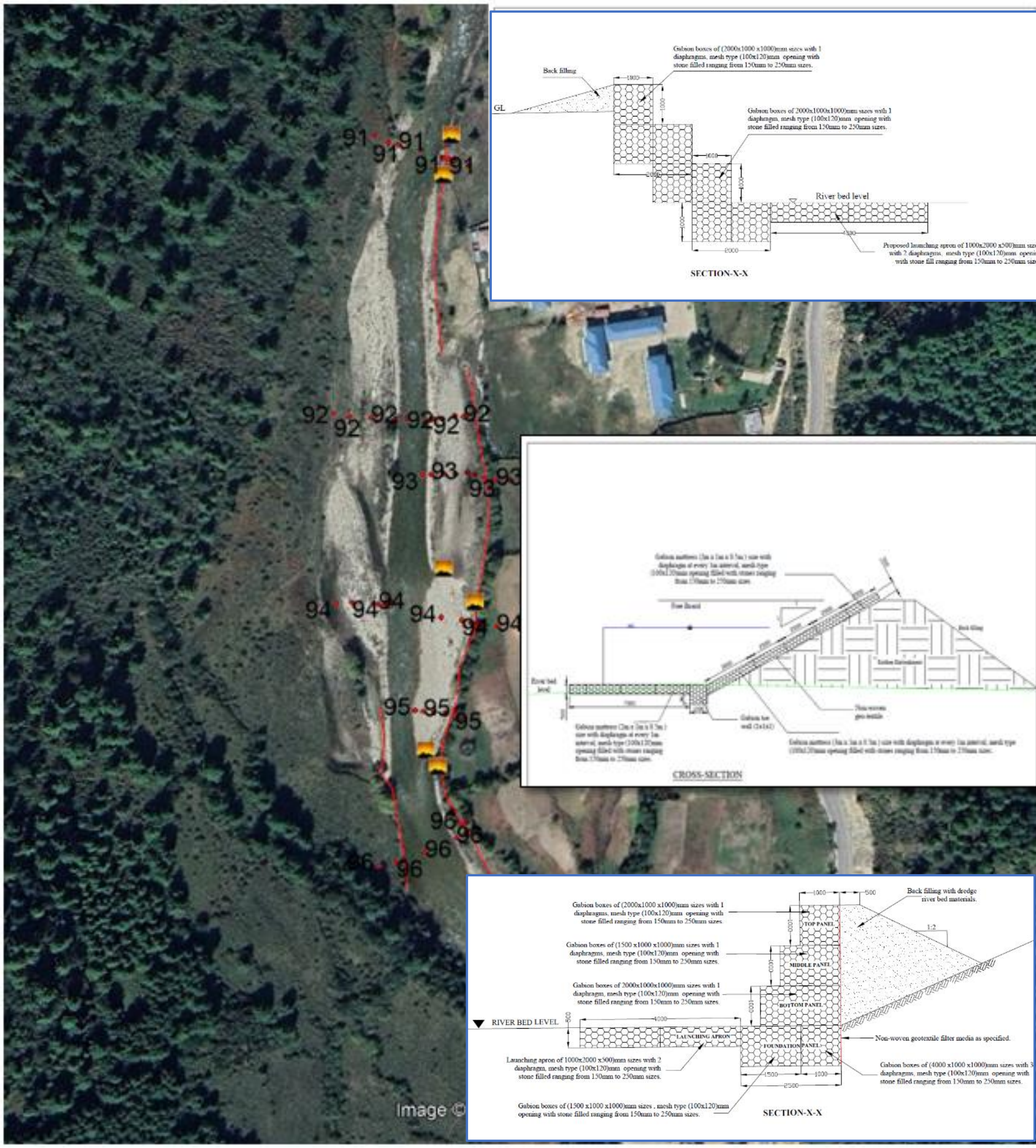


Figure 65: Tshaphel School, Gepa area

Table 15: Uesu review outcomes

Category	Resolution
Within FMP/Review	Helipad area: Upgrade the left bank existing structures with a step gabion wall. Workshop area: Existing structures (both left and right), with a gabion wall. Above NRDCL depot: upgrade the existing riprap structure to gabion revetment left bank, however, limiting the space to the government land. Behind Tshaphel School: Rehabilitation of the existing structure on the upstream and revetment where space is available, rehabilitation of the existing structure at the right bank of Haachu.
Beyond FMP/Assessment request	Helipad area: Propose a gabion wall on the left bank to protect the agricultural lands and human settlements. Above NRDCL depot: Proposal of gabion Spurs at the right bank.

9.2.3. Typical Cross-Section of intervention

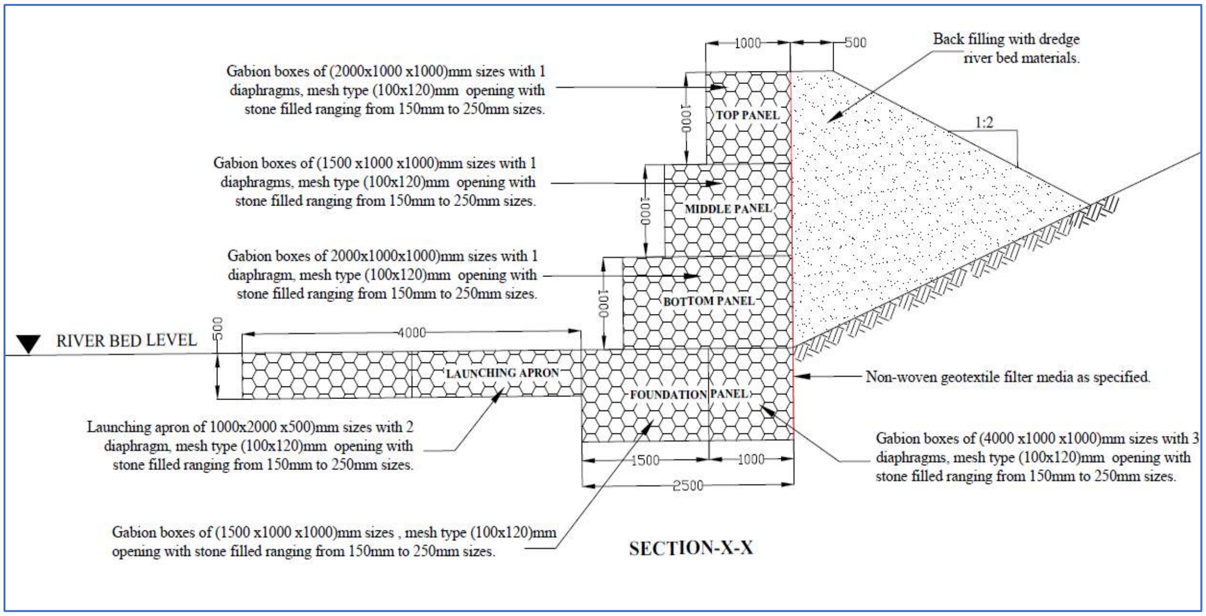


Figure 67: Gabion Wall

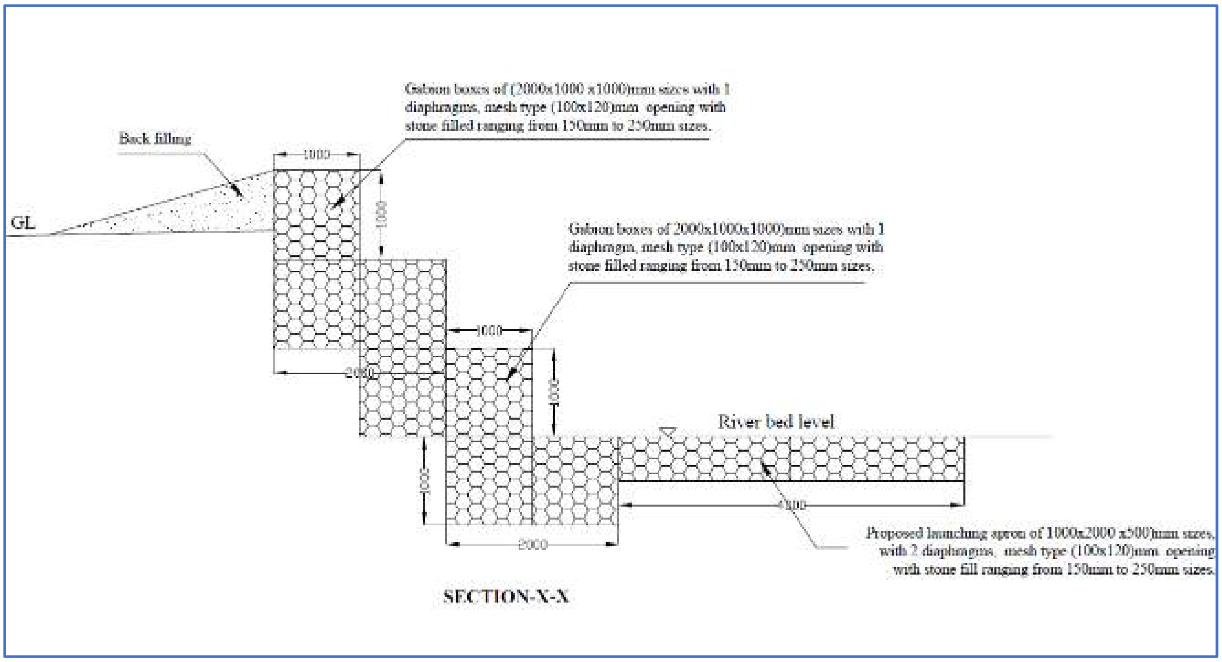


***Figure** 68**: Stepped Gabion Wal**l*

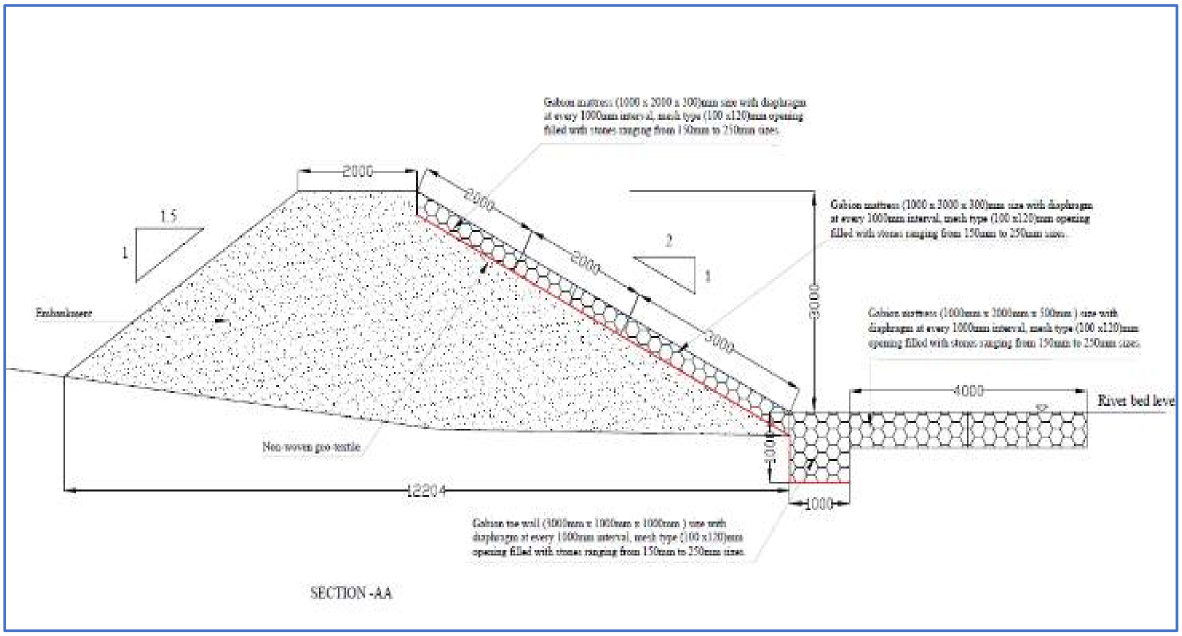


Figure 69:Gabion Revetment

11. Investment Plan

11.1. Introduction

Cost-benefit analysis (CBA) is a critical tool for evaluating the investment worthiness of a project, with financial and economic analyses serving as the main criteria in the decision-making process. Financial cost-benefit analysis focuses on the project's direct financial returns and reflects its private profitability, making it a primary indicator of financial viability. In contrast, economic cost-benefit analysis assesses the project's broader impact on society, including externalities and alignment with national development goals. It evaluates whether the project contributes to public welfare and long-term policy objectives. In the context of economic feasibility, climate-resilient flood mitigation measures have been assessed in terms of their economic benefits, particularly their role in enhancing resilience, reducing future flood-related risks, and supporting sustainable development.

Financial and Economic Analysis, specifically cost-benefit comparison, measures the investment worth of the Project. The following are the key parameters of economic feasibility of the Project that are to be calculated. These are

- Tangible benefits (Economic value of damage avoidance),
- Investment and Maintenance costs of the Project,
- Economic indicators namely, Benefit Cost Ratio (BCR), Net Present Value (NPV), and Internal Rate of Return (IRR),
- To assess the economic viability of the Project.

11.2. Approach to Analysis

The discounted cash flow (DCF) method has been employed to assess the economic viability of the proposed flood mitigation project through a cost-benefit analysis framework. The analysis quantifies project benefits as the avoided damages to physical infrastructure (including residential and non-residential buildings), agricultural land, and other socio-economic assets resulting from flood events. The estimation of benefits is based on hydrological and hydraulic modeling outputs derived from the engineering analysis of the project. In parallel, the capital investment, operation, and maintenance costs associated with the implementation of climate-resilient flood mitigation measures have been integrated into the evaluation. These cost parameters are informed by detailed engineering assessments conducted by the project's design and planning consultants.

The estimation of net economic benefits has been carried out by comparing the expected outcomes under the "With Project" and "Without Project" scenarios. The "With Project" condition assumes the implementation of flood protection interventions, resulting in a reduction in the frequency and severity of flood-induced damages. Conversely, the "Without Project" scenario reflects the baseline condition, where damages are projected to escalate in line with an assumed annual development growth rate of 2.9%.

To estimate the stream of economic benefits from flood prevention, the annual flood damage value is multiplied by a factor representing projected annual development growth under the "Without Project" scenario. This adjustment captures the expected escalation in damages over time due to continued development in flood-prone areas. The resulting stream of annual benefits is then discounted at a rate of 12%, which reflects the opportunity cost of capital, over a project lifespan of 30 years. This enables the calculation of the present value of avoided damages, which serves as a key input for the cost-benefit comparison.

For the economic cost-benefit analysis, financial costs and benefits are converted into their economic equivalents to better reflect their true resource cost to the economy. This involves adjusting for market distortions, taxes, and subsidies. In particular, for non-traded goods and services, economic values have been derived using the Standard Conversion Factor (SCF) methodology. The SCF is applied to convert financial prices into border price equivalents, thereby aligning the valuation of inputs and outputs with their real economic opportunity cost in an open economy context.

11.3. Financial and Economic Parameters

The following parameters are used to derive the economic costs and benefits of the Project. These are:

- Financial values of the cost and benefits of the Project have been adjusted to economic values of the Project to reflect the opportunity cost of the Project;
- Economic life of the Project 30 years;
- Discount rate for calculating present value (PV) of cost and benefit flows would be 12 %;
- Taxes and subsidies, and all transfer payments, have been excluded from the estimate.

11.4. Investment Cost of the Project

The heavy monsoon rainfall and flash floods cause damage to agricultural land, residential areas, and commercial. These recurrent damages turn into economic losses to both households in the vicinity of the streams and at the national level. The structural intervention has been designed to prevent flood damage, and the details for each intervention are presented in Table 166**.**

Table 166: Investment cost (Millions in Nu.)

Sl.No	Location	Location Details	River/Stream / channel bank	Rehabilitation measures	Type of Rehabilitation	Length (m)	Cost (Round in

							million Nu.)
1	Chunap + Chukap	Downstream of Sawmill, Bji	Chunap, LB	Gabion wall	Vertical rehabilitation	57	0.79
		Near the wooden bridge, Bji	Chukap, LB	Gabion wall	Vertical rehabilitation	30	
		Near the wooden bridge, Bji	Chukap, RB	Gabion wall	Vertical rehabilitation	30	
2	Talung Haachu Junction	Chundu School hostel, Bji	Talungchu, LB	Gabion wall	Longitudinal rehabilitation	140	20.87
		Talungchu & Haachu junction, Bji	Haachu, RB	Gabion revetment/ riprap	Longitudinal upgrade	650	
3	Pharikha	Pharikha, Katsho	Haachu, LB	Gabion Revetment	Longitudinal upgrade	984	60.76
		Pharikha, Katsho	Haachu, RB	Gabion wall	Longitudinal rehabilitation	797	
4	Lhayulkha chu	Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), LB	Gabion stepped wall/bed armor	Vertical rehabilitation	268	17.01
		Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), RB	Gabion stepped wall/ bed armor	Vertical rehabilitation	274	
5	Helipad	Helipad, Uesu	Haachu, LB	Gabion wall	Longitudinal upgrade	284	12.04
		Below Helipad, Uesu	Haachu, LB	Gabion wall	Vertical rehabilitation	268	

		Below Helipad, Uesu	Haachu, RB	Gabion wall with Hume pipe	Vertical rehabilitation	238	
6	Workshop ,	Workshop, Uesu	Haachu, LB	Gabion stepped wall	Longitudinal upgrade	624	28.28
		Workshop, Uesu	Haachu, RB	Gabion stepped wall	Longitudinal upgrade	99	
7	NRDCL Depot	NRDCL Depot, Uesu	Haachu, LB	Gabion stepped wall	Longitudinal upgrade	140	5.67
8	Tsaphel	Tshaphel School, Uesu	Haachu, LB	Gabion stepped wall	Vertical upgrade	135	28.59
		Tshaphel Agriculture fields, Uesu	Haachu, LB	Gabion Revetement	Longitudinal upgrade	359	
		Tshaphel Agriculture field, Uesu	Haachu, RB	Gabion wall	Longitudinal rehabilitation	115	
Total Cost							175
Contingency (5%)							8.75
Grand Total							**183.76**

For the analysis, the maintenance cost of the intervention after every five years is estimated at 10% of the cost, and the total amount is estimated to be Nu. 12 million.

11.5. Benefits of the Project

The flood protection interventions protect agricultural land (both dry land and wet land) and infrastructure. The annual crop yield from the agricultural lands protected is estimated to calculate the annual damage value. The estimated annual damage value for the entire proposed rehabilitation measure is given in Table 17.

Table 17: Estimated annual damage value

Estimated annual damage value (in million (Nu))	
Infrastructural damage (residential and commercial)	Wetland and Dryland crops

Estimated annual damage value (in million (Nu))	
53.58 Million	**18.073 Million**

11.6. Cost-Benefit Comparison

The discounting method of Project evaluation is used for calculating the present value of cost and benefit streams. Financial and Economic indicators are computed to examine the viability of the project. These are Benefit Cost Ratio (BCR), Net present value (NPV), and Internal Rate of Return (IRR). The results of the indicators, including IRR, NPV, and B/C ratios, have been estimated.

11.6.1 Benefit Cost Ratio (B/C)

The present worth of the benefit is divided by the present worth of the cost stream. The equation is given below:

$$BCR = \sum_{t=1}^{t=n} \frac{Bt}{(1+i)^t} \div \sum_{t=1}^{t=n} \frac{Ct}{(1+i)^t}, \text{ (adopted)}$$

Where:

Bt = benefit in each year, *Ct = cost in each year,*

t (time) = 1, 2…, n., *i = for discount rate*

n = number of years.

The benefit-cost ratio is used as one of the selection criteria. A project with a B/C ratio greater than one is acceptable when the cash flow (net incremental benefit) is discounted with the discount rate of 12% signifying the opportunity cost of capital.

11.6.2 Net Present Value (NPV)

It measures the present value of the future net incremental benefit of the project over 50 years, i.e., the economic life of the project. For better understanding, the equation is presented below:

$$NPV = \sum_{t=1}^{t=n} \frac{Bt-Ct}{(1+i)^t}.$$

As a selection criterion, the project is acceptable when the value of NPV is greater than zero (0). Usually, a higher positive value of NPV is more attractive to decision makers.

11.6.3 Internal Rate of Return (IRR)

IRR is the most important measure of assessing project viability. IRR is the discount rate that makes the NPV of the cash flow (incremental net benefit flow) zero (Gittenger, 1982). The equation is as follows:

$$\text{IRR: the discount rate } \textit{is such that } NPV=\sum_{t=1}^{t=n} \frac{Bt-Ct}{(1+i)^t} = 0$$

As a selection criterion, the value of IRR must be equal to or greater than the discount rate (12%), signifying the opportunity cost of capital. The rate at which an investment breaks even level (the discounted value of revenue minus the discounted value of cost is equal to zero). As a rule, a higher value of IRR is more attractive than a lower value, provided it remains above the discount rate (12%). In this project, the estimated values of the indicators show the viability of the project, because all the criteria follow the acceptance rules. The results are given in Tables 18 and 19 for the project as a whole. The acceptance rules for the economic indicators are presented in Table 20.

Table 18: Result of Cost-Benefit Analysis (Financial Analysis)

Indicators		
B/C	**NPV (in million Nu.)**	**IRR**
2.79	577.22	41.61%

Table 19: Result of Cost-Benefit Analysis (Economic Analysis)

Indicators		
B/C	**NPV (in million Nu.)**	**IRR**
2.43	520.650	36.10%

Table 20: Acceptance rules for the economic indicators

Indicators	Acceptance Rules
B/C	>1.0
NPV (in million Nu)	Positive value
IRR	=>12%

11.7. Sensitive Analysis

The sensitivity analysis has been carried out in economic perspectives, and the analysis shows the impact on the values of the indicators due to changes in the important variables, i.e., costs and benefits, in an uncertain situation. The values of the indicators in four scenarios for the 5 River Projects are given in Tables 21 and 22, respectively.

Table 21: Sensitivity Analysis (Financial Analysis)

Indicator	Base case	Scenario 1: Benefit decreased by 10%	Scenario 2: Cost increased by 10%	Scenario 3: (best case) benefits increased by 10% and costs decreased by 10%)	Scenario 4: (worst case) benefits decreased by 10% and costs increased by 10%
BCR	2.79	2.51	2.54	3.41	2.28
NPV (in million Nu.)	577.22	519.49	577.22	63.49	519.5
IRR	41.61%	37.33%	37.72%	51.10%	33.83%

Table 22: Sensitivity Analysis (Economic Analysis)

Indicator	Base case	Scenario 1: Benefit decreased by 10%	Scenario 2: Cost increased by 10%	Scenario 3: (best case) benefits increased by 10% and costs decreased by 10%)	Scenario 4: (worst case) benefits decreased by 10% and costs increased by 10%
BCR	2.43	2.19	2.21	2.97	1.99
NPV (in million Nu.)	520.65	468.59	520.65	57.27	468.59
IRR	36.10%	32.36%	32.70%	44.37%	29.29%

The results of the sensitivity analysis show that projects indicated in the above figure/table seem to be consistent with the adverse situation as well.

11.8. Conclusion

According to the values of the economic indicators and acceptance rules, the Project is economically viable.

12. Implementation Plan

12.1 Rationale of Implementation Plan

Floods are a climatological phenomenon and are a part of nature; they have existed and will continue to exist, and Bhutan experiences frequent hydro-meteorological disasters. The report on "Analysis of Historical Climate and Climate Projection for Bhutan, 2019" by the National Centre for Hydrology and Meteorology (NCHM) indicates an increase in temperature and rainfall for Bhutan in the future climate scenarios, Representative Concentration Pathways 4.5 and 8.5. The mean annual rainfall is likely to increase about 10% - 30% in summer under RCP4.5 and 10%-20% under RCP8.5 during 2021-2050. Hence, it is likely that climate change will increase the frequency and severity of flood disasters in Bhutan. The southern part of the country experiences a flash flood triggered by the intense monsoon; nevertheless, structural measures (defense structures) remain important elements, primarily focusing on the protection of human health and safety, and valuable goods and property through proper research, planning, and implementation. Moreover, sporadic planning lacking detailed scientific and technical studies, has constrained the implementation of appropriate mitigation measures. To address the gap, both structural and non-structural measures are proposed with specific recommendations based on mounting scientific evidence. While critical, mitigation investment in this unpredictable, ever-changing climate is challenged by limited sources, and therefore, the need for an investment plan comes to the point for priority-based implementation. The recommendations, once implemented, will reduce loss of life, property damage, negative effects on the economy, and the environment.

12.2 Investment Priority Plan

The Investment Priorities Plan (IPP) was formulated based on field assessment, model assessment, financial analysis, and criticality of location. Its main objective is to identify and inform decisions on when and where to make investments. The investment plan was categorized into three priorities (High, Medium, and Low) with an indicative cost estimation of each activity (Refer to Table 23). The proposed activities are in areas where there is an urgent need to intervene, and those activities are prioritized accordingly based on financial analysis, accounting for the short-term outcomes and potential long-term outcomes.

Based on the model assessment and financial analysis, the critical location-based priorities are as follows:

Table 23: Critical location-based priorities

Sl. No	Location	Location Details	River/Stream/ channel bank	Rehabilitation measures	Length (m)	Cost (Round in	Priority

						million Nu.)	
1	**Chunap + Chukap**	Downstream of Sawmill, Bji	Chunap, LB	Gabion wall	57	0.79	Medium
		Near the wooden bridge, Bji	Chukap, LB	Gabion wall	30		
		Near the wooden bridge, Bji	Chukap, RB	Gabion wall	30		
2	**Talung Haachu Junction**	Chundu School hostel, Bji	Talungchu, LB	Gabion wall	140	20.87	High
		Talungchu & Haachu junction, Bji	Haachu, RB	Gabion revetment/ riprap	650		
3	**Pharikha**	Pharikha, Katsho	Haachu, LB	Gabion Revetment	984	60.76	Medium
		Pharikha, Katsho	Haachu, RB	Gabion wall	797		
4	**Lhayulkha chu**	Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), LB	Gabion stepped wall/bed armor	268	17.01	High
		Main town, Katsho	Lhayulkhachu (confluence of Bali-Atam), RB	Gabion stepped wall/ bed armor	274		
5	**Helipad**	Helipad, Uesu	Haachu, LB	Gabion wall	284	12.04	Low
		Below Helipad, Uesu	Haachu, LB	Gabion wall	268		
		Below Helipad, Uesu	Haachu, RB	Gabion wall with Hume pipe	238		
6	**Workshop**	Workshop, Uesu	Haachu, LB	Gabion stepped wall	624	28.28	Medium

		Workshop, Uesu	Haachu, RB	Gabion stepped wall	99		
7	**NRDCL Depot**	NRDCL Depot, Uesu	Haachu, LB	Gabion stepped wall	140	5.67	Medium
8	**Tsaphel**	Tshaphel School, Uesu	Haachu, LB	Gabion stepped wall	135	28.59	High
		Tshaphel Agriculture fields, Uesu	Haachu, LB	Gabion Revetement	359		
		Tshaphel Agriculture field, Uesu	Haachu, RB	Gabion wall	115		

12.3 Benefits of Investment

There are lots of benefits that will be achieved through implementing these proposed activities, but not necessarily limited to the following:

- Bank protection will be ensured, and bank erosion will be reduced.
- Boost in agricultural production.
- Environment-friendly and durable solution.
- A huge life and property safety value will be gained.
- A one-time investment will give protection for at least 50 years with some recurring maintenance costs.
- The local administration will be able to invest in other development sectors.
- Employment opportunities for skilled and unskilled workers.

12.4 Operation and Maintenance

In practice, complete protection against the flood is almost impossible; however, regular inspection and maintenance of flood mitigation works would ensure the serviceability of the structures to withstand flood events up to the design flood event. The functions of the flood mitigation works cannot be maintained well without care, degradation or aggregation of the river or stream bed, river or stream bank erosion, damage to the structures, etc. Therefore, such care is important not only for maintaining the functions of the structures but also for accomplishing the objectives of the project.

12.5 General

a) The structures constructed for flood protection shall be continuously maintained or repaired to obtain the maximum benefits.
b) It shall be the duty of the Dungkhag/Gewog Administration to submit an annual report to the Dzongkhag Administration covering inspection, maintenance, and operation of the protection works.
c) Maintenance measures or repairs shall be promptly taken or made by the Dzongkhag/Dungkhag/Gewog Administration after the flood event.

d) Any activities taken by the Dzongkhag Administration concerning flood protection works are to be coordinated with the Ministry of Infrastructure and Transport.

e) The Dzongkhag/Dungkhag/Gewog Administration should not allow any unauthorized excavation or construction in, on, or adjacent to the flood mitigation works, as it will affect the integrity and performance of the flood mitigation works.
f) The Dzongkhag/Dungkhag/Gewog Administration should inspect flood events to monitor the performance of the flood mitigation works.

12.6 Maintenance of Flood Protection Structures

The maintenance of flood protection structures is required to ensure the serviceability of the structures in the event of a flood. Inspections shall be made by the Dzongkhag/Dungkhag/Gewog Administration to be certain that:

a) No trees exist; the roots of which might extend under the walls or revetment and which may lead to accelerated seepage paths;
b) The concrete has not undergone cracking, chipping, or breaking to an extent that might affect the stability of the wall or its water tightness;
c) There are no encroachments upon the right-of-way which might endanger the structure or hinder its functioning in the time of the flood;
d) Care is being exercised to prevent the accumulation of trash and debris adjacent to walls.
e) No bank caving conditions exist riverward of the RCC wall, gabion wall, or gabion revetment, which might endanger its stability;

12.7 Maintenance of channel or flow path

Such inspections shall be made before the beginning of the flood season, and immediate steps will be taken to remedy any adverse conditions disclosed by such inspections. Periodic inspections of the flow path shall be made by the Dzongkhag/Dungkhag/Gewog Administration to be certain that:

a) The channel or flow path is clear of debris, weeds, and wild growth;

b) The flow path is not being restricted by the depositing of waste materials, the building of unauthorized structures, or other encroachments;
c) The capacity of the channel or flow path is not being reduced by the deposition of sediments and debris;
d) Banks are not being damaged, and no sloughing of banks has occurred;
e) Riprap sections and deflection dikes, and walls are in good condition;

12.8 Maintenance of miscellaneous facilities

Miscellaneous structures and facilities constructed as a part of the protective works shall be periodically inspected by the Dzongkhag/Dungkhag/Gewog Administration, and appropriate maintenance measures shall be taken. Damaged or unserviceable parts shall be repaired or replaced without delay. Areas used for ponding in connection with pumping plants or for the temporary storage of run-off during flood periods shall not be allowed to become filled with silt, debris, or dumped material. Enough bridge openings shall be kept to accommodate the flow during the monsoon season or high flows.

13. Conclusion

1. Fourteen streams and a river (Haachu) were assessed for potential flood hazards.

2. Two different assessments were carried out, namely the hydrological and hydrodynamic assessments.

3. A hydrological model was developed using the Soil and Water Assessment Tool (SWAT) to delineate the watershed, to classify the slopes, soils, and land use and land cover classes. The model was developed for 14 individual streams and the Haachu River, the hydrographs for which have been created to be incorporated in developing the hydrodynamic model.

4. Using the measured discharge (available for 1996-2021) at the Haachu flow station, the SWAT model was calibrated. However, owing to the unsatisfactory results, the simulated flow discharges were adopted to set up a hydrodynamic model since the measured discharge didn't cover the whole river stretch of the AoI.

5. 2D HEC-RAS was developed to assess the hydrodynamic behavior of the river. Two separate terrains were analyzed. The first one uses the ALOS 10 m DEM, and another one with merged DEMs of Haa 1m and ALOS 10 m.

6. From the hazard maps resulting from the assessments, critical locations along Haachu were identified, and appropriate rehabilitation measures were proposed.

7. Since the Haachu River and its tributaries were mostly river trained, the designs include rehabilitative measures instead of new measures.

8. Other critical areas identified through stakeholder consultation and site investigation require more O&M solutions, such as clearing the flow path and leaving enough room for the stream flow.

13. Annexure

Annexure I: Design and drawing

Annexure II: Estimate

Annexure III: Specifications