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Final Report

Preparation of Flood Management Plan for Paro Dzongkhag

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Abbreviations and Acronyms

ALOS	Advanced Land Observing Satellite
AoMI	Areas of Mitigation Interest
AWBM	Australian Water Balance Model
BCR	Benefit/ Cost Ratio
BTFEC	Bhutan Trust Fund for Environmental Conservation
BWSIS	Bhutan Water Security Index System
CGCM	Coupled General Circulation Model
CMIP5	Coupled Model Intercomparison Project 5
CN	Curve Number
CNRM-CM5	Earth system model designed to run climate simulations
DDMC	District Disaster Management Committee
DEM	Digital Elevation Model
DES	Department of Engineering Services
DHS	Department of Human Settlement
DM	Disaster Management
DPSIR	Framework for describing the interactions between society and the environment
EAD	Expected Annual Damage
ECoP	Environmental Code of Practice
EIA	Environmental Impact Assessment
Eta	Actual evapoTranspiration
EWS	Early Warning System
FEMD	Flood Engineering Management Division
FRA	Flood Risk Assessment
GCF	Green Climate Fund
GEF	Global Environment Facility Trust Fund
GIS	Geographic Information System
GIUH	Geomorphologic Instantaneous Unit Hydrograph
GLOF	Glacial Lake Outburst Floods
GLUE	Generalized Likelihood Uncertainility Estimation
GNHC	Gross National Happiness Commission
HRU	Hydrologic Response Unit

ICIMOD	International Centre for Integrated Mountain Development
IFAS	Integrated Flood Analysis System
IRR	Internal Rate of Return
LDC	Least Developed Country
Ma	Mega annum
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
MCMC	Markov Chain Monte Carlo
MoWHS	Ministry of Works and Human Settlement
NASA	National Aeronautics and Space Administration
NCHM	National Center for Hydrology and Meteorology
NDA	National Designated Authority
NDMA	National Disaster Management Authority
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
NIE	National Implementing Entity
NPV	Net Present Value
NSB	National Statistics Bureau
NSE	Nash-Sutcliffe efficiency
PBIAS	Mean relative bias
PET	Potential Evapo Transpiration
PSO	Particle Swarm Optimization
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
RSR	Ratio of root mean square error to the standard deviation of measured data
SAARC	South Asian Association for Regional Cooperation
SDSM	Statistical Downscaling Model
SEM-SHA	Small-Watershed of Hilly Areas
SFVI	Social Flood Vulnerability Index
SIDS	Small Island Developing States
SPCR	Strategic Program for Climate Resilience
SPRC	Source-Pathway-Receptor-Consequence
SRTM	Shuttle Radar Topography Mission
SUFI	Sequential Uncertainty Fitting

SW	South West
SWAT	Soil and Water Assessment Tools
TOPEX	The Ocean Topography Experiment POSEIDON
TRMM	Tropical Rainfall Measuring Mission
VFM	Variable Fuzzy Method
WBMP	Wangchu Basin Management Plan
WMG	Water Management Group
WMO	Water Management Organization
WWF	World Wide Fund for Nature

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 infrastructure.

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 lives, properties, agricultural products during such a disaster leaving them to start their living 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, Flood Engineering and Management Division in its endeavor to combat the flooding hazard in all the Dzongkhags would like to start the comprehensive flood management program from Paro.

Like in most parts of the country, rivers and streams in Paro Dzongkhag also flow through the settlement, infrastructure, and agricultural area. There is a history of flooding in the main Paro Town, the Nyemiazampa Area, and the villages in the Gewogs. 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 the need to conduct proper studies of the rivers and the streams in the Dzongkhag, with particular emphasis on their flooding nature in order to place the appropriate measures.

1.2 Rationale

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 moraine dam ruptures. Bhutan's sloppy and mountainous terrain makes for easy surface runoff, and the rivers, running through deep gorges and ravines, receive huge volumes of surface runoff during monsoon. All these set up a perfect backdrop for water-indu ced disasters.

According to The Asian Development Bank's (ADB) climate change country risk assessment for Bhutan, Bhutan will experience more extreme weather events with increased frequency. The ADB identifies flood risk, and particularly flooding from heavy downpours and GLOFs as one of the key climate threats for Bhutan. Paro is not an exceptional as well. Paro City has warming trends and melting glaciers pose serious threats to its inhabitants Further, monsoon variability is now an established fact.

1.3 Objective

The main objective of the study is to prepare a climate resilience flood management plan for Paro Dzongkhag.

The specific objectives are:

- To assess flood threat to the settlements and prepare the flood management plan;
- To assess the potential adverse impacts of the flood hazard areas; and
- To provide appropriate recommendations and mitigation measures to be adopted.

1.4 Study Approach

The approach for flood risk assessment and risk management are presented in **Figure 1.1**. Three main steps are associated with the flood risk management: i) data collection and literature review to find out flood hazard and vulnerability, ii) flood risk assessment using hazard and vulnerability, and iii) flood mitigation measure.

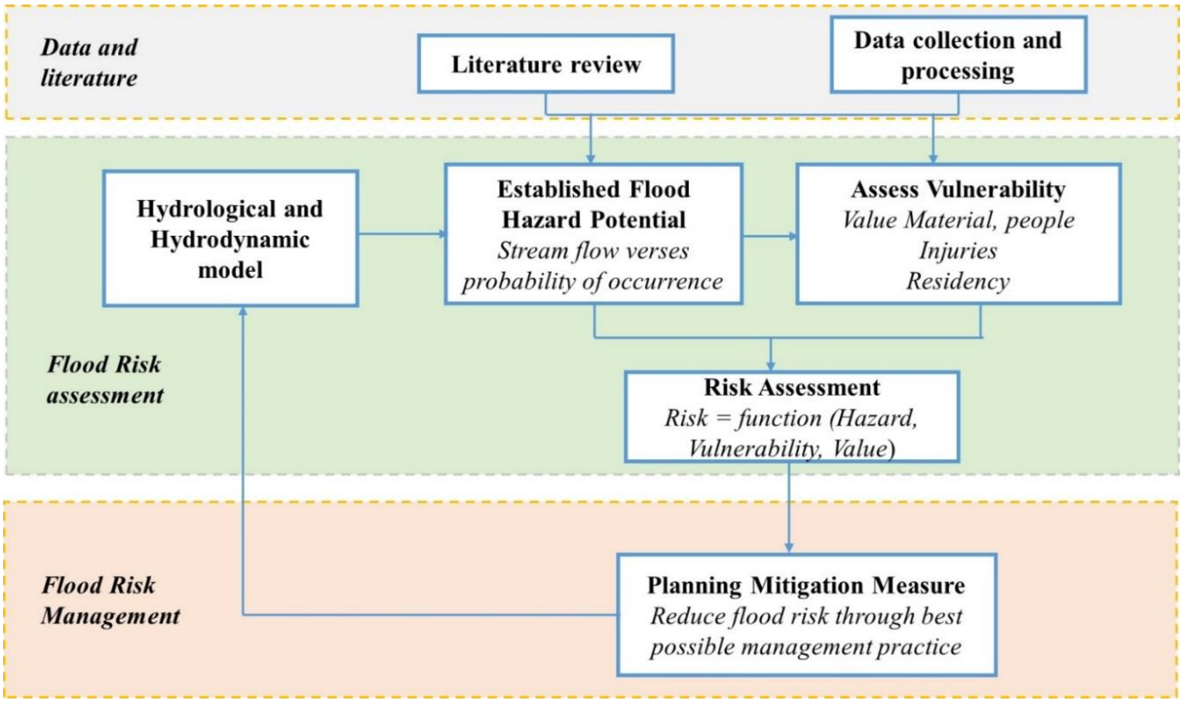


Figure 1.1: Approach of the Study

Available existing data and literature was reviewed to get an overview of the hazard and vulnerability of the area. Besides, hydrological and hydrodynamic models were used to generate flooding scenarios. The flood risk was estimated based on flood hazard and vulnerability. Finally, flexible and climate resilience flood management measures were formulated depending on the hydrological and hydraulic characteristics of river basin and socio-economic conditions of the area. The performance of the measures were evaluated using the model.

1.5 Study Limitations

- Weather data inside the river basin is limited both in terms of a number of stations and data duration which is the main input for hydrological modeling for a catchment. Only three weather stations are available, mainly located at the downstream part of the basin;
- Available rainfall data is summarized daily whereas sub-daily rainfall data is essential for the assessment of flood hazard for small-steep slope basin;
- Discharge data is available for only one station for the entire catchment area. Besides, reliable data is available only for the period of 2014-2019;
- No water level or historical flood extent map is available for the calibration of hydrodynamic and flood model;
- Unavailability of damage assessment data; and
- Time constraint for the study.

2. Description of Study Area

2.1 Study Location

The study focuses on the Paro Dzongkhag which is situated in the north-western part of Bhutan. It covers a total area of 1,293 Square kilometers. The Dzongkhag has a population of around 35,260. It is one of the most important and historical Dzongkhag in Bhutan with many sacred sites and historical buildings scattered throughout. It is situated between the coordinates of 27.4286° N and 89.4167° E. The only International Airport (Paro International Airport) within the jurisdiction makes the Dzongkhag an aerial gateway to the Kingdom of Bhutan. The Dzongkhag is comprised of 10 Gewogs. They are Dogar Gewog, Dopshari Gewog, Doteng Gewog, Hungrel Gewog, Lungnyi Gewog, Naja Gewog, Shaba Gewog, Tsento Gewog, Lamgong Gewog, and Wangchang Gewog. The Dzongkhag is bordered by Haa District to the west, Tibet to the north, Thimphu District to the east, and Chukha District to the south. **Figure 2.1** presents the map for the location of the study area.

2.2 Topography

The Paro Dzongkhag is situated in the hilly region, located at an altitude of 2,250 m above mean sea level. The Dzongkhag consists mostly of steep and high mountains crisscrossed by a network of swift rivers, which form on deep valleys. The average elevation of the area is about 3,630 m from the mean sea level. The elevation of the city ranges from the minimum elevation of 1,334 m to the maximum elevation of about 5,773 m above the mean sea level.

Table 2.1: Elevation range of study area

Elevation Range (m Mean Sea Level)	Percentage of Area	Cumulative Percentage
1948-2483	10.51	10.51
2483-2768	13.10	23.61
2768-3041	13.79	37.40
3041-3315	13.08	50.48
3315-3600	11.28	61.76
3600-3903	9.93	71.69
3903-4203	12.12	83.81
4203-4485	11.55	95.36
4485-5656	4.65	100.00

By analyzing the Digital Elevation Model (DEM) of the study area, it is observed that more than half of the Paro Dzongkhag is situated within the elevation range of (1948-3600) m from the mean sea level. Paro City is also developed in this elevation range. As the Dzongkhag is comprised of a lot of steep valleys, the elevation of those areas is way above the average values in the elevation range of (3903-5656) m above the mean sea level. **Figure 2.2** presents a map of the DEM for the study area.

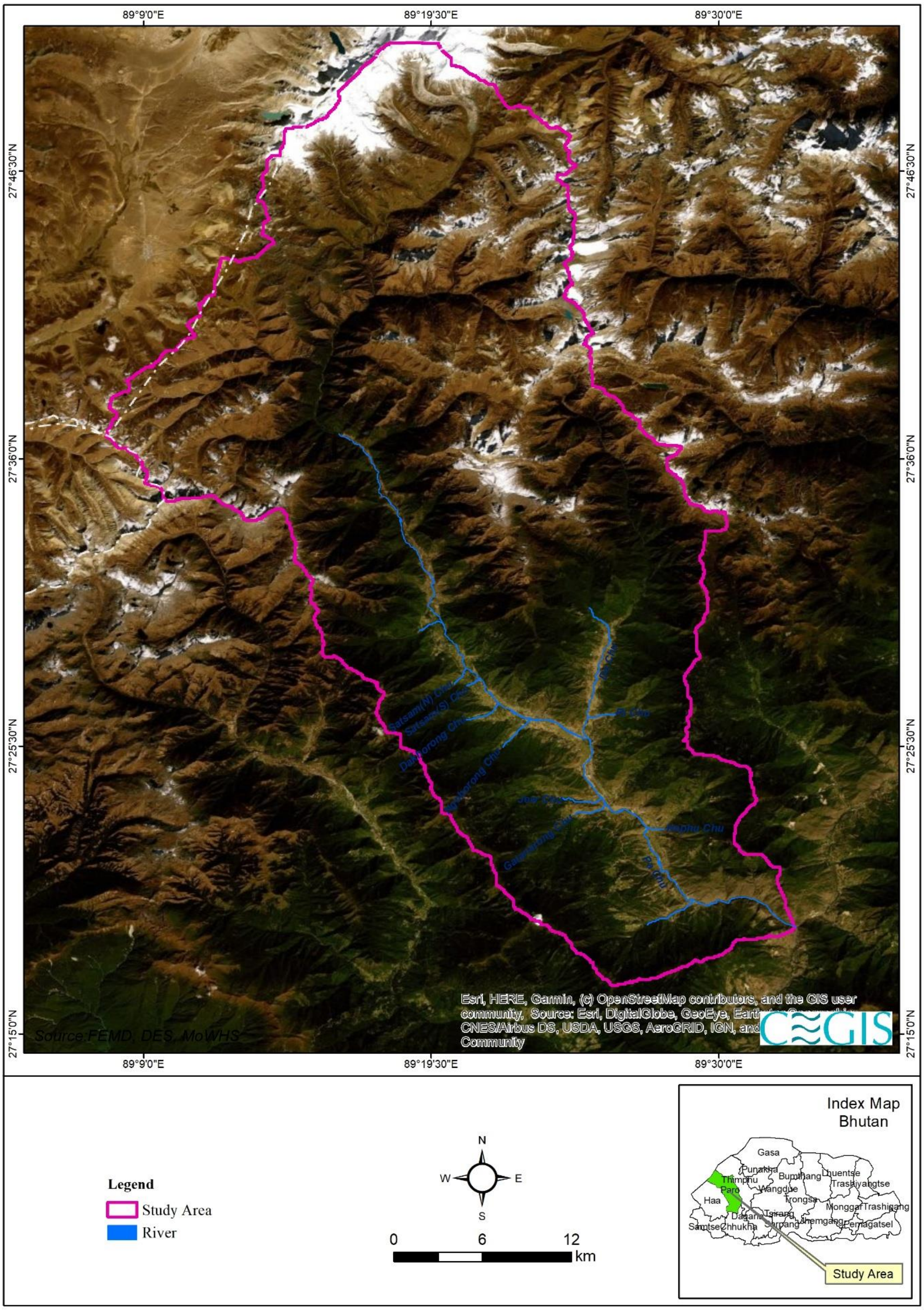


Figure 2.1: Location of Study Area

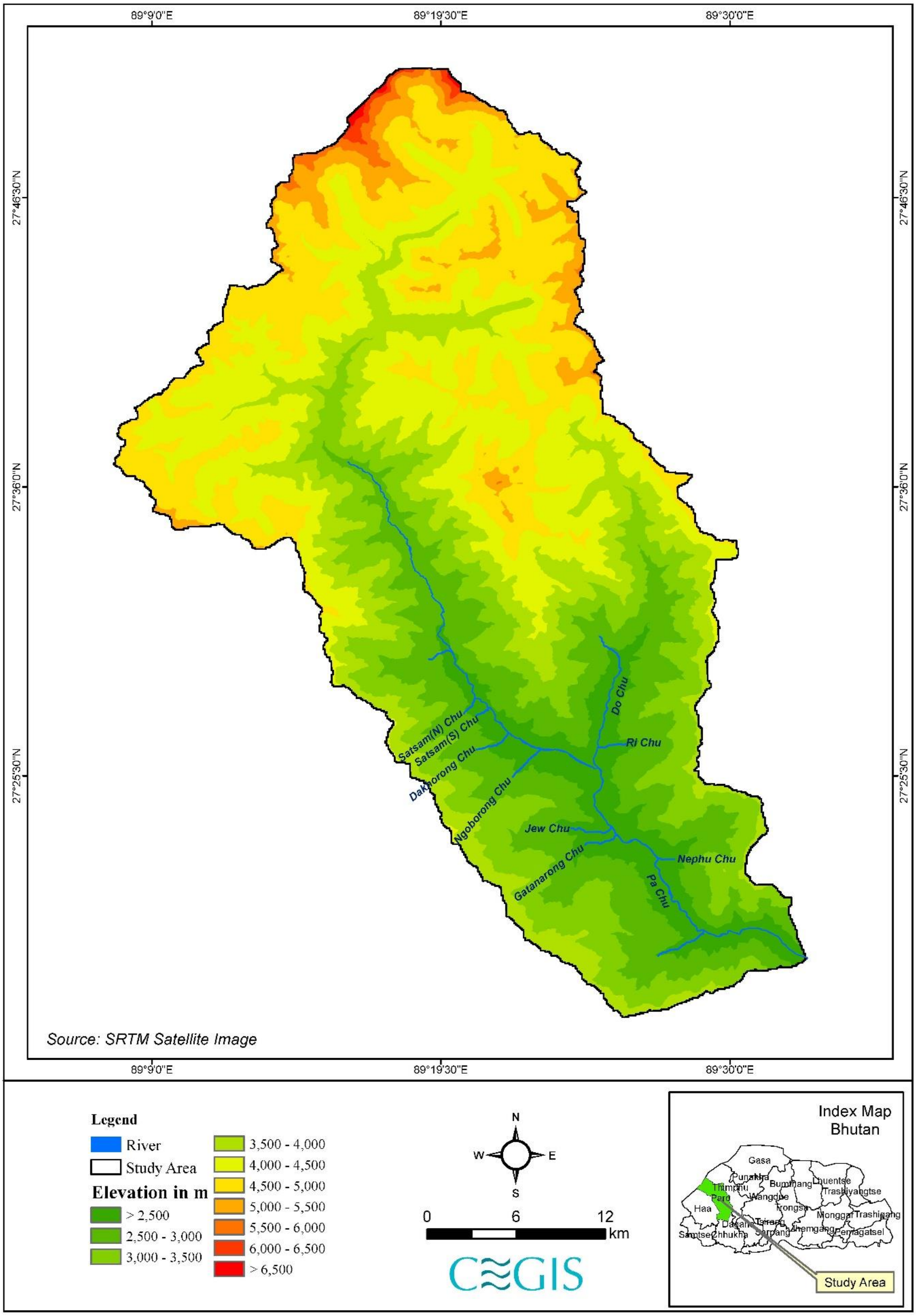


Figure 2.2: Topography of Study Area

2.3 Geology

The Geology of the study area reveals several geological formations having a varying potential of groundwater availability depending upon their porosity, permeability, and hydro-geomorphological characteristics. The geology of Bhutan is shaped by the intense tectonic activities that resulted from the collision of the Indian and Eurasian continental plates, the closure of the intervening Tethys Ocean, and the uplift of the Himalayas. Although the intercontinental collision occurred about 50-40 million years (Ma) ago, the main uplift began at about 25-20 Ma. Bare rock accounts for less of Bhutan than expected from the mountainous terrain, and much of the surface is mantled with drift materials. The most widespread deposits at high altitudes are glacial and periglacial mixtures of stones and sand. At lower altitudes, many of the slopes are covered with colluvium, which is a mixture of soil and stones deposited by slow creep and many small landslips and slumps. Some slopes have deposits from large landslips. These are larger, more frequent, and more extensive in the South.

2.4 Weather and Climate

Weather patterns within the small confinements of Bhutan are highly variable and depend to a great extent on the altitude. The northern parts of the country where mountains rise up to 7,000m experiences weather conditions are similar to the snow-clad peaks of the Himalayas; whereas the lower southern regions with elevations as low as 100 m experience hot and humid weather in the summer and cool in the winter. The monsoon season usually sees heavy rainfall. Amidst the variations brought on by altering freeze-thaw and temperate climate, seasons in Bhutan can be divided into four types which are furnished below –

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

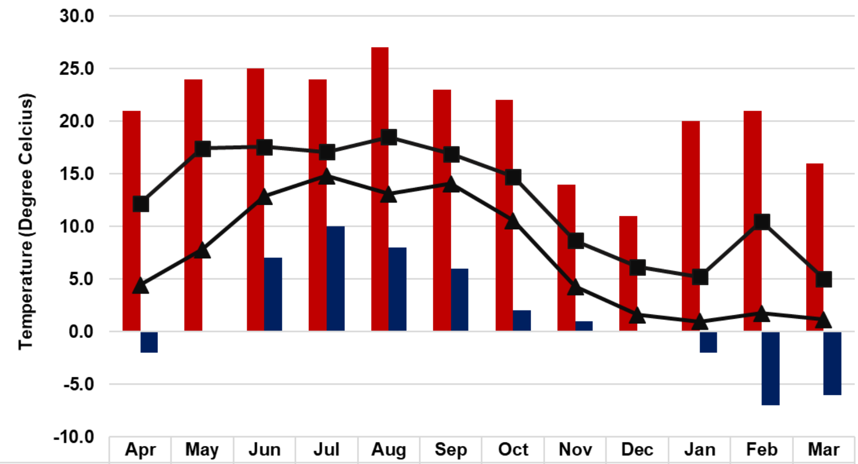
If broadly categorized, the dry period in the country, especially the northern parts that house the study area falls within the months of October-April and the wet period is from May-September. Weather and climatic characteristics for the study region is assessed through analysis of temperature and rainfall data for selected stations. These analyses are elaborated below.

2.4.1 Temperature

To assess the annual variations of maximum and minimum temperature, analysis of temperature data of three stations (ParoDSC, Drukgyel and Gunitsawa) was performed.

Gunitsawa Station

In the Gunitsawa Station, the temperature data from 2011 to 2017 was analyzed. It has been observed that the average maximum annual temperature varies between 5.03˚C to 18.52˚C at this station. While the average minimum annual temperature varied from -7˚C to 10˚C. From the analysis of maximum and minimum monthly temperature data, it has been also observed that the average temperature falls during the months of November to March. During this season snowfall in this region is also a major reason for the falling down of temperature. The maximum temperature was in the month of August (27˚C) and the minimum temperature was (-7˚C) in February.

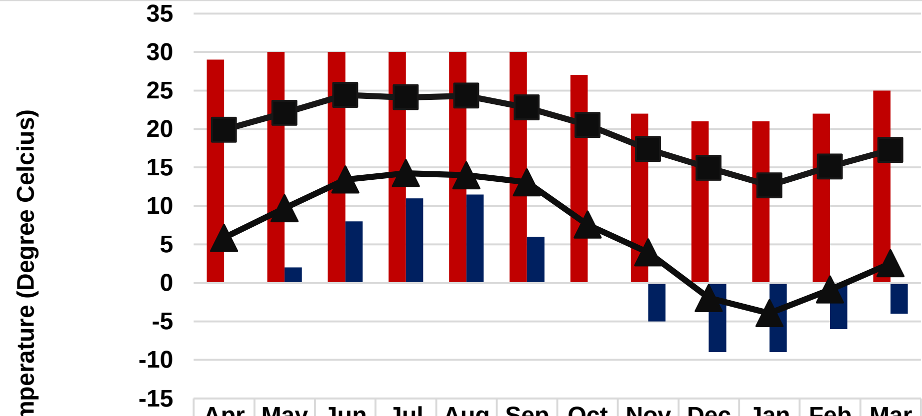


	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Maximum	21.0	24.0	25.0	24.0	27.0	23.0	22.0	14.0	11.0	20.0	21.0	16.0
Minimum	-2	0	7	10	8	6	2	1	0	-2	-7	-6
Average of Maximum	12.18	17.42	17.57	17.08	18.52	16.88	14.73	8.63	6.16	5.22	10.49	5.03
Average of Minimum	4.42	7.81	12.88	14.81	13.11	14.07	10.55	4.27	1.58	0.98	1.74	1.16

Figure 2.3: Monthly Maximum and Minimum Temperatures Gunitsawa Station (2011-2017)

ParoDSC Station

In the ParoDSC Station, the temperature data from 2011 to 2018 was analyzed. It has been observed that the average maximum annual temperature varies between 12.65˚C to 24.41˚C at this station. While the average minimum annual temperature varied from -3.93˚C to 13.99˚C. From the temperature analysis, it has been also observed that the average temperature falls down during the months of November to March. During this season snowfall in this region is also a major reason for the falling down of temperature. The maximum temperature is in the month of May-August (30˚C) and the minimum temperature was (- 9˚C) in December and January.

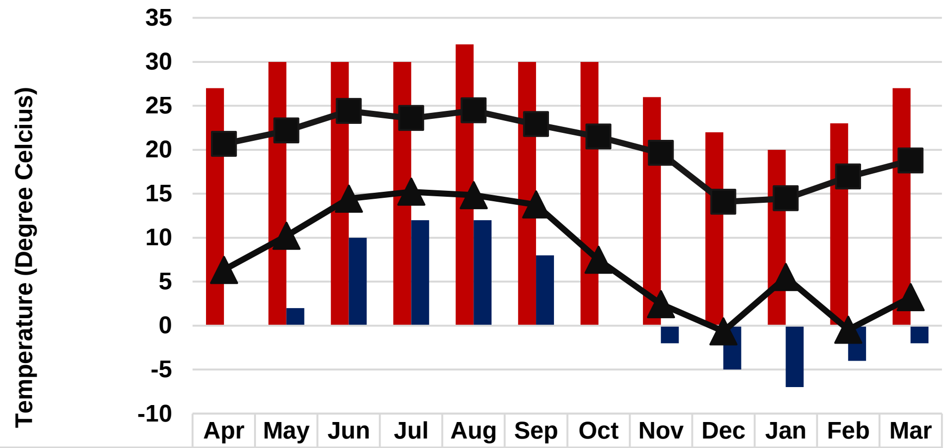


	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Maximum	29	30	30	30	30	30	27	22	21	21	22	25
Minimum	0	2	8	11	11.5	6	0	-5	-9	-9	-6	-4
Average of Maximum	19.88	22.08	24.41	24.09	24.30	22.76	20.50	17.36	14.95	12.65	15.12	17.27
Average of Minimum	5.85	9.72	13.44	14.25	13.99	13.08	7.58	3.95	-1.95	-3.93	-0.86	2.55

Figure 2.4: Monthly Maximum and Minimum Temperatures ParoDSC Station (2011-2018)

Drukgyel Station

In the Drukgyel Station, the temperature data from 2011 to 2017 was analyzed. It has been observed that the average maximum annual temperature varies between 14.07˚C to 24.46˚C at this station. While the average minimum annual temperature varied from -0.48˚C to 15.22˚C. From the temperature analysis, it has been also observed that the average temperature falls down during the months of November to March. During this season snowfall in this region is also a major reason for the falling down of temperature. The maximum temperature is in the month of August (32˚C) and the minimum temperature was (-7˚C) in January.



	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Maximum	27	30	30	30	32	30	30	26	22	20	23	27
Minimum	0	2	10	12	12	8	0	-2	-5	-7	-4	-2
Average of Maximum	20.66	22.17	24.40	23.59	24.46	22.90	21.48	19.63	14.07	14.46	16.92	18.76
Average of Minimum	6.33	10.21	14.44	15.22	14.84	13.77	7.47	2.44	-0.65	5.51	-0.48	3.22

Figure 2.5: Monthly Maximum and Minimum Temperatures Drukgyel Station (2011-2017)

2.4.2 Rainfall

ParoDSC Station

In the ParoDSC Station, the rainfall data from 2011 to 2018 was analyzed (**Figure 2.6**). It has been observed that the average maximum annual rainfall varies between 3.8 (mm/month) in November to 229 (mm/month) in July at this station. While the average minimum annual rainfall varied from 0 (mm/month) in the winter season to 65.7 (mm/month) in May. From the rainfall data analysis, it has been also observed that the average rainfall varies throughout the year. The highest average rainfall was 114.45 (mm/month) in July and the lowest average rainfall was 0.96 (mm/month) in November. From the data analysis, it is also observed that rainfall events start in late April and peaks in the month of July. After this period of time, rainfall starts to decrease. From November to February, the amount of rainfall decreases on a rapid scale.

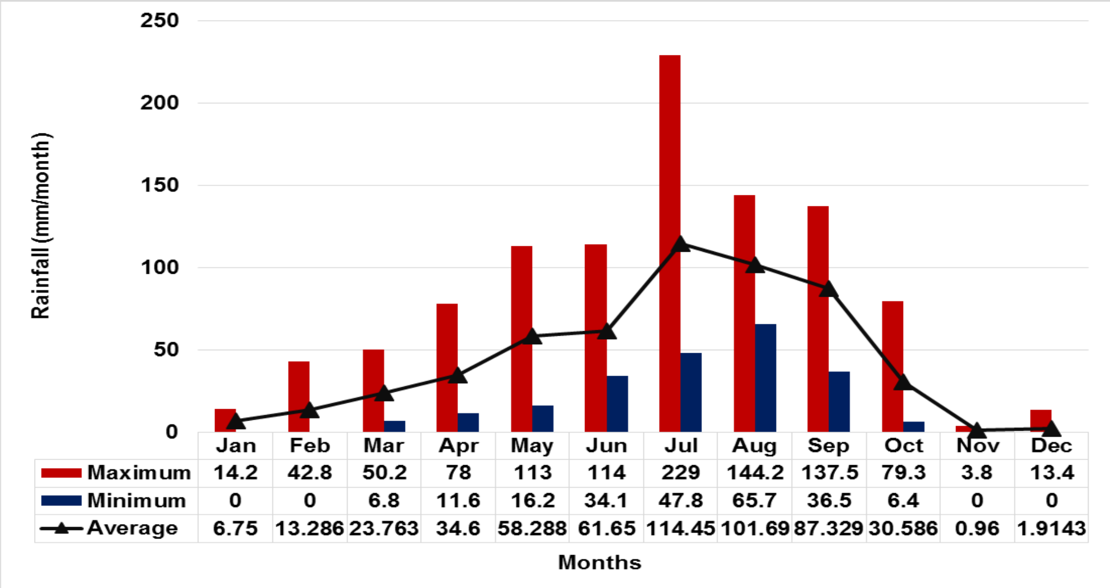


Figure 2.6: Monthly Maximum and Minimum Rainfall ParoDSC Station (2011-2018)

Monthly rainfall distribution analysis is done for 1996-2019 at Paro DSC Station which represents the variance of monthly rainfall increase with the increase of rainfall amount (**Figure 2.7**). The rainfall is noticed from May to October. In June, July and August a large Inter-Quartile Range (IQR) indicate clustering rainfall distribution near the 25th and 75th percentile and large whiskers indicate how markedly the extremes are from the remaining sample. The highest maximum is observed in July which is 180 mm. From January to April the rainfall is comparatively low but these months represent a different distribution of rainfall. There is no rainfall from November to December. From January to April the rainfall is distributed about the median but in February the long tail of maximum extreme indicates large dispersion of the relative outliers.

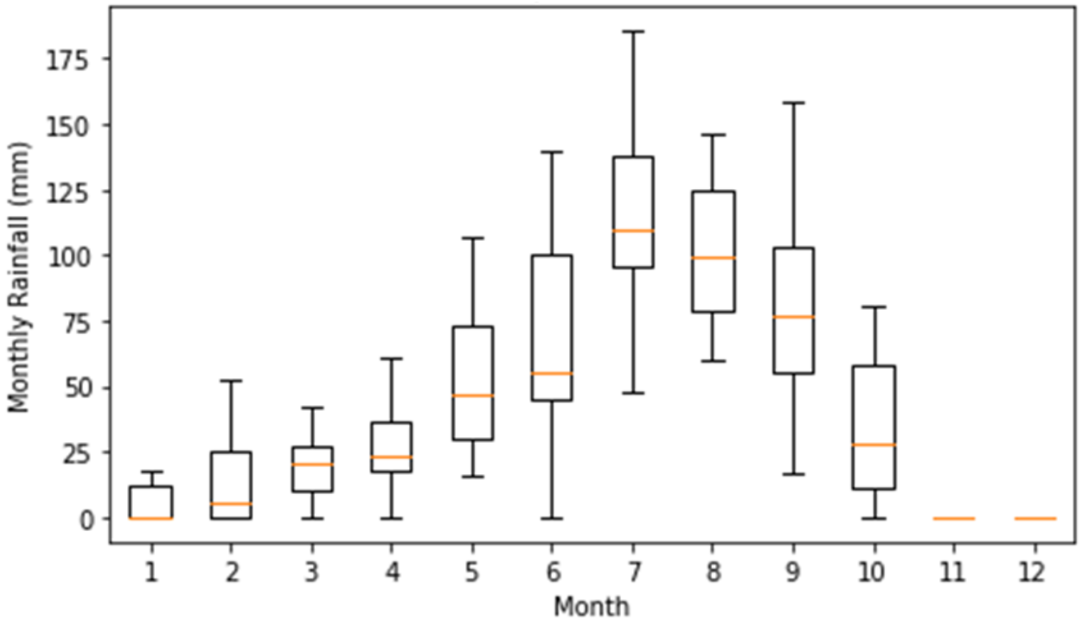


Figure 2.7: Distribution of monthly rainfall at Paro DSC Station

The analysis of skewness forms this dataset represents that January, February, June, and October show positive skewness of rainfall dataset. In these months, the median is shifted to the lower portion of the box indicating that the rainfall dataset is approached closer to the median in the negative direction with a wider range of observations in the upper quartile as compared to the lower quartile. In terms of other month's dataset, the data are mostly distributed symmetrically about the median.

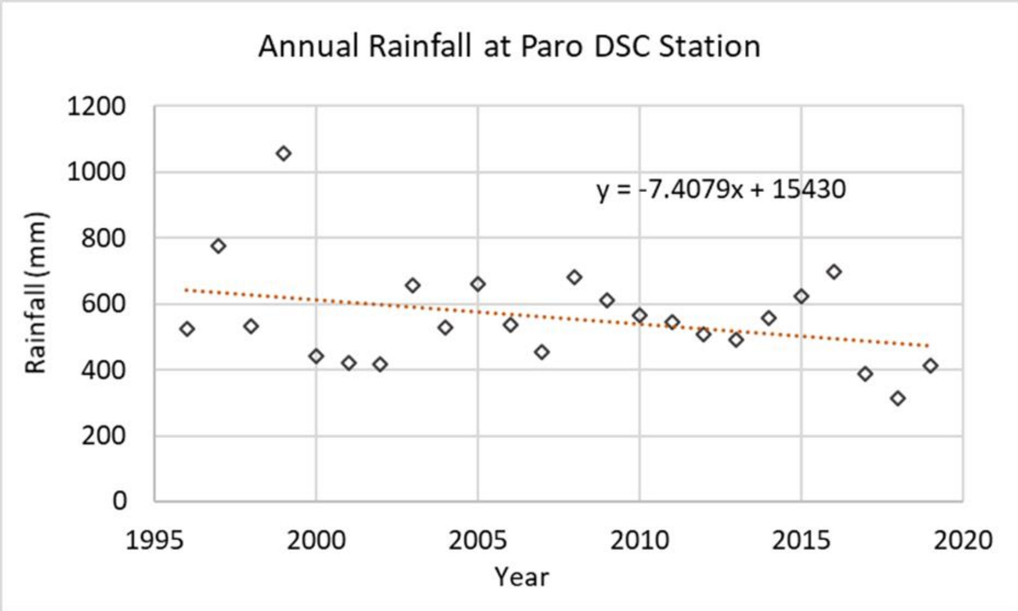


Figure 2.8: Annual rainfall trend at Paro DSC Station

The annual rainfall trend of at Paro DSC Station is shown in **Figure 2.8**. It has been observed that the rainfall is in a decreasing trend. From the rainfall data analysis, annually around 7.41 mm rainfall is being decreased. The average annual rainfall is 560 mm and the annual rainfall varies from 313 to 1058 mm.

Drukgyel Station

In the Drukgyel Station, the rainfall data from 2011 to 2017 was analyzed **(Figure 2.9)**. It has been observed that the average maximum annual rainfall varies between 2 (mm/month) in February to 295.5 (mm/month) in August at this station. While the average minimum annual rainfall varied from 0 (mm/month) in the winter season to 50 (mm/month) in July. From the rainfall data analysis, it has been also observed that the average rainfall varies throughout the year. The highest average rainfall was 203.8 (mm/month) in July and the lowest average rainfall was 0 (mm/month) in February. From the data analysis, it is also observed that the rainfall event starts in late April and peaks during the month of July and August. From November to February, the amount of rainfall is negligible at this station.

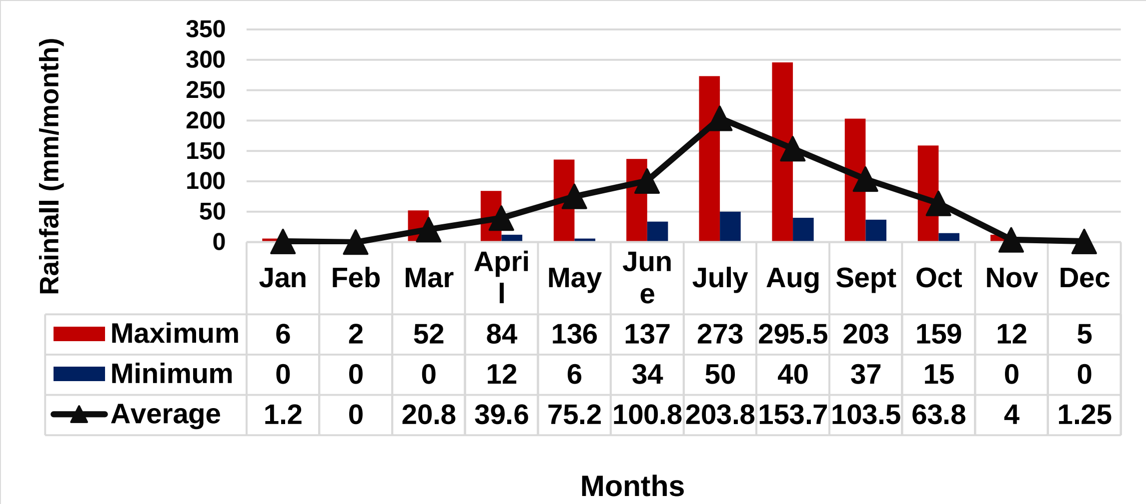


Figure 2.9: Monthly Maximum and Minimum Rainfall Drukgyel Station (2011-2017)

Gunitsawa Station

In the Gunitsawa Station, the rainfall data from 2011 to 2018 was analyzed **(Figure 2.10)**. It has been observed that the average maximum annual rainfall varies between 23.3 (mm/month) in November to 1399 (mm/month) in July at this station. While the average minimum annual rainfall varied from 0(mm/month) in the winter season to 41.2 (mm/month) in May. From the rainfall data analysis, it has been also observed that the average rainfall varies throughout the year. The highest average rainfall was 279 (mm/month) in July and the lowest average rainfall was 5 (mm/month) in November. From the data analysis, it is also observed that rainfall events start in late April and peaks during the month of July and August. After this period of time, rainfall starts to decrease. From November to February, the amount of rainfall decreases tremendously.

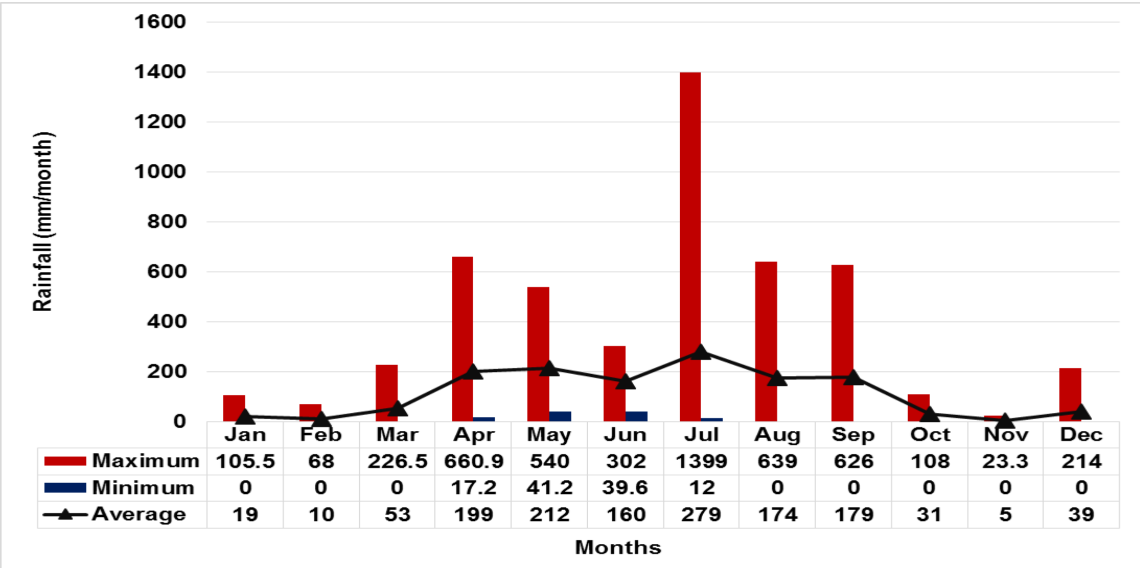


Figure 2.10: Monthly Max and Min Rainfall Gunitsawa Station (2011-2018)

2.5 Hydrology

2.5.1 River System

Pa Chu

Paro City is known to be situated at the height of about 2280 meters on the banks of Pa Chu River, which is spread across an area of 1259 sq.m. The Pa Chu River is the lifeline of Paro, adding a glorious touch to it. The Pa Chu is a river of Western Bhutan and flows through the Paro Valley, which is the site of one of Bhutan's main towns, Paro, and many important monasteries. It is a tributary of the Wang Chu, which is known as the Raidak in its lower reaches. The Pa Chu rises from a glacier to the north of the old fort of Drukgyel Dzong on the southern slopes of the main Himalaya. Thereafter it flows in a general direction towards south-east and merges with the Wang Chu at Confluences. The length of the river is approximately 83 km. The average width of the river ranges between 30-70m. The upper tracts of the Paro catchment are under a perpetual cover of snow. Alpine meadows are found on the debris that occurs along the upper course of this river. Sub-alpine and temperate forests are found along with its middle and lower courses. The terraces around Paro and downstream of it are under cultivation. Amongst the main human settlements that have come up along this river are Drukgyel Dzong and Paro. There are two famous monasteries named Taktshang ("Tiger's nest" in Dzongkha), and Paro Dzong. Taktshang clings to a ledge of a high cliff approximately 15 km north of Paro. Earlier versions of this bridge were removed to protect the dzong. There are many important public infrastructures, agricultural land, tertiary institutes, national airports, and settlements along with the Pa Chu. During the monsoon seasons, the river discharge increases and poses a flooding threat to the settlement and infrastructure. There was a history of Pa Chu flooding in the year 2009 recently and a deadly one in 1968 where the part of Paro's main town has been inundated and severe impacts occured. Below the Dzong, a traditional wooden covered bridge called Nyamai Zam spans the Pa Chu. The original bridge was washed away in a flood in 1969 and the present one is a reconstruction. Although massive flood protection works have been carried out along the river, the risk of flooding cannot be ruled out.

Do Chu

It is a tributary of Pa Chu and flows via villages under the Dopshashari, Doteng, and Hungrel Gewog in Paro. There are many important public infrastructures; agricultural land along the river. The length of the river is approximately 23 km. The average width of the river ranges between 25-60m. As per the hazard report, it was found that the BPC Colony and agriculture land are found to be a flood hazard zone. Moreover, this river poses a threat to the Hungrel Gewog administration office area.

The peak flows at Nyemezampa in Paro, which is on the main river, after the confluence of Dotengchu and main Pa Chu. A case study had been done to estimate the magnitude of 100 years flood of magnitude and 378 m^3/s was used to determine the extent of flooding. The stretch of Pa Chu from Gunitsawa to Tshongdue, Dotey (near Kuenga HSS) to Tshongdue, and Tshongdue to Isuna with a total length of about 45 km was analyzed. According to the analysis, it is found that a lot of the Paro Valley is under flood threat, although parts of the river banks are fairly well protected. However, there are parts of the valley that definitely need more attention and study, such as the villages in Tsento Gewog behind Drukgyel Dzong, Parts of Hungrel Gewog after the confluence towards the base of the Rimpung Dzong, parts of Woochu, and Shaba near the riverside.

Streams

Satsham Chu (Southside): This is the Satshamchu north side stream which gets bifurcated just above the Zhiwaling Resort. It then runs down through Udumvara Resort and finally joins Pa Chu.

The pie chart illustrates how different land-use type contributes to the catchments of Satsam (S) Chu. **Figure 2.11** indicates that Water and Pasture contributed least to the overall land-use type of Satsam (S) Chu while the Mixed Forest occupies about 80 percent of the total area. There is no human settlement though around 20 percent of agricultural land exists.

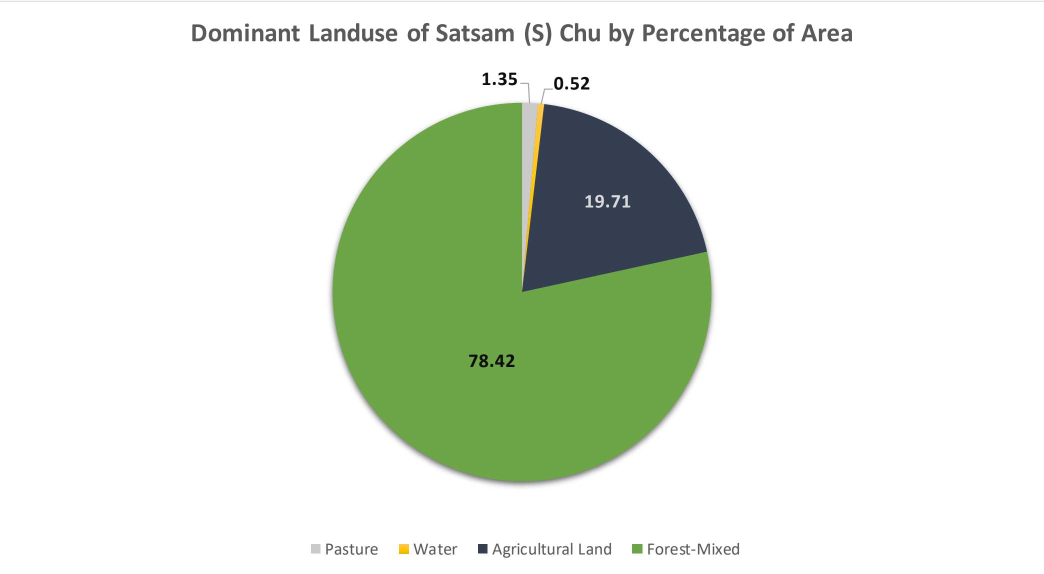


Figure 2.11: Land Use of Satsam (S) Chu

Table 2.2 shows area coverage of each land-use type of Satsam (S) Chu catchment

Table 2.2: Land-use type of Satsam (S) Chu catchment

Landuse type	Area [ha]
Forest-Mixed	127.695
Agricultural Land	32.0931
Pasture	2.2016
Water	0.8468

Figure 2.12 shows the area elevation curve for the Satsam (S) Chu. It is observed that overall elevation in this catchment ranges between 2400 to 2800 m maintaining slight variation in altitudes.

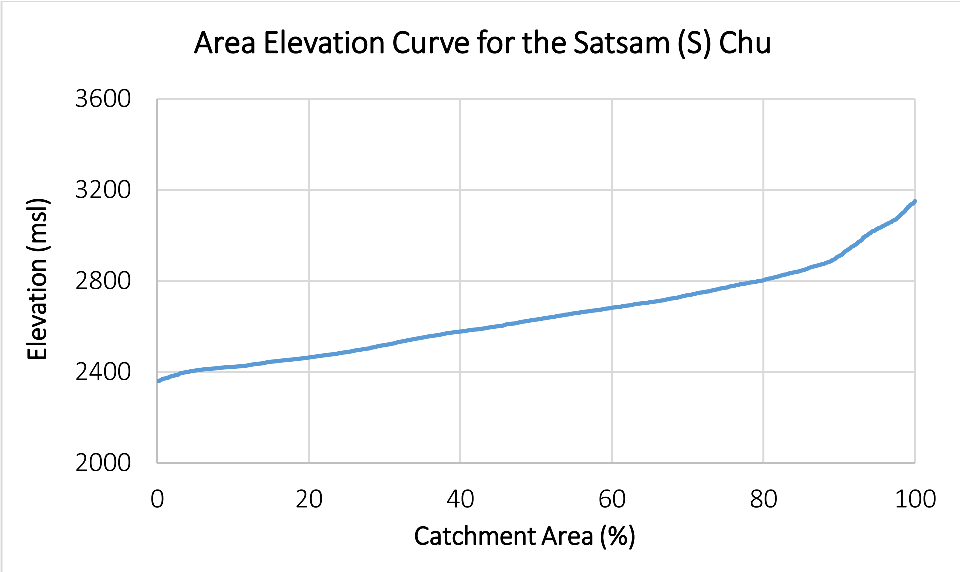


Figure 2.12: Area Elevation Curve for the Satsam (S) Chu

Figure 2.13 illustrates the longitudinal profile of Satsam (S) Chu. The profile shows a slightly varying steep slope having an altitude variation of 100 m in about 1.1 km.

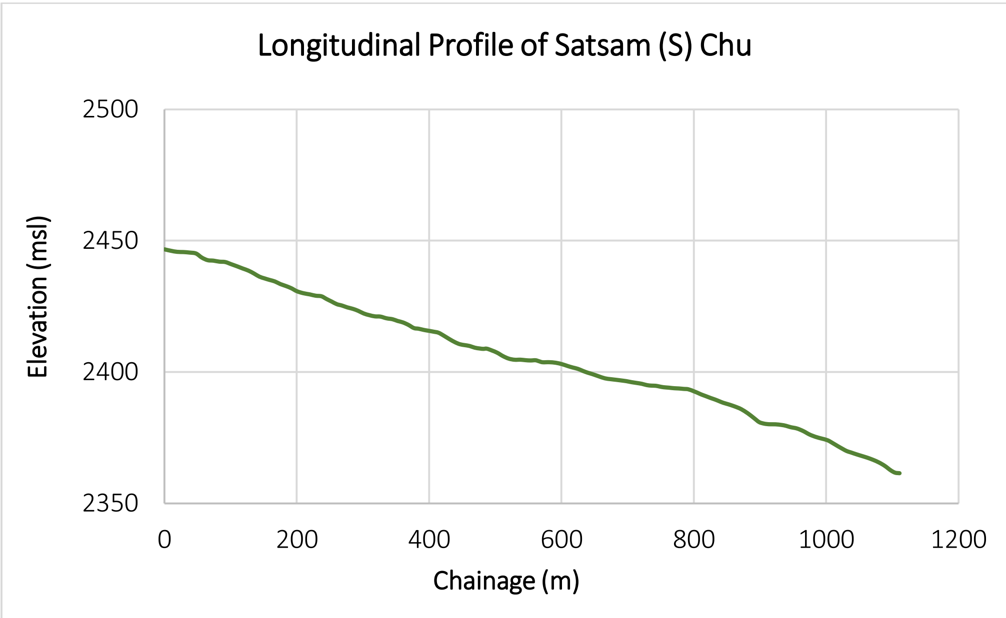


Figure 2.13: Longitudinal Profile of Satsam (S) Chu

Satsham Chu (Northside): This stream flows from upper Satsam Village and runs down through the middle of agriculture land and finally joins the Pa Chu. Both South and North Satsam Chu falls under the Tshento Gewog.

The pie chart illustrated below shows the existing land-use to the surroundings of Satsam (N) Chu. **Figure 2.14** shows that Water, Pasture, and Agricultural land contributed least to the overall land-use type of Satsam (N) Chu. The Mixed forest occupies about 90 percent of the area. In spite of having no human settlement, a little portion of the agricultural area is observed.

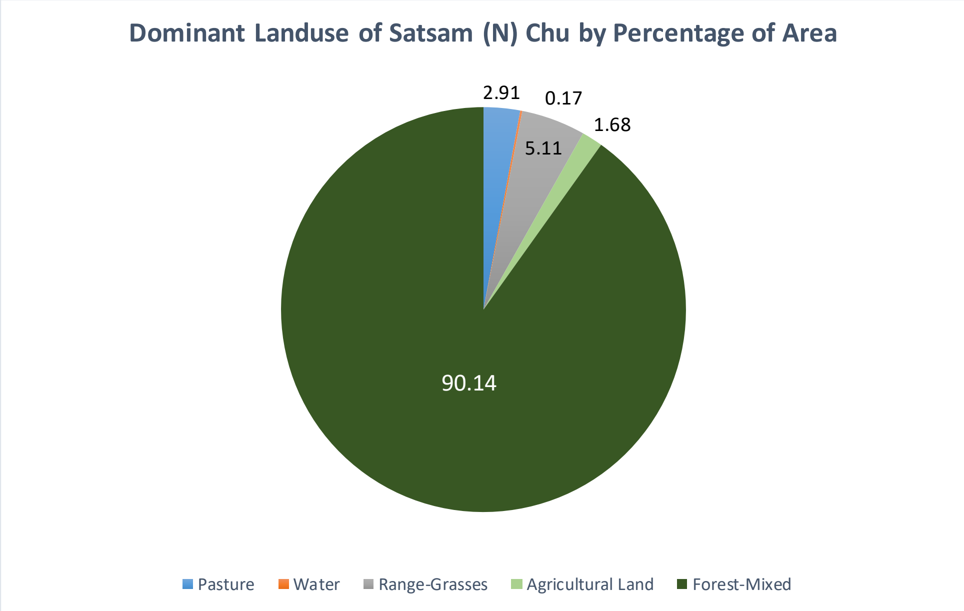


Figure 2.14: Land Use of Satsam (N) Chu

Table 2.3 shows area coverage of each land-use type of Satsam (N) Chu catchment.

Table 2.3: Land-use type of Satsam (N) Chu catchment

Landuse type	Area [ha]
Forest-Mixed	944.5164
Range-Grasses	53.5223
Pasture	30.4874
Agricultural Land	17.6149
Water	1.7784

Figure 2.15 shows the area elevation curve for the Satsam (N) Chu. Satsam (N) shows a rapid variation in elevation which ranges between 2400 m to 4000 m. Altitudes of more than 50% of total catchment vary in between 3000 m to 3500m.

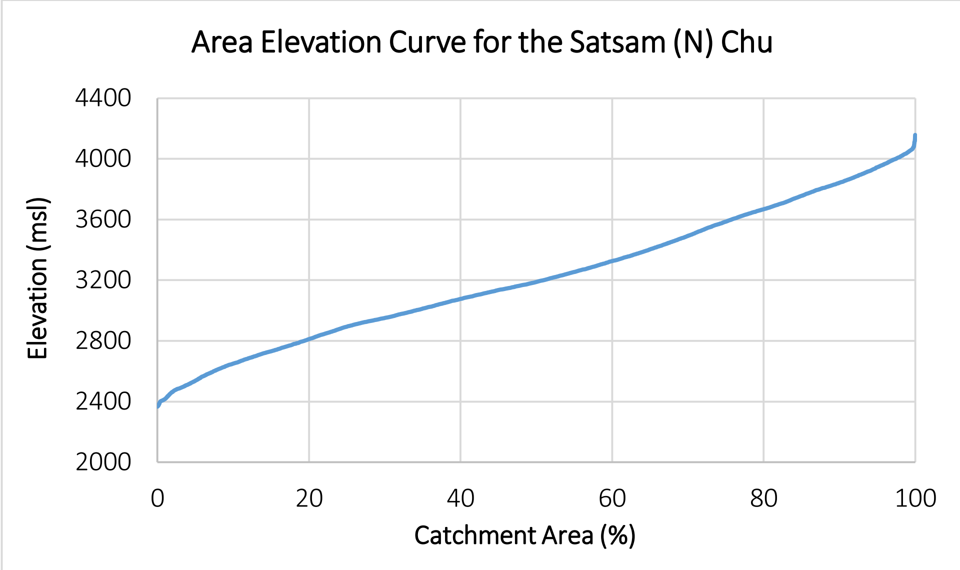


Figure 2.15: Area Elevation Curve for Satsam (N) Chu

Figure 2.16 shows a longitudinal profile of Satsam (N) chu. The profile shows a very steep slope of 19% in just 1.3 km of length.

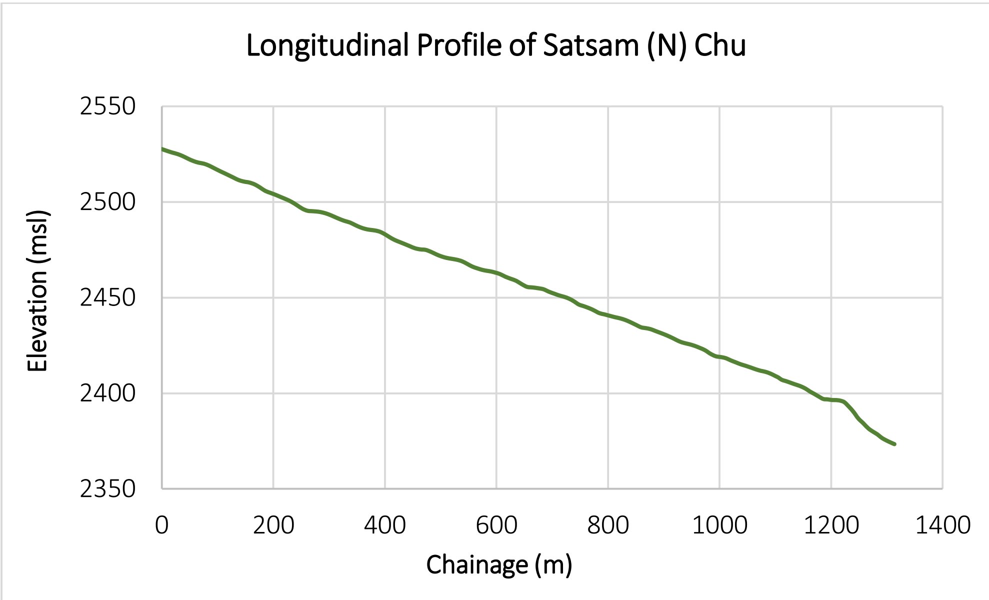


Figure 2.16: Longitudinal Profile of Satsam (N) Chu

Dakhorong Chu: This stream runs down via Lamgong MS School, Lamgong Town area and then joins Pa Chu. Agricultural lands have been mostly affected due to the Dakhorongchu flooding.

The pie chart describes the existing land-use of Dakhorong Chu catchment. According to **Figure 2.17,** Pasture and Water contributed least to the overall land-use type of Dakhorong Chu while the Mixed Forest contains more than 90 percent of the area. Besides, Agricultural land contains about 5 percent of the total land-use type and no human settlement in the surroundings.

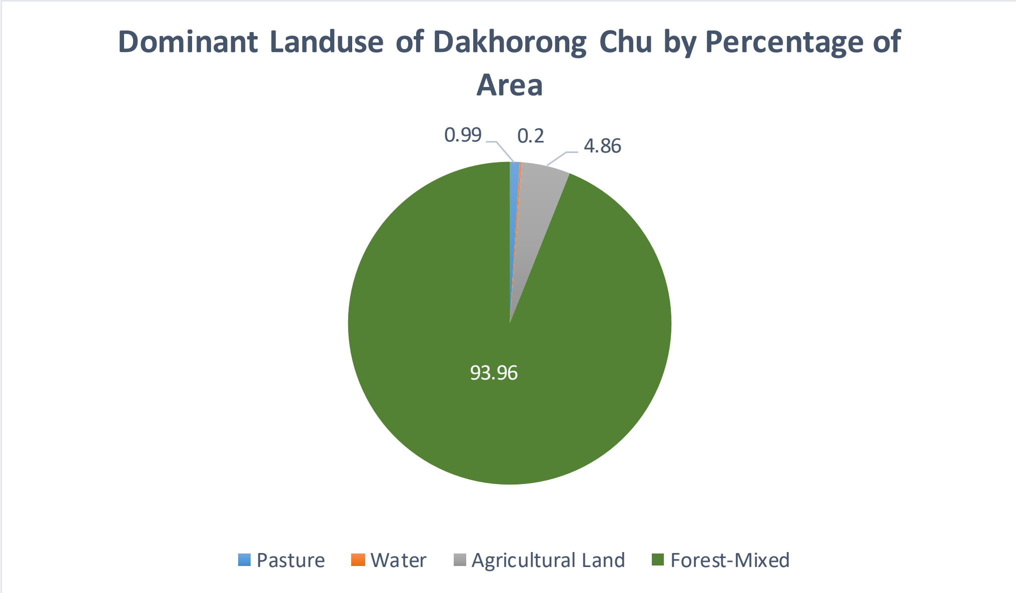


Figure 2.17: Land Use of Dakhorong Chu

Table 2.4 shows area coverage of each land-use type of Dakhorong Chu catchment.

Table 2.4: Land-use type of Dakhorong Chu catchment

Landuse type	Area [ha]
Pasture	9.485
Water	1.9478
Agricultural Land	46.578
Forest-Mixed	900.903

Figure 2.18 shows an Area Elevation Curve for the Dakhorong Chu. According to **Figure 2.16**, it is observed that a dominant percentage of the area contains an elevation ranges between 2800 to 3600 by maintaining a steep slope. **Figure 2.19** shows the longitudinal profile of Dakhorong Chu which illustrates a steep profile of stream.

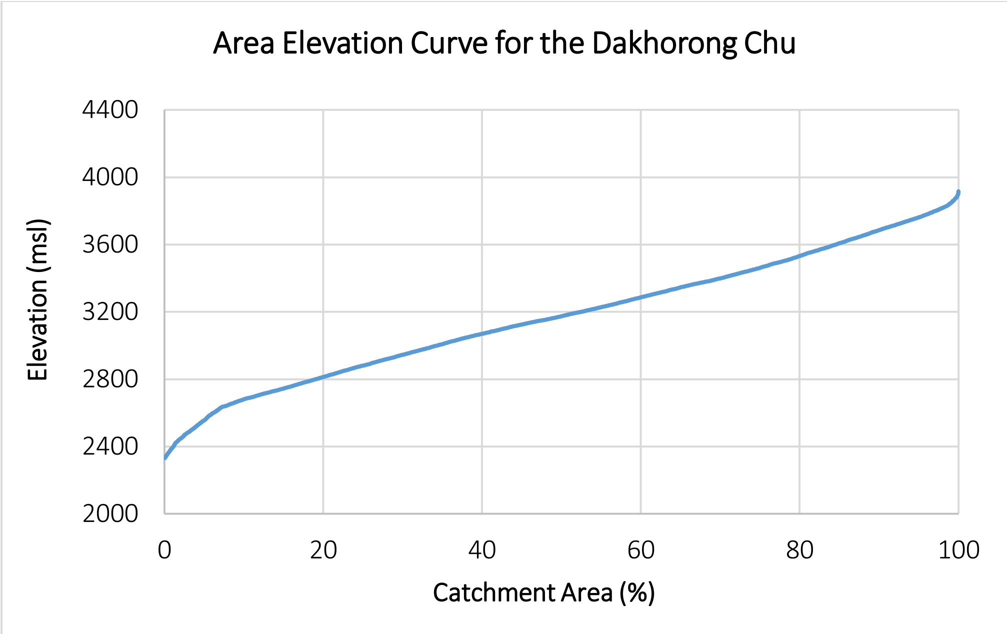


Figure 2.18: Area Elevation Curve for the Dakhorong Chu

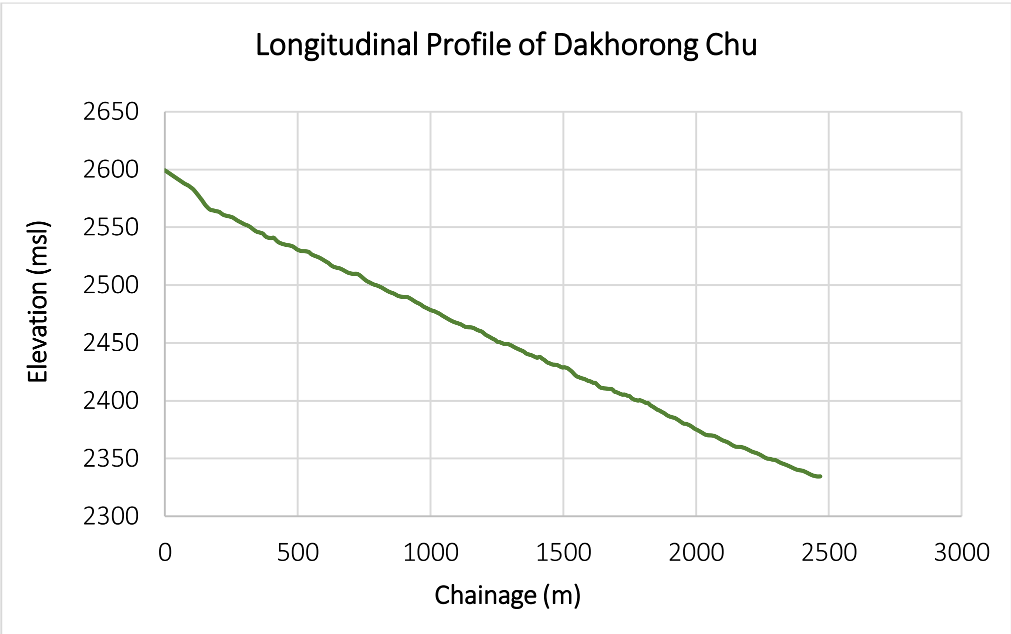


Figure 2.19: Longitudinal Profile of Dakhorong Chu

Ri Chu: This stream flows from Rinchending Village and down towards the Dopshari Village and adjacent to the gewog administration office. Before joining Do Chu the stream also flows through agriculture land and some settlements of Shari Village. The stream falls under the Dopshari Gewog.

The pie chart illustrates how different land-use type contributes to the surroundings of Ri Chu. According to **Figure 2.20,** Arid Range and Evergreen Forest contributed least to the overall land-use type of Ri Chu while the Mixed Forest contains the most significant part. Besides, Agricultural land contains more than one-tenth to the total land-use type.

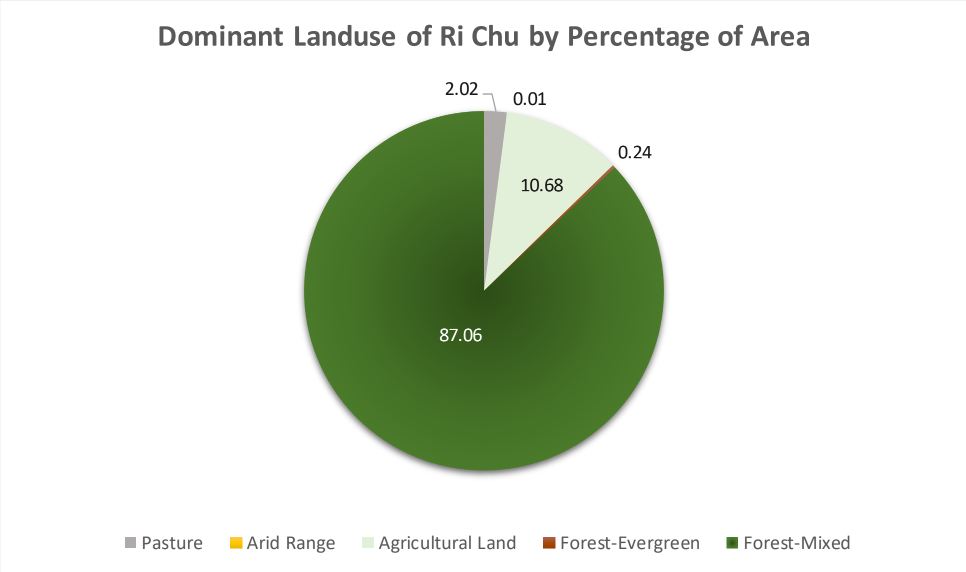


Figure 2.20: Land Use of Ri Chu

Table 2.5 shows area coverage of each land-use type of Ri Chu catchment.

Table 2.5: Land-Use Type of Ri Chu catchment

Landuse type	Area [ha]
Pasture	37.6011
Arid Range	0.2541
Agricultural Land	199.0149
Forest-Evergreen	4.4884
Forest-Mixed	1621.929

The line graph of **Figure 2.21** gives information about elevation concerning the area of the Ri Chu. The overall elevation of surrounding regions varied from 2200 m to 3800 m in between more than 70% of the area lies in the elevation ranges from 2600 to 3400 m. Besides, about 20% area lies in between elevation ranges from 2200 to 2600 m, and the rest one-tenth portion of the total area lies in higher altitude, ranges from 3400 to 3800m.

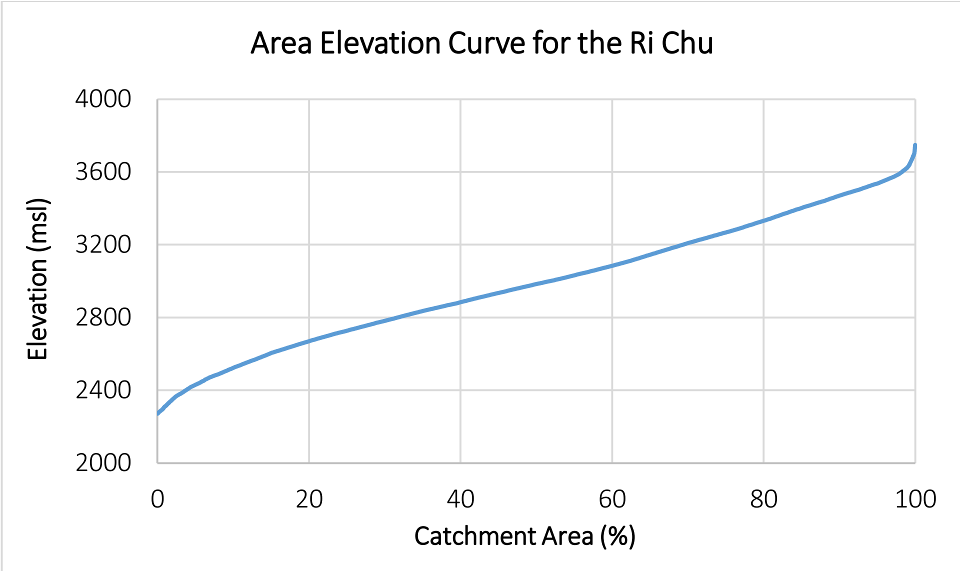


Figure 2.21: Area Elevation Curve for the Ri Chu

Figure 2.22 shows the longitudinal profile of the Ri Chu. Profile illustrates a steep slope having a slope of 7% where the elevation falls from 2400 m to 2275 m in about 1700 m of length.

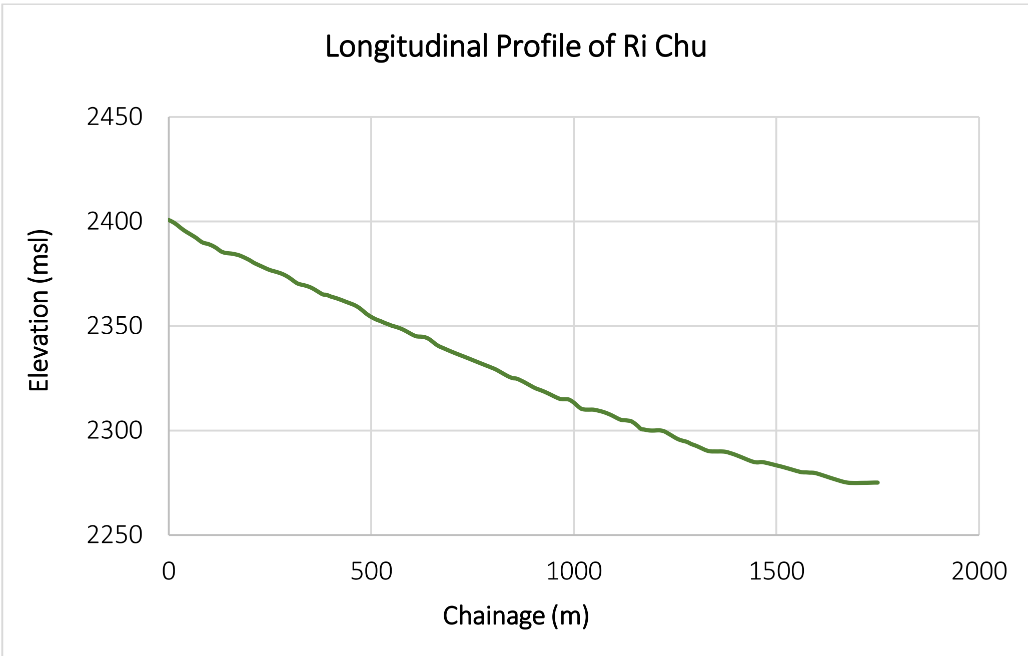


Figure 2.22: Longitudinal Profile of Ri Chu

Ngoborong Chu: It flows though the Meta Resort, Tenzin HS School and few of the settlements and then joins Pa Chu. Agricultural lands have been mostly affected due to the flooding. The present area below the Kichu Lhakhangs was mostly inundated during the flooding.

The pie chart illustrates how different land-use type contributes to the surroundings of Ngoborong Chu. According to **Figure 2.23,** Water and Pastureland type contributed least to the overall land-use type of Ngoborong Chu while the Mixed forest contains the most significant part. Besides, Agricultural land contains abdout 4 percent of the total land-use type.

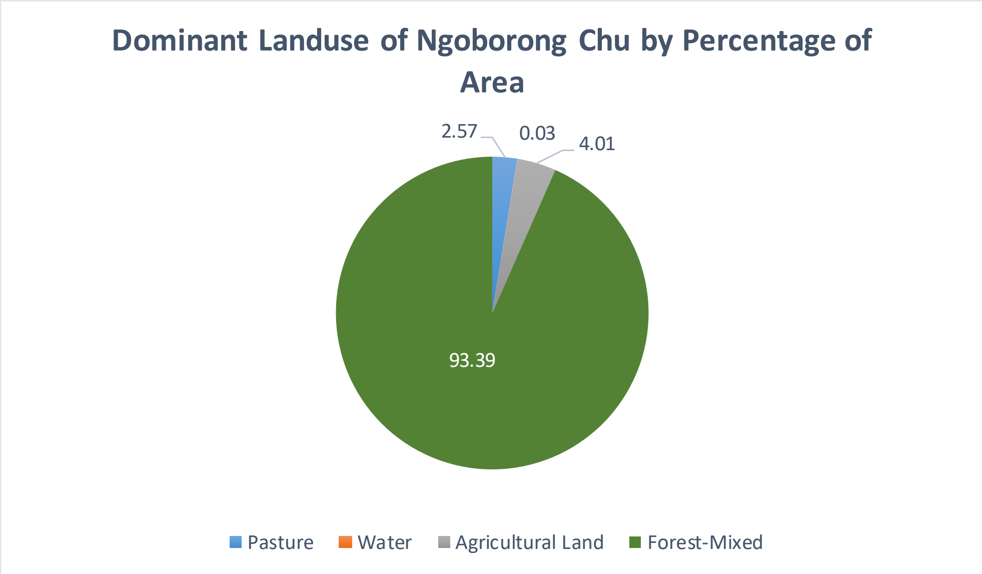


Figure 2.23: Land Use of Ngobarong Chu

Table 2.6 shows area coverage of each land-use type of Ngobarong Chu catchment.

Table 2.6: Land-Use Type of Ngobarong Chu catchment

Landuse type	Area [ha]
Forest-Mixed	1482.111
Agricultural Land	63.6848
Pasture	40.8192
Water	0.5081

Figure 2.24 shows an area elevation curve for the Ngoborong Chu, it shows the overall elevation of Ngoborong catchment ranges between 2800m to 3600m. About 80% of the entire catchment area lies under this elevation range.

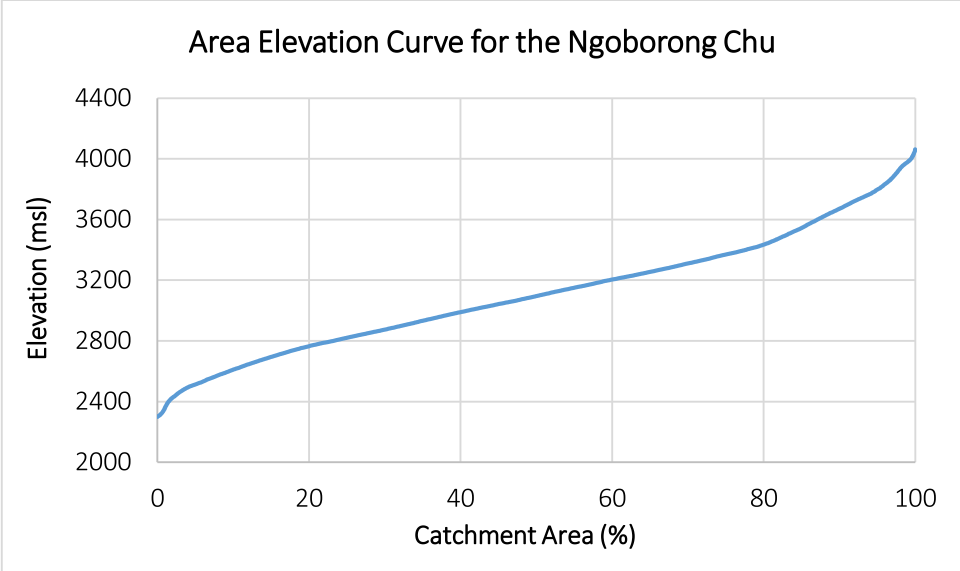


Figure 2.24: Area Elevation Curve for the Ngobarong Chu

Figure 2.25 shows the longitudinal profile of Ngoborong Chu. The profile shows a 1% steep slope where the elevation falls from 2550 m to 2300 m in about 2500 m of length.

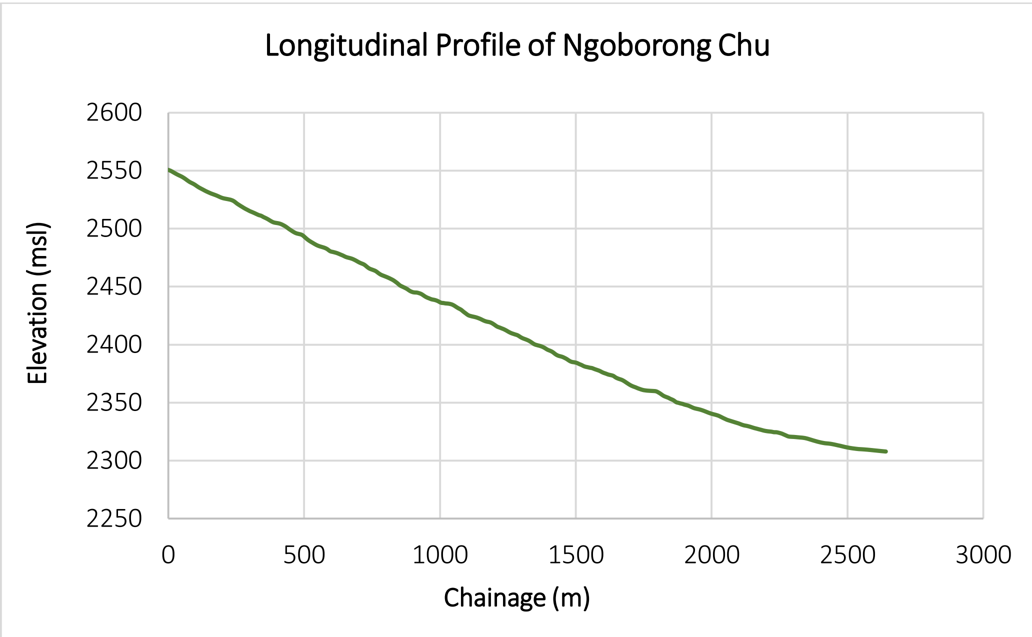


Figure 2.25: Longitudinal Profile of Ngobarong Chu

Jew Chu: Under Lungnyi Gewog, Jew Chu flows through the villages, agricultural land, town and the Gewog administration office before joining Pa Chu. Jew Chu and Gatanarong Chu both fall under the Lungnyi Gewog.

The pie chart describes the existing land-use to the surroundings of Jew Chu. According to **Figure 2.26,** Arid Range and Evergreen forest contributed least to the overall land-use type of Jew Chu while the Mixed forest contains the most significant part. Besides, Agricultural land contains about 5 percent of the total land-use type. Around 20 percent area surrounding the Chu has settlement having medium or low density

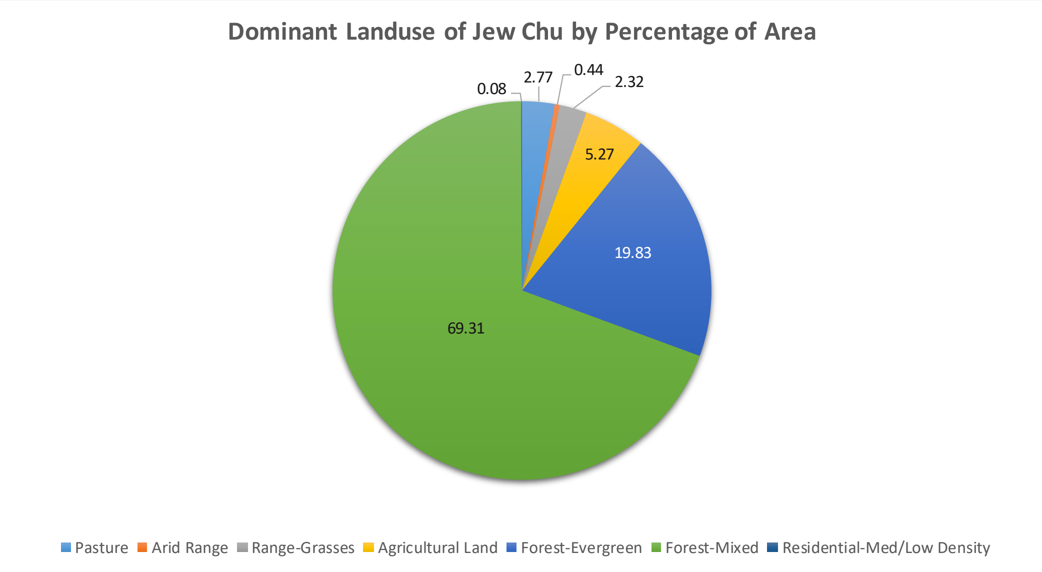


Figure 2.26: Land use of Jew Chu

Table 2.7 shows area coverage of each land-use type of Jew Chu catchment.

Table 2.7: Land-Use Type of Jew Chu catchment

Landuse type	Area [ha]
Pasture	77.4041
Arid Range	12.449
Range-Grasses	64.7857
Agricultural Land	147.4404
Forest-Evergreen	554.7012
Forest-Mixed	1939.168
Residential-Med/Low Density	2.1172

The line graph of **Figure 2.27** gives information about elevation concerning the catchment area of the Jew Chu. The overall elevation of surrounding regions varied from 2200 m to 3800 m in between more than 70% of the area lies in the elevation ranges from 2600 to 3400 m. Besides, about 20% area lies in between elevation ranges from 2200 to 2600 m, and the rest one-tenth portion of the total area lies in higher altitude, ranges from 3400 to 3800m. Overall the area obtained a dominant altitude of 3000m to 3600m where the overall slight variation of altitude is observed from the curve.

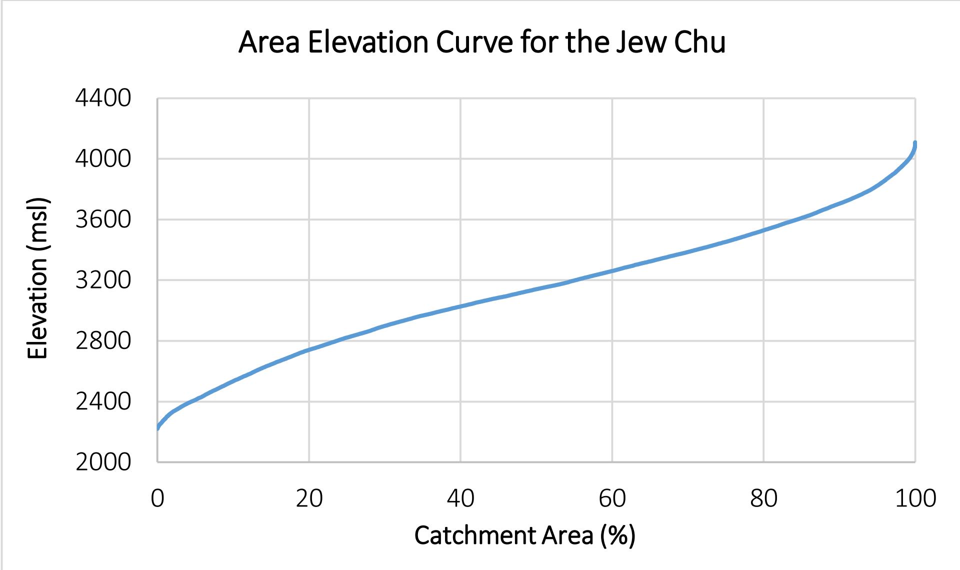


Figure 2.27: Area Elevation Curve for Jew Chu

Figure 2.28 shows the longitudinal profile of the Jew Chu. Profile illustrates a varying steep slope having a slope of 7.5% where the elevation falls from 2400 m to 2275 m in about 2700 m of length.

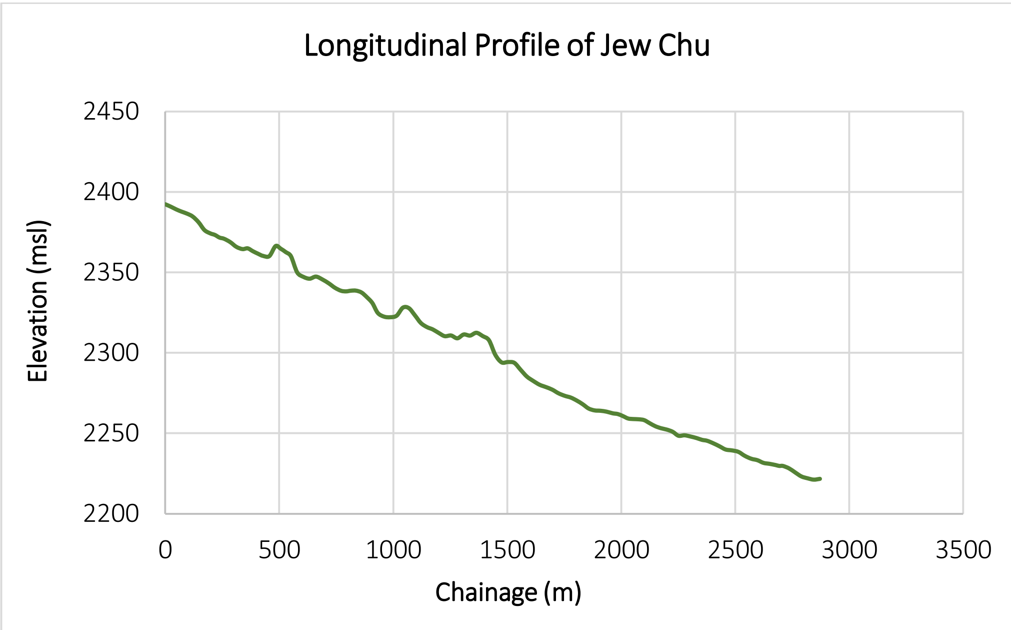


Figure 2.28: Longitudinal Profile of Jew Chu

Gatanarong Chu: Flows through the villages behind the Bondey Town along with the present AMC office. Hence, its impact has also been mostly on the agricultural lands in the past. In 1994, the stream flooding washed away a policeman. It is also a tributary to Pa Chu.

The pie chart illustrates how different land-use type contributes to the surroundings of Gatanarong Chu. **Figure 2.29** indicates that Forest Evergreen and Pasture contributed least to the overall land-use type of Nephu Chu. The Mixed forest occupies about 90 percent of the area. The human settlement comprises less than 1 percent and around 10 percent of agricultural land exists.

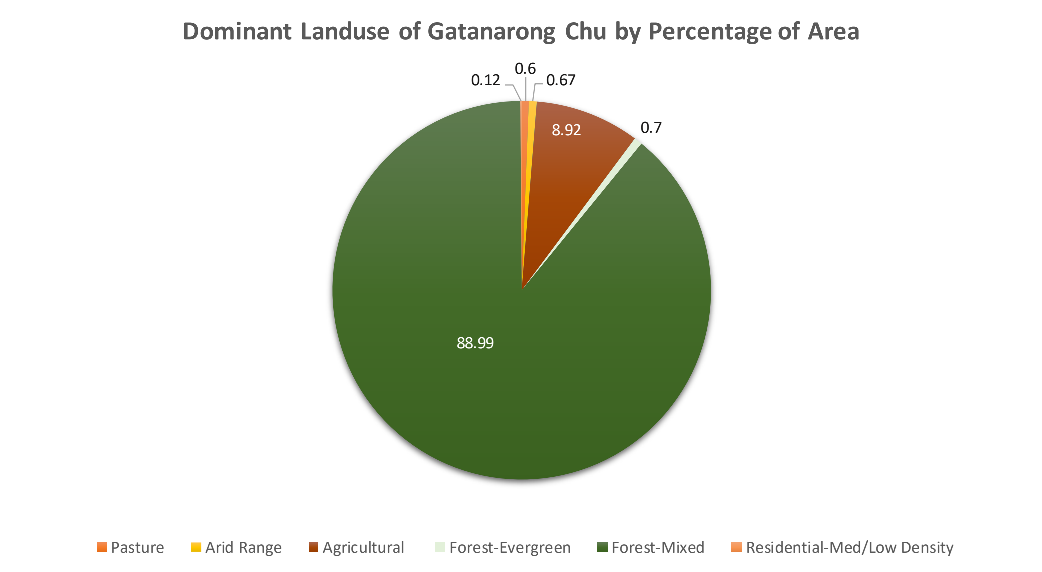


Figure 2.29: Longitudinal Profile of Gatanarong Chu

Table 2.8 shows area coverage of each land-use type of Gatanarong Chu catchment.

Table 2.8: Land-Use Type of Gatanarong Chu catchment

Landuse type	Area [ha]
Pasture	17.869
Arid Range	19.8168
Water	0.2541
Agricultural	263.8853
Forest-Evergreen	20.6637
Forest-Mixed	2633.01
Residential-Med/Low Density	3.5569

The line graph of **Figure 2.30** illustrates Area Elevation Curve of the Gatanarong Chu where the overall elevation of surrounding regions varied from 2200 m to 3800 m in between more than 70% of the area lies in the elevation ranges from 2600 to 3400 m. Besides, about 20% area lies in between elevation ranges from 2200 to 2600 m, and the rest approximate 10% of the total area lies in higher altitude, ranges from 3400 to 4000m

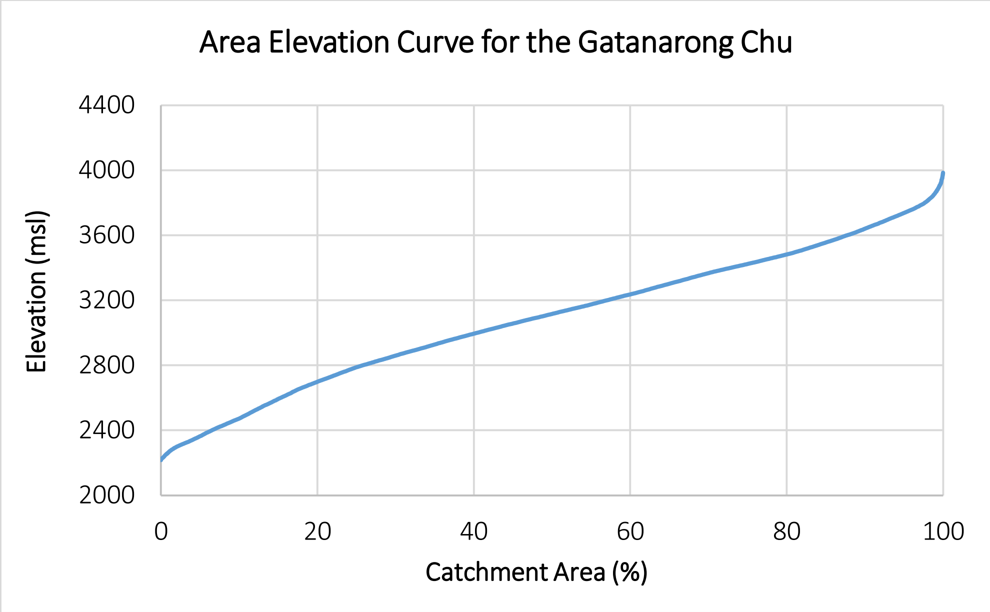


Figure 2.30: Longitudinal Profile of Gatanarong Chu

Figure 2.31 shows the longitudinal profile of Gatanarong Chu and the profile illustrates a varying steep slope having a slope of 6.5% where the elevation falls from 2330 m to 2200 m in about 2200 m of length.

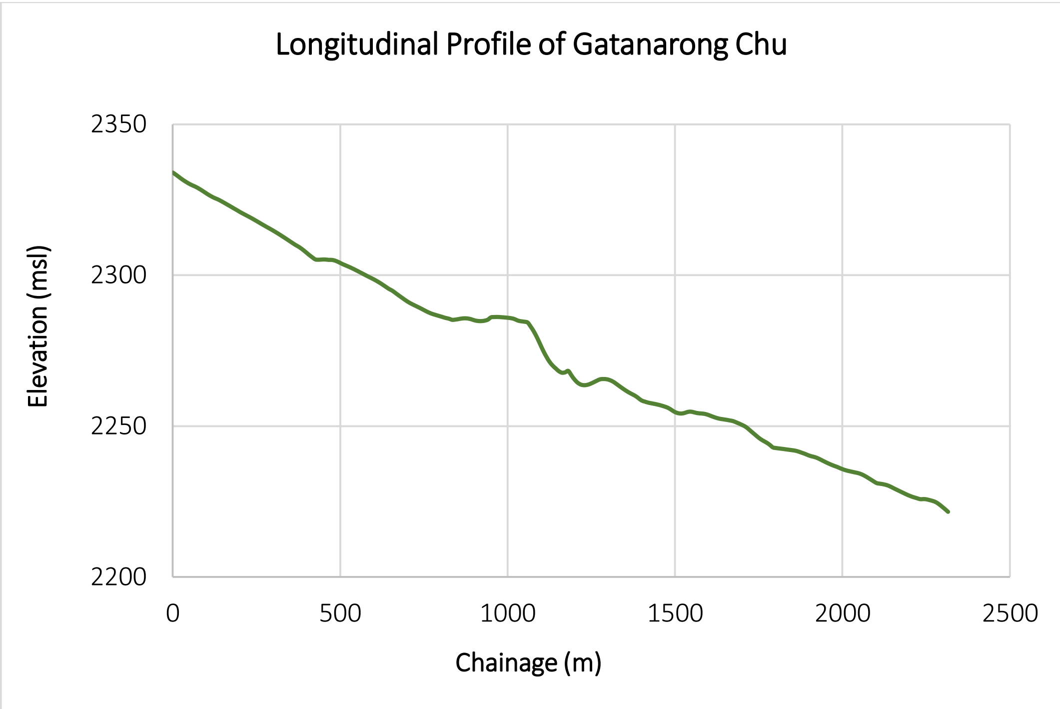


Figure 2.31: Longitudinal Profile of Gatanarong Chu

Nephu Chu: It flows through the Nephu Village adjacent to Shaba Primary School, some residential area, and joins to Pa Chu. The stream falls under the Shaba Gewog.

The pie chart illustrated below shows the existing land-use of Nephu Chu catchment. **Figure 2.32** shows that Range Grasses contributed least to the overall land-use type of Nephu Chu. The Mixed forest occupies about 80 percent of the area. There is no human settlement but a little portion of the agricultural area does exist

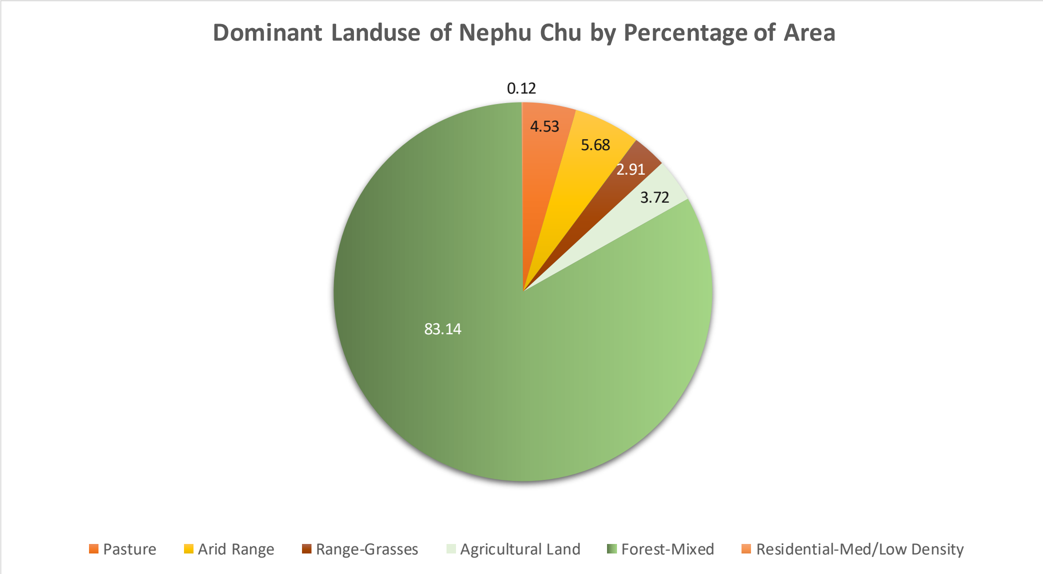


Figure 2.32: Longitudinal Profile of Nephu Chu

Table 2.9 shows area coverage of each land-use type of Nephu Chu catchment.

Table 2.9: Land-Use Type of Nephu Chu catchment

Landuse type	Area [ha]
Forest-Mixed	2190.858
Pasture	119.4937
Arid Range	149.727
Agricultural Land	98.0678
Range-Grasses	76.7266
Water	0.5081

The line graph of **Figure 2.33** shows the area elevation curve for the area of the Nephu Chu. According to the curve, it is observed that the overall elevation of the catchment varied from 2200 m to 3800 m where more than 70% of the area lies in the elevation ranges from 2600 to 3400 m. Besides, about 20% area lies in between elevation ranges from 2200 to 2600 m, and the rest one-tenth portion of the total area lies in higher altitude, ranges from 3400 to 3800m.

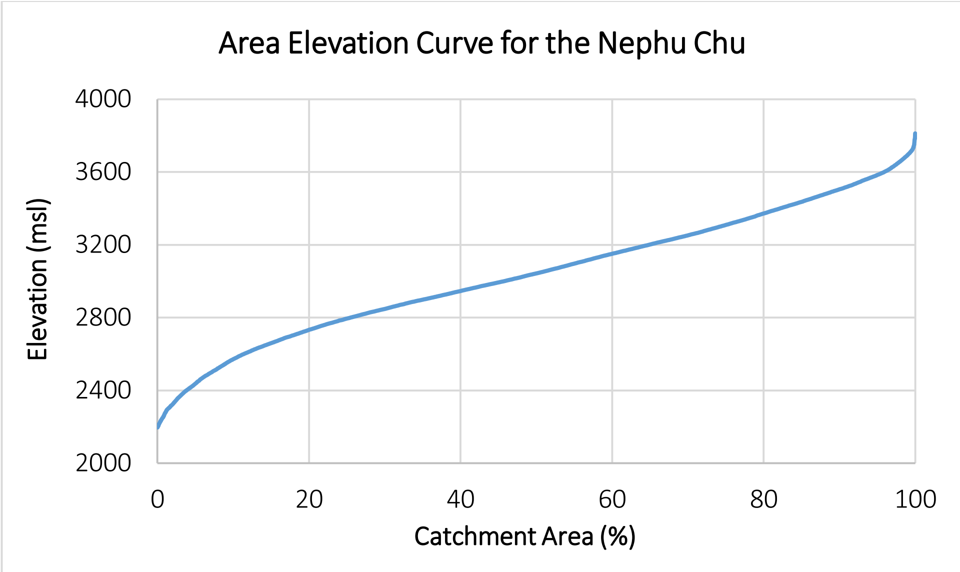


Figure 2.33: Area Elevation Curve for the Nephu Chu

Figure 2.34 shows the longitudinal profile of Nephu Chu. Profile illustrates a varying steep slope where the elevation falls from 2300 m to 2200 m in about 1000 m of length having a slope of 10%

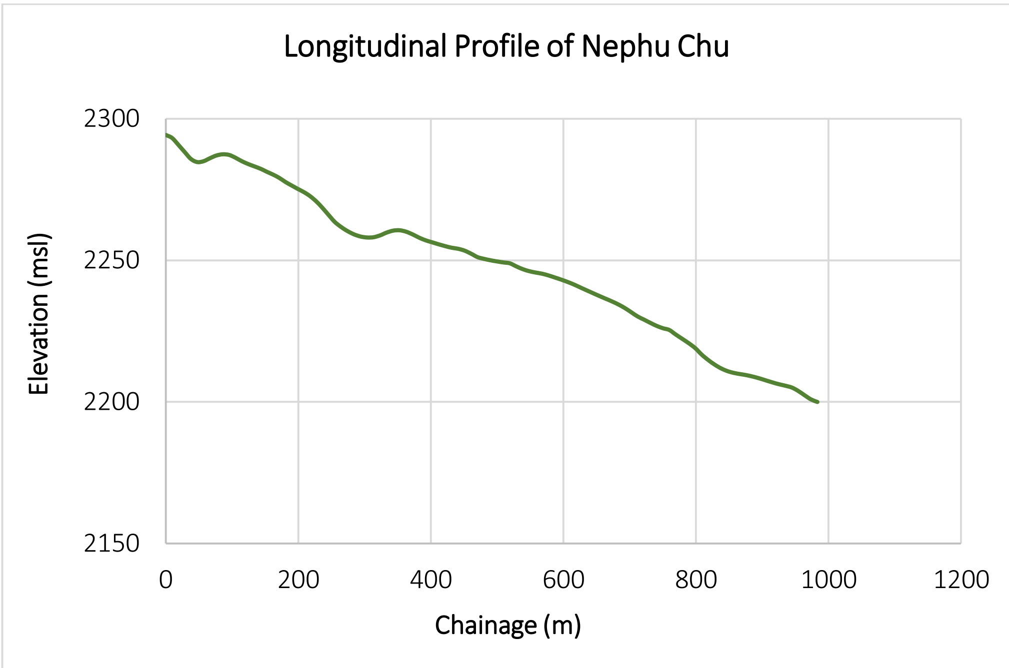


Figure 2.34: Longitudinal Profile of Nephu Chu

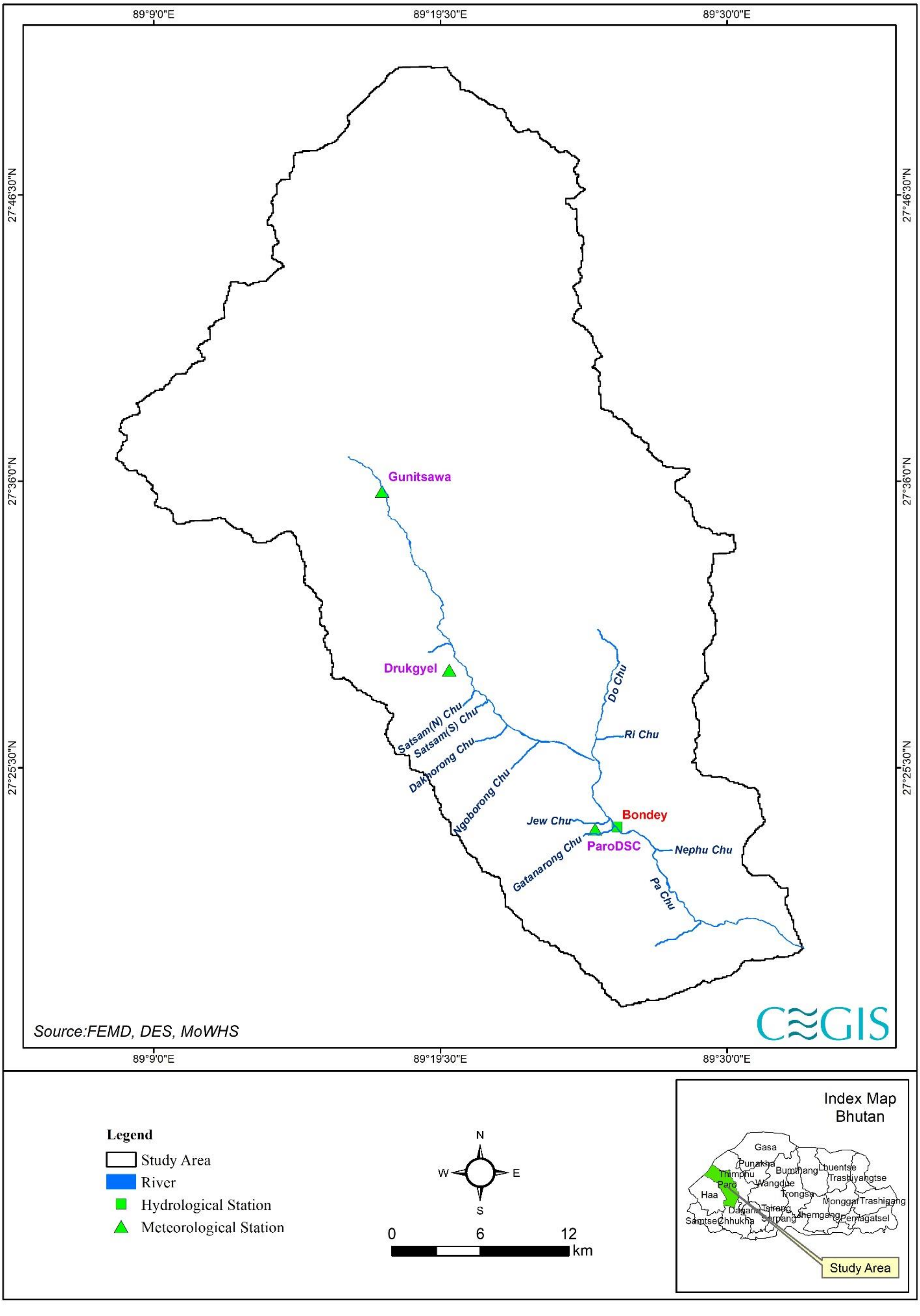


Figure 2.35: River and stream system in the study area

Combined Area Elevation Curve of Streams

The line graph of **Figure 2.36** illustrates the area elevation curves of the eight streams. All the streams except Balaka Chu and Satsam (South) Chu represent a steady steep slope where a gentle variation of altitude is observed with respect to the percentage of area. But soaring of Balaka Chu is observed in the graph. Balaka Chu also experienced a wide range of altitude varieties compared to other streams while Satsam (South) illustrated a very steady slope and gentle variation of altitude over the catchment area.

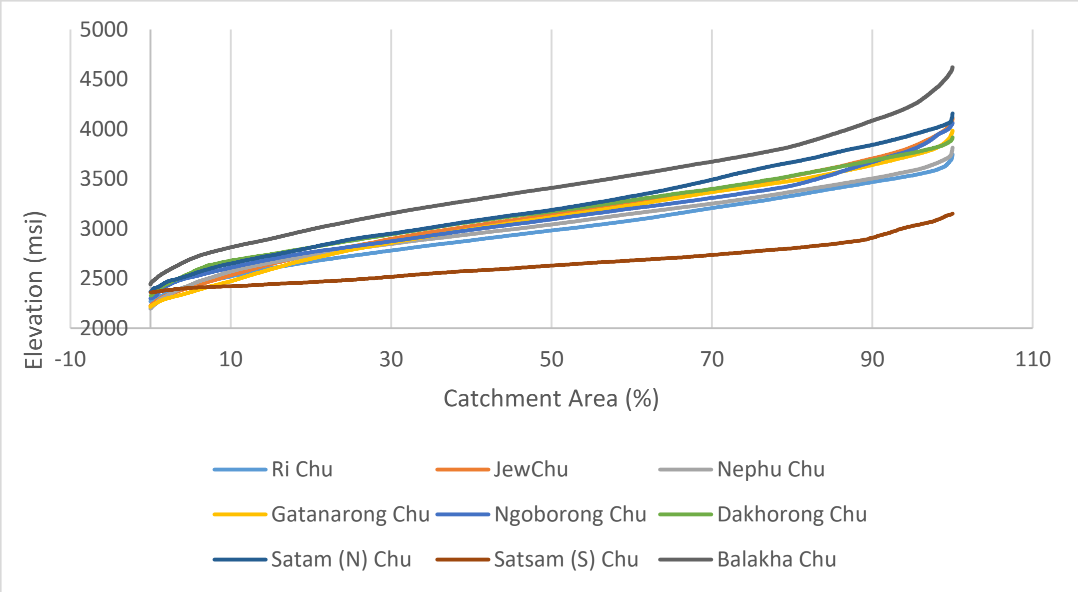


Figure 2.36: Area Elevation Curves of Streams

Combined Longitudinal Profile of Streams

The line graph of **Figure 2.37** illustrates a combination of the longitudinal streams. Overall the profile of Jew Chu, Ghatanarong Chu, Satsam (S) Chu and Ri Chu streams has shown a gentle slope. Ri Chu and Ghatanarong Chu have shown almost the same profile over the length. On the other hand, Balaka Chu, Dakhorong Chu, and Nephu Chu show a steep slope. Dakhorong Chu shows a most dramatic fall over the distance.

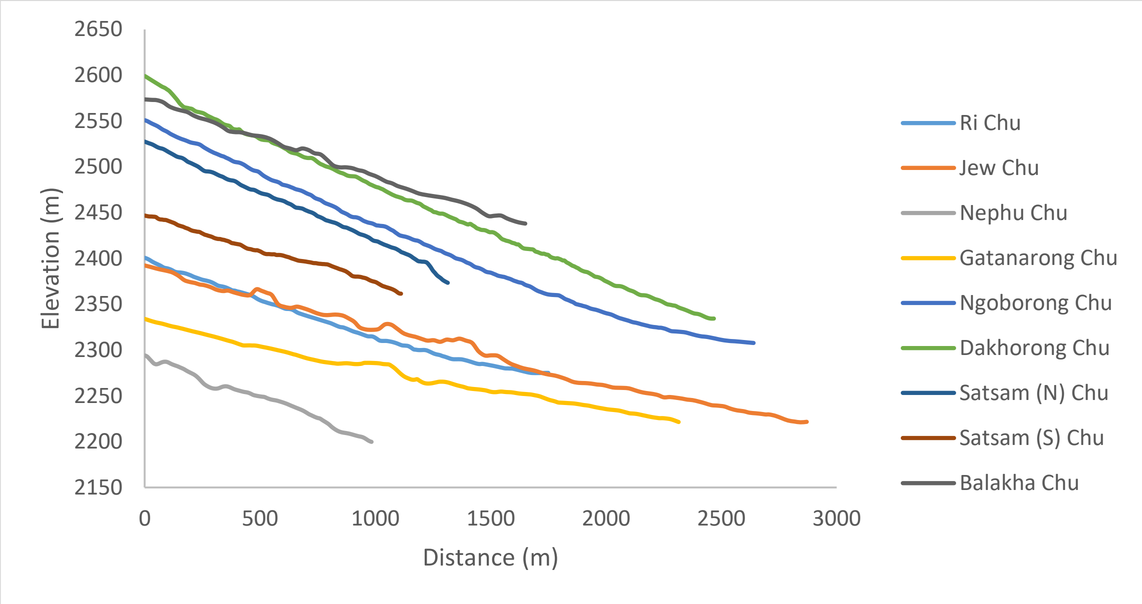


Figure 2.37: Combined Longitudinal Profile of Streams

2.5.2 Glacier Lake

The Wang Chu basin constitutes Pa Chu, Ha Chu, and Thim Chu Sub-basins. According to the Glacier Lake Inventory of Bhutan (NCHM 2019a), the Pa Chu, Thim Chu, and Ha Chu have a total of 31, 13, and 3 glaciers respectively. The inventory for the glacier lakes of the Paro Basin is given in **Annex-I**. While Pa Chu sub-basin has the highest glacier area (28.39 sq. km) and Ha Chu sub-basin has the smallest (0.27 sq. km). The glaciers in this region are mostly mountain glaciers and small ice apron and valley glaciers having aspects in various directions. Glacier tongue elevation ranges from 4,799 to 6,862 m above sea level.

Glaciers in the Bhutan Himalaya are less well studied than those in other countries. Nonetheless, there is some indication of glacier retreat in the Bhutan Himalaya. Ageta et al. (2000) found that the rate of retreat of some selected large debris-covered glaciers associated with large lakes by comparing archived photographs, satellite images, and maps of previous years. Using lake expansion rates up-valley to calculate retreat rates for the related glaciers, the authors reported retreat rates in the range of 30–35m per year. The Tarina Glacier retreat rate was 35m per year from 1967 to 1988 (Ageta et al. 2000).

However, the rates were found to be variable with time, a phenomenon attributed to irregular calving at the tongue of the mother glacier, which is in contact with the lake water (Ageta et al. 2001). Debris free or 'clean' glaciers (C-type) are considered more sensitive to climate change than debris-covered (D-type) ones. Karma et al. (2003) examined the terminus variation for 103 debris-free glaciers in the Bhutan Himalaya over a period of 30 years (from 1963 to 1993). Retreat rates (on the horizontal projection) as high as 26.6 m/year were reported for these glaciers.

A ground survey of the C-type, Jichu Dramo Glacier was conducted in the Bhutan Himalaya as part of fieldwork in 1998; the glacier was resurveyed in 1999 to assess the changes. Naito et al. (2000) recorded a 12m retreat (from 1998-1999) and estimate that the surface was lowered by 2–3m. The retreat rates for C-type glaciers in the Bhutan Himalaya were compared with retreat rates for some glaciers in Eastern Nepal. Karma et al. (2003) report that the retreat rates were higher for glaciers in the Bhutan Himalaya than for glaciers in Eastern Nepal; attributing the sensitivity of these glaciers to the intensity of the monsoon. Karma et al. (2003) studied 66 glaciers by comparing 1963 topographic maps with 1993 satellite images and found that the glaciers had retreated by 8 percent. The glacier area from the 1963 data was 146.87 sq.km and from the 1993 data only 134.94 sq.km a considerable decrease in 30 years. Smaller glaciers retreat at a higher rate than larger ones; some of the smaller glaciers.

Potentially dangerous glacial lakes in Bhutan Twenty-four (24) lakes were identified as potentially dangerous based on a set of criteria such as water level rise, the associated mother glacier, and the conditions of the dams and topographical features of the surroundings. Considering these criteria, five (5) lakes in the Mo Chu Sub-basin, eight (8) lakes in Pho Chu Sub-basin, seven (7) lakes in the Mangde Chu Sub-basin, three (3) lakes in the Chamkhar Chu Sub-basin and one (1) lake in the Kuri Chu Sub-basin were identified as potentially dangerous. Having said all these, none of the 31 glacier lakes that grace the Pa Chu Basin falls within the "potentially dangerous" category (NCHM 2019b).

2.5.3 Stream Flow

Figure 2.38 illustrates the average monthly discharge of Paro Bondey for the year 2014 to 2019. In Bhutan, dry season is considered from October to April whereas the wet season is considered from May to August. Paro Bondey Station recorded about 50 m^3/s of flow during the wet season with a maximum of 74.5 m^3/s while in the dry season, about 13.5 m^3/s of flow with a maximum of 28 m^3/s. In the month of July and August, Paro Bondey recorded the maximum discharge of 72-75 m^3/s.

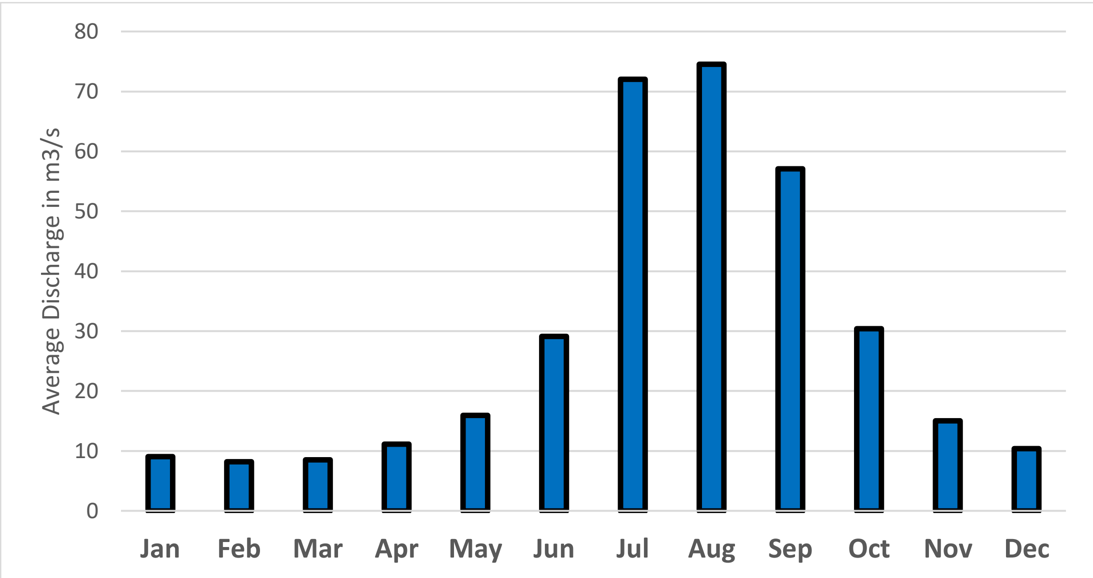


Figure 2.38: Average Monthly Discharge of Paro Bondey (2014-2019)

The Box and Whisker plot of the monthly flow distribution of Pa Chu is shown in **Figure 2.39**. The boxes are bound by the 25th and 75th percentiles of the datasets, while the heavy mid-line displays the median value. The graph indicates that streamflow is high from July to October as the streamflow is above the median level during these months. The maximum streamflow is observed from July to August which are above 120 cumec. During the month from November to February the dispersion of stream is small also the maximum and minimum stream flow lies close to where the whisker ends, whereas April to May shows that despite the smaller dispersion of stream values where the maximum value is far away from the whisker end. The month of May to June also indicates that the streamflow data is clustered about the median where the long tails represent a large dispersion of the relative outliers which includes the maximum and minimum streamflow.

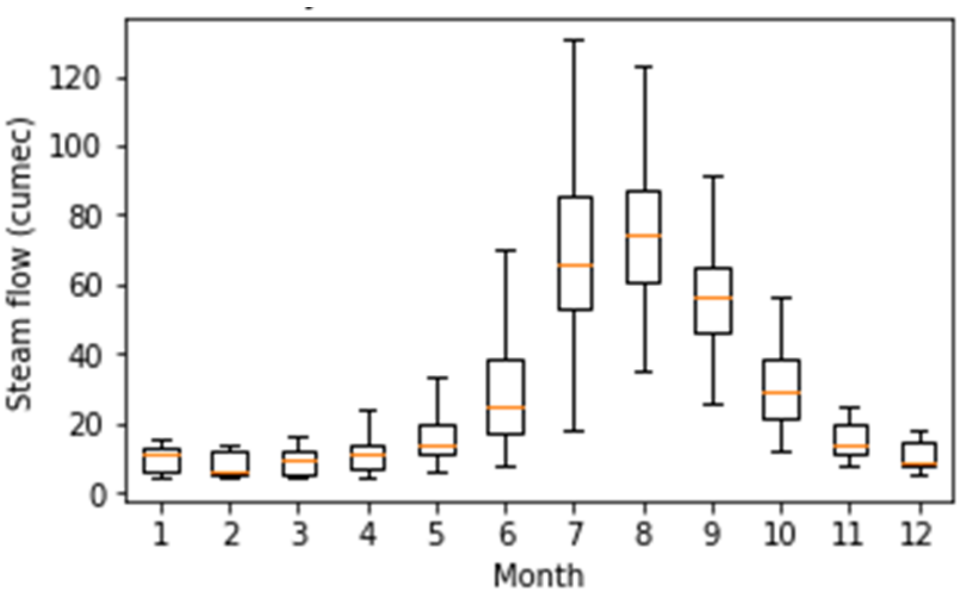


Figure 2.39: Variability of streamflow at Paro station (Bondey) during 2014-2019

The analysis of skewness forms this dataset represents that January, March, and April the median is shifted upward portion of the box shows negative skewness. These months indicate the rainfall dataset is approached closer to the median in the positive direction with a wider range of observations in the lower quartile as compared to the upper quartile. The month of March and April represents the positive skewness of the dataset. From May to October, the datasets mostly distributed symmetrically about the median.

2.6 Land Use

Eight major land-use types are found in this study area: 1) Agriculture, 2) Glacier/Snow, 3) Landslips, 4) Rock Outcrops, 5) Forest, 6) Plantations, 7) Settlements, and 8) Water Spreads. The total land-use area in Bhutan is 1,264 km^2. Paro Dzongkhag has an altitudinal range between 2000 m to 5600 m asl and has a temperate climatic condition with warm summer and cold and dry winter. The Dzongkhag lies in the temperate zone, where conifer species (23.61%) dominant forest type. The Broadleaf Forest, however, constitutes only about 0.12%. The Northern part of Dzongkhag falls under the Jigme Dorji National Park. Paro Valley is also considered as the country's most fertile agricultural land. The main agriculture land-use types are Chuzhing, Kamzhing, and horticulture. Rice, apple, wheat, potatoes, and other vegetables are grown as important crops.

Agricultural land and Horticulture account for 3.9% and 0.4% respectively. The Snow Cover constitutes 5. 5% and Rocky Outcrops 1.28% while water bodies cover 0.3% of the total land area. Landslides constitute 8% of the total land cover. **Table 2.10** shows the landcover and **Figure 2.40** illustrates the Land Use practices for the study area.

Table 2.10: Land cover of the study area

Category	Sub-category	Area (Sqkm)	Area (%)
Agriculture	Agriculture	49.4	3.9
	Horticulture	5.2	0.4
Forest	Blue pine	241.9	19.1
	Broadleaf	1.5	0.1
	Broadleaf with Conifer	14.2	1.1
	Fir	45.2	3.6
	Mixed Conifer	298.5	23.6
	Scrub forest	77.7	6.1
Glacier/Snow		69.7	5.5
Plantations		2.5	0.2
Landslips		101.3	8.0
Rock Outcrops		16.27	1.28
Marshy Areas		128.86	10.19
Meadows		207.24	16.39
Settlements		0.2	0.0
Water Spreads		4.3	0.3

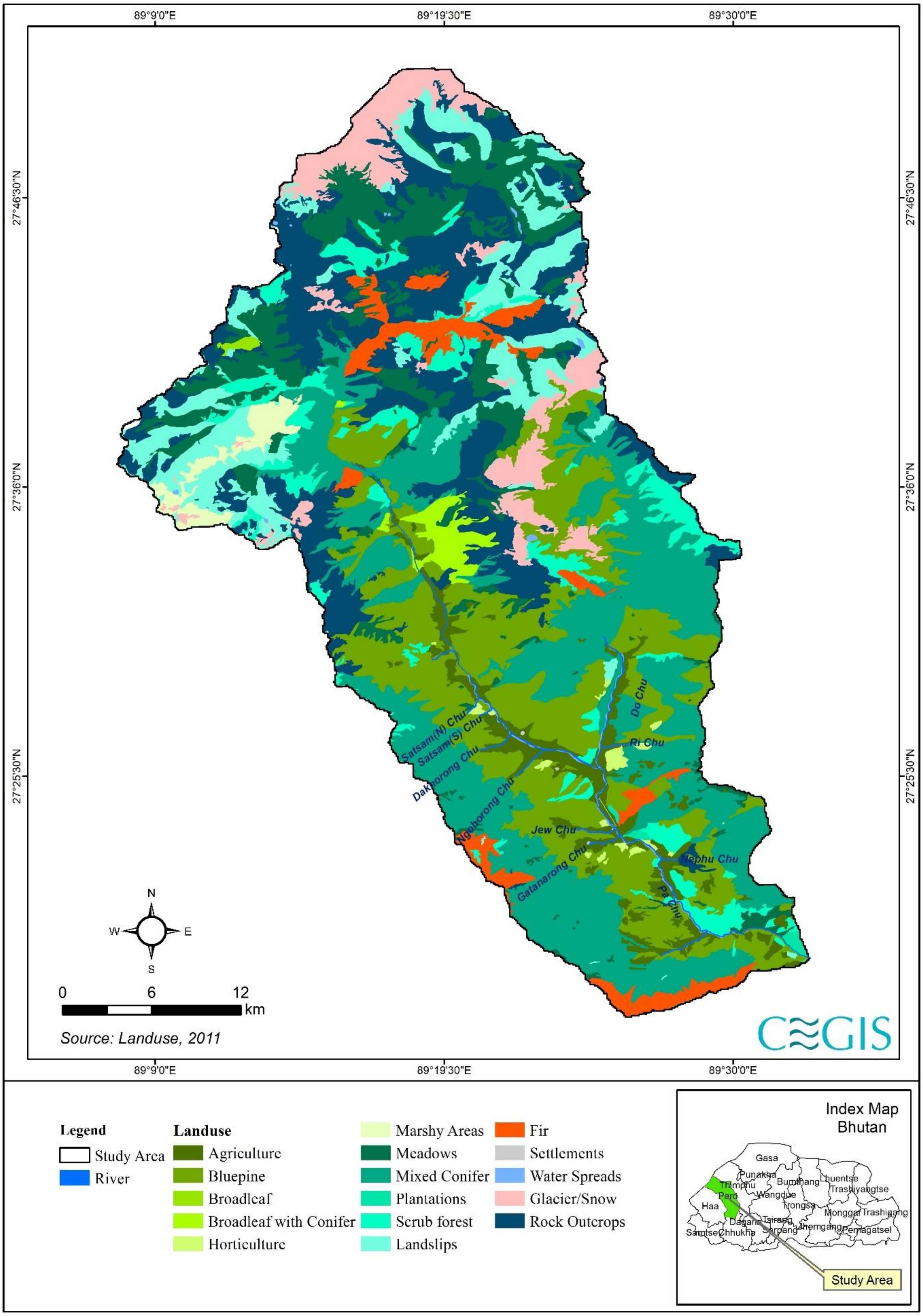


Figure 2.40: Land use practices in the study area

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 results in unfavorable conditions for undisturbed soil formation. Soil profiles of the study area resemble that 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 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 ration 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 a higher soil nutrient 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 years flood might be tomorrows 70 years flood because of climate change.

Flash floods are typically associated with short, high-intensity rainstorms. As such, they are characterized by short response time 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 mud slides, 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.

Figure 3.1: Typical Flash Flood at Bhutan

Figure 3.2: Typical Flash Flood at Wangchu tumbling down from the Lungtenzampa Bridge

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 monsoon. All these set up a perfect backdrop for water-induced disasters like flash flood. Against this backdrop, it is imperative to investigate the underlying causes of flood. 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 water-carrying 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 posses 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 Encroachments

Encroachment is a term that describe the advancement of structures, roads, railroads, improved paths, utilities, and other development, into natural areas including floodplains, river corridors, wetlands, lakes and ponds, and the buffers around these areas. The term encroachment also encompasses the placement of fill, the removal of vegetation, or an alteration of topography into such natural areas. These encroachments cause impacts to the functions and values of those natural areas, such as a decline in water quality, loss of habitat, disruption of equilibrium conditions, loss of flood attenuation, or reduction of ecological processes.

Constructed encroachments within river corridors and floodplains are vulnerable to flood damages. Placing structures in flood prone areas results in a loss of flood storage in flood plains and wetlands and heightens risks to public safety. Moreover, protection of these encroachments often result in the use of river channelization practices including bank armoring, berming, dredging, floodwalls, and channel straightening to protect these investments. The removal of vegetation to improve viewscapes or access, and the removal of woody debris from rivers to facilitate human use can increase resource degradation and the property's susceptibility to flood damages, causing higher risks to public safety. As described in the channel erosion stressor chapter, such practices result in greater channel instability, excessive erosion, and nutrient loading by concentrating flows and increasing stream velocities and power.

Encroachment increases impervious cover adjacent to lakes, rivers and wetlands, thereby increasing the rate and volume of runoff, loading of sediment and other pollutants, and temperature of the receiving water. The cumulative loss of wetlands that provide water quality protection to adjacent surface waters can result in ongoing reduction in water quality. The extent of encroachment, the cumulative effects of impervious cover, and the degree to which natural infiltration has been compromised can also contribute to the instability of the stream channel.

Encroachment in lake shorelands usually is comprised of residential development and associated vegetation removal; it can also include roads, parks and beaches and urban areas. Recent development patterns on lakeshores have seen replacement of small "camps" with larger houses suitable for year-round use. This new development generally is accompanied by substantial lot clearing, lakeshore bank armoring and an overall increase in lawn coverage and impervious surface. Research in Vermont and nationally has shown this land conversion and development results in degraded shallow water habitat and increased phosphorus and sediment runoff. Encroachments into the lake itself include docks, retaining walls, bridges, fill and dredging. The table below documents the effects of encroachment upon surface waters. Figure 4 and 5 illustrates the typical and schematic diagram of river encorachment.

Figure 3.3: Typical Encroachment at Nephu Chu

3.3 Scour Depth and Gabion Failure

Scouring can be judged as a process due to which the particles of the soil or rock around the amplitude of the pier of the highway bridge spanning over a water body, gets eroded and removed over a certain depth called scour depth. Scouring usually occurs when the velocity of the flowing water crosses the limited value that the soil particles can easily handle.

Scouring can be executed during the flood being passed through that water body. Scouring is initiated at the nose of the piers or at the sharp bends. Estimation of scour depth is very important for the design of foundation for pier. Scouring compromises the structural integrity and thus causes failure of the structure. It has been estimated that over 60 % of the highway bridges are being collapsed due to scouring.

When the discharge within the water body passes the allowed discharge, which is usually the case when flood is there, the scour is initiated, the scour depth can easily be obtained after the flood by finding the depth of the scour in reference with the surroundings or existing structures. If this is not possible the mean depth of scour may be easily obtained by a mathematical formula for natural streams in the alluvial depth

$$Y_{gs} = Y_{max} \left[(0.0685\ Vm^{0.8}) / (Yh^{0.4}\ Se^{0.3}) - 1\right]$$

Where,

Y_{gs} = general scour depth (ft),

Y_{max} is maximum depth of flow,

Vm is the average velocity of flow(ft/sec),

Yh is hydraulic depth of flow (ft) and

Se is the energy slop (ft)

From actual field measuring scour depth charts to estimate scour depth,This method is applicable only for coarser sands where the bed slope ranges from 0.004 ft to 0.008 ft. Other empirical methods are also there like Neil, Blench and Lacey for estimation of the scour depth

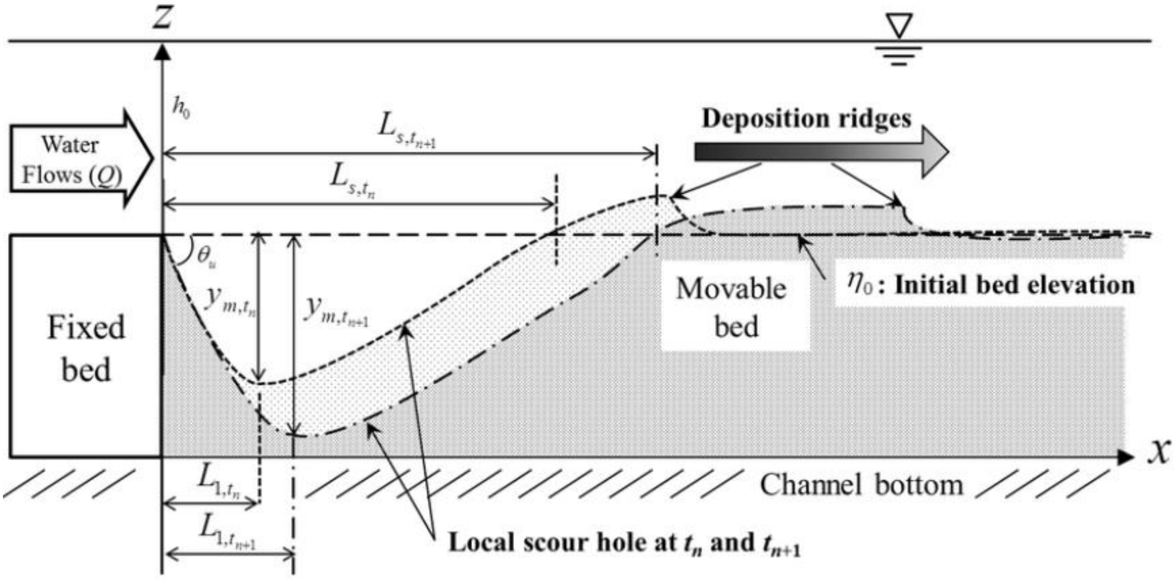


Figure 3.4: Schematic Diagram of Local Scouring

3.4 Problems and Issues for River/Streams within Study Region

Balaka Chu

Balaka Chu originated from relatively uphill terrain which outfalls at Pa Chu. Traverse steep slope has been observed before it discharges into Pa Chu. An old bridge with inadequate opening constricted the flow in the upstream. Monsoon water comes to the bridge level often. Substantial flow has been diverted via irrigation canals which can reduce flood risk. Vegetation around both the banks included forest trees and bushes need to be cleared. Boulders need to be removed from the flow path to increase conveyance capacity.

Figure 3.5: Balakha Chu

Jew Chu

The flow of Jew Chu is obstructed due to unplanned settlements, regular farming practices and heavy sediment depositions. Passage of flow has been constricted due to abutments and pipes with inadequate diameter. Clearing of boulders may provide some immediate solution for smooth flow passage. Roads need to be elevated in designated portion. Impact of erosion results in failure of right-bank gabion in the u/s and d/s of the structure. Streams seemed to be widened up substantially in the d/s. Clearing of dense vegetation and bushes need to be done. It is recommended to construct a box culvert with guide wall at designated portion. Furthermore, adequacy of channel section will be checked via hydro dynamic model simulations.

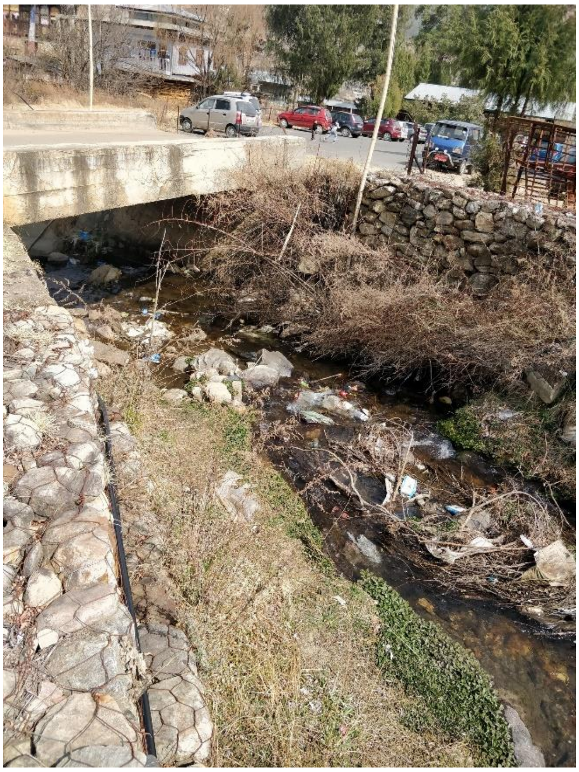


Figure 3.6: Jew Chu

Gatanarong Chu

Flow of Upstream portion of Gatanarong Chu is being constricted due to heavy siltation and random landslides. In some portion intentionally bed filling to accommodate vehicular and pedestrian crossing is observed which is highly recommended to be replaced by bridges or culverts. Box culvert is recommended at some places. An irrigation canal is observed at d/s portion which helps to reduce the vulnerabilities of flood. Some bridges with no railing has been observed and recommended to repair. Near d/s approximate 150 m to 200m of channel should be guided with retaining wall on both banks for protection against encroachment. Downstream portion is covered by dense bushes which are recommended to be cleared for reducing increased roughness co efficient.

Figure 3.7: Gatanarong Chu

Nephu Chu

The streams started with the combination of wild vegetation and settlements which causes severe narrowing of flow passage at the up streams. Steep slopes have been observed. Unplanned development in association with unsafe hill cuts for construction works causing imminent landslide risks. Encroachment along d/s right-bank from unplanned settlements severely constricting flow passage which is recommended o demolish to increase the conveyance capacity. Stream is observed narrowed in d/s, which is incapable of conveying design discharge. Debris near outfall where stream traverses highway bridge need to be cleared.

Figure 3.8: Nephu Chu

Satsam (North) Chu

Upstream of Satsam (North) Chu is being generated debris from temporary stone grinding site which causes siltation of stream bed and banks. This portion is crisscrossed across road where flow is accommodated via pipe culverts. Cross drainage structures reduced the cross section of streams which results in constricted flow passage. Some construction site obstructed the flow via filling up bed for vehicle passage which is recommended to be re-sectioned. A local resort block entirely of flow passage via illegal expansion of property is recommended to demolish immediately. Dense bushes in d/s are recommended to be cleared. Narrow highway culvert at out fall is recommended to be widened.

Figure 3.9: Satsam (North) Chu

Satsam (South) Chu

Upstream portion were inaccessible due to dense vegetation and forest and is becoming narrow as it traverses across hill-side road through a narrow culvert, restricting flow passage near which bed is at road level. Culvert with adequate capacity is recommended here. Unplanned waste disposal observed which obstructs the flow passage. A septic tank in very close quarters along the left bank is observed which is recommended to be removed. Regular cleaning of bushes are required for ensuring the flow in d/s. Heavy downpour cause severe flooding at the d/s most portion due to narrow flow passage. In the d/s portion a highway culvert is recommended to be widened up.

Figure 3.10: Satsam (South) Chu

Dakhorong Chu

In the upstream portion dense bushes along both banks are recommended to be cleared immediately. Clearing of boulders is also recommended to increase conveyance capacity of the streams. Further towards downstream three-piped culvert layout with adequate opening but unnecessarily wide spacing has been observed. Clearing of shrubs and cleaning of dumped waste near stream mid-section is recommended. Mid portion of this streams is narrowed due to encroachment and settlement. In some portion cross drainage structures are recommended. Downstream portion is protected and stream passes through highway culvert which might have to be raised to maintain adequate flow section. Overall the channel sections seemed wide enough in the u/s and d/s portions with some substantial narrowing in the middle portion.

Figure 3.11: Dakhorong Chu

Ngoborong Chu

Substantial portion of u/s is protected along both banks due to settlements but section adequacy checking may be required. Excessive siltation from bank erosion and unplanned rural settlement make the mid portion of the channel narrowed. Some key locations are being obstructed by large boulders which affects smooth conveyance capacity. Dense bushes cleared and narrow culverts re-sectioned to increase conveyance. Though downstream portion of this stream is guided and regulated some unregulated land filling in downstream may be severely obstructed the flow which is recommended to be cleared immediately. A two-piped culvert blockage in d/s side causing flow obstruction at outfall and have to be cleared. D/s portion of outfall blocked as water seepages through geobags and slowly discharges into the Pa Chu.

Figure 3.12: Ngoborong Chu

Ri Chu

Upstream portion inaccessible due to dense forests. Rich dam, which was constructed for irrigation water diversion is silted up and almost non-functional. The depth of reservoir is insufficient so a deeper reservoir is recommended which would allow more storage as well as give incentive for fisheries practices. Siltation and unplanned settlement make stream section significantly narrower in d/s portion, which may need re sectioning furthermore the discharge point to Do Chu is wide but proper connection has to be established via re-sectioning of the u/s segments.

Figure 3.13: Ri Chu

Pa Chu

The bank protection structures and assessed the necessity of further protective measures that might be required along designated stretches. At some portion will be recommended for the necessary excavation works. The flowing nature and existing bed conditions will guide to suggest necessary excavation and re-sectioning works that might be required at certain portions.

Figure 3.14: Pa Chu

4. Flood Hazard Assessment

4.1 Hydrological Analyses

Hydrological processes such as floods are complex natural events. Therefore, it is difficult to model the hydrological process analytically. Furthermore, planning and design with flooding and drainage issues require the selection of extreme events. Hence, frequency analysis of rainfall and streamflow data was carried out to address above mentioned reasons, which will facilitate flood management and design for the drainage system.

4.2 Frequency Analysis of Rainfall Data

Frequency analysis of rainfall data was carried out using the time series rainfall data of Paro DSC Station. Available time-series data from 1996 to 2019 was used for this study. Successive rainfall analysis data was carried out using 1-day, 2-day, 3-day, 4-day, and 5-day consecutive annual maximum rainfall data from 1996 to 2019. The storm event for different return periods (2, 10, 25, 50, and 100 years) was found out applying Log-Normal Distribution.

Table 4.1: Annual Successive Rainfall Analysis (in mm) for the ParoDSC Station

Year	1-day	2-days	3-days	4-days	5-days
1996	34.0	34.0	34.7	37.4	41.9
1997	66.0	73.4	83.4	93.0	109.6
1998	43.0	54.0	55.5	59.1	63.6
1999	64.6	84.1	102.6	118.6	134.6
2000	34.5	52.2	54.7	80.2	81.3
2001	23.5	46.0	52.2	56.2	56.2
2002	16.8	22.4	27.6	33.2	36.2
2003	29.4	43.0	59.0	60.0	60.0
2004	43.4	56.5	56.5	56.5	56.5
2005	50.9	75.1	97.1	109.1	110.3
2006	27.2	35.0	40.0	43.0	49.7
2007	38.8	57.4	65.4	72.6	78.0
2008	36.0	43.0	48.2	61.6	72.2
2009	107.4	122.4	136.0	137.2	137.8
2010	41.0	75.0	76.4	78.8	83.4
2011	35.0	35.0	57.6	61.4	61.4
2012	44.2	58.8	64.0	68.6	70.6
2013	40.6	51.6	71.4	71.4	71.4
2014	65.6	84.2	94.0	94.0	94.0
2015	34.8	52.2	54.4	56.3	65.5
2016	46.2	68.2	83.2	87.6	92.0
2017	37.2	39.0	40.0	40.0	41.8
2018	16.6	22.6	29.4	31.0	39.0
2019	20.6	25.6	36.0	38.2	44.6

Analysis of successive annual maximum (**Table $.1**) rainfall represents the highest amount of rainfall during 2009 due to the effect of Cyclone Aila. For a 1-day rainfall event, maximum rainfall was estimated at 107.4 mm in 2009, which is highest among all other years. In 2009, 2-day, 3-day, 4-day, and 5-day consecutive maximum rainfall were estimated as 122.4, 136.0, 137.2, and 137.8 mm, respectively.

Frequency analysis for 2, 10, 25, 50, and 100 year return period was carried out taking 1-day, 2-day, 3-day, 4-day, and 5-day consecutive maximum annual rainfall and shown in **Table 4.2**. The result of 1-day, 2-day, 3-day, 4-day, and 5-day consecutive rainfall was 65.3 mm, 85.9 mm, 97.4 mm, 105.1 mm, and 109.4 mm, respectively for a 10 year return period. Similarly, for 1 in 100 year return period 1-day, 2-day, 3-day, 4-day, and 5-day consecutive rainfall were 101.8 mm, 133.1 mm, 147.5 mm, 158.5 mm, and 160.9 mm, respectively.

Table 4.2: Storm Event for Different Return Periods (Year) for the Paro DSC Station

Return Period	Successive Rainfall (mm)				
	1 day	2 Day	3 Day	4 day	5 day
2	37.9	50.1	58.5	63.5	68.1
10	65.3	85.9	97.4	105.1	109.4
25	79.8	104.5	117.4	126.4	130.1
50	90.7	118.7	132.4	142.4	145.6
100	101.8	133.1	147.5	158.5	160.9

4.3 Flood Frequency Analysis

Pa Chu is the dominating rivers in this study area which are flashy by nature. Flood frequency analysis was conducted with respect to the maximum annual river flow. The annual maximum discharge was calculated for the time period of 1989-2019. The discharge measurement station at Bondey was used for flood frequency analysis. Frequency analysis was conducted using the Log Pearson III method and analysis results are given in **Table 4.3**. The difference in water level in different return periods is significant for making the decision. It would help flood protection designers for considering 20 or 50 years return period flood. For a 2 year return period, the estimated flood discharge was 158 m^3/s while it was 330 m^3/s for 100 year return period. The flood event resulted from Aila 2009 was estimated as a 25 year return period flood (**Table 4.4**).

Table 4.3: Frequency analysis annual maximum discharge of Bondey Station, Pa Chu

Si. No.	Return period T (yr)	Probability P (percent)	Frequency factor K	y = log (Q)	Flood discharge Q (m^3/s)
1	2	50	0.063	2.2	158
2	5	20	0.855	2.327	213
3	10	10	1.233	2.389	245
4	25	4	1.612	2.45	282
5	50	2	1.843	2.487	307
6	100	1	2.042	2.519	330
7	200	0.5	2.217	2.547	353

Table 4.4: Comparison of maximum water level with matching return period value at Bondey

Year	Max Discharge (m3/s)	Return period (year)	Year	Max Discharge (m3/s)	Return period (year)
1989	153	2	2004	139	< 2
1990	142	< 2	2005	187	~ 3
1991	329	100	2006	139	< 2
1992	189	~ 3	2007	190	~ 3
1993	147	2	2008	149	2
1994	82	< 2	2009	282	25
1995	70	< 2	2010	236	10
1996	64	< 2	2011	281	25
1997	112	< 2	2014	168	~ 3
1998	136	< 2	2015	131	< 2
1999	202	5	2016	206	5
2000	139	< 2	2017	140	< 2
2001	175	~ 3	2018	127	< 2
2002	170	~ 3	2019	132	< 2
2003	165	2			

4.4 Climate Change Scenario Generation

Future climate change impact on stormwater may be exacerbated the flooding and drainage problems with increased frequency of short duration but intensive rainfall and flood events. Understanding the future climate change seasonal anomalies is thus essential to anticipate potential impact of climate change on Paro Basin. This chapter focuses on future climate change scenarios of Paro Basin in particular, through analysis of downscaled climate data. Efforts have been made to keep data sources as same as the datasets of national level projections made by the National Center for Hydrology and Meteorology (NCHM).

4.4.1 National Level Projections

Bhutan being a climate vulnerable country is well aware of the future climate change scenarios for the country as a whole. National Center for Hydrology and Meteorology (NCHM) conducted a study to analyze the historical climate and future climate change projections for Bhutan. NHCM (2019) considered generated national level projections analyzing downscaled climate data of 6 ensemble GCM members under the CMIP5 experiments. As per the analysis, following noteworthy national level projections have been made for Bhutan, albeit the projections outcome may contain large range of uncertainties due to presence of biases among datasets of GCM:

Temperature

- The overall climate projection for surface temperature under the RCP4.5 scenario indicated an increase in about of 0.8°C -2.8°C during 2021-2100 and under the RCP8.5 scenario, the climate projection for surface temperature indicated an increase of about 0.8°C -2°C during 2021-2050 and increase of about 3.2°C towards the end of the century (2070-2099).

- The whole country is expected to experience an increase in temperature with a larger increase projected in the high lands along with larger warming during MAM and DJF seasons.

Rainfall

- Under the RCP4.5 scenarios, the annual rainfall over Bhutan indicates an increase of about 10%-30% in summer (JJAS) rainfall between 5%-15%. While the increase in rainfall is likely in DJF in Bhutan, some parts of the Northern and Northern west are likely to experience a decrease in rainfall. Bhutan is likely to experience an increasing trends in rainfall during 2021-2050 and will also experience a marginal decrease in rainfall at the end of the century (2070-2099).
- Under the RCP8.5 scenario, the mean annual rainfall indicates an increase of about 10%-20% during 2021-2050 and with more than 30% increase all over Bhutan towards the end of the century. The projections also suggest increasing rainfall during the JJAS while the winter (DJF) seasons are likely to receive a decrease in rainfall in some parts of the country, in particular in Northwestern region of Bhutan. Overall a marginal increase in rainfall trend is indicated under the RCP8.5 scenarios.

4.4.2 Bias Correction of Downscaled Ensembles of GCM

Downscaling exercise based on only one single GCM may inform less confidence on the generated future projections range due to uncertainties and lack of auditability of the selected GCM assessment in the Paro Basin. In addition, NCHM (2019) only generated national level projections, which are generalized and may not represent the actual local climatic condition of the Paro Basin. Therefore, bias correction of ensemble mean of downscaled GCM output has been carried out to get the local level future climate change anomalies to make the output consistent with the national level projections.

Downscaled Data of Ensembles Mean: NASA NEX-GDPP

Ensemble mean data has been collected from NCHM and processed in NetCDF format suing statistical tool R x64 3.6.3[1], while actual data source is the NASA NEX-GDPP[2]. The NASA (National Aeronautics and Space Administration) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Inter-comparison Project Phase 5 (CMIP5). The NEXGDDP dataset includes downscaled projections for RCP 4.5 and RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. Each of the climate projection includes daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 through 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km x 25 km).

Bias correction has been performed for maximum temperature, minimum temperature and rainfall data taking ensemble mean of spatially downscaled 6 GCMs data. The selected 6 GCMs are ACCESS1-0, CNRM-CM5, IPSL-CM5A-LR, MIROC5, MPI-ESM-MR and MRI-CGCM3 keeping similarities with NCHM

[1] https://www.r-project.org/

[2] https://www.nccs.nasa.gov/services/data_portal

(2019)3 national level climate change projections. In contrast, the historical climate datasets of Paro DSC and Drukgyel Stations have been used to establish the correlation and estimate the correction factor to adjust biases.

Bias Correction using Quantile Mapping

For the bias correction, R language-based climate4R[4] open framework has been utilized (Iturbide et al., 2019). In this R-package, there are three types of quantile mapping methods to do the bias correction i.e. empirical quantile mapping (eqm), detrended quantile matching (dqm) and quantile delta mapping (qdm). All these three methods have some pros and cons. Therefore, initially sensitivity of these three bias correction methods have been checked using the historical rainfall and temperature data of Paro DSC Station and found empirical quantile mapping (eqm) and quantile delta mapping (qdm) methods produce best among three and almost similar level of bias corrected data. Finally, quantile delta mapping (qdm) method has been selected for performing bias correction of climate data from Paro DSC Station by comparing the number of non-rainy days and peak rainfall matching capabilities.

Quantile delta mapping (qdm) (Cannon et al. 2015) consists of following steps: (i) detrending the individual quantiles; (ii) QM is applied to the detrended series; (iii) the projected trends are then reapplied to the bias-adjusted quantiles. It explicitly preserves the change signal in all quantiles. It allows relative (multiplicative) and additive corrections. In the case of precipitation, a frequency adaptation has been implemented in all versions of quantile mapping to alleviate the problems arising when the dry day frequency in the raw model output is larger than in the observations (Wilcke et al. 2013).

Figure 4.1 and **Figure 4.2** show annual scale bias correction performance using the QDM method for rainfall and maximum temperature respectively for Paro DSC Station.

Table 4.5: Performance of bias correction using Climate 4R and QDM in Paro DSC

Climate Variable	Before Bias Correction		After Bias Correction	
	Rho*	bias	Rho*	bias
MaxT	0.84	-0.34	0.84	0
MinT	0.92	-0.86	0.92	0
Rain	0.48	1.32	0.45	0

*Rho = Spearmen's correlation coefficient is a statistical measure of the strength of a monotonic relationship between paired data. Its interpretation is similar to that of Pearsons, e.g. the closer is to the (+/-) 1 stronger the monotonic relationship.

[3] NCHM (2019), Analysis of Historical Climate and Climate Projection for Bhutan, National Center for Hydrology and Meteorology, Royal Government of Bhutan.

[4] https://github.com/SantanderMetGroup/climate4R

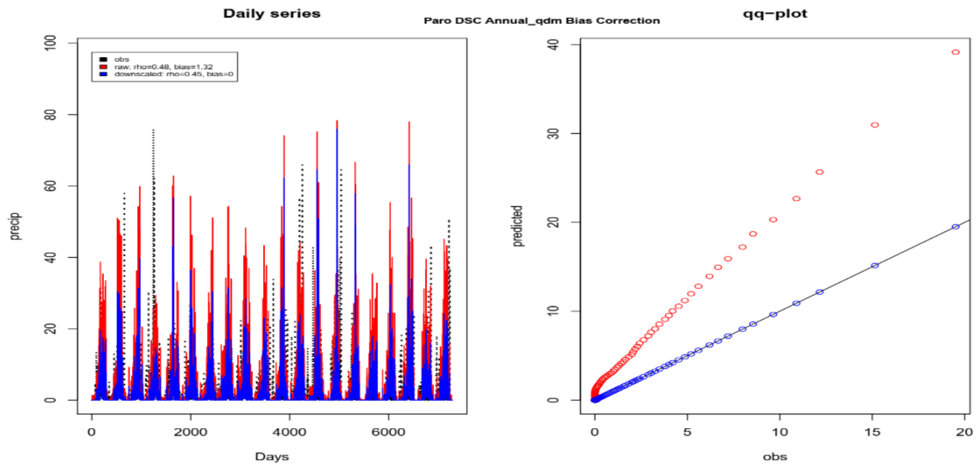


Figure 4.1: Bias correction performance of QDM using Climate4R for rainfall of Paro DSC Station (1986-2005)

Later, bias correction has been carried out for same three time slices as SDSM projections i.e. 2030s (2021-2040), 2050s (2041-2060) and 2080s (2071-2090) considering RCP4.5 and RCP8.5 to generate future climate change anomaly information.

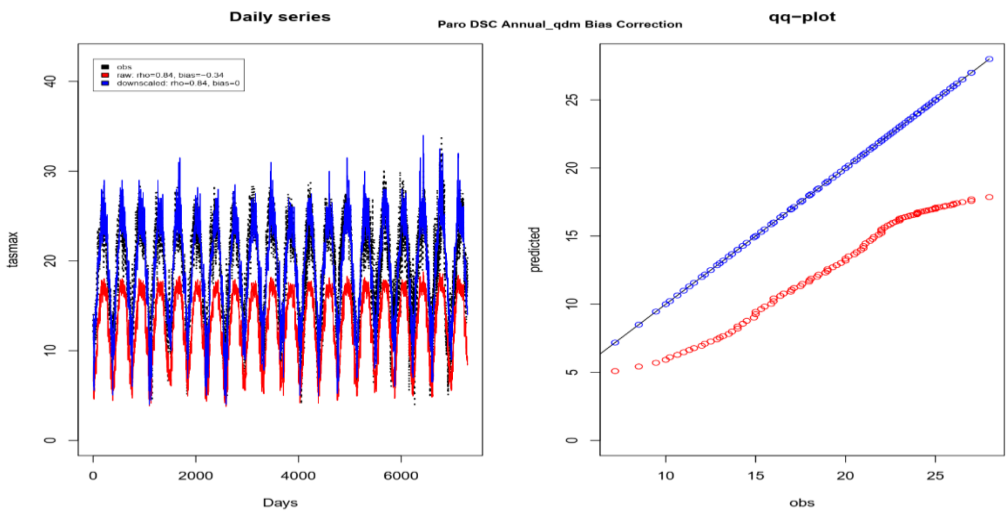


Figure 4.2: Bias correction performance of QDM using Climate4R for maximum temperature of Paro DSC station (1986-2005)

4.4.3 Future Climate Change Anomalies

Future climate change anomalies have been determined comparing the future projections with the present climate scenario. In nutshell, comparing both analyses, its output and uncertainties following could be concluded as the climate change anomalies of Paro Basin considering future climate change scenarios:

- Monsoon rainfall may change up to 25%-45% under RCP 4.5 and 30%-405% under RCP8.5 by 2050s with respect to present climate.
- Dry season may become dryer as per future anomalies information.
- Highest maximum temperature may increase up to 3.0°-3.3° by 2050s and highest minimum temperature may increase up to 3.1°-3.5° by 2050s considering both RCPs.

- High rate of increment in minimum temperature than maximum temperature indicates gradual potential warming of the basin.

Following table illustrate key future climate change anomalies information of both Paro DSC and Drukgyel Stations.

Table 4.6: Future climate change anomalies for rainfall in Paro Basin

Station	Season	Base in mm	Percentage Change in Rainfall					
			RCP4.5			RCP8.5		
			2030s	2050s	2080s	2030s	2050s	2080s
Paro DSC	DJF	31	-92	-95	-91	-91	-93	-93
	MAM	137	-2	11	46	1	29	90
	JJAS	508	28	47	55	35	46	53
	ON	53	-21	-31	-38	-37	-34	-40
Drukgyel	DJF	20	-87	-92	-87	-85	-88	-90
	MAM	148	14	32	82	18	59	144
	JJAS	746	22	45	52	30	43	50
	ON	70	-93	-34	-42	-41	-41	-43

Table 4.7: Future climate change anomalies for temperature in Paro DSC Station

Variable	Season	Base	Change in Degree Celsius					
			RCP4.5			RCP8.5		
			2030s	2050s	2080s	2030s	2050s	2080s
MaxT	DJF	13.0	-0.1	2.2	1.0	-0.5	1.6	4.3
	MAM	20.3	-0.2	1.8	1.0	-0.3	1.3	3.5
	JJAS	24.0	0.6	2.9	1.7	0.5	1.8	4.5
	ON	17.9	1.7	3.0	2.5	1.9	2.9	4.8
MinT	DJF	1.8	0.3	1.4	2.4	0.5	2.1	4.3
	MAM	8.7	2.0	3.1	3.9	2.1	3.5	5.5
	JJAS	17.5	0.6	1.5	2.3	0.6	1.6	3.9
	ON	8.6	-0.2	0.3	0.6	0.2	0.9	2.2

Table 4.8: Future climate change anomalies for temperature in Drukgyel Station

Variable	Season	Base	Change in Degree Celsius			Change in Degree Celsius		
			RCP4.5			RCP4.5		
			2030s	2030s	2030s	2030s	2030s	2030s
MaxT	DJF	12.8	-0.4	2.1	-0.9	0.8	1.5	4.2
	MAM	20.1	-0.3	1.7	-0.4	0.9	1.2	3.4
	JJAS	23.6	0.6	2.9	0.6	1.8	1.9	4.6
	ON	17.3	2.0	3.3	2.2	2.7	3.2	5.2
MinT	DJF	-1.5	0.2	1.4	2.7	0.1	2.0	4.7
	MAM	5.6	1.9	2.9	3.7	2.0	3.3	5.1
	JJAS	13.3	0.6	1.4	2.3	0.8	1.6	3.8
	ON	5.2	0.1	0.6	0.8	0.5	1.2	2.4

4.5 Development of Hydrological Model

Two hydrological models are available for the Paro River Basin developed using IFAS (Integrated Flood Analysis System) and SWAT (Soil and Water Assessment Tool) modeling tools which were developed by the Flood Engineering Management Division (FEMD), Bhutan. For any flood management project planning and design, the accuracy, reliability, and robustness of the hydrological model are very crucial as it estimates the discharge which is the prime requirement for the design of any flood protection or management structure. Efforts were put forth to understanding the tools and techniques used for model development. The schematization, boundary condition, data used for model setup were thoroughly reviewed for a better understanding of the assumptions and limitations of the developed model. Based on extensive dissection, the following shortcomings of the hydrological models were observed –

- The orographic effect of rainfall was not considered during model development which is very important for mountainous terrain like Paro Valley;
- All the streams were not captured during the delineation of catchment and stream network for both IFAS and SWAT Model;
- The models were calibrated for only one hydrological year. Thus, the robustness of the model is questionable;
- No validation of the models was performed considering new data set which is a primary requirement for any model development;
- The performance of the models was poor (NSE was 0.37 and 0.52) considering statistical evaluation criteria; and
- Sensitivity and uncertainty analyses of the model were not performed.

Considering the shortcomings of the models and importance of the study, it was needed to set up a reliable and robust hydrological model that could simulate the physical process of the catchment. Thus, a new hydrological model was developed utilizing available locally and globally data and information using SWAT. SWAT is a physically-based, semi-distributed, continuous time step model used for simulated watershed hydrology. The following sections discuss the model schematization, simulation, calibration, and validation of the model.

4.5.1 Data Availability and Data Sources

Various types of data are required to develop a SWAT model. These data are collected from different sources. The main input data were a Digital Elevation Model (DEM), land use/cover data, soil type data, weather data (maximum and minimum temperature, rainfall, relative humidity, evapotranspiration, wind speed, solar radiation), and discharge data for calibration. From the DEM slope gradient, the slope length of the terrain and the stream network characteristics such as channel slope, length, and width were derived. Some parameters such as infiltration, root depth, and Manning's coefficient were derived from the land use map. Data on textural and physicochemical properties such as soil texture, available water content, hydraulic conductivity, bulk density, and organic carbon content for different layers of each soil type were required for setting up the SWAT model. Meteorological data can either be read from a measured data set or be generated by a weather generator model. There are many parameters for calibrating the model such as discharge, evapotranspiration, soil moisture condition, leaf area index, etc. As it is a water balance model, only discharge data were used for model calibration and validation. The input data and the sources required for the SWAT model are given in **Table 4.9**.

Table 4.9: Summary of data used for hydrological model development

Si. No.	Data Type	Specification	Data Source
1	DEM	30 m resolution	SRTM
2	Landuse	Year 2011 data	MoAF, Bhutan
3	Soil	1 : 5,000,000 scale	FAO Global soil
4	Daily rainfall	Observe station and TRMM	NCHM and TRMM
5	Daily temperature	Observe station	NCHM
6	Discharge	Daily data for 2014 - 2019	NCHM

4.5.2 Model Schematization

Five sequential steps were followed to set up the SWAT Model, which are watershed delineation, HRU definition, weather data definition, edit SWAT inputs, and simulation. The descriptions of these steps are given in the following sections.

Watershed Delineation

The first step in the model setup involves a delineation of the basin and sub-basin boundaries. This is accomplished using the automatic watershed delineation tool of SWAT 2012 employing a 30 m resolution DEM. The Drukref 03 TM was used for the DEM and all other GIS layers. All the watershed delineation steps such as filling the sink, defining flow direction, and accumulation was done automatically through the user interface. After delineation, the basin has been divided into 43 watersheds based on the threshold area of 1,000 ha (**Figure 4.3**). The threshold area defines the minimum area for River initiation. Special emphasis was given to capture all of the eight streams increasing the number of sub-basin in order to increase the computational efficiency of the model. The average area of the delineated sub-basin is around 3000 ha. The summary statistics of the sub-basin are given in **Table 4.10**.

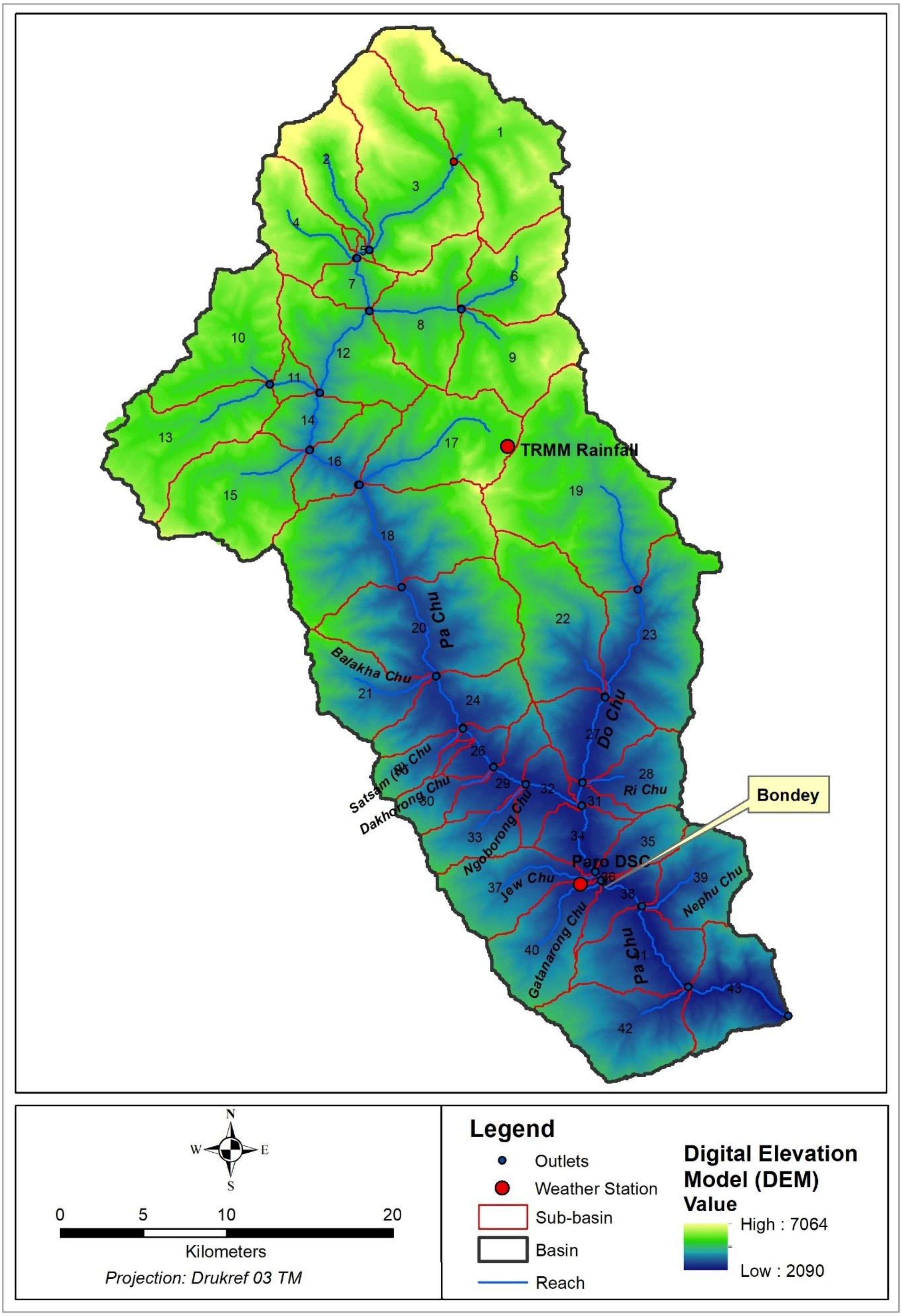


Figure 4.3: Delineated sub-basin along with weather station and calibration location

Table 4.10: Area and elevation of the delineated sub-basins for the Paro River Basin

Sub-basin	Area [ha]	Avg Elev [msl]	Min Elev [msl]	Max Elev [msl]	Remarks
1	6688	4867	4076	6848	
2	2653	4900	3796	6489	
3	6514	4757	3794	7057	
4	2647	4728	3745	5771	
5	99	3981	3745	4535	
6	2988	4675	3772	5656	
7	1141	4194	3554	5100	
8	3374	4300	3555	5233	
9	3409	4609	3771	5573	
10	4132	4503	3756	5122	
11	538	3949	3159	4694	
12	3862	4116	3166	4938	
13	4173	4435	3754	5339	
14	1343	3707	2969	4834	
15	4384	4386	2974	5557	
16	2003	3586	2802	4465	
17	4203	4191	2809	5553	
18	7267	3664	2602	5513	
19	8676	4153	2786	5575	
20	6016	3305	2441	4744	
21	2645	3428	2443	4622	Balakha Chu
22	4429	3635	2345	5070	
23	5273	3284	2343	4793	
24	2754	2987	2367	4097	
25	1048	3226	2367	4158	Satsam (N) Chu
26	1002	2566	2329	3249	Satsam (S) Chu
27	2469	2659	2271	3789	
28	1863	2991	2271	3748	Ri Chu
29	1488	2719	2299	3780	
30	959	3172	2330	3917	Dakhorog Chu
31	404	2578	2255	3272	
32	1277	2535	2254	3178	
33	1587	3113	2299	4062	Ngoborong Chu
34	1476	2487	2220	3139	
35	1331	2929	2217	3742	
36	25	2292	2218	2472	
37	2798	3135	2221	4109	Jew Chu

Sub-basin	Area [ha]	Avg Elev [msl]	Min Elev [msl]	Max Elev [msl]	Remarks
38	1156	2547	2195	3434	
39	2635	3042	2196	3813	Nephu Chu
40	2959	3094	2217	3986	Gatanarong Chu
41	2971	2657	2162	3605	
42	3663	3133	2163	4022	
43	3150	2756	2090	3701	

Hydrological Response Unit (HRU)

The overlay of land use, soil layer, and slope class defines the HRUs. The discretization of the basin into HRUs allows a detailed simulation of the hydrological processes. HRU is the smallest unit for hydrological simulation with a unique combination of soil, land use, and slope. During HRUs definition, the land use, soil, and slope are overlaid to determine the areas of their unique combination within each watershed (**Figure 4.4**). For this study area, the topography has been divided into three slope classes using the mean value and standard deviation (mean + half of SD and mean - half of SD as the break of slope classes). The combination of 11 land-use type, 2 soil classes, and 3 slope classes for the Paro Basin finally resulted in 600 HRUs.

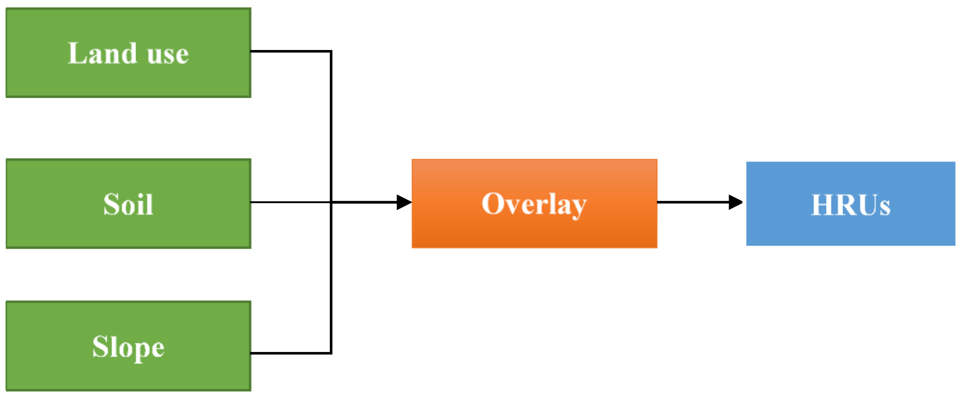


Figure 4.4: Schematic diagram of HRUs definition

Weather Data Definition

The climatic variables required for SWAT are the daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity and which are obtained from existing weather stations. In the case of missing data, SWAT has a build-in weather generator to generate missing data (WXGEN, Neitsch, et al., 2005).

Daily rainfall, maximum and minimum temperature data are available for the three weather stations inside the Paro Basin. The weather stations are mainly located at the Southern (downstream) part of the basin area. After a thorough analysis of data consistency, availability, and data gape, it was found that the Paro DSC Station has more consistent and longer time period data (1996 to 2019). Thus, the daily rainfall and maximum and minimum temperature data were used during model schematization. As mentioned earlier, the Paro DSC Station is located at the downstream portion of the basin which only represents the rainfall and temperature characteristics of the downstream part. In this regard, Tropical Rainfall Measuring Mission (TRMM) data was used for the upper part of the catchment. TRMM is a satellite-based rainfall measurement for the tropical and sub-tropical regions. Daily and sub-daily data are available with a special resolution of 0.250 for the time period of 1998 - present. Daily and 3-hourly rainfall data were collected from available global sources (https://giovanni.gsfc.nasa.gov/giovanni/). The data was checked and necessary modification was made through correlation with the observed rainfall data of ParoDSC Station. Finally, the daily rainfall from TRMM and Paro DSC Station was used during model development for the upstream and downstream parts of the basin, respectively as shown in **Figure 8.1** for the period of 1998 – 2019.

Regarding the temperature data, the daily maximum and minimum temperature of the Paro DSC Station were used and it was adjusted using the temperature lapse rate for each sub-basin during the model simulation.

Input Modification

Orographic precipitation is a significant phenomenon in the Paro Basin Area. To account for orographic effects on both precipitation and temperature, 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. The precipitation and temperature 'lapse rates' were used to adjust precipitation and temperature for elevation bands in the sub-basin, respectively. To adjust the precipitation and temperature, 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 Paro River Basin including the fraction of the sub-basin area within the elevation bands are given in **Table 4.11**.

Table 4.11: Delineated elevation bands and the fraction of sub-basin

Sub-basin	Area [sq.km]	Elevation at the center of the band (MSL)			Fraction of sub-basin		
		Band 1	Band 2	Band 3	Band 1	Band 2	Band 3
1	66.88	4538	5462	6386	0.75	0.23	0.02
2	26.53	4245	5143	6040	0.39	0.5	0.11
3	65.14	4338	5426	6513	0.68	0.29	0.03
4	26.47	4083	4758	5433	0.16	0.74	0.1
5	0.99	-	-	-	-	-	-
6	29.88	4086	4714	5342	0.25	0.56	0.19
7	11.41	3812	4327	4842	0.36	0.5	0.14
8	33.74	3835	4394	4953	0.31	0.45	0.24
9	34.09	4071	4672	5273	0.21	0.68	0.11
10	41.32	3984	4439	4894	0.1	0.62	0.28
11	5.38	3415	3927	4438	0.21	0.53	0.26
12	38.62	3461	4052	4643	0.21	0.51	0.28
13	41.73	4018	4547	5075	0.25	0.7	0.05
14	13.43	3280	3902	4523	0.43	0.43	0.14
15	43.84	3405	4266	5127	0.07	0.77	0.16
16	20.03	3079	3634	4188	0.35	0.38	0.27
17	42.03	3266	4181	5096	0.16	0.73	0.11
18	72.67	3087	4058	5028	0.49	0.42	0.09
19	86.76	3251	4181	5110	0.16	0.73	0.11

Sub-basin	Area [sq.km]	Elevation at the center of the band (MSL)			Fraction of sub-basin		
		Band 1	Band 2	Band 3	Band 1	Band 2	Band 3
20	60.16	2825	3593	4360	0.48	0.37	0.15
21	26.45	2806	3533	4259	0.31	0.52	0.17
22	44.29	2799	3708	4616	0.28	0.51	0.21
23	52.73	2751	3568	4385	0.45	0.44	0.11
24	27.54	2655	3232	3809	0.52	0.33	0.15
25	10.48	2666	3263	3860	0.31	0.42	0.27
26	10.02	2482	2789	3096	0.68	0.26	0.06
27	24.69	2524	3030	3536	0.67	0.3	0.03
28	18.63	2517	3010	3502	0.28	0.46	0.26
29	14.88	2546	3040	3533	0.62	0.32	0.06
30	9.59	2595	3124	3653	0.24	0.45	0.31
31	4.04	2425	2764	3103	0.58	0.28	0.14
32	12.77	2408	2716	3024	0.61	0.27	0.12
33	15.87	2593	3181	3768	0.31	0.51	0.18
34	14.76	2373	2680	2986	0.63	0.27	0.1
35	13.31	2471	2980	3488	0.31	0.46	0.23
36	0.25	-	-	-	-	-	-
37	27.98	2536	3165	3794	0.27	0.5	0.23
38	11.56	2402	2815	3228	0.63	0.28	0.09
39	26.35	2466	3005	3544	0.2	0.52	0.28
40	29.59	2512	3102	3691	0.26	0.46	0.28
41	29.71	-	-	-	-	-	-
42	36.63	-	-	-	-	-	-
43	31.50	-	-	-	-	-	-

Model Simulation

Model simulation has been done based on daily data. The simulation period was selected from 1998 to 2019 because most of the data are available within this time period. In this simulation, the skewed normal probability distribution function was used to describe the distribution of rainfall amounts. Water is routed through the channel network using the Variable Storage method. For estimating runoff, the SCS Curve Number method has been used. For calculating Potential Evapotranspiration (PET) for the Hargreaves method was used since it requires less data (air temperature only).

4.5.3 Calibration and Validation

Model calibration is the process of adjustment of the model parameters and forcing within the margins of the uncertainties (in model parameters and /or model forcing) to obtain a model representation of the processes of interest that satisfies pre-agreed criteria. This approach aims to improve the model by developing correction factors that can be applied to generate predicted values and may result in an improved model description. The reliability of the model depends on the model simulated results and when the model results match with the observed values, the users get greater confidence. To facilitate the evaluation of model quality, a visual comparison was normally done between observed and simulated hydrographs; also, some statistical analyses were applied. For the calibration and uncertainty analysis of the present study SWAT-CUP, a computer program for calibrating SWAT models was used.

Calibration Tool: SWAT-CUP

Automated model calibration requires that the uncertain model parameters are systematically changed, the model is run, and the required outputs (corresponding to measured data) are extracted from the model output files. The main function of an interface is to provide a link between the input/output of a calibration program and the model. The simplest way of handling the file exchange is through text file formats. SWAT-CUP is an interface that was developed for calibration of SWAT. Using this generic interface, any calibration/uncertainty or sensitivity program can easily be linked to SWAT. SWAT-CUP is a public domain program, and as such may be used and copied freely. The program links Sequential Uncertainty Fitting (SUFI2) (Abbaspour et al., 2004; 2007), Particle Swarm Optimization (PSO) (Eberhart and Kennedy, 1995), Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (ParaSol) (Van Griensven and Meixner, 2003a), and Markov chain Monte Carlo (MCMC) (e.g., Kuczera and Parent, 1998; Marshall et al., 2004; Vrugt et al., 2003; Yang et al., 2007) algorithm to SWAT. It can perform sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models.

The technique of Model Performance Analysis

Model performance was evaluated by performing calibration and validation. In calibration and validation, the model evaluation was done statistically and graphically. Mainly four objective functions were assessed in model simulations:

- Nash–Sutcliffe Efficiency (NSE)
- Coefficient of determination (R2)
- Mean relative bias (PBIAS)
- The ratio of the root mean square error to the standard deviation of measured data (RSR)

NSE is normalized statistics. The comparison of the relative magnitude of the residual variance (noise) and the measured data variance (information) is determined by NSE (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi, 2007). The NSE value of 1 indicates a perfect fit (**Table 4.12**).

The coefficient of determination (R2) describes the proportion of the variance in the observations explained by the model. The range of R2 is from 0 to 1 where higher value (1) gives less error variance and values greater than 0.5 are considered as an acceptable range (Santhi et al., 2001, Van Liew et al., 2003). It only measures the deviation from the best fit line.

PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. Positive values of PBIAS indicate model underestimation bias, and negative values indicate model overestimation bias of total volume (Gupta et al., 1999).

RSR has been calculated applying the ratio of the Root Mean Square Error (RMSE) between simulated and observed values to the standard deviation of the observations (STDEVobs) (Moriasi et al., 2007). RSR should be less than 1. The lower the RSR is the better the model simulation performance. The equations and the interpretation of the values of the statistical functions are given in **Table 4.12**. After automatic calibration, the monthly streamflow has been compared against the observed data.

Table 4.12: General performance ratings for NSE, PBIAS, RSR, and R2 for the calibration and validation process (adopted from Rossi et al., 2008)

Formula	Value	Performance Rating
NSE $= 1 - \left[\frac{\sum_{i=1}^{n} (x_{obs}(i) - y_{model}(i))^2}{\sum_{i=1}^{n} (x_{obs}(i) - \overline{x}_{obs})^2} \right]$	> 0.65 0.54 to 0.65 > 0.50	Very good Adequate Satisfactory
$PBIAS = \left[\frac{\sum_{i=1}^{n} (x_{obs}(i) - y_{model}(i))}{\sum_{i=1}^{n} (x_{obs}(i))} \cdot 100 \right]$	< ±20% ±20% to ±40% >± 40%	Good Satisfactory Unsatisfactory
$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n} (x_{obs}(i) - y_{model}(i))^2} \right]}{\sqrt{\sum_{i=1}^{n} (x_{obs}(i) - \overline{x}_{obs})^2}}$	0.00 < RSR < 0.50 0.50 < RSR < 0.60 0.60 < RSR < 0.70 RSR > 0.70	Very good Good Satisfactory Unsatisfactory
$R^2 = \frac{\left[\sum_{i}^{n} (x_{obs}(i) - \overline{x}_{obs}) (y_{model}(i) - \overline{y}_{model}) \right]^2}{\sum_{i}^{n} (x_{obs}(i) - \overline{x}_{obs})^2 \sum_{i}^{n} (y_{model}(i) - \overline{y}_{model})^2}$	$R^2 > 0.5$	Satisfactory

Here,

X_{obs} = Observed data

$\overline{X}_{obs}$= Mean of Observed data

Y_{model} = Output data after model simulation

$\overline{Y}_{obs}$= Mean of Output data after model simulation

The graphical model evaluation technique is used to see a visual comparison of simulated and measured constituent data and the first overview of model performance (ASCE, 1993). The graphical evaluation is essential for determining appropriate model evaluation (Legates and McCabe, 1999). In this report, both graphical techniques and quantitative statistics were used to evaluate the model.

Model Calibration and Validation

Watershed models contain many parameters; these parameters are classified into two groups: physical parameters and process parameters. A physical parameter represents physically measurable properties of the watershed (e.g. areas of the catchment, a fraction of impervious area and surface area of water bodies, surface slope, etc.) while process parameters represent properties of the watershed which are not directly measurable e.g. average or effective depth of surface soil moisture storage, the effective lateral inflow rate, and the coefficient of non-linearity controlling the rate of percolation to the groundwater (Sorooshian and Gupta, 1995). Thus, calibrations against available streamflow observations are often conducted to tune the model. Parameter sensitivities have been determined using the Latin Hypercube-One factor At a Time (LH-OAT) sensitivity analysis method, which is embedded in the SWAT-CUP (Usermanual_Swat_Cup). **Table 4.13** shows the list of sensitive parameters and their range used for auto-calibration.

Table 4.13: List of parameters and their description used in model calibration (Arnold et. al, 2011)

Si no	Parameters	Description	Lower Limit	Upper Limit
1	r__cn2.mgt[a]	Initial SCS runoff curve number for moisture condition II. The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. CN2 may be updated in plant, tillage, and harvest/kill operation.	-0.1	0.1
2	v__alpha_bf.gw[b]	Baseflow alpha-factor [days]. The baseflow recession constant is a direct index of groundwater flow response to changes in recharge. It is best estimated by analyzing measured streamflow during periods of no recharge in the watershed.	0	1
3	r__sol_awc().sol	Available water capacity of the soil layer (mm H_2O/mm soil). The plant available water is estimated by determining the amount of released between in situ field capacity and the permanent wilting point.	-0.1	0.1
4	v__ch_n2.rte	Manning's "n" value for the main channel.	0.02	0.06
5	v__ch_k2.rte	Effective hydraulic conductivity in main channel alluvium [mm/hr]. For perennial streams with continuous groundwater contribution, the effective conductivity will be zero.	5	20
6	v__gwqmn.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O).	0	1000
7	v__PLAPS.sub	Precipitation lapse rate (mm H_20/km)	0.05	0.1
8	v__TLAPS.sub	Temperature lapse rate (^{0}C/km)	-10	-5
9	v__SMFMN.bsn	Melt factor for snow on December 21 (mm H_2O/^{0}C-day)	2	8
10	v__SMTMP.bsn	Snow melt base temperature (^{0}C)	0	10
11	v__TIMP.bsn	Snow pack temperature lag factor	0	0.5

[a]The qualifier (r_) refers to the relative change in the parameter where the initial value from the SWAT database is multiplied by (1+parameter value).

[b]The qualifier (v_) refers to the substitution of a parameter by a value from the given range. The initial value from the SWAT database is replaced by the parameter value.

The model was calibrated and validated against daily observed discharge at Bondey Station in the Pa Chu. The calibration and validation period was selected as 2014 – 2016 and 2017 – 2019, respectively based on the available reliable streamflow data. The calibrated parameters including their sensitivity rank and fitted value are given in **Table 4.14**. A total of eleven parameters were found from SWAT-CUP as being the most sensitive parameters for the Paro Basin area. The curve number (CN2) was the highest sensitivity for generating daily streamflow and then precipitation lapse rate (PLAPS).

Table 4.14: Most sensitive parameters and their calibrated values

Sensitivity Rank	Parameter	Fitted Value
1	V__PLAPS.sub	0.0605
2	R__CN2.mgt	-0.097
3	V__TLAPS.sub	-6.175
4	V__CH_N2.rte	0.0342
5	V__TIMP.bsn	0.3375
6	V__SMTMP.bsn	9.235001
7	R__SOL_K(..).sol	-0.3775
8	R__SOL_AWC(..).sol	-0.017
9	V__GWQMN.gw	945
10	V__ALPHA_BF.gw	0.595
11	V__SMFMX.bsn	4.31

For visual comparison, daily observed and simulated streamflows were plotted for the calibration period (**Figure 4.5**) and the validation period (**Figure 4.6**). For both calibration and validation periods, the model could simulate the behavior of the observed flow. For most years, the peaks were well captured which is very important for flood impact assessment and design of flood management structures. For the dry season, the model slightly underestimates. During the validation period, dry season flow was simulated with good accuracy while the model overestimates for one year.

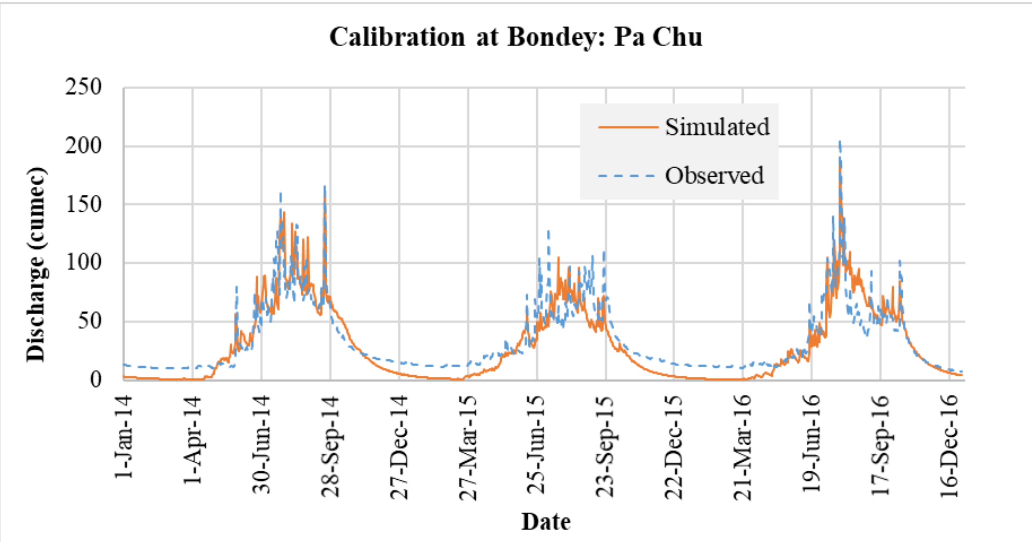


Figure 4.5: Daily observed and simulated streamflow during the calibration period (2014 – 2016)

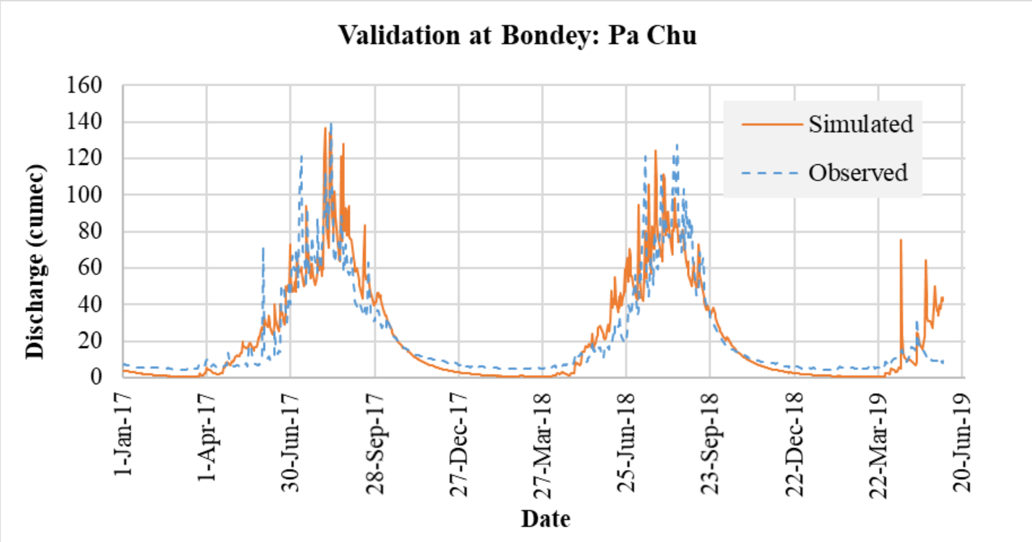


Figure 4.6: Daily observed and simulated streamflow during the validation period (2016 – 2019)

The statistical comparison of observed and simulated values is shown in **Table 4.15**. The simulated mean is slightly underestimated compared to the observed mean. The NSE values for the calibration and validation periods are 0.74 and 0.75 which are in the range of "very good". The PBIAS and R^2 values are also in the range of "good". The RSR value for the calibration and validation period is in the range of "good".

Table 4.15: Most sensitive parameters and their calibrated values

Modeling Phase	Drainage Area (km^2)	Observed Mean (m^3/s)	Simulated Mean (m^3/s)	Model Performance			
				NSE	PBIAS	RSR	R^2
Calibration	1119	33.1	28.8	0.74	13.02	0.51	0.81
Validation		21.8	21.9	0.75	-0.68	0.50	0.78

The good performance of the model during both calibration and validation period indicates that the calibrated parameters can be a representative set of parameters for the Paro Basin area.

4.5.4 Model Uncertainty Analysis

Sequential Uncertainty Fitting (SUFI-2) algorithm, embedded with SWAT-CUP was used to assess the uncertainty of the developed SWAT model. In SUFI-2, uncertainty in parameters, expressed as ranges (uniform distributions), accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. Propagation of the uncertainties in the parameters leads to uncertainties in the model output variables, which are expressed as the 95% probability distributions. These are calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable generated by the propagation of the parameter uncertainties using Latin hypercube sampling. This is referred to as the 95% prediction uncertainty, or 95PPU (Abbaspour et al., 2007).

In SUFI-2, uncertainty is measured with the R-factor, which indicates the thickness of the 95PPU envelope. A high value of the R-factor indicates high uncertainty of model output. During uncertainty analysis, the R-factor was found as 1.23 which is reasonable (around 1) according to the manual of SWAT-CUP. The 95PPU envelop is presented in **Figure 4.7**.

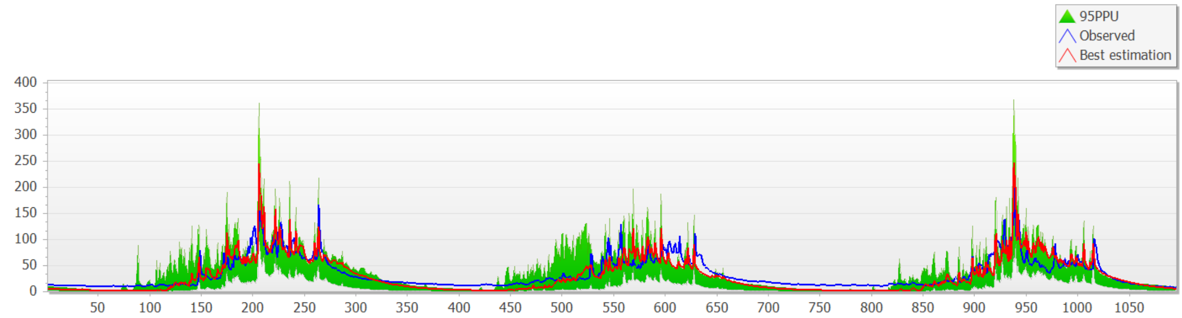


Figure 4.7: 95PPU envelop of simulated model output for uncertain model parameters

4.6 Stream Flow Assessment

The calibrated and validated SWAT model was simulated for the time period of 1998 to 2019 to compute design discharge for rivers and streams. Design discharge was estimated using frequency analysis of annual maximum discharge during the period of 1998 to 2019. Log Pearson Type III distribution was used for the estimation of discharge for different return periods. This design discharge is the primary requirement for the planning and design of any flood management project and design of channels, cross-drainage structures, river training works, etc. The discharge of rivers and streams for different return period is summarized in **Table 4.16**. The Nephu Chu had the highest discharge among the streams, followed by the Jew Chu and Gatanarang Chu. This frequency analysis data was used for the generation of flooding scenarios and the design of flood management structures.

Table 4.16: Discharge of rivers and streams for different return periods during existing condition

Stream Name	Stream Flow at different Return Period (m^3/s)					
	2	5	10	25	50	100
Satsam chu (N)	2.3	3.4	3.8	4.1	4.2	4.3
Satsam chu (S)	0.4	0.5	0.6	0.6	0.7	0.7
Dakhorong Chu	2.1	3.0	3.3	3.4	3.4	3.4
Ngoborong Chu	2.1	3.5	4.3	5.0	5.5	5.8
Ri Chu	2.2	4.1	5.2	6.4	7.2	7.8
Jew Chu	3.7	6.1	7.6	9.1	10.0	10.8
Gatanarang Chu	4.0	6.5	7.9	9.2	10.0	10.6
Nephu Chu	3.3	5.9	7.5	9.3	10.5	11.5
Pa Chu at Confluence	122.5	157.9	182.9	216.2	242.4	269.8
Do Chu at Confluence	33.5	43.2	48.4	53.9	57.4	60.4
Pa Chu at Bondey	153.7	198.0	228.2	267.4	297.5	328.2

The hydrological model was also simulated considering the climate change condition. Due to the high variation of bias correction results, national level downscale result was used for climate change impact assessment. RCP4.5 scenario was considered for 2050s period and the simulated discharge was analyzed using Log Pearson Type III distribution. The discharge due to climate change condition for different return period is given in **Table 4.17**. The discharge due to climate change followed the same pattern with an average increase of about 20%.

Table 4.17: Discharge of rivers and streams for different return periods for 2050s considering RCP 4.5 scenario

Stream Name	Stream Flow at different Return Period (m³/s)					
	2	5	10	25	50	100
Satsam chu (N)	2.9	4.0	4.5	4.5	4.5	4.5
Satsam chu (S)	0.4	0.6	0.7	0.7	0.7	0.7
Dakhorong Chu	2.6	3.7	4.1	4.2	4.3	4.3
Ngoborong Chu	2.5	4.4	5.4	6.4	7.0	7.4
Ri Chu	2.7	4.8	6.1	7.3	8.1	8.7
Jew Chu	4.5	7.7	9.6	11.7	13.0	14.1
Gatanarang Chu	4.8	8.2	10.2	12.2	13.4	14.4
Nephu Chu	4.0	7.0	8.8	10.7	11.8	12.8
Pa Chu at Confluence	140.7	188.6	223.6	271.9	310.8	352.4
Do Chu at Confluence	38.4	52.9	61.2	70.6	76.8	83.1
Pa Chu at Bondey	176.5	236.1	278.3	334.7	379.1	425.5

4.7 Hydrodynamic Model Development for Pa Chu and Do Chu

The hydrodynamic model for the streams and rivers were developed by FEMD using HEC-RAS tool. Ten separate models were developed for each streams and rivers. Both 1D and 2D modeling techniques were used for model development depending on the data availability. For the Pa Chu and Do Chu, the model was developed using global and national DEM as opposed to surveyed cross-section which is very coarse for real world representation of the main river. On the other hand, the tributaries of the rivers (streams) were not considered during model schematization. Therefore, a new model was developed for the Pa Chu and Do Chu using surveyed cross-section and considering all the streams. The following sections briefly discuss the development of hydrodynamic model for the rivers.

4.7.1 Selection of Modeling Package

'SOBEK' modeling suite developed by Deltares of the Netherlands was utilized in this study. SOBEK is an integrated software package for river, urban or rural water management. SOBEK is an implicit, finite difference model for computation of unsteady flows, where advanced computational modules are included for description of flow. Specifically, coupling of hydrological, hydrodynamic (1D) and overland flow (2D) module of SOBEK model can be used to assess both hydrologic and hydraulic phenomena of the study area, including rainfall-runoff, flooding and drainage condition. The 1D and 2D modules are implicitly coupled and solved simultaneously based on momentum balance and mass conservancy between separate computational layers while both layers use finite difference formula based on a staggered grid approach.

4.7.2 Model Development

The 1D-2D modeling approach was used for this study. The main rivers were schematized as 1D river network which the floodplain were represented in 2D. Both 1D and 2D (overland flow) were dynamically coupled and simulated simultaneously. The model setup was completed performing the following steps:

- Model Schematization;

- Incorporating model inputs;
- Defining boundary condition and boundary data;
- Model simulation setup; and
- Model calibration and validation.

The Pa Chu, Do Chu and streams located inside the selected model domain were considered for model schematization as shown in **Figure 4.8**. Eight upstream and one downstream boundary were used for model development. Discharge and water levels were used as upstream and downstream boundary conditions respectively. The discharge boundary data was generated using the hydrological model for the catchment.

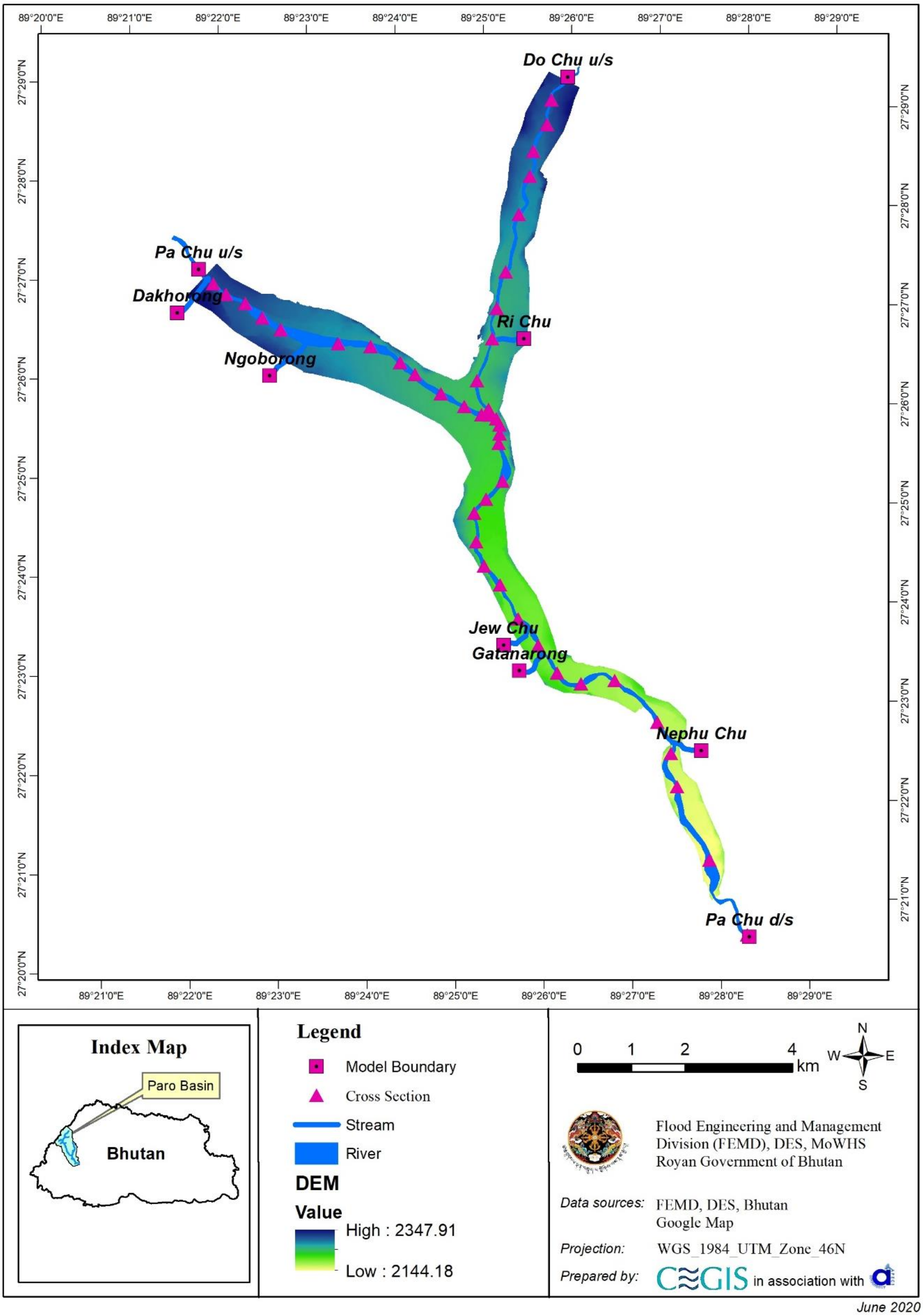


Figure 4.8: Computational domain for the hydro-dynamic model for Pa Chu and Do Chu

NCHM surveyed cross-section data was used for model setup for the Pa Chu and Do Chu as shown in **Figure 4.8**. For overland flow analysis (flood extent and flood depth map generation), the DEM from DHS was utilized. The resistance parameter, Manning's 'n' was chosen as 0.05 for the Pa Chu and Do Chu as the channel bed mainly consist of cobble and small size boulders.

The developed Hydrodynamic (1D) and overland (2D) flow models were dynamically linked and simulated simultaneously with a time step of 10 seconds. The model was simulated for water level, water depth, discharge and flow velocity. It was not possible to calibrate the model against observed data due to the unavailability of flood level or flood extent data.

4.7.3 Sensitivity Assessment of Roughness

Sensitivity analysis of the model was performed to assess the uncertainty of simulated flood level against different roughness value as the model was not calibrated. The model simulated water level near Paro Town on Pa Chu for different Manning's 'n' is shown in **Table 4.18**. The water level varies around 20 cm for each 0.01 difference in 'n' value.

Table 4.18: Model simulated water level near Paro Town for different channel roughness

Manning's 'n'	Water level near Paro Town (msl)
0.02	2234.957
0.03	2235.228
0.04	2235.45
0.05	2235.646
0.06	2235.82

4.8 Generation of Flooding Scenario

The flood depth and flood extent maps were generated through simulating developed hydro-dynamic model for the Pa Chu, Do Chu and other small streams. The models were simulated considering discharge of 2, 5, 10, 25, 50, and 100 years return period. The simulated flood maps for 25 years return period for the Pa Chu, Do Chu and eight streams considering the existing condition are shown in **Figure 4.9 – 4.20**. It was observed that there is a change of flooding for the Paro Town through overtopping of the gabion revetment. The Paro International Airport area was found flood free even for 100 year return period flood event. The Nephu Chu was found highly flood prone due to the encroachment and grabbing of channel. Besides, the downstream part of Ngoborong Chu had some inundation area due to the narrowing of channel at the downstream part. The simulated flood depth maps for climate change scenario are shown in **Figure 4.21 – 4.24**. Flood hazard maps for all return periods and for existing and climate change condition are given in **Appendix-III**.

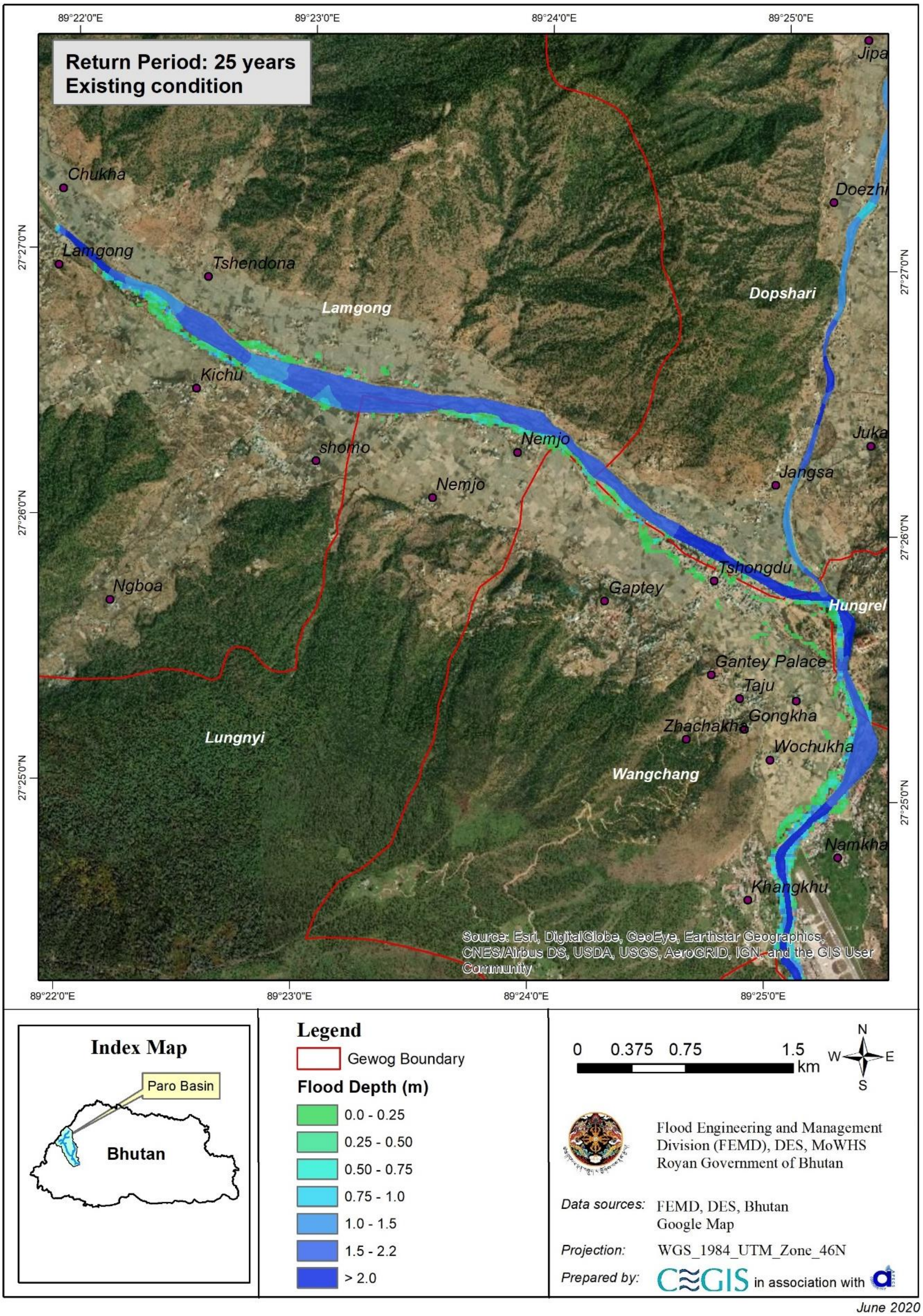


Figure 4.9: Flood map for Pa Chu (Lamgong – Wanchang Gewog) for existing condition

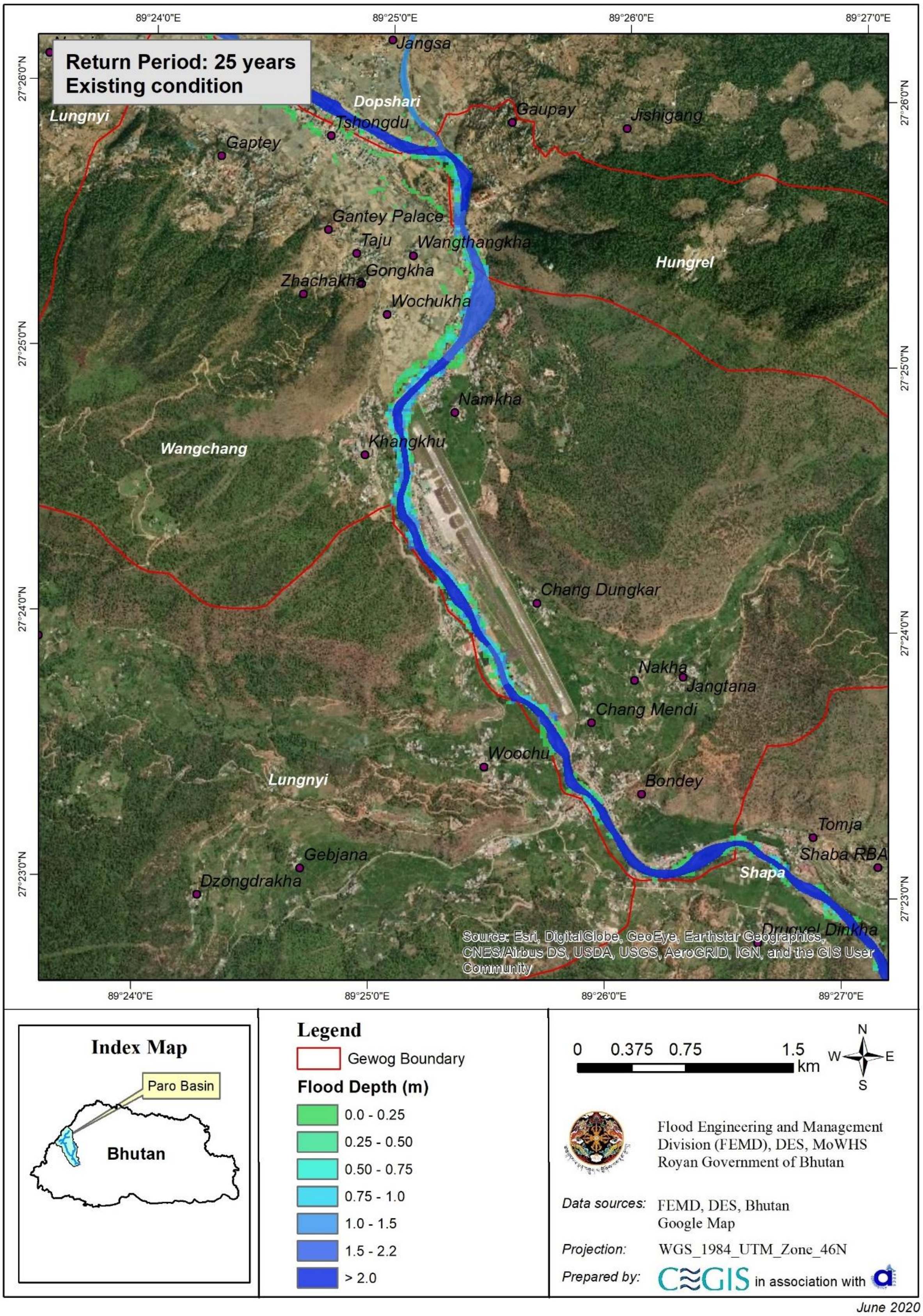


Figure 4.10: Flood map for Pa Chu (Hungrel – Shapa Gewog) for existing condition

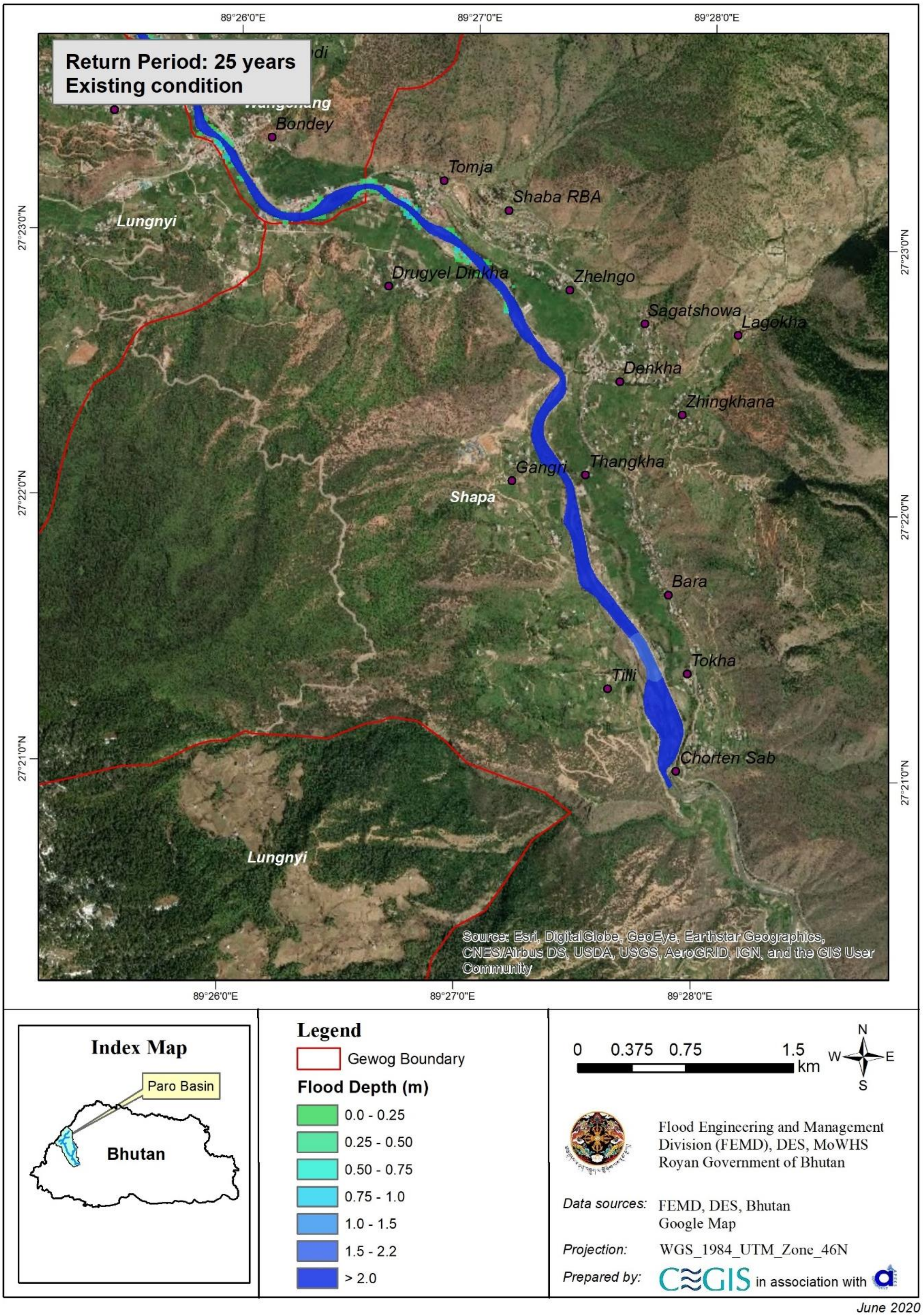


Figure 4.11: Flood map for Pa Chu (Shapa Gewog) for existing condition

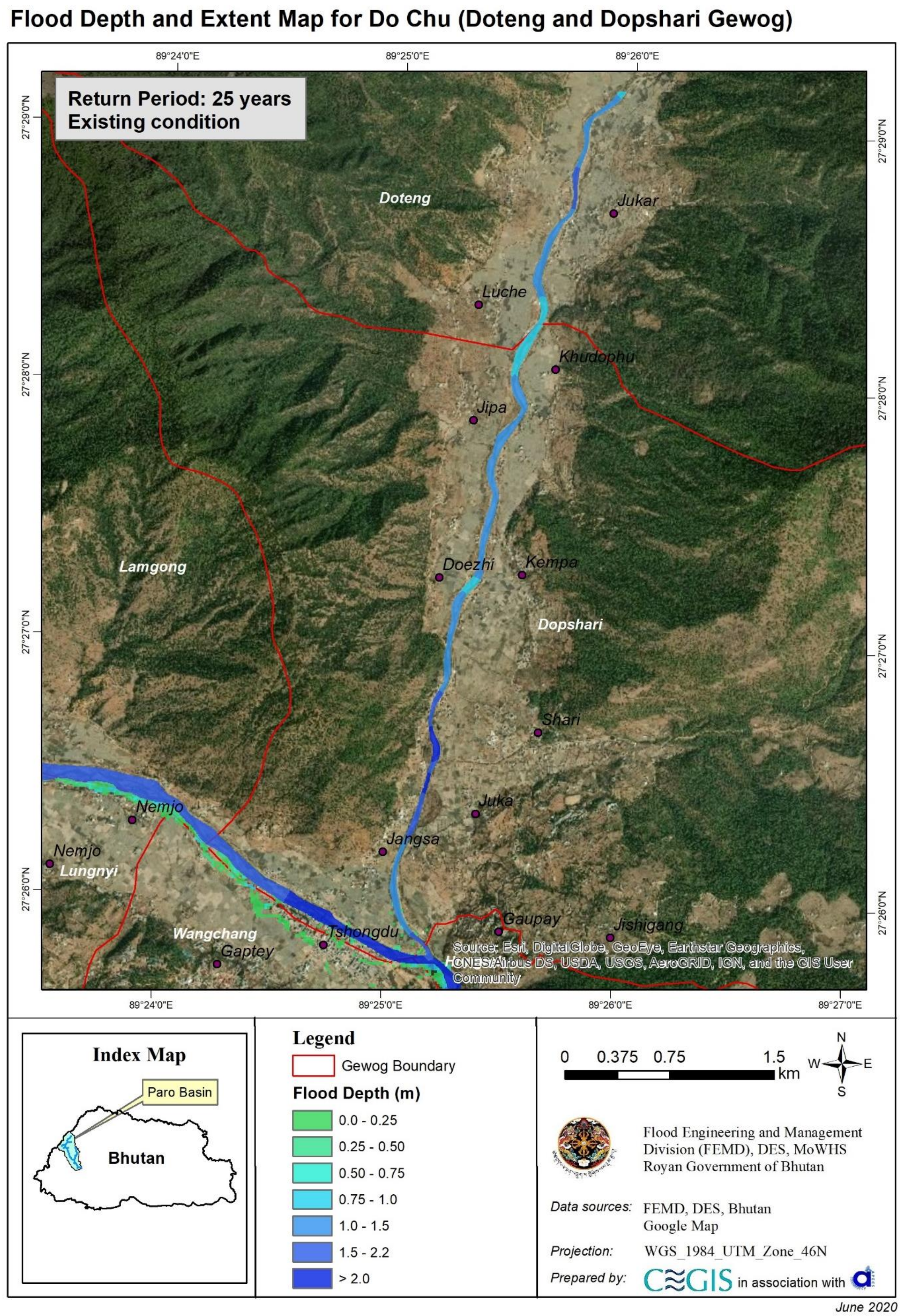


Figure 4.12: Flood map for Do Chu (Doteng and Dopshari Gewog) for existing condition

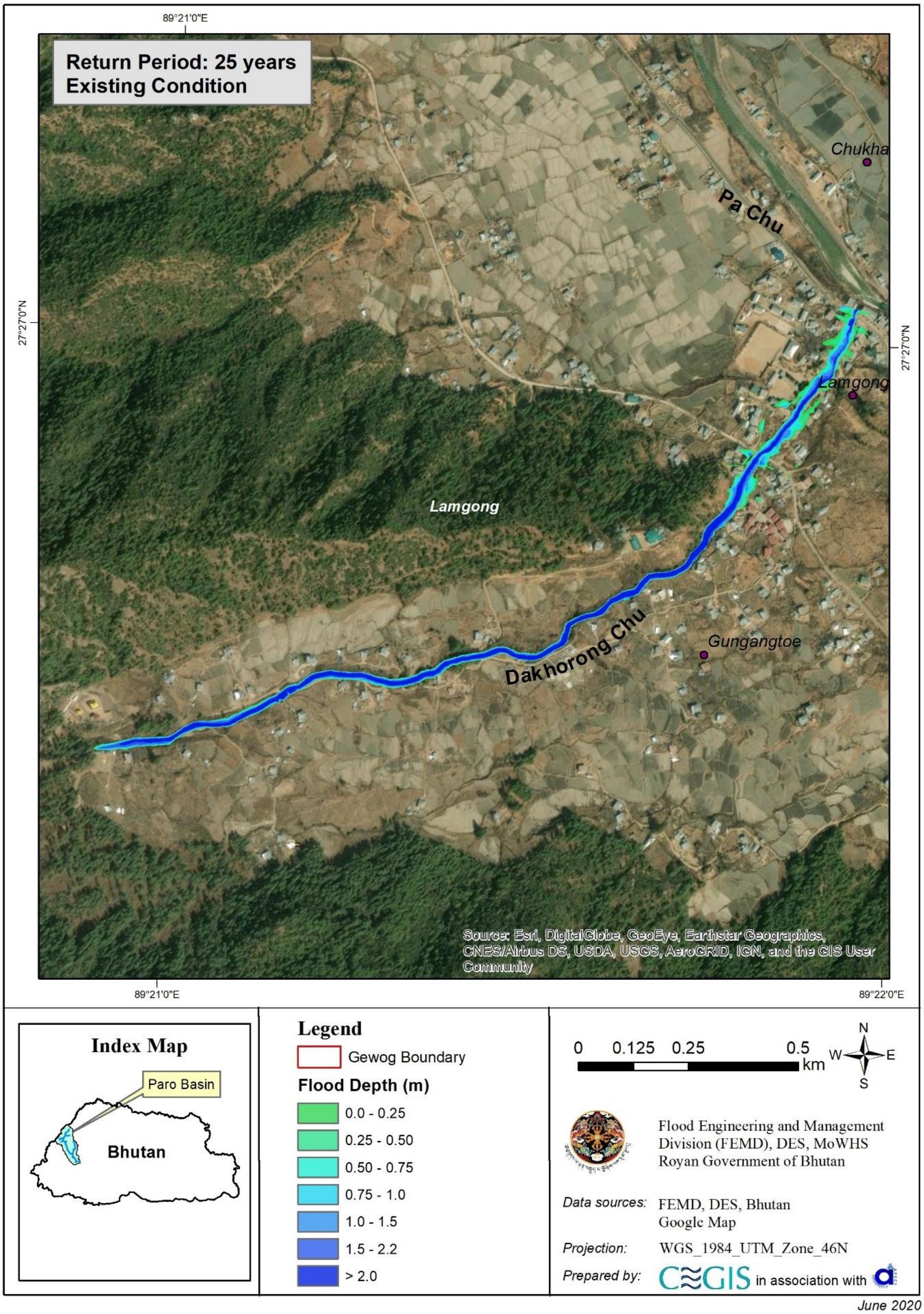


Figure 4.13: Flood map for Dakhorong Chu for existing condition

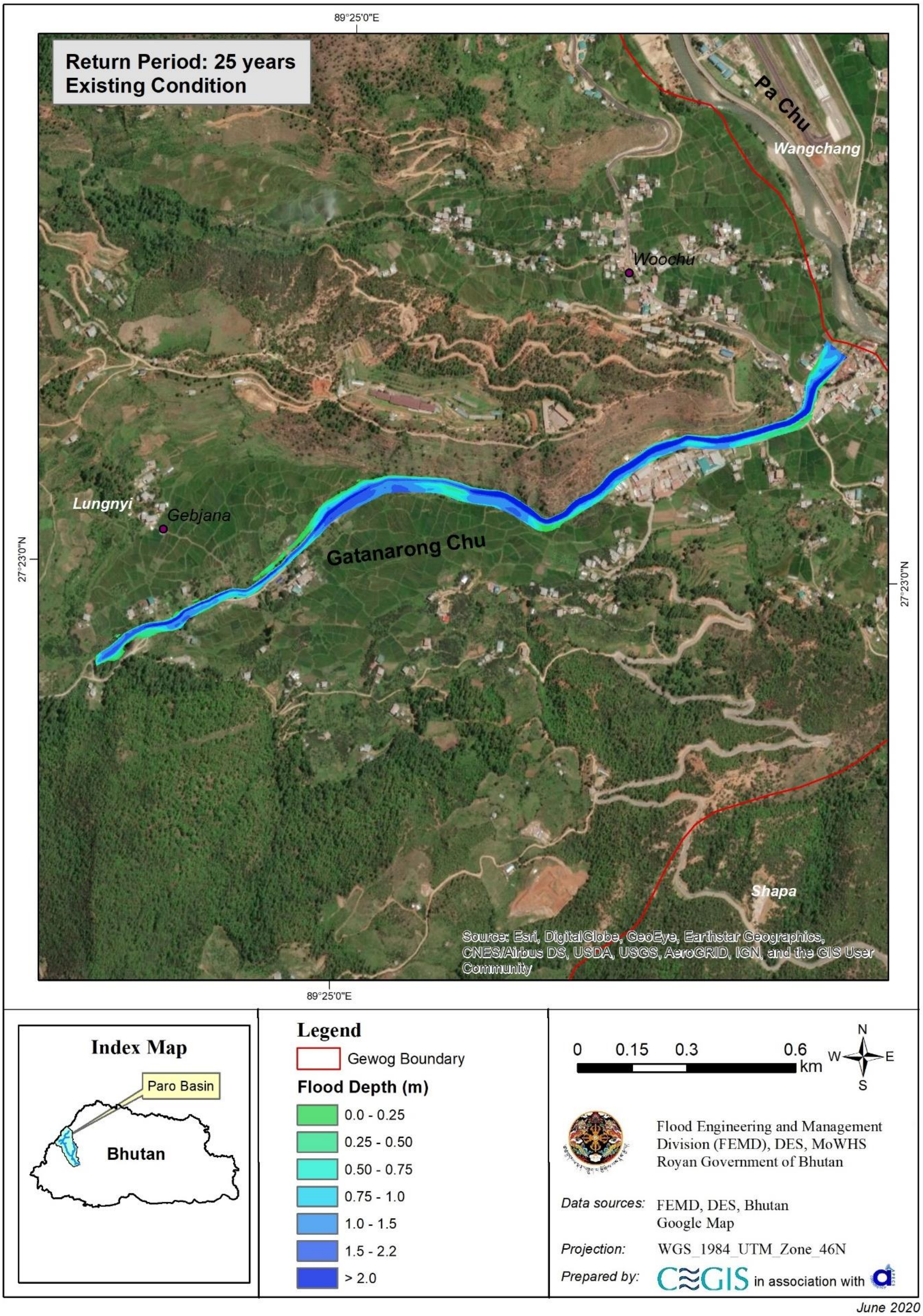


Figure 4.14: Flood map for Gatanarong Chu for existing condition

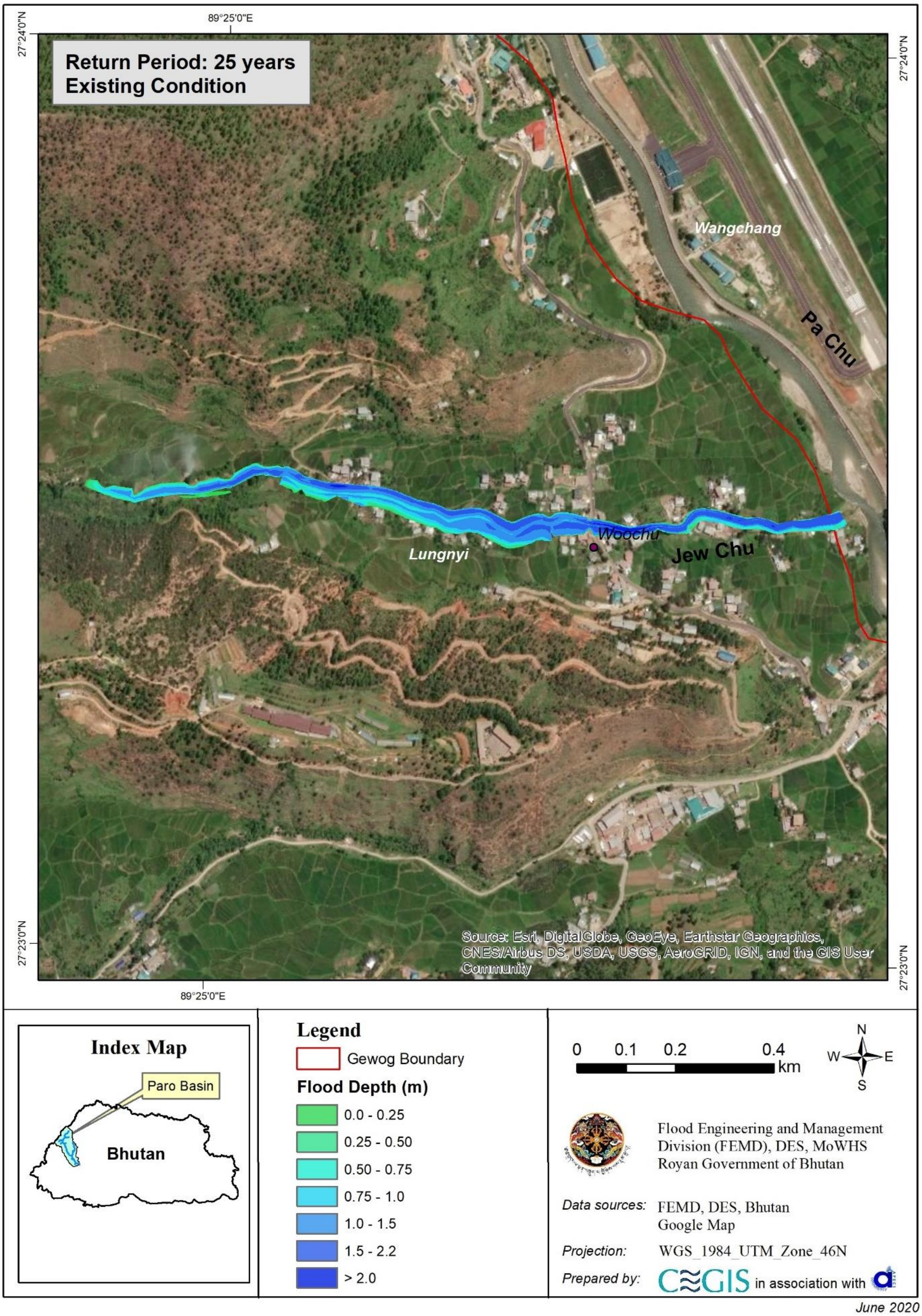


Figure 4.15: Flood map for Jew Chu for existing condition

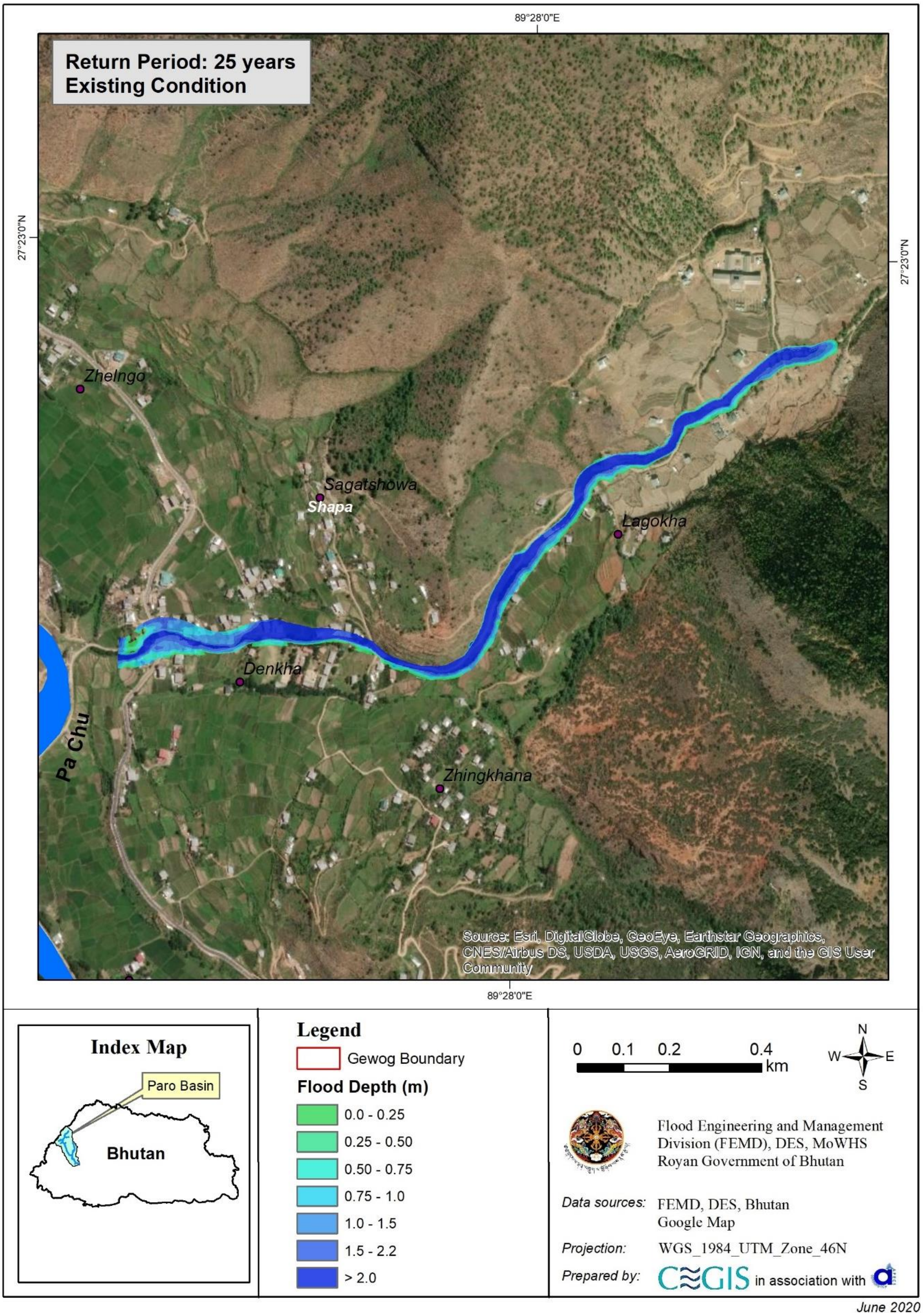


Figure 4.16: Flood map for Nephu Chu for existing condition

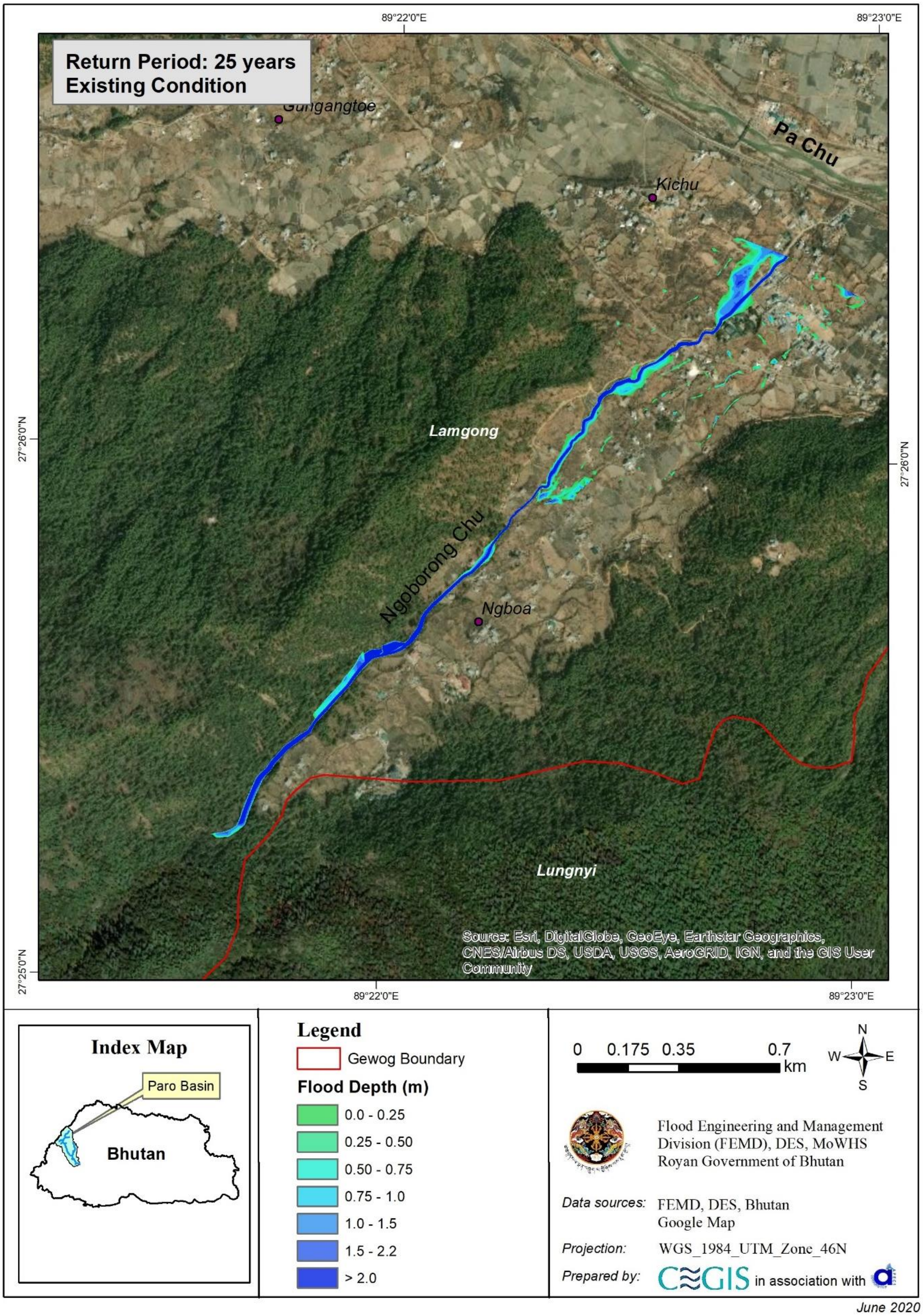


Figure 4.17: Flood map for Ngoborong Chu for existing condition

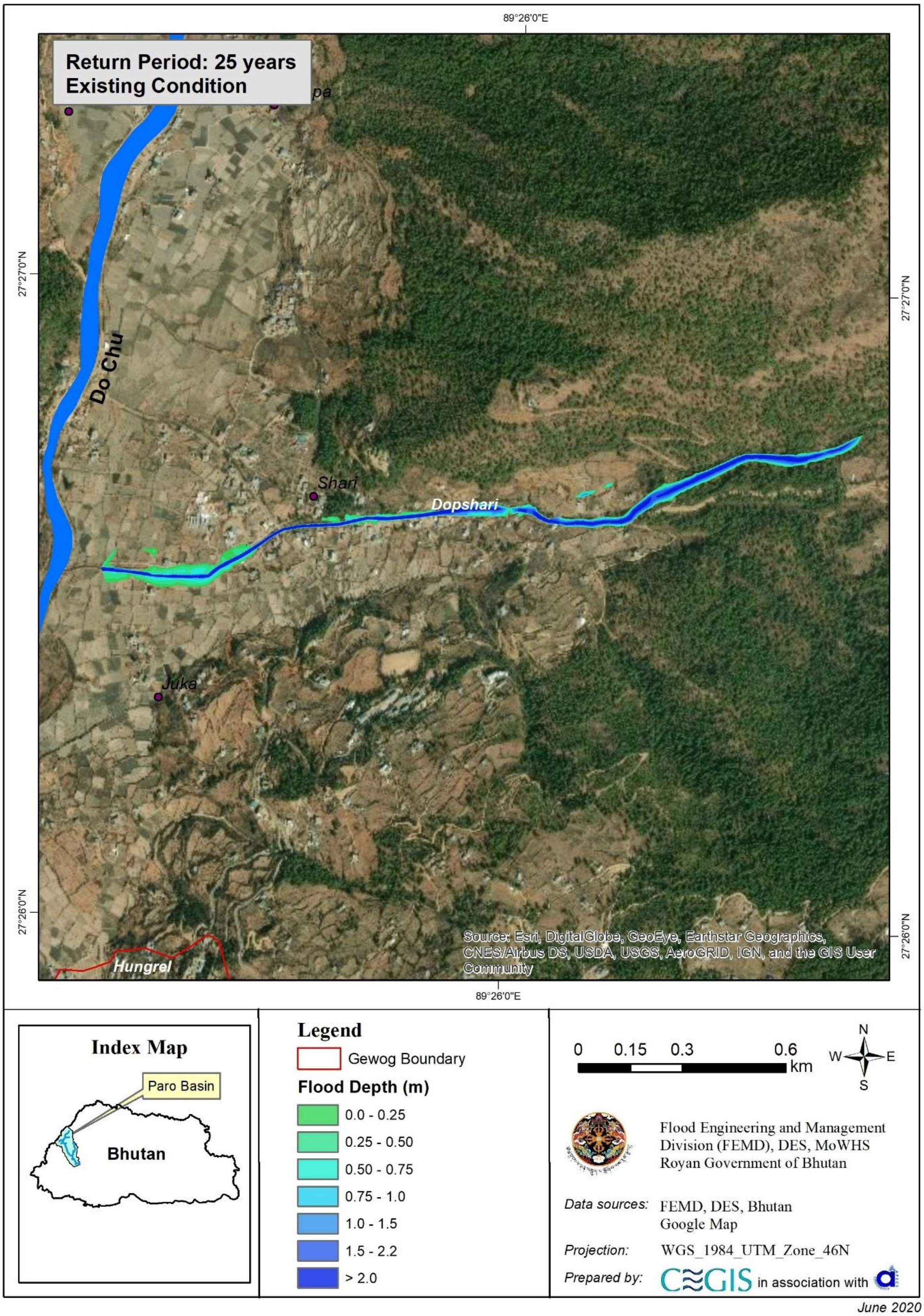


Figure 4.18: Flood map for Ri Chu for existing condition

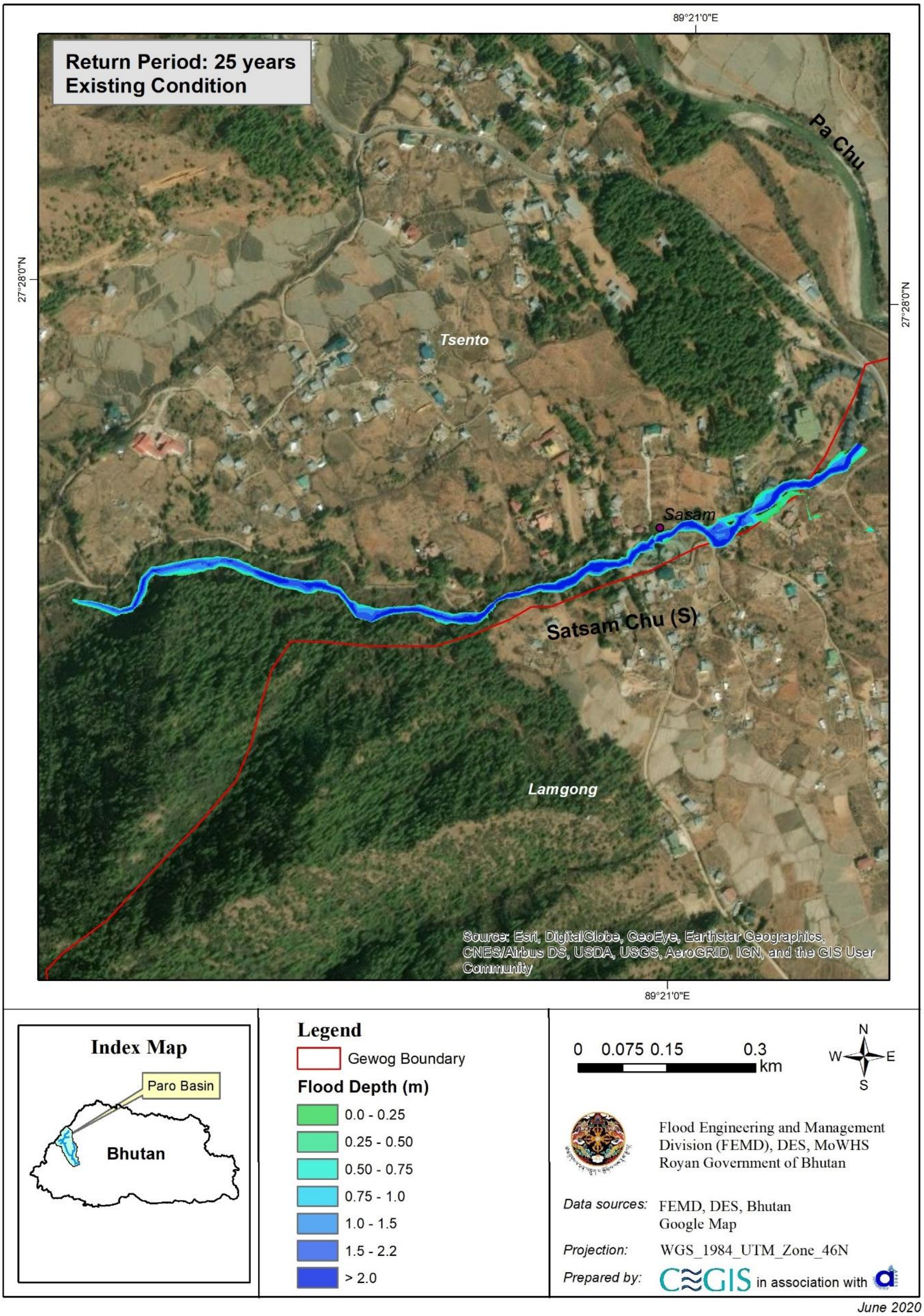


Figure 4.19: Flood map for Satsam Chu (S) for existing condition

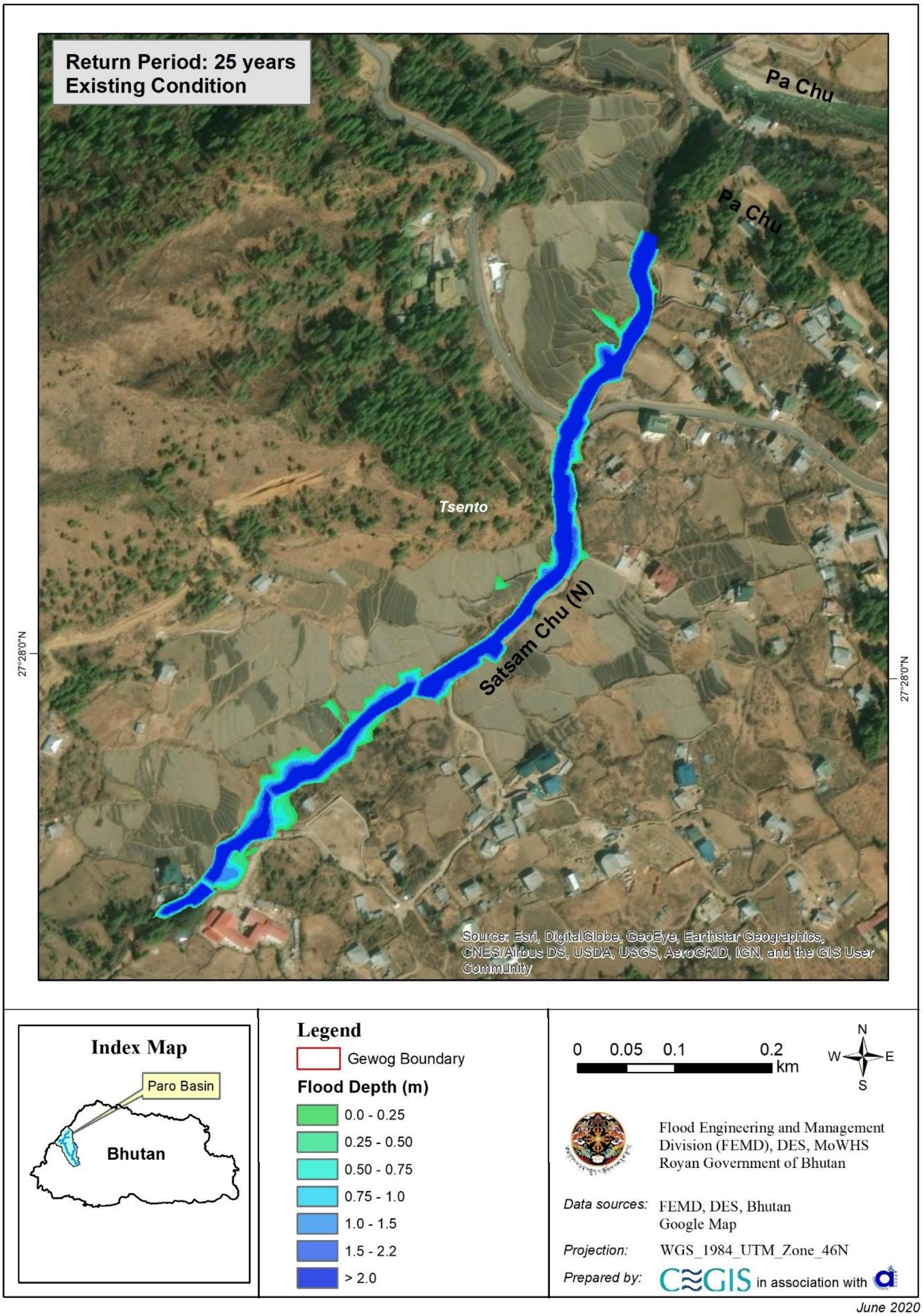


Figure 4.20: Flood map for Satsam Chu (N) for existing condition

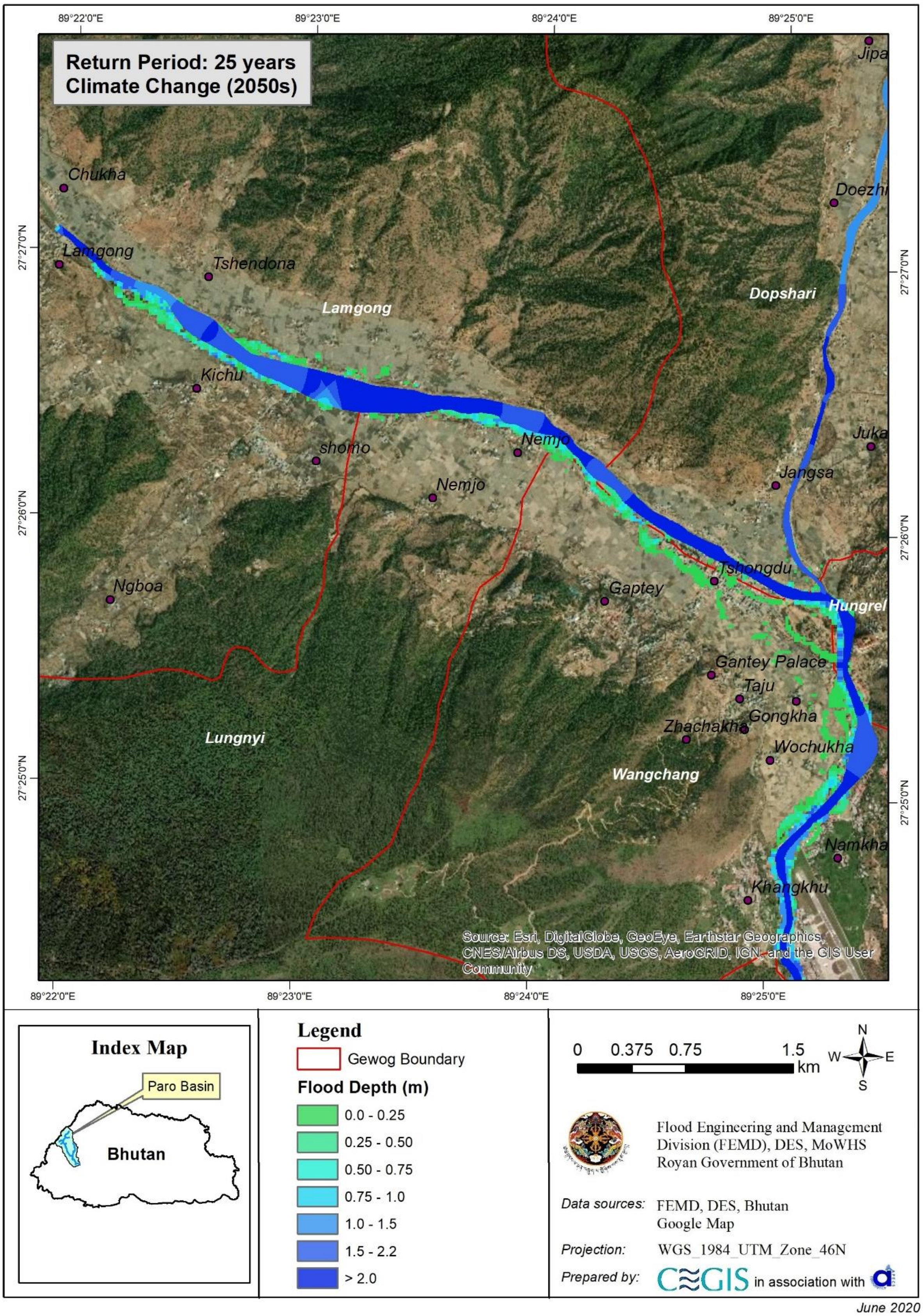


Figure 4.21: Flood map for Pa Chu (Lamgong – Wanchang Gewog) for climate change condition

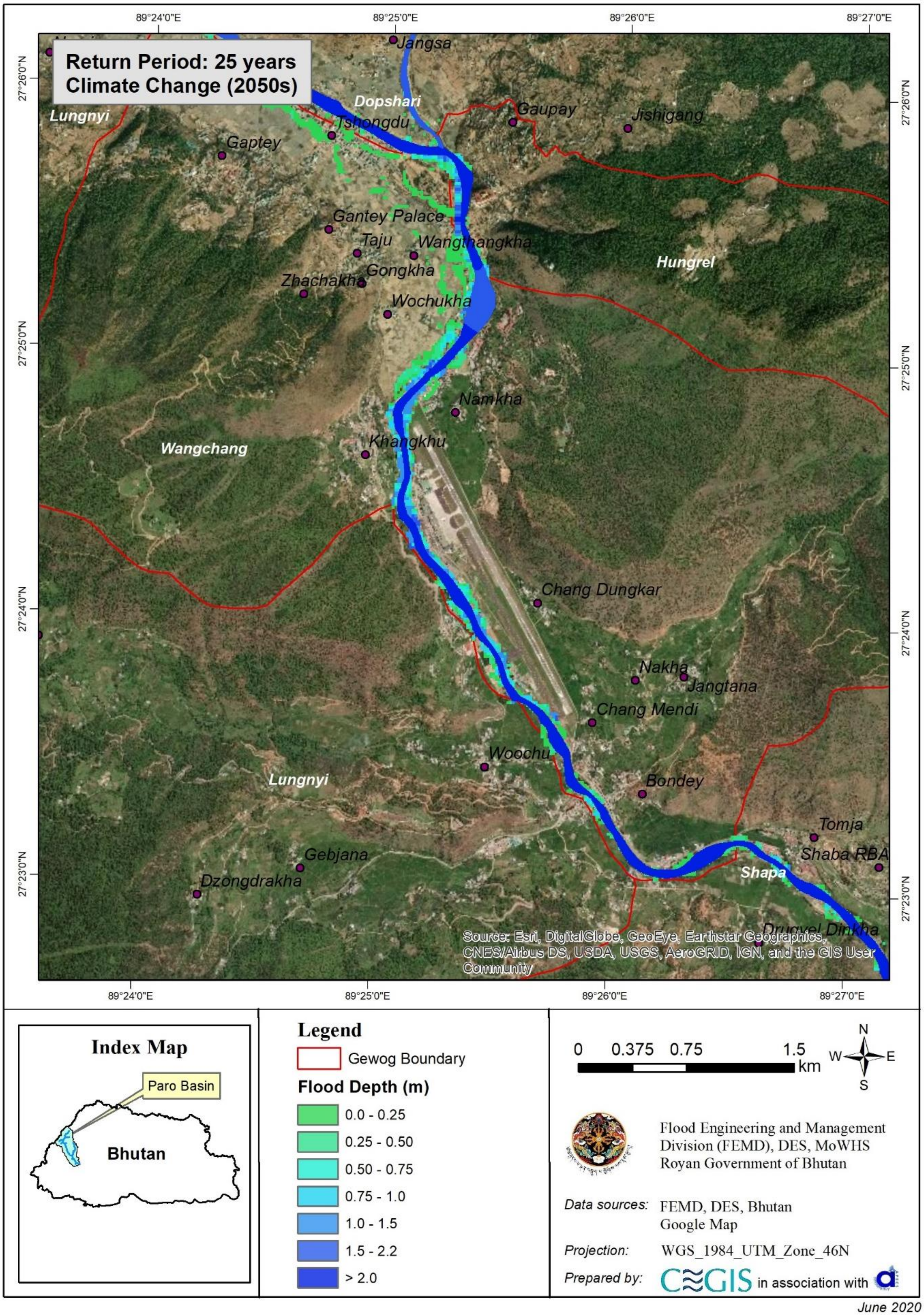


Figure 4.22: Flood map for Pa Chu (Hungrel – Shapa Gewog) for climate change condition

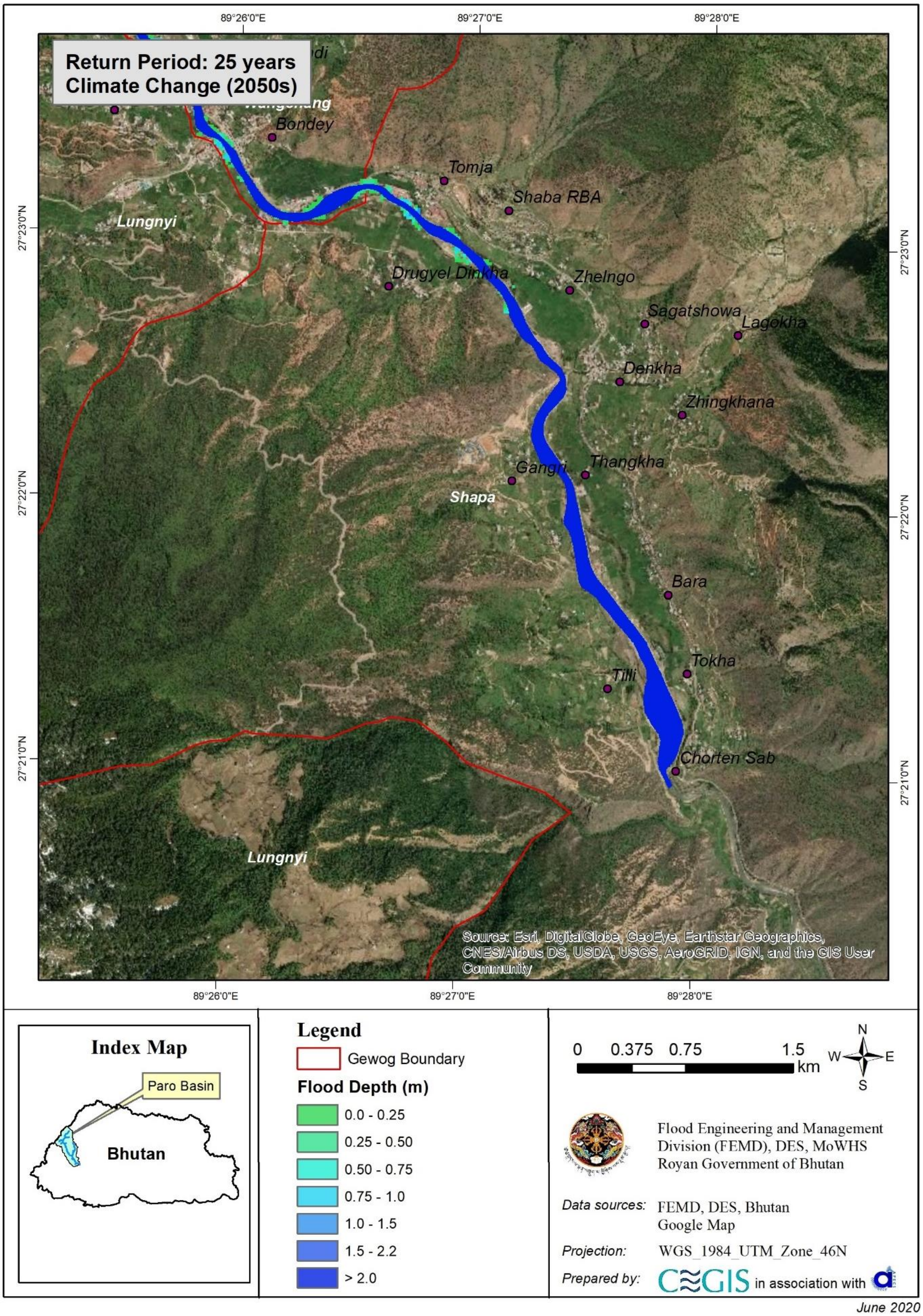


Figure 4.23: Flood map for Pa Chu (Shapa Gewog) for climate change condition

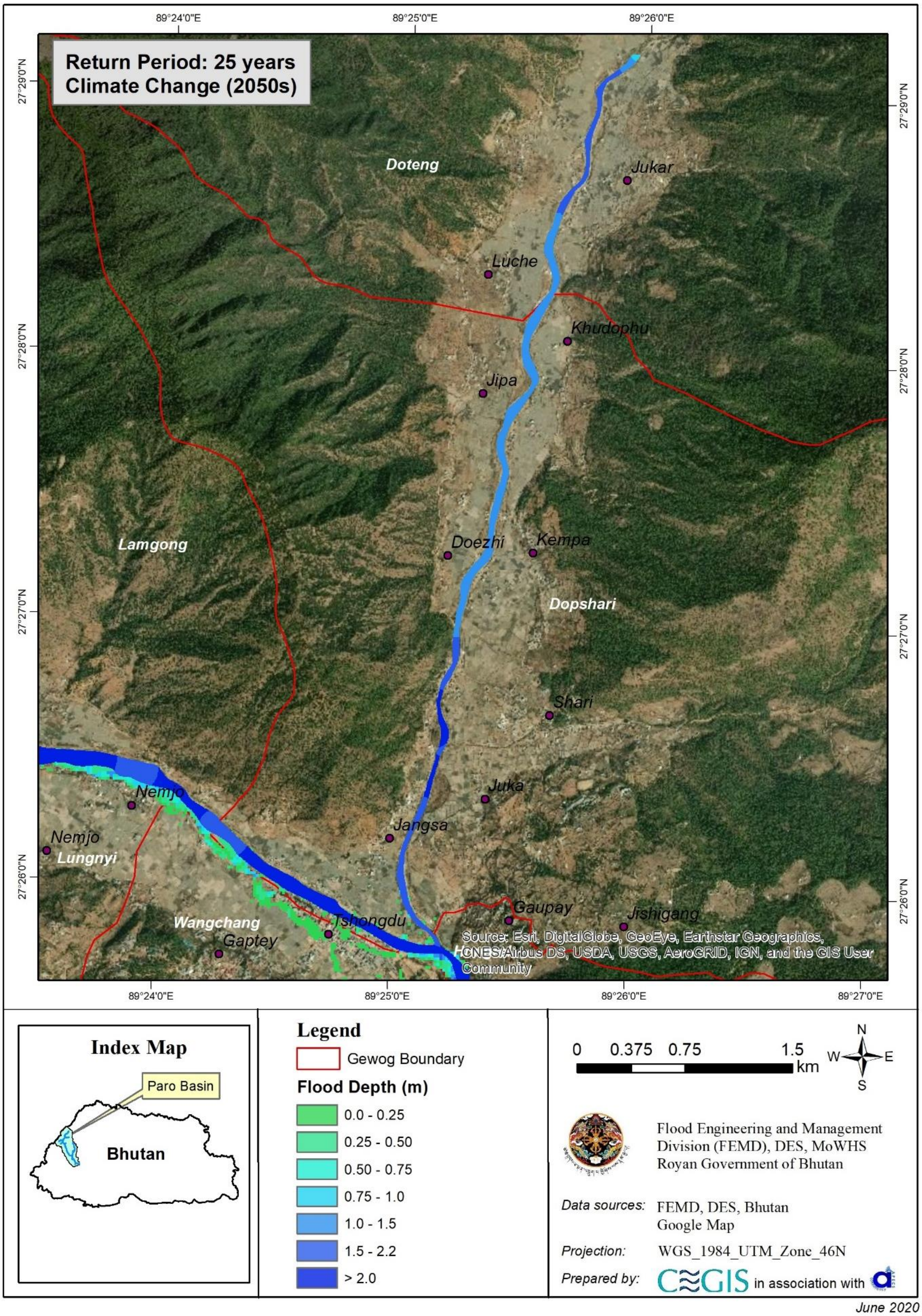


Figure 4.24: Flood map for Do Chu (Doteng and Dopshari Gewog) for climate change condition

5. Flood Risk Assessment

5.1 Socio-economic Assessment

The purpose of undertaking Social Assessment (SA) is to make explicit, through participatory information collection and dissemination, key social factors that affect and are affected by the development impacts and results of the projects.

Both primary and secondary data was used for social assessment. Population and Housing Census of Bhutan of Paro Dzongkhag- 2017, carried out by National Statistics Bureau (NSB) of Bhutan, was used as main secondary source of data. On the other hand, household/property level surveys were carried out in Paro for this assessment. Two-stage surveys were carried out in Paro. Firstly, a vulnerability assessment was conducted by FEMD, MoHS, Bhutan comprising of 341 sample households/entities; and secondly, 16 households/entities were surveyed by APECS Consultant under the supervision of CEGIS intending to collect missing data and, importantly, to triangulate and check validity of the previously collected data. The survey questionnaire and collected data is given in **Annex-IV**.

5.1.1 Demographic Profile

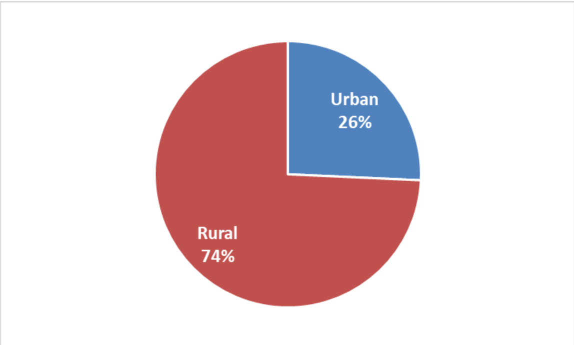
The study area includes 46,316 population, of which 23,941 are males and 22,375 are females. The highest concentration of population is in Paro Town (24.7% of total population in the study area). The male-female distribution shows 107 sex ratio referring to 107 males per 100 females (**Table 5.1**).

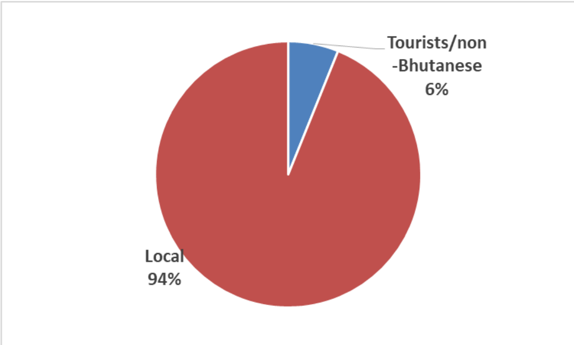
Table 5.1: Distribution of Population in the Study Area

Area type	Name of Gewog/Town	Number of Persons			Percent			Sex Ratio
		Male	Female	Total	Male	Female	Total	
Urban	Paro Town	5828	5620	11448	50.9	49.1	24.7	103.7
	Beteykha Town	230	235	465	49.5	50.5	1.0	97.9
Rural	Dokar	1116	1211	2327	48.0	52.0	5.0	92.2
	Loong-nyi	2453	2274	4727	51.9	48.1	10.2	107.9
	Nagya	1664	1623	3287	50.6	49.4	7.1	102.5
	Sharpa	3258	2683	5941	54.8	45.2	12.8	121.4
	Dopshar-ri	1623	1710	3333	48.7	51.3	7.2	94.9
	Doteng	651	652	1303	50.0	50.0	2.8	99.8
	Hoongrel	266	70	336	79.2	20.8	0.7	380.0
	Lamgong	2972	2874	5846	50.8	49.2	12.6	103.4
	Tsento	3122	2824	5946	52.5	47.5	12.8	110.6
	Wangchang	758	599	1357	55.9	44.1	2.9	126.5
Total in PARO		**23,941**	**22,375**	**46,316**	**51.7**	**48.3**	**100.0**	**107.0**

Source: National Statistics Bureau, 2018

In Paro Dzongkhag, out of total population about 26% are living in urban area i.e. in Paro and Beteykha Towns. The Census report shows that about 6% tourist/non-Bhutanese people were found in a day of Census time, which refers to the importance of Paro as tourist area.



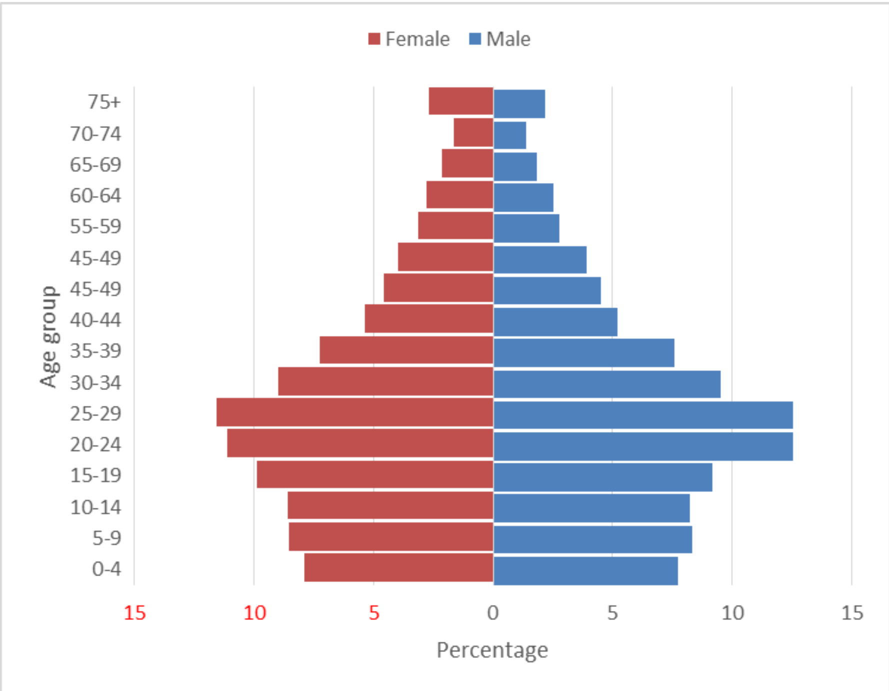


Source: National Statistics Bureau, 2018

Figure 5.1: Distribution rural and urban population

Figure 5.2: Distribution Local and Tourists/non-Bhutanese people in Census day

According to the population pyramid (**Figure 5.3**), the highest population including both male and female belong to age group of 25 to 29 years. The number of female in age group 20 to 24 is relatively lower than that of male. However, the number of youths is higher in Paro, which shows the strong presence of economically active population.

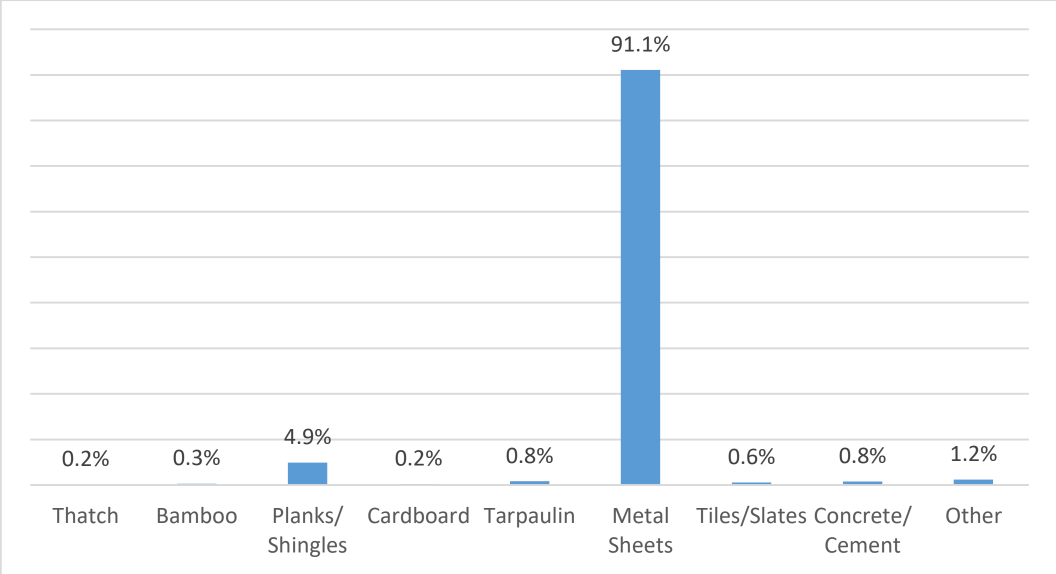


Source: National Statistics Bureau, 2018

Figure 5.3: Population pyramid

5.1.2 Construction Materials of Houses

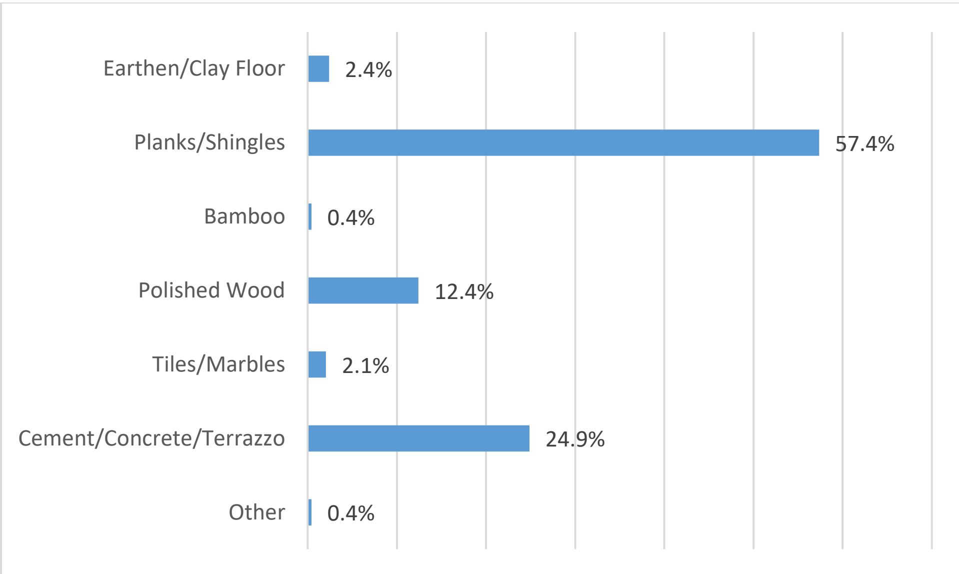
Most of the houses are made of metal sheets on roof. Use of planks and shingles on top was also found (4.9%). However, use of other materials such as cardboard, tiles/slates, and concrete/cements although found, but are not significant.



Source: National Statistics Bureau, 2018

Figure 5.4: Materials used for roofs of houses

Floors of the most of the houses are made of planks/ shingles, which is followed by cement/ concrete/ terrazzo. Use of polished wood although is also found at a considerable rate (12.4%). However, use of earth/clay, Tiles/marbles, and Bamboo although found but are not dominant.



Source: National Statistics Bureau, 2018

Figure 5.5: Materials used for floor of houses

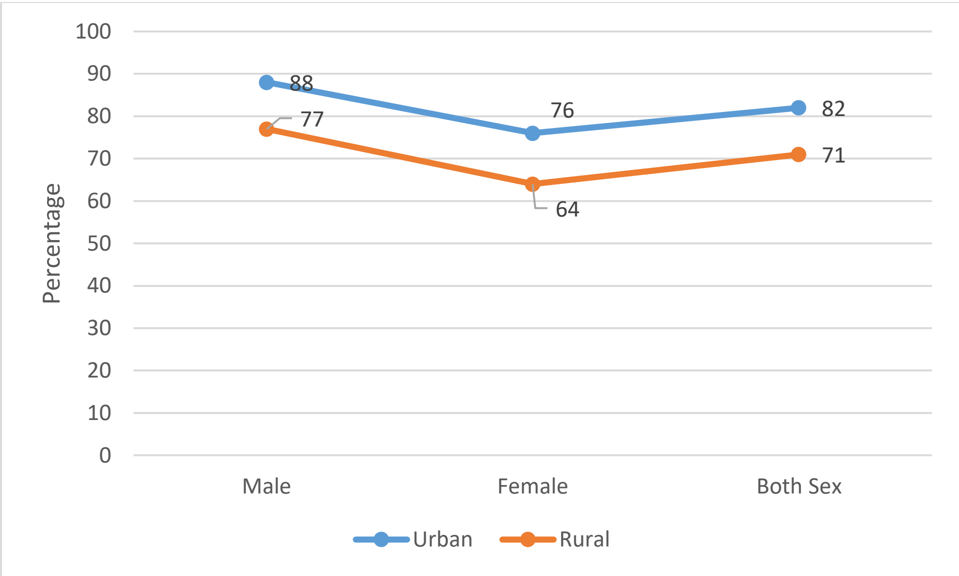
5.1.3 Household Amenities

With respect to sanitation system, most of the household have flush toilet facilities (70.6%). About 12.2% houses have pit latrines with slab, whereas about 10.1% houses use open pit as latrines. On the other hand, about 1.2% houses has no sanitation facility, therefore, they use bush or open field. (PHCB, 2017).

For lighting about 98.6% house has electricity facility. Whereas, about 89.7% house use LPG for cocking. About 58.4% house has piped water inside the dwelling for drinking water, whereas, about 40% house has piped water but located at the outside of their dwelling. (PHCB, 2017).

5.1.4 Education

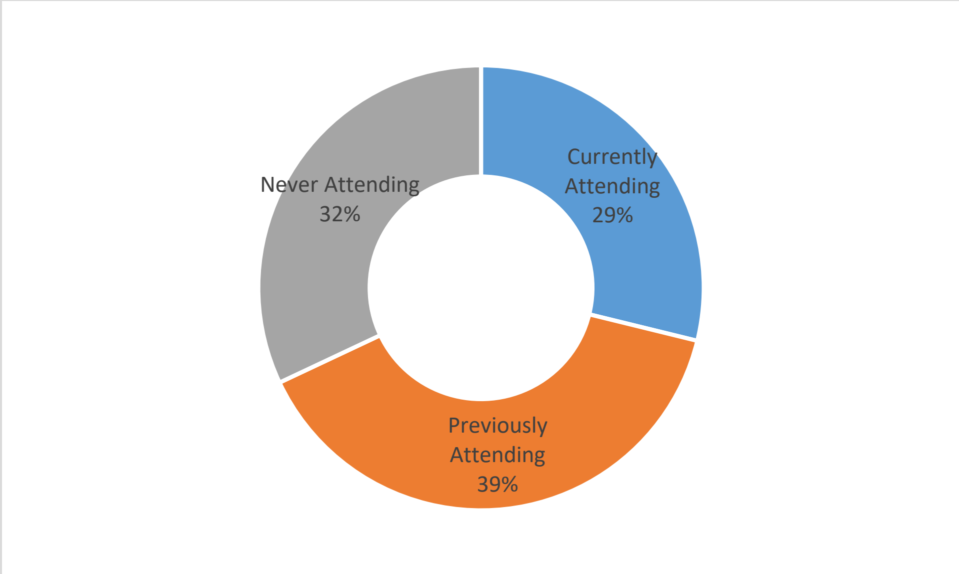
Urban population is more literate (82%) than that of rural population (71%). In both rural and urban area, however, males are more literate than that of females.



Source: National Statistics Bureau, 2018

Figure 5.6: Literary Rate

In terms of school/institute attendance, 32% population of 6 and above years old never attended any school/institute as found in Census of 2017. About 39% attended previously and 29% are currently attended.

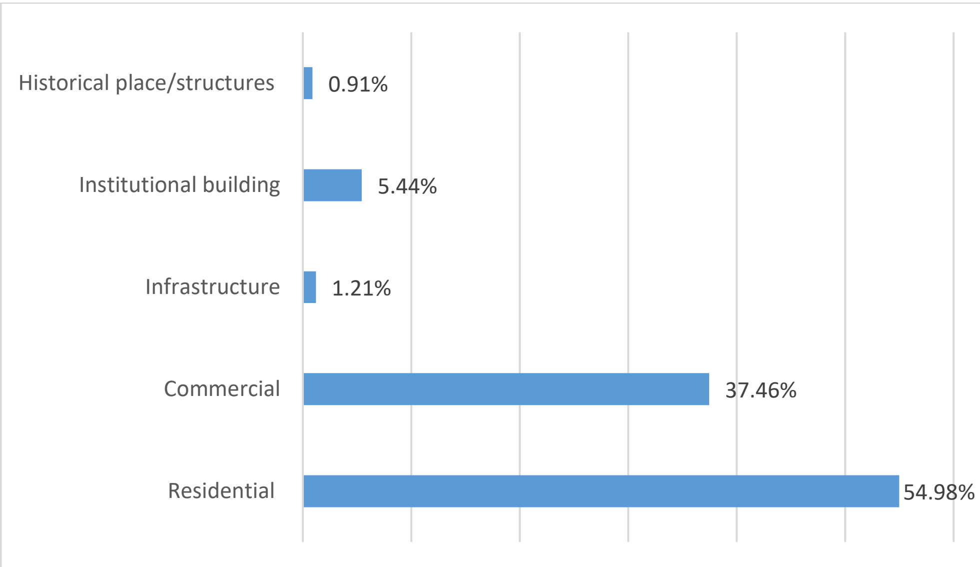


Source: National Statistics Bureau, 2018

Figure 5.7: School/institute attendance rate

5.1.5 Land/Property Holding

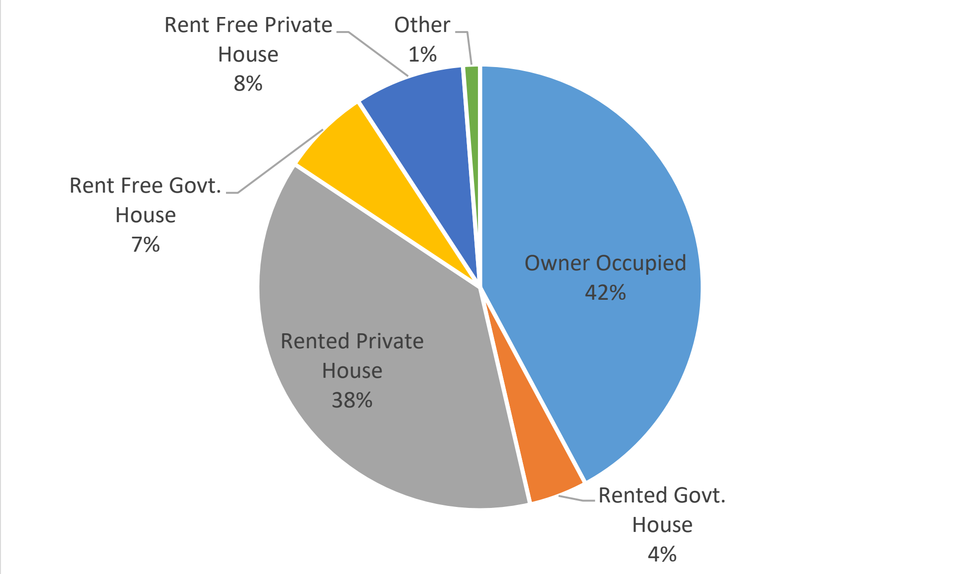
As the survey found, the majority of the surveyed properties are used for residential purposes (54.98%), followed by commercial (37.46%). There were also 5.44% institutional buildings.



Source: Household survey, FEMD, 2019

Figure 5.8: Uses of surveyed structure

Of these houses/properties, 42% are occupied by owners, followed by 38% as rented private house. These both categories together with rent free-private house (8%) shows that the majority land and properties (88%) are privately owned. Whereas, the government-owned land and properties comprises of 11% only.

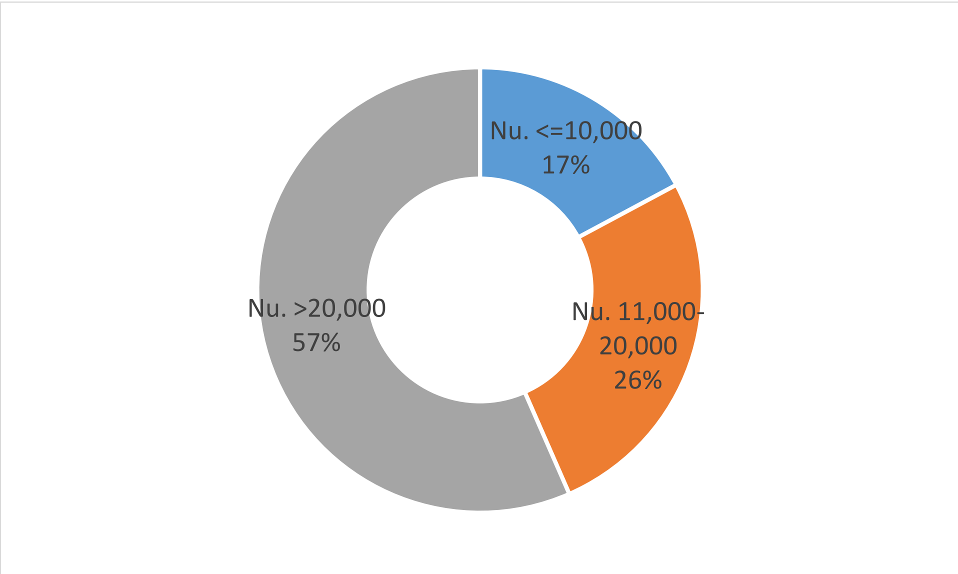


Source: National Statistics Bureau, 2018

Figure 5.9: Distribution of Property occupancy

5.1.6 Household Income

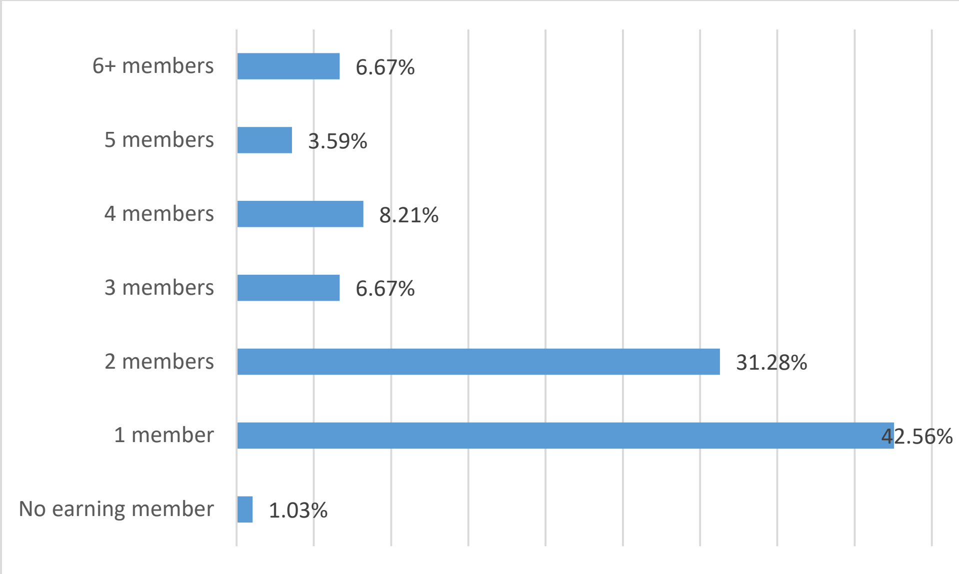
Out of total surveyed population, about 57% earned more than Nu. 20,000 monthly. Whereas, about 17% earned less than Nu. 10,000 per month.



Source: Household survey, FEMD, 2019

Figure 5.10: Distribution of family income

The majority families have one or two earning members, whereas about 1.03% families have no earning member. Agricultre is the dominant sector of earning, which is followed by petty business and service employement.

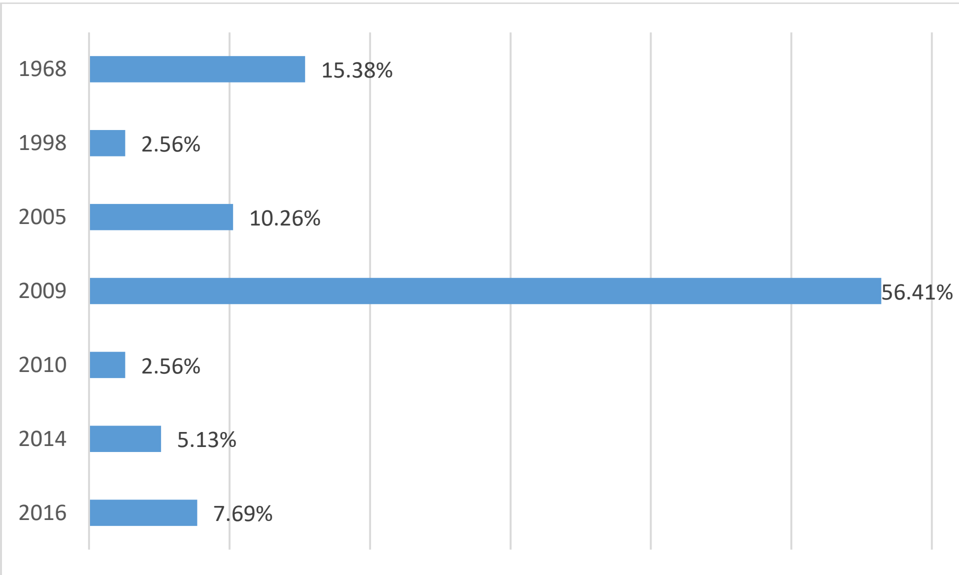


Source: National Statistics Bureau, 2018

Figure 5.11: Earning member per family

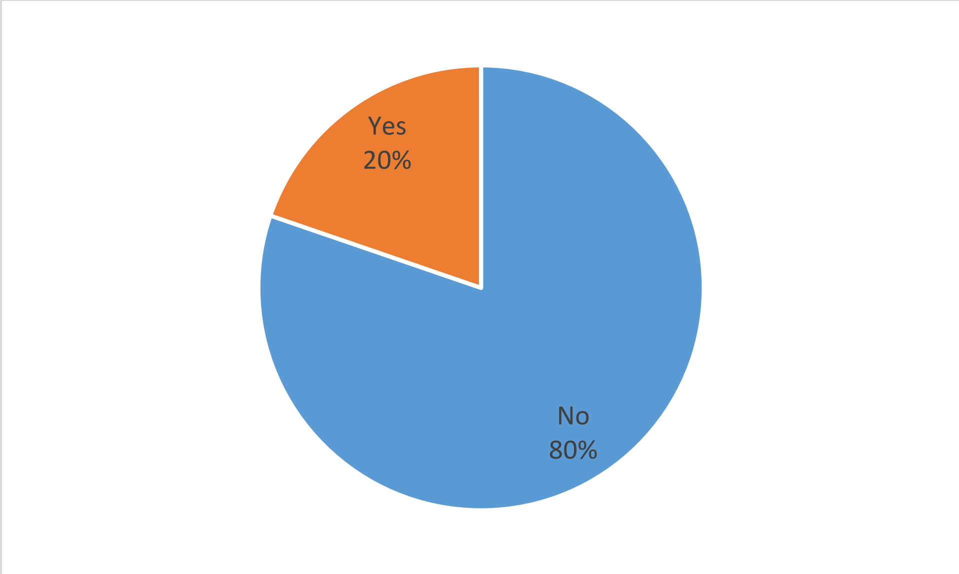
5.1.7 Effect of Flood on Assets and Property

The local people reported that their wetland and houses have been flooded for the last 40 years. Some reported that their timber/trees and land were washed away, their basement floor remained inundated for a certain time period, etc. Flood in 2009 was the most notable one which affected houses, vegetable garden, interrupted agricultural activities. However, according to local reports a recently constructed wall has protected a few of flood victims.



Source: Household survey, FEMD, 2019

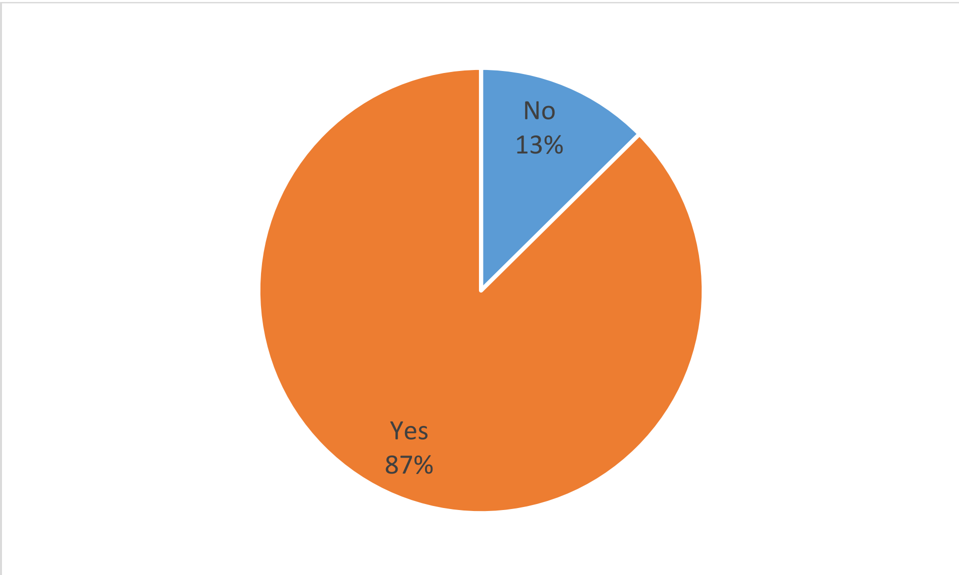
Figure 5.12: Reported flood affectedness by years



Source: Household survey, FEMD, 2019

Figure 5.13: Reported damages of crops and properties by debris

Of the flood affected people, however, about 20% reported their damages of both crops and other properties due to debris.



Source: Household survey, FEMD, 2019

Figure 5.14: Reported family savings to tackle flood emergency

Savings is an important financial capital, which can help the flood victims to get back to their earlier status immediately. About 87% of surveyed people reported to have saving to cope with the flood damage, whereas the remaining 13% whose income level is cooperatively lower reported having no saving for an emergency period.

5.1.8 Recurring Cost of Construction

The recurring cost for the Pa Chu and Do Chu is given in **Table 5.2**. For Pa Chu, total 34.7 Million Nu. was expensed for gabion works, masonry works, construction of culverts or river dredging during the period of 2009 to 2020 with an annual average of 2.9 Million Nu. On the other hand, 2.3 Million Nu was required for gabion works on the Do Chu during 2015 to 2016.

Table 5.2: Recurring cost of construction for Pa Chu and Do Chu

Name of River	Year	By Agency/Dzongkhag/Municipal office or gewog (insert as appropriates)	Structure type (Gabion works/masonry works/Dry wall/ culvert or river dredging)	Amount (Million Nu)	Remarks (Person(s) interviewed or source of Funding etc.)	Source
Do chu	2015-2016	Paro Dzongkhag (Dotey)	Gabion wall	2.3	RGoB	Dzongkhag
Pa Chu	2016-2017	Paro Dzongkhag	Gabion wall	1.4	RGoB	Dzongkhag
	2017	Paro Dzongkhag (Lamgong)	Gabion wall	0.8	RGoB	Dzongkhag
	2018	Paro Dzongkhag (Lamgong)	Gabion wall	3.0	RGoB	Dzongkhag
	2019	Paro Dzongkhag (Lamgong)	Gabion wall	5.0	RGoB	Dzongkhag
	2019-2020	Wangchang Gewog	Gabion wall	1.5	RGoB	Dzongkhag
	2016-2017	Paro Dzongkhag	Gabion wall	2.1	RGoB	Dzongkhag
	2016-2017	Paro Dzongkhag (Tsento)	Gabion wall	1.8	RGoB	Dzongkhag
	2012-2013	Paro Dzongkhag (Tsento)	Gabion wall	1.7	RGoB	Gup
	2017-2018	Shaba Gewog	Gabion wall	1.0	RGoB	Dzongkhag
	2017-2018	Shaba Gewog	Gabion wall	0.5	RGoB	Dzongkhag
	2019-2020	Shaba Gewog	Gabion wall	1.2	RGoB	Dzongkhag
	2009	Shaba Gewog	Bridge	9.0	RGoB	Gup
	2009	Shaba Gewog	Gabion Wall	3.7	RGoB	Gup
	2013	Shaba Gewog	Re-sectioning of Pa-chhu river	0.5	RGoB	Gup
	2016-2017	Paro Dzongkhag (Lungnyi)	Gabion wall	1.5	RGoB	Dzongkhag

5.1.9 Population Projection

National Statistics Bureau (NSB) conducted the second Population and Housing Census of Bhutan (PHCB) in 2017. The 2017 PHCB provides useful data to inform evidence-based policy making and plan formulation. The NSB, with technical support from UNFPA, prepared the population projections at the national levels as well as for the 20 Dzongkhags for a period of 30-years. Since the reference period of 2017 PHCB is 30th May, the projected population makes reference to the same reference period for future years. The population projections report at the national level presents the projected populations by age-sex distributions up to 2047 at the national level and projected total populations for each Dzongkhag. **Table 5.3** represents the population projection by sex from 2017-2047.

Table 5.3: Population projection by sex from 2017-2047

Year	Male	Female	Total
2017	23,941	22,375	46,316
2018	24,335	22,885	47,220
2019	24,735	23,402	48,137
2020	25,137	23,924	49,061
2021	25,540	24,450	49,990
2022	25,944	24,979	50,922
2023	26,402	25,510	51,912
2024	26,861	26,044	52,905
2025	27,320	26,579	53,899
2026	27,778	27,115	54,892
2032	30,475	30,302	60,777
2037	32,599	32,865	65,464
2042	34,581	35,312	69,892
2047	36,419	37,648	74,067

5.2 Flood Risk Assessment

For efficient flood management practice, knowledge of the present and probable future hazards and risks are required. This knowledge about the hazards and risks should include the type of floods (fluvial/ coastal/ flash/pluvial), the probability of a particular flood event, the flood magnitude, flood extent, water depth, flow velocity, consequences (on assets and people), etc. A Flood Risk Assessment (FRA) identifies the level of flood risk to a property or site. The flood risk can be defined as the following equation:

Flood risk = Flood hazard * (exposure) * vulnerability (of the society/ area)

The definition specifies the two quintessential elements of flood risk, namely floods posing a hazard, which means that they potentially have harmful effects, as well as a vulnerable society/ area, which means that it can be harmed by those floods. Without exposure to a certain flooding depth, not even a very vulnerable society/area will be harmed. So, if any one of these elements is zero, there is no flood risk. On the other way, flood risk can be defined as the combination of the probability of a flood and its consequences.

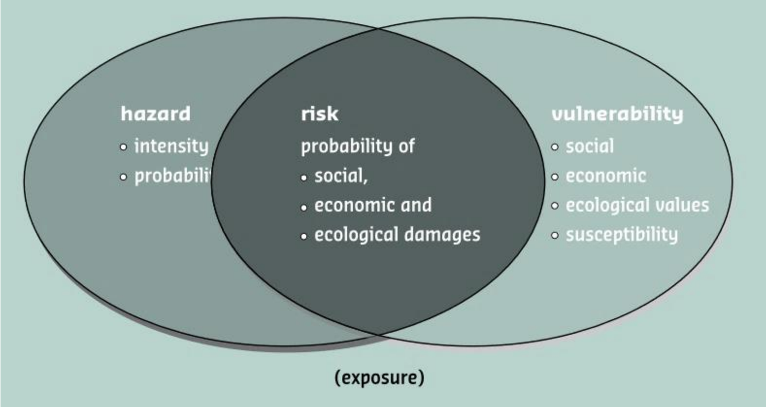


Figure 5.15: Flood risk and its components

5.2.1 Flood Hazard Assessment

Hazard may be defined as a source of potential harm or a condition that may cause loss of life or initiate any failure to the natural, modified or human systems. Regarding hazard identification and estimation, two approaches can be identified based on the ANCOLD Guidelines (2003) and the ISDR principles (2004): traditional deterministic approach and probabilistic approach. Probabilistic approach is mainly used for flood hazard assessment. It is based on the theory of probability and regards hazard estimation as the estimation of the probability of occurrence of a particular natural event with an estimated frequency within a given period of time. It can be applied on hazards of natural origin and it represents a very common method used in most flood plain delineation studies when the potential for loss of life is considered negligible in terms of historical floods. The probabilistic approach tends to assume that events in the future are predictable based on the experience of the past. Now a day, the application of hydraulic model in flood hazard assessment is becoming popular. In this study, the flood extent and flood depth maps (**Figure 4.9 – Figure 4.20**), generated for different return period using hydrological and hydrodynamic modeling were used as flood hazard assessment.

5.2.2 Flood Vulnerability Assessment

Flood vulnerability can be expressed as the extent of harm, which can be expected under certain conditions of exposure, susceptibility and resilience.

Vulnerability = Exposure + Susceptibility – Resilience

Water resource systems are vulnerable to floods due to three main factors; exposure, susceptibility and resilience.

Exposure: Exposure can be understood as the values that are present at the location where floods can occur. These values can be goods, infra-structure, cultural heritage, agricultural fields or mostly people. The indicators for this component can be separated in two categories; the first one covers the exposure of different elements at risk and the second one give details on the general characteristics of the flood.

Susceptibility: Susceptibility relates to system characteristics, including the social context of flood damage formation. Especially the awareness and preparedness of affected people regarding the risk they live with (before the flood), the institutions that are involved in mitigating and reducing the effects of the hazards and the existence of possible measures, like evacuation routes to be used during the floods.

Resilience: Resilience to flood damages can be considered only in places with past events, since the main focus is on the experiences encountered during and after the floods.

Flood vulnerability for the Pa Chu, Do Chu and eight streams were assessed based on methodology and questioner survey as described in *Detailed Flood Risk Assessment for Paro Dzongkhag* report (FEMD 2019b), conducted by FEMD, Bhutan. In the vulnerability assessment, five land use categories, namely residential, commercial, infrastructure, institution (including hospitals) and historical place were selected as vulnerable land use due to flood. Total 408 questioner survey were conducted for five different land use category. The number of the questionnaire survey samples collected for each category and sub-category is summarized in **Table 5.4**.

Table 5.4: Questionnaire categories and sample sizes

SI.No	Landuse category	Sub categories	Questionnaire Samples
1	Residential	Core town (Paro town)	28
2		Satellite town (Bonde town)	28
3		Rural (other areas)	126
4	Commercial	Core town (Paro town)	50
5		Satellite town (Bonde town)	28
6		Rural (other areas)	46
7	Infrastructure	Infrastructure	4
8	Institution	Hospital	1
9		Each school	4
10		Other institutions	13
11	Agriculture	Wet land	26
12		Dry land	54
	Total		408

Sources: FEMD, 2019b

For each land use category and sub-category, the vulnerability was estimated for four different indices, namely social, economic, physical and exposure based on the survey data. Finally, vulnerability for each category were estimated using the weighted average of each index. **Table 5.5 to 5.8** shows the estimated vulnerabilities for different landuse. The spatial extent for the vulnerability was selected as 600 m buffer region of the Pa Chu and Do Chu as per the longest distance of concerned agricultural areas by local residents from the main rivers while 100 m buffer for the streams was kept considering the maximum flood extent during extreme event.

Table 5.5: Vulnerability index estimation for residential land use category

Residential Category	Vulnerability Index			Weight
	Paro town	Bonde town	Rural	
Social	49.3	47.9	54.1	25
Economy	43.5	45.1	45.8	25
Physical	36.8	58.5	51.6	25
Exposure	28.1	45.6	66.1	25
Vulnerability Index	39.4	49.3	54.4	

Sources: FEMD, 2019b

Table 5.6: Vulnerability index estimation for commercial land use category

Commercial Category	Vulnerability Index			Weight
	Paro town	Bonde town	Rural	
Social	57.9	51.4	67.9	25
Economy	47.7	44.4	52.1	25
Physical	26.7	47.3	45.5	25
Exposure	27.0	36.1	79.0	25
Vulnerability Index	39.8	44.8	61.1	

Sources: FEMD, 2019b

Table 5.7: Vulnerability index estimation for institutional land use category

Institution Category	Vulnerability Index						Weight
	Institution	NIE	School1	School2	School3	School4	
Social	43.4	68.8	39.5	75.0	48.0	50.0	25
Economy	57.8	66.7	33.3	66.7	38.8	66.7	25
Physical	34.6	13.3	54.2	80.0	67.5	53.3	25
Exposure	28.0	57.1	14.3	39.3	7.1	14.3	25
Vulnerability Index	40.9	51.5	35.3	65.2	40.4	46.1	

Sources: FEMD, 2019b

Table 5.8: Vulnerability index estimation for agriculture land use category

Agriculture Category	Vulnerability Index		Weight
	Wet Land	Dry Land	
Crops	100.0	40.3	100
Vulnerability Index	100.0	40.3	

Sources: FEMD, 2019b

The overall vulnerability index for the study area was estimated based on the vulnerability index of different land use categories using the following equation.

Vulnerability Index = Wr* Residential Vulnerability Index + Wc* Commercial Vulnerability + Wi*Institution Vulnerability + Wa*Agriculture

Where, Wr, Wc, Wi, and Wa represent the weightage of residential, commercial, institutional and agriculture vulnerability indices respectively.

Equal weightage was considered for vulnerability index estimation for this study. Finally, index value was normalized within the range of 0 to 1 and shown in **Figure 5.16**. It was found from the map that relatively higher vulnerable area located along the Pa Chu and Do Chu. Paro core town has moderately flood vulnerability. The streams have comparatively lower vulnerability than the main rivers.

5.3 Flood Risk Mapping

Flood hazard map and flood vulnerability map were used to estimate flood risk map using the following relation.

Flood Risk Map = Flood Hazard Map * 50 + Flood Vulnerability Map* 50

Generated flood risk map for Paro Dzongkhag is shown in **Figure 5.17 and 5.18.** It was observed from flood risk map that Paro Town falls under risk of flooding from Pa Chu from inundation in Nemjo area, where irrigation channel intake is constructed at present. Besides, Lungnyi, Dopshari, Lamgong and Hungrel Gup office, Thuksel Private School, Shaba Primary School, Bondey vegetable market area, and stretches of residential and agriculture area were found under relatively higher flood risk zone. Flood risk map for 50 and 100 year return period is given in Appendix-III.

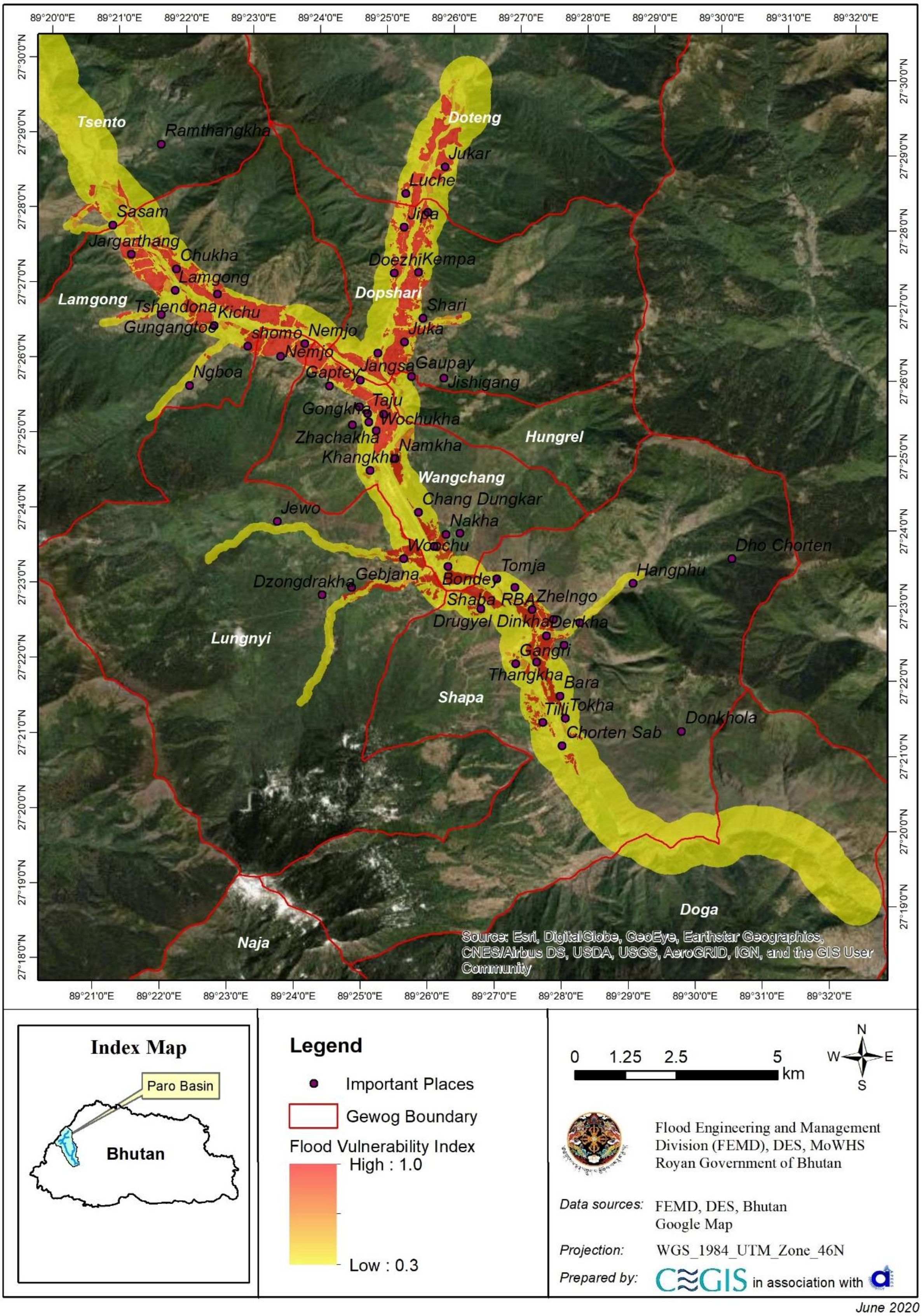


Figure 5.16: Flood vulnerability map for Paro Dzongkhag

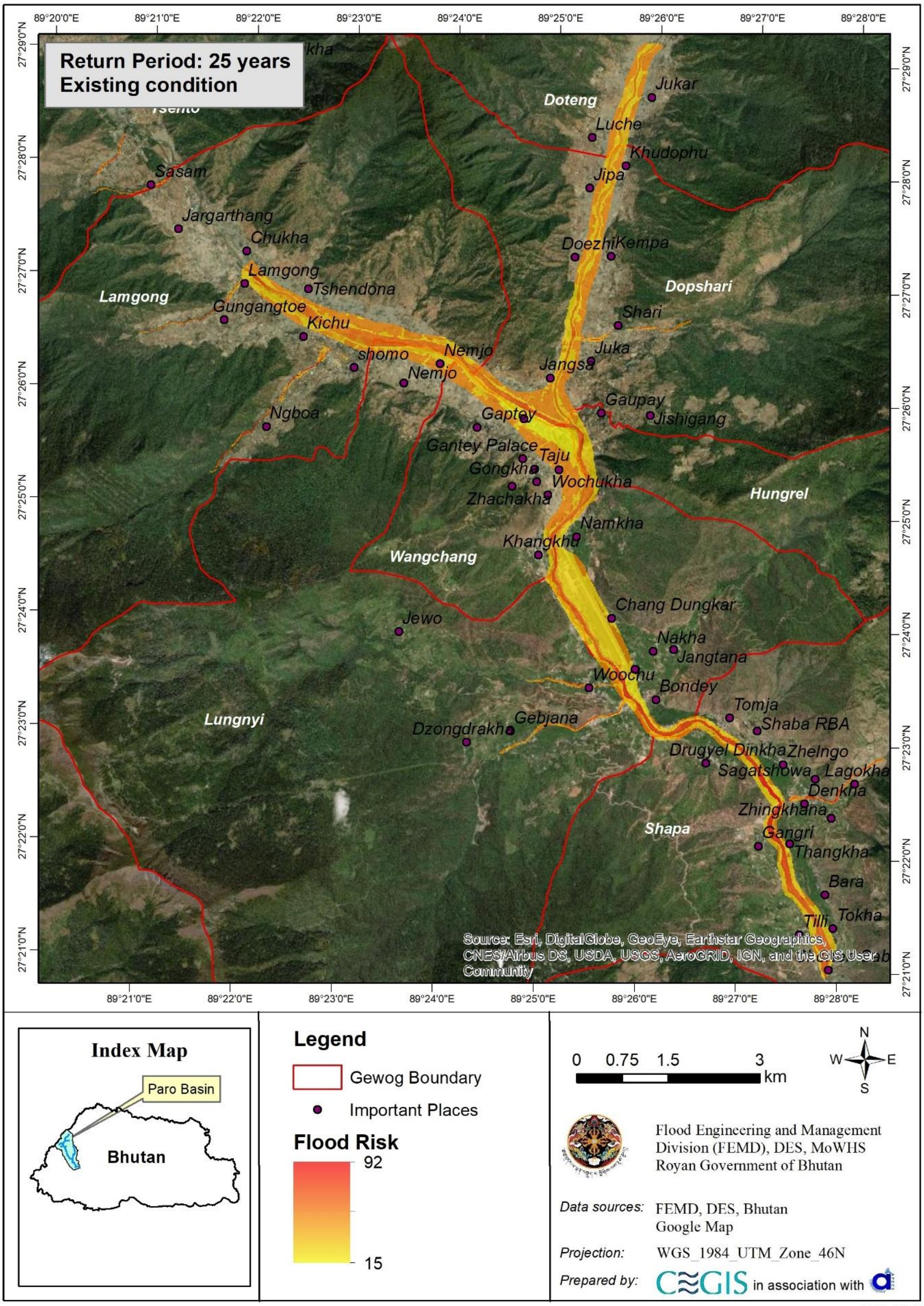


Figure 5.17: Flood vulnerability map for Paro Dzongkhag for existing condition

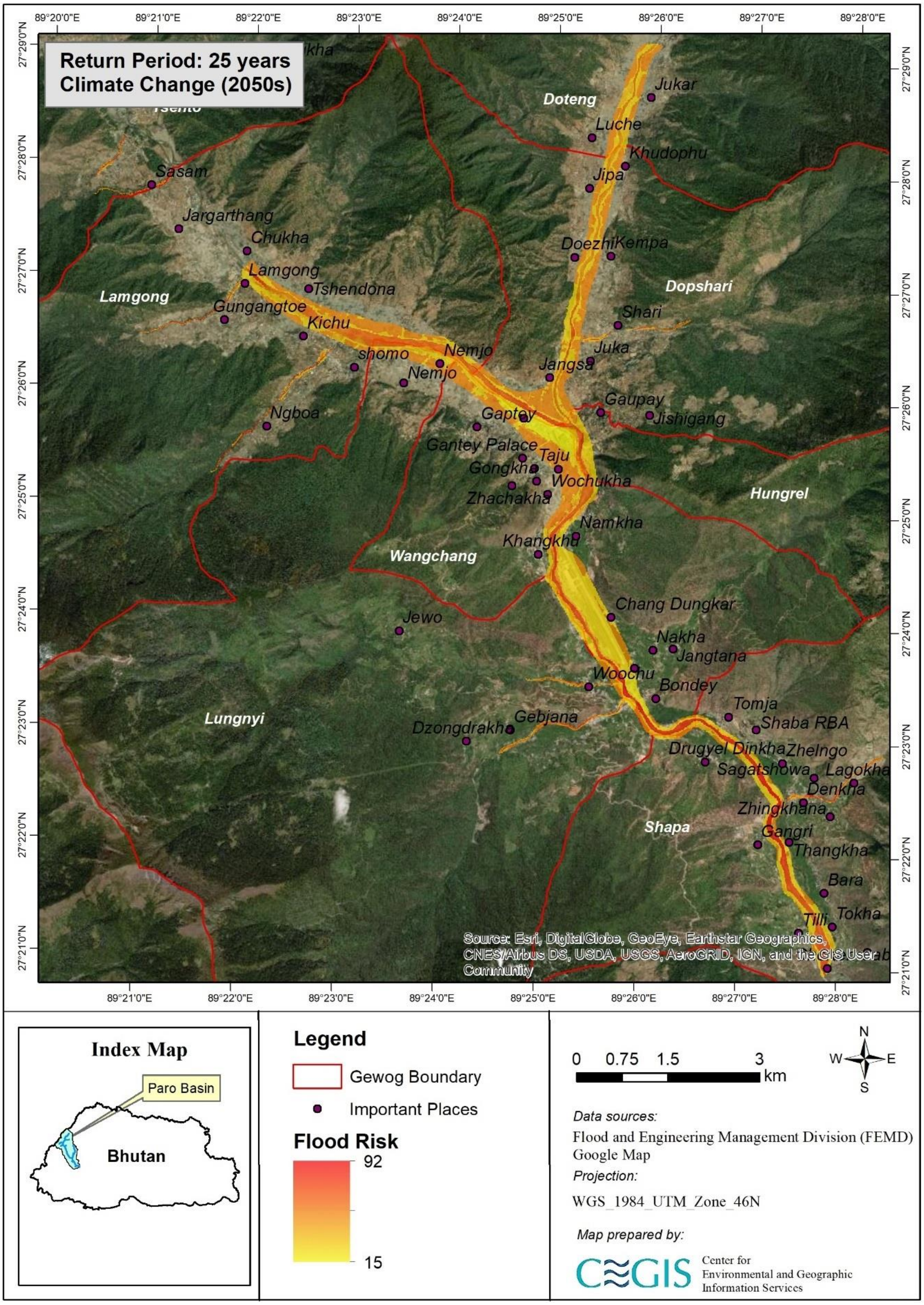


Figure 5.18: Flood risk map for Paro Dzongkhag for existing condition

5.4 Flood Damage Assessment

The assessment of flood damage in the connection with flood risk management is a relatively new concept. In flood damage assessment, hydrological knowledge (e.g. flood frequency analysis, inundation modeling and damage corresponding to flood depth are combined. There is mainly two type of flood damage: i) direct damage occurs due to direct contact with floodwater, and ii) indirect damage occurs as a consequence of flood event. In this study direct flood damage on residential, commercial, and agriculture was estimated. Flood damage was assessed based on sample based questioner survey conducted by FEMD where data on present value of residential and commercial buildings, present value of properties and probable damage for different magnitude of inundation were collected. Based on that data, a depth-damage relationship was established for different land use. The depth-damage curve, in combination with the inundation depth, flood damage was estimated for certain return period of flood. The depth-damage curve for residential and commercial building considering only the ground floor are shown in **Figure 5.19**. The damage curve for Asia agriculture (**Figure 5.20**) was adopted from *Huizinga et., al, 2017*.

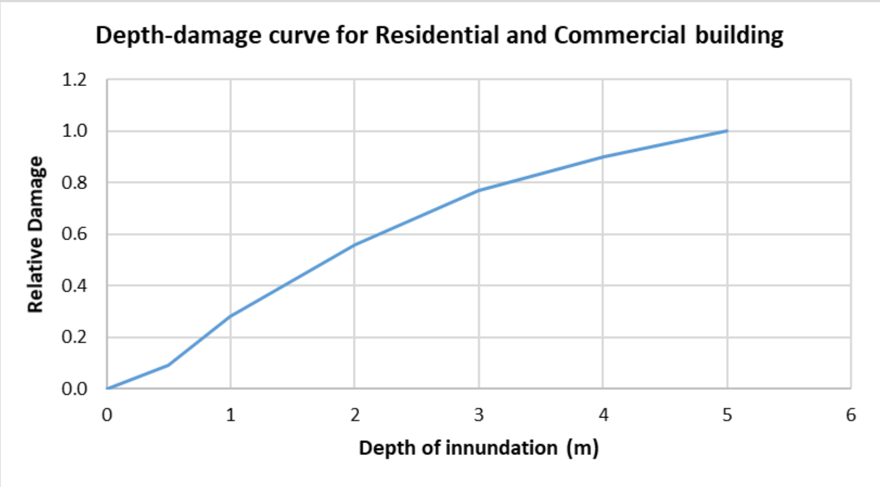
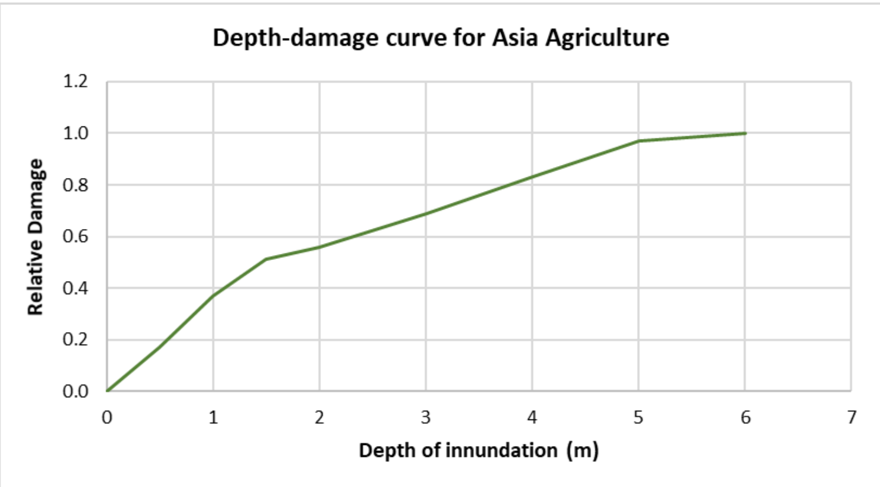


Figure 5.19: The depth-damage curve for residential and commercial building (assuming only ground flood)



Source: Huizinga et., al, 2017

Figure 5.20: The depth-damage curve for Asia agriculture

From survey data analysis, present value of building and properties are assessed only for the ground floor as the flood depth in the Paro Dzongkhag area are only limited within the ground floor (**Table 5.9**). Present value of ground floor was approximated by equal distribution of building and properties value among the stories.

Table 5.9: Present value of building and properties (only for ground floor)

Location	Present value of building (Million Nu.)	Present value of properties (Million Nu.)
Paro Town	3.67	2.17
Bondey Town	2.64	1.35
Rural	3.62	1.22

The concept of hydro-economic EAD (Expected Annual Damage) model was used to estimate flood damage for residential, non-residential and agriculture as shown in **Figure 5.21** and **5.22**. The bottom left panel shows the probability distribution of flow rates. The stage-discharge relationship is shown in the top left panel, and flood damage curve in the top-right quadrant. These three relationships yield the damage-probability curve (bottom right panel). Considering the concept of EAD = probability x consequence, the area under the damage-frequency curve represents expected annual damage due to flood.

From the hydro-economic EAD model, the expected annual damage was estimated as 10.5 Million Nu. for residential and non-residential buildings and properties and 0.29 Million Nu. for agricultural damage for existing condition.

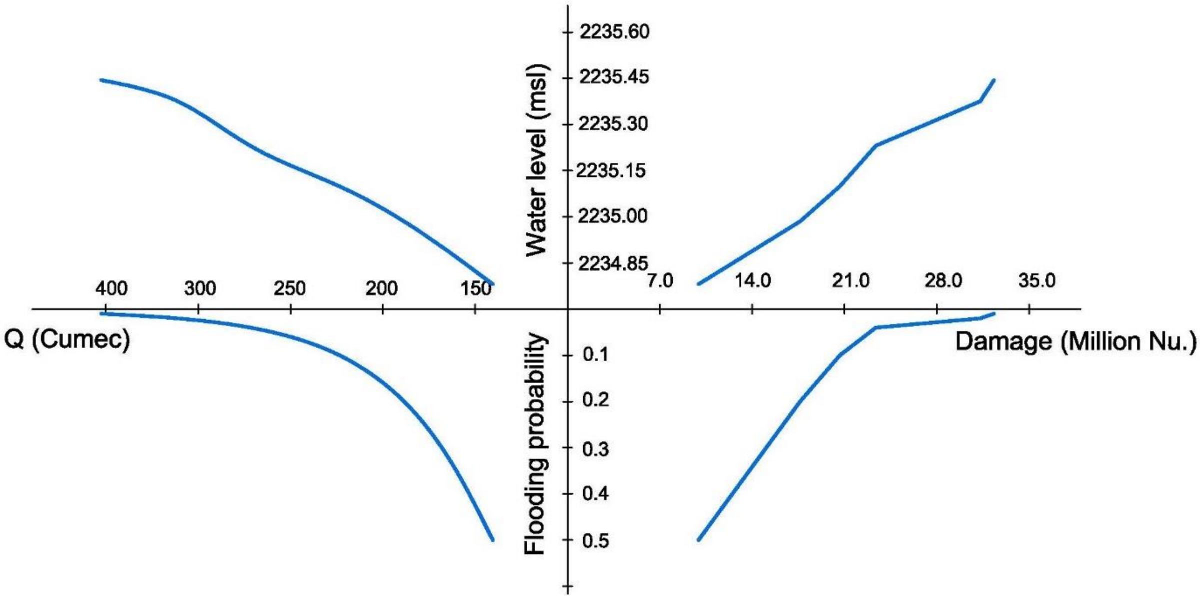


Figure 5.21: EAD model for residential and non-residential buildings and properties

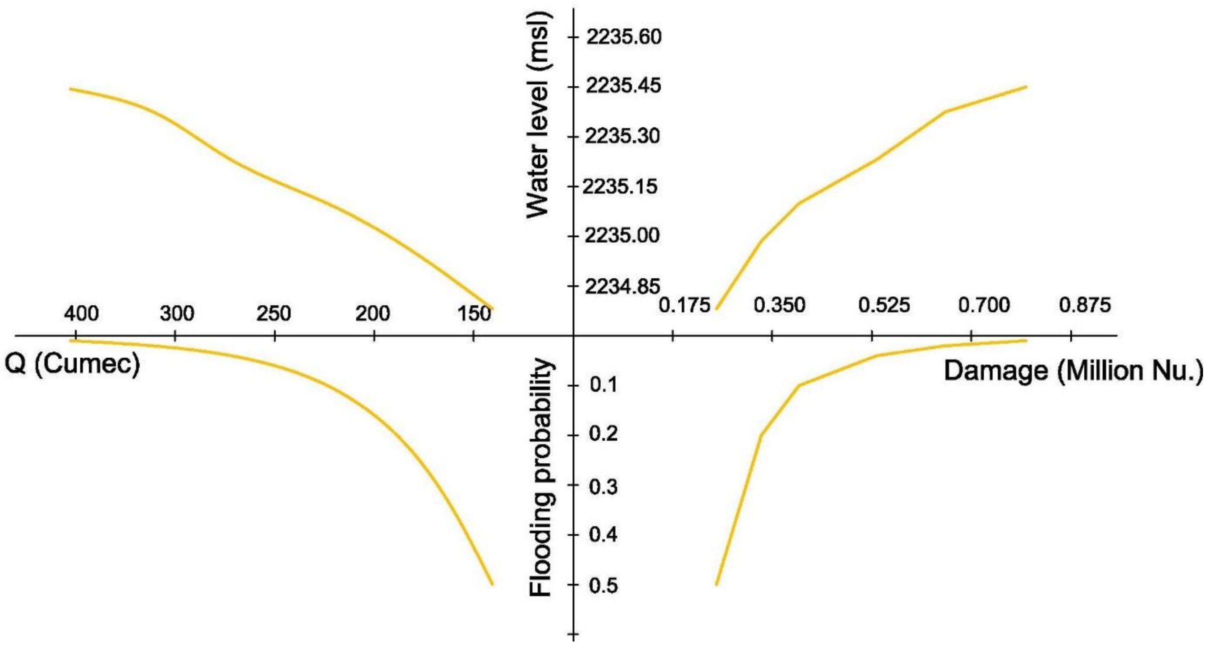


Figure 5.22: EAD model for Agriculture

Flood damage for residential and non-residential properties as well as agricultural damage were estimated and given in **Table 5.10**.

Table 5.10: Estimated flood damage for residential and commercial

Location	Expected annual damage (Million Nu.)	
	Existing condition	Climate Change
Residential and non-residential buildings and properties	10.5	14.7
Agriculture	0.29	0.34

5.5 Flood Risk Assessment through SPRC Model

Effective flood management/ mitigation measures can be derived through effective flood risk assessment. An effective means of visualizing flood risk is the Source – Pathway – Receptor – Consequence (SPRC) conceptual model (Sayers et al 2002). Large-scale flood risk studies have adopted the SPRC model for system state descriptions within broader conceptual frameworks such as the Driver – Pressure – State – Impact – Response (DPSIR) (Evans et al., 2004). However, there is no widely accepted rigorous definition of the model which enables it to be more flexible in that it can be tailor-made to fit the study region and its ambient environment and drivers.

Flood risk can be reduced either by reducing the flood probability or reducing the consequences. The best solution is location-specific considering the hazard and vulnerability. The Source-Pathway-Receptor-Consequence (SPRC) model has been used for analyzing flooding risk and formulating mitigation measures for this project. The cause of the risk of flooding (source) is often beyond control. The pathway of the flood in terms of the topography, land use and the stream network can be managed to a limited extent. The impacted recipients (people and property) can be managed most. People and property can be protected, or if possible, moved out of the way of the flood.

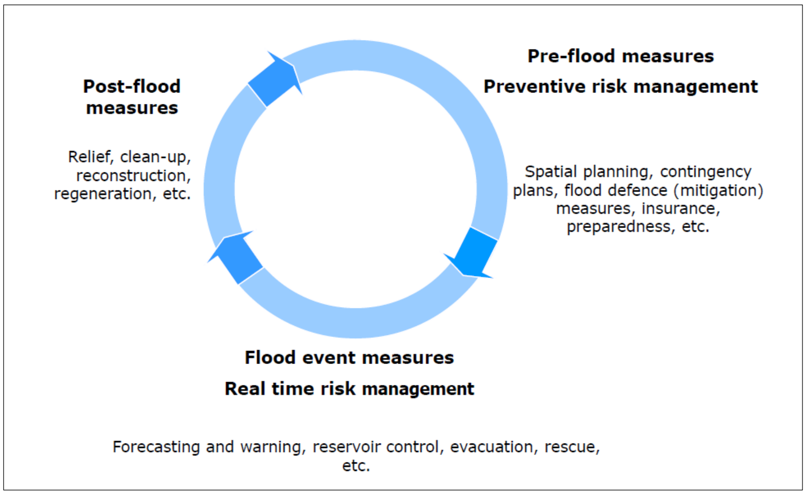


Figure 5.23: Three phases of flood risk management

5.5.1 Conceptualization of SPRC Model Components

Figure 5.24 illustrates application and components of the SPRC model.

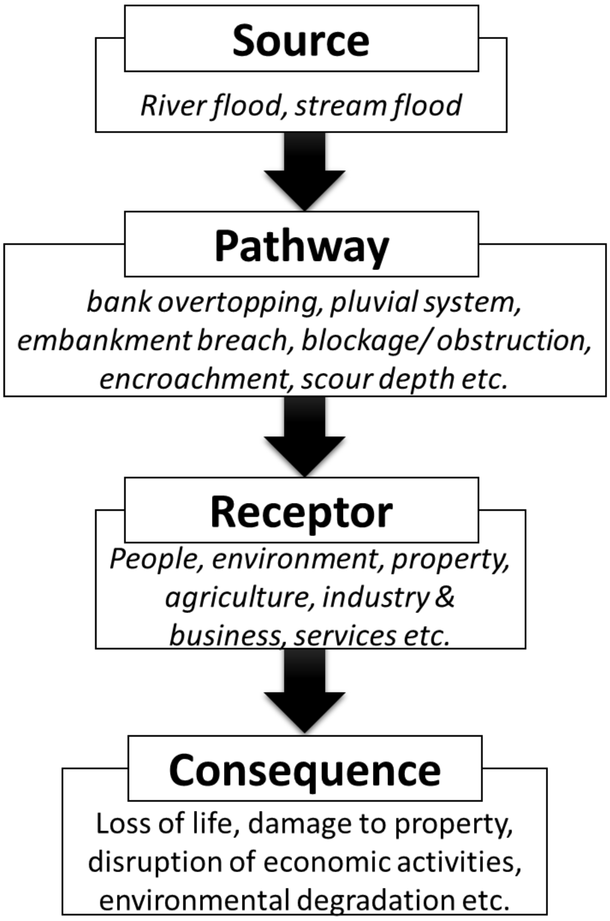


Figure 5.24: Components of Applied SPRC Model in Paro FMP

Each element of the coastal area system needs to be defined at an appropriate level of detail. For this study, the components have been defined as following:

Sources (river flooding due to combination of rainfall, snowmelt, GLOF, Landslide etc.)

Pathways (bank overtopping, pluvial system, embankment breach, blockage/ obstruction, encroachment, scour depth etc.);

Receptors (people, environment, property, agriculture, industry & business, services etc.); and

Consequences (loss of life, damage to property, disruption of economic activities, environmental degradation etc.).

The range of information required to undertake a very detailed flood risk assessment is beyond the study scope as such a study on an area the size of this site at anything more than a cursory level is immense. For this purpose, assessment was done at a coarser level, starting with a basic level of information at the whole basin scale, based on existing landuse of the basin and introducing more detail through firsthand knowledge gained during detailed field assessments and combining that with model generated outputs. Consequently the S-P-R-C analysis for the Paro basin has been done at basic level with a unidirectional systems approach which is explained in following paragraphs. The unidirectional systems approach has been adopted as river flood has been found to be the only viable cause of damage within the area, especially as GLOFs are very scarce in recent times. Due to the large area and relatively small area of affect, focus has been given to the two rivers within the basin and adjacent floodplain regions (**Figure 5.25**).

Sources

Prediction of the source variables is a logical start and a necessary prerequisite for all detection and flood forecasting methods in the area. The assessment of the flood discharge, water levels and corresponding velocities as the Paro basin has both steep surface slopes as well as river longitudinal slopes. This coupled with rainfall and snowmelt has the potential to generate hefty surface runoff that quickly accumulate into the rivers and flow downstream. The previous chapters have analyzed hydro-meteorological data for the stations within the region as well as generate projections for climatic data and generate flood discharge for varying return periods. These are the quantifiable sources for the predictant model.

Pathways

In this study site, the pathways are primarily the steep longitudinal river slope, basically the passage way of flood flow into the floodplain and other adjacent locations. These include overtopping of banks, breach in existing embankment/ bank protection structures etc. Along the river banks, and certainly within the basin itself, the flood defense type and construction can vary over very short distances. Information on crest levels, condition, age, beach mobility and so on have been assessed from the detailed field visit. Potential pathways have been identified in the S-P-R-C diagrams. The most likely pathways have been identified by combining information on the structures with the source information. That is, for example, where there is a long reach of embankment/ gabion protection that is vulnerable due to height/ bed scouring.

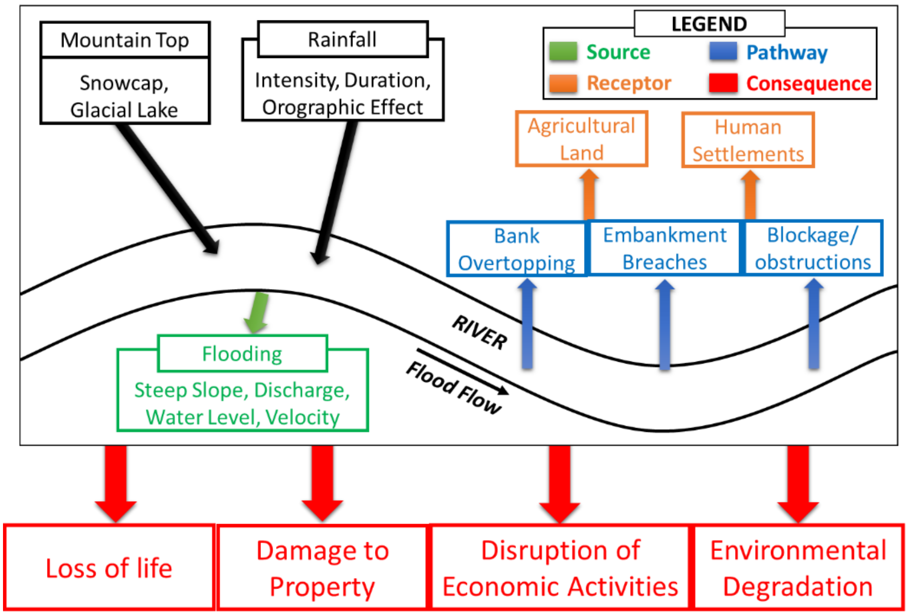


Figure 5.25: Schematic representation of SPRC for study region (Pa Chu River)

Receptors

The land-use data at local scale was received from FEMD and linked to the local background mapping. Receptor regions have been identified on the basis of land use and limited, where appropriate, by applying topographic information. The prime receptor in this case is the agricultural land that is in abundance on both banks of the rivers. Also, the settlements along Pa Chu especially, are prone to flooding.

Consequences

This is the stage where the flood areas are combined with socioeconomic and ecological information to define damage or benefits in terms of financial measures. In this particular case, flood directly impacts agriculture and urban setting along river banks. In relevance, the impact to business, industry is somewhat indirect.

5.5.2 Application of SPRC Model

The following **Figure 5.26** presents the Source-Pathway-Receptor (SPR) map for the Paro Basin with the different elements classified as per landuse of the region. Mostly, the region exhibits mountainous terrain with high elevation and steep sloped gradually forming the rivers downhill. Both banks of the rivers are dominated by agricultural practices with prominent human settlements in a few locations.

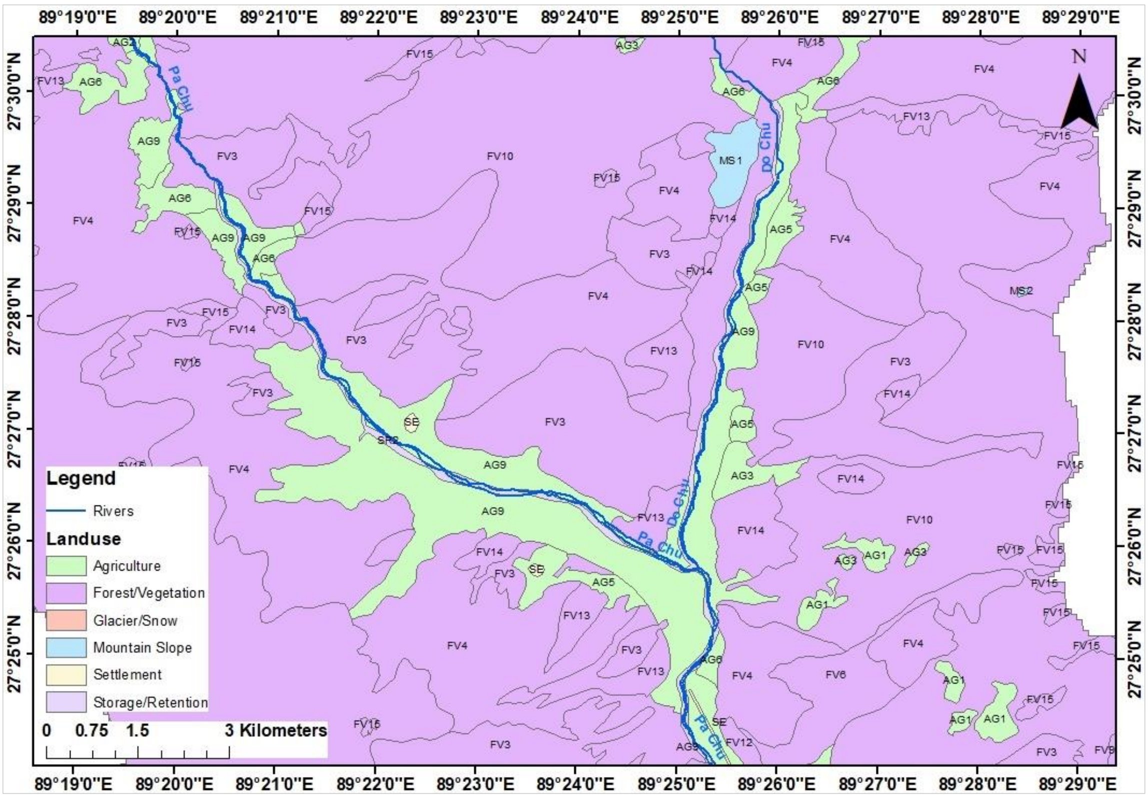


Figure 5.26: Paro basin (Pa Chu and Do Chu) SPR map with elements classified by landuse

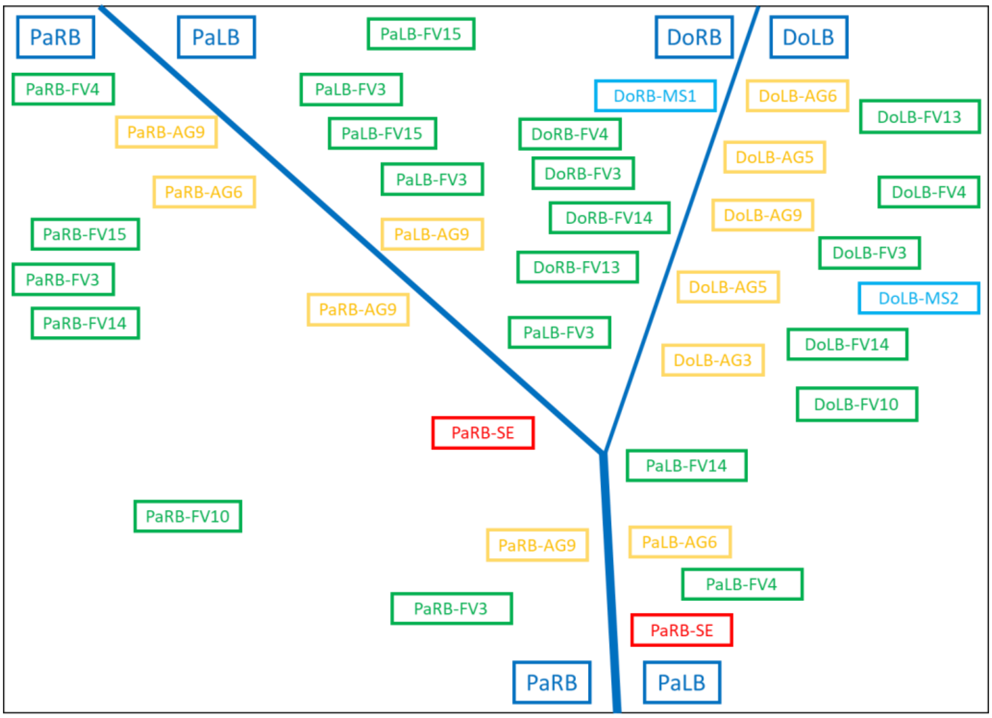


Figure 5.27: Simplified stretched schematic of the combined Paro Basin showing various elements of interest on both banks as well as source (river: flooding)

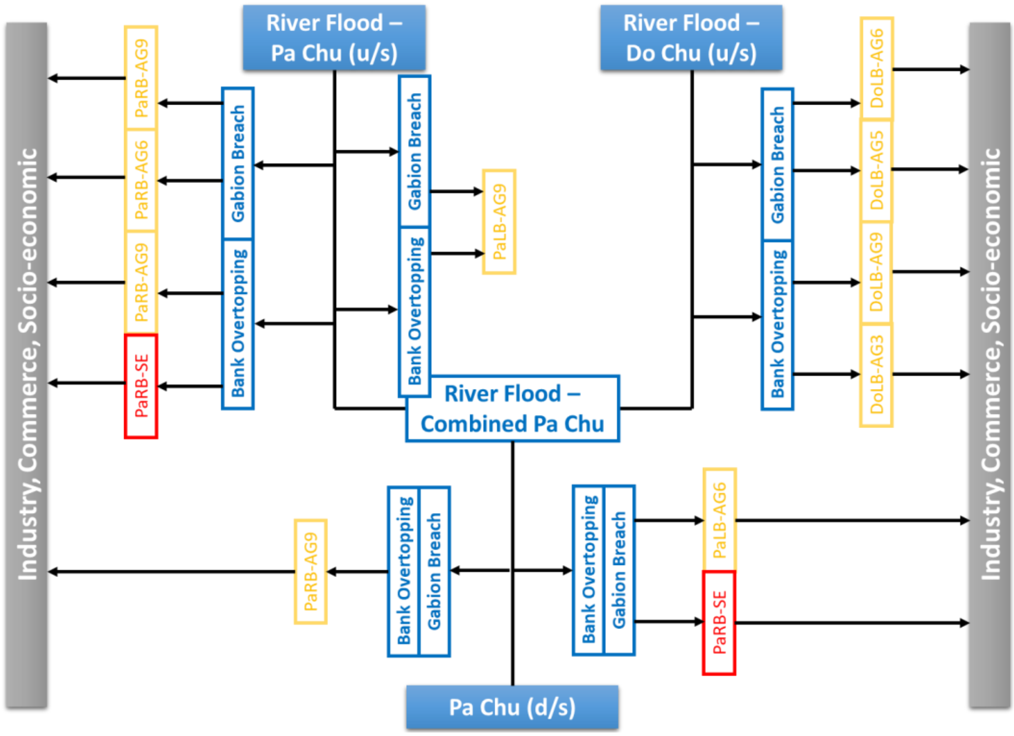


Figure 5.28: Unidirectional SPR system diagram with sources from one direction, illustrating the linkages between sources and elements along both banks of the rivers in the study region

The simplified stretched schematic of the combined Paro Basin presented in **Figure 5.27** shows the various elements of interest on both banks as well as source, conveyed through the two rivers. Flood flow enters the valley due to either bank overtopping or breach in existing river embankments namely the gabion structures. At locations the structures have been breached and in many locations, they have collapsed or are on the verge of collapsing due to bed souring, as scour depth have not been taken into consideration during design.

A unidirectional SPR system diagram has been presented in **Figure 5.28**. The SPR system diagram in the figure allows a rapid broad-scale assessment of the flood system within the Paro Basin. Receptors identified using this approach enables to pinpoint specific engineering and flood management issues such as the necessity of increasing channel conveyance in particular sections and alternatively rehabilitate existing embankment layout. This has helped identify critical locations that are more vulnerable to flood along both rivers and to pinpoint engineering measures, which were later verified via detailed field visit.

6. Mitigation Measures

6.1 Introduction

Flood Management for Paro Dzongkhag has been perceived and conceptualized through a combination of firstly review of available literature and application of field knowledge and mathematical modeling exercises. Formulation of proper mitigation measures and adaptation options against the flood hazards considering the climate change impact in Bhutan calls for reviewing the existing knowledge base regarding impact of climate change induced disasters in Bhutan and measures taken so far. This was more so the case for Paro as this was not a virgin location flood management-wise wherein prominent measures have already been taken especially along the two governing rivers, Pa Chu and Do Chu. As such, preliminary identification of measures and their locations as well as reasoning behind said measures were ascertained through literature, followed by two successive field visits to get a firsthand idea of both field conditions and location and consequent impact of applied measures. The finding of the past studies taken in this regard facilitated the study team to do a preliminary conceptualization of the prevailing scenarios and other associated issues. After which, field experience coupled with hydrological and hydrodynamic modeling was used to devise potential set of flood management measures and thus formulate subsequent strategies. This chapter further elaborates on the aforementioned activities that have already been explored and expanded in previous chapters and provides details on the formulation of flood management strategies and measures.

6.2 Flood Management Concept

The Paro Valley exhibits a mountainous terrain with jagged ravines making for flashy surface runoff accumulation into the nearby channels. Steep longitudinal slopes in both the rivers and associated streams result in high velocity flood flow which when obstructed has the potential for causing devastating flooding. Although this might not be prolonged events but still can impound serious damage if left unchecked. Proper flood flow management measures are thus of order for both the rivers and the 8 streams in question. The measures devised from the study has been done so through the chronological completion of each and every study activity. **Figure 6.1** illustrates the conceptualization, realization, formulation and validation of flood management measures. Conceptualization of measures initiated during literature review and continued through the reconnaissance visit. Then the concepts materialized during the detailed field visit to the study region whereby a tentative list of measure and associated locations were selected. These measures were then finalized through data analyses and hydrological modeling exercises where appropriate river and stream flow were generated to ascertain the measures required for flood management. The formulated measures were then validated through hydrodynamic modeling of rivers and streams and after proper qualitative and quantitative analyses, measures were finalized and subsequently clustered for incorporation within the flood management plan. A number of criteria and type can be attributed to categorizing the devised measures, among which they overlap. These include the following –

- Timing (Pre-, During- & Post-Flood) such as forecasting/ early warning;
- Structural/ non-structural measures such as embankment/ flood zoning;
- River/ stream specific measures gabion/ bush clearing; and
- Site specific measures such as culverts.

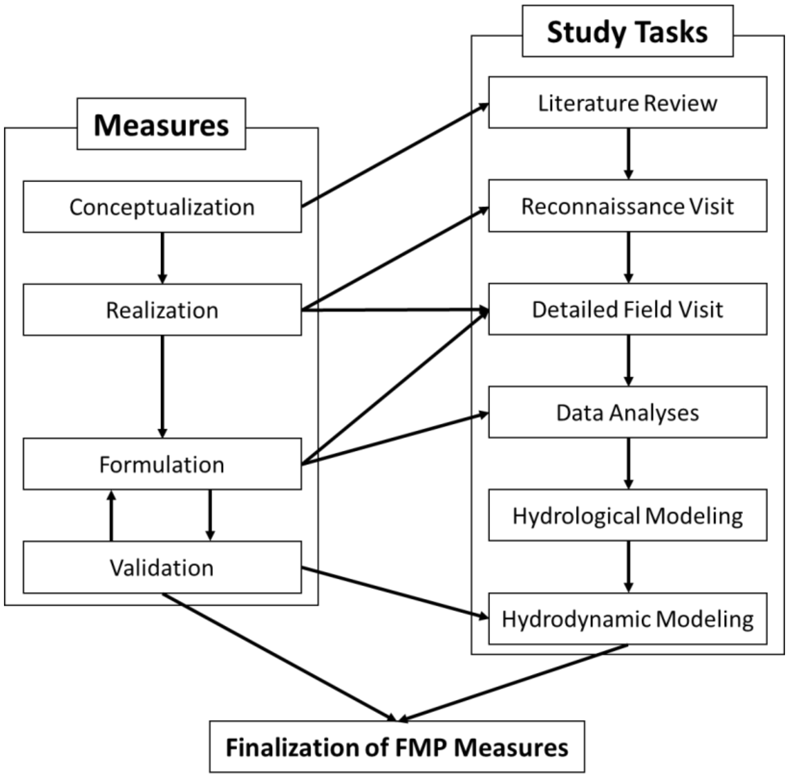


Figure 6.1: Conceptualization and gradual formulation of FMP measures

Since Glacial Lake Outburst Floods (GLOF) are somewhat of a rarity in the Paro in the recent decades, this Flood Management Plan primarily deals with river flooding which are of a flashy nature given the topography of the Dzonkhag. With a mean elevation of 3790 m and elevation ranging from 2090-7064 m within a seemingly small area of just over 1260 square kilometers, any water droplet that were to befall on higher elevation surface takes minimal time and effort to reach the nearest flowing channel. These channels converge into the prime outlet within the basin, Pa Chu. Without considering the miniscule contributions from GLOFs, the prime contributors to excess surface runoff thus flooding are the following –

- Glacier melted flow
- Rainfall during monsoon

The above two contributors, coupled with the fact that runoff surface is more of the semi to impermeable nature, water flows quickly through steep sloped surface and onto nearby channels and accumulates into rivers. **Figure 6.2** presents the hypsometric plot for Paro Basin. It illustrates the steep slope nature of the area. **Table 6.1** presents the corresponding data. It can be seen from the figure that there is a sharp dip near the end. This dip can also be surmised from observing the corresponding table, which indicates that this dip reflects the high percentage of area lying at a relatively smaller range of elevation. To elaborate, if we observe the red highlighted row in the table, it states that 54% of land area of the basin falls within the elevation range of 2090-4000 m that is less than a 2000 m range. This indicates that although there are lesser elevation bands in between the transition from high to low surface i.e. the basin possesses high terrain which takes a sharp transition into relatively mild terrain, increasing potential for flow accumulation.

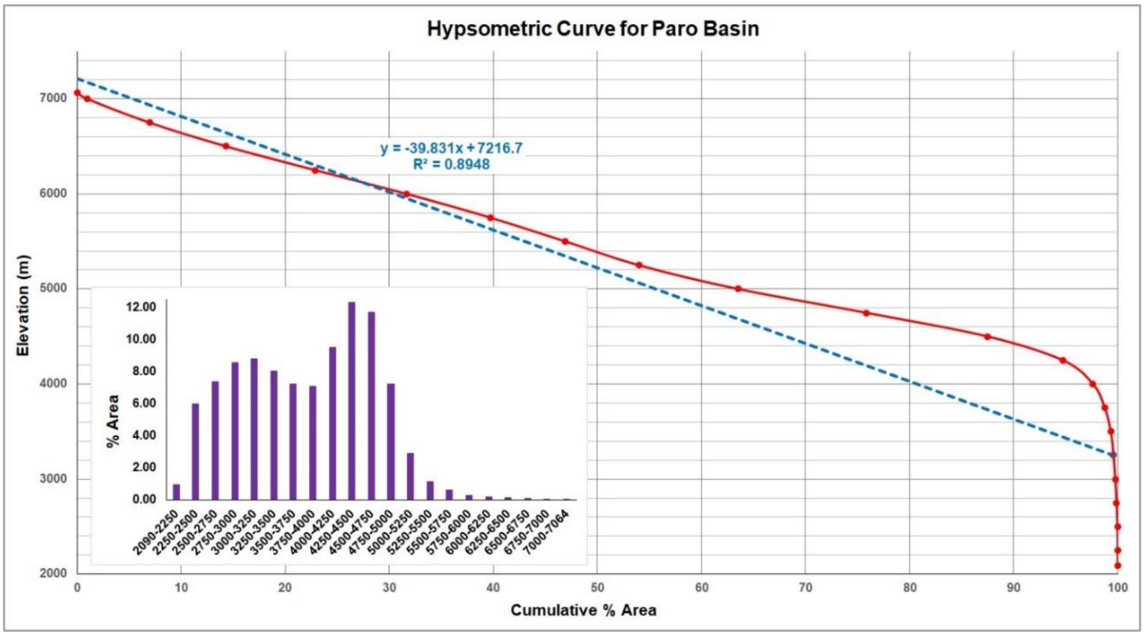


Figure 6.2: Hypsometric Curve for Paro Basin

Table 6.1: Area-Elevation Data for Paro Basin

Sl	elevation range (m)	Area (sqkm)	Cumulative Area (sqkm)	% Area	Cumulative % Area
1	2090-2250	12.02	12.02	0.95	0.95
2	2250-2500	75.88	87.90	6.00	6.95
3	2500-2750	93.20	181.10	7.37	14.32
4	2750-3000	108.40	289.51	8.57	22.89
5	3000-3250	111.10	400.61	8.78	31.67
6	3250-3500	101.80	502.41	8.05	39.72
7	3500-3750	91.05	593.46	7.20	46.92
8	3750-4000	89.48	682.94	7.07	53.99
9	4000-4250	120.46	803.40	9.52	63.52
10	4250-4500	155.76	959.16	12.31	75.83
11	4500-4750	147.72	1106.88	11.68	87.51
12	4750-5000	91.24	1198.11	7.21	94.72
13	5000-5250	36.61	1234.72	2.89	97.62
14	5250-5500	14.25	1248.98	1.13	98.75
15	5500-5750	7.33	1256.30	0.58	99.32
16	5750-6000	3.38	1259.68	0.27	99.59
17	6000-6250	1.99	1261.67	0.16	99.75
18	6250-6500	1.70	1263.37	0.13	99.88
19	6500-6750	1.04	1264.41	0.08	99.97
20	6750-7000	0.42	1264.82	0.03	100.00
21	7000-7064	0.02	1264.84	0.00	100.00

The entire Paro Basin has an area of 1265 square kilometers. However, notable river flooding occurs within only 8.86 square kilometers or 886 hectares of floodplain area within the basin and as such, modeling analyses and subsequent flood management measures have been formulated for this portion of the floodplain. Having said that, flood management concept for the region has been envisaged via managing both the upstream as well as the aforementioned downstream floodplain. The concept being that the structural measures such as bank protection, re-sectioning and cross-drainage structures have all been designed for implementation in the rivers and streams itself and/or adjacent to the floodplain. These hardcore measures are to be supplemented and complimented by non-structural measures such as floodplain zoning intended for greater area within the Paro Basin, early warning system which considers and relies on flow generation in the upstream catchment portion of channels and preservation of natural wetlands in the upstream catchments for ample flow retardation and dampening of peak flows while simultaneously increasing base flow potential. This enables the impedance of flow accumulation into the adjacent channels thus reducing potential flood discharges. Flood management for the Paro Basin will be fully achieved through priority-based implementation of these structural and non-structural measures both on a short and long term as well as through a blend of structural with non-structural measures. These are elaborated below.

6.3 Proposed Structural Measures

The purpose of any Flood Management Plan (FMP) is to provide climate resilient flood management solutions via assessment of flood hazard and vulnerability of a given area through relevant analyses. This is usually done via fixing multiple return period events for which flood flow is estimated via hydrological modeling and subsequent flood extent and flood depth is calculated by hydrodynamic modeling. Using the model results in conjunction to field knowledge and socio-economic analysis and other relevant analyses, detailed flood risk and vulnerability analyses is carried out to isolate the locations more prone to be affected adversely by flood events.

Flood risk/ vulnerability maps and corresponding flood damage statistics are then generated, after which a consensus is reached via stakeholder consultations on the approach to formulating flood management/ mitigation measures. Since an FMP targets flood management for the long-term, measures are devised as such. Having said that, more localized solutions are also sought after based on specific requirements. The FMP for Paro Dzongkhag blends measures for both the short- and long-term with the prime focus on flood management for the short-term, i.e. on flood mitigation. Thus and as per requirements learned from client consultations and field visits, in a nutshell, the following are the primary structural intervention types that have been proposed for flood management/ mitigation for both short- and long-terms in Paro –

- **River Bank protection –** Bank protection structures such as through graded boulder placement viagabion mesh at precisely 1:3 slope for better stability and to reduce bank erosion, placement of CC block revetment for bank stability.
- **Channel re-sectioning –** Re-sectioning of existing river and stream sections to accommodate flood flow for varying return periods.
- **Cross-drainage structures –** Implement cross-drainage structures such as culverts for maintaining passage across streams whilst maintaining adequate passage for flow through streams as well.

The following sections present detailed account of the river/ stream wise proposed measures. As can be seen from the following maps and tables, the prime measure for the two rivers in question namely Pa Chu and Do Chu are the re-sectioning of existing cross sections. This is for two primary purposes. One is to accommodate a 25 year return period rainfall flow and the other is for proper channelization purposes whereby the constriction or reduced section conveyance capacity of existing sections has to be alleviated. Besides these, additional protection along riverbank in the form of bank protection will be assessed as viable alternative. However, it is to be mentioned here that for the sake of immediate implementation, localized measures along the right bank of Pa Chu has been considered. For the streams, channel resection also lies at the core of a variety of localized solutions that have been proposed. These include cross-drainage culverts especially at points where flow crossing through a road has been made possible via constricted piped flow, cleaning of bushes, removal of encroachment etc. The proposed measures have been presented in map and tabular form as per channel reach and measure location.

6.3.1 Pa Chu and Do Chu

For the immediate and short-terms there are no measures deemed necessary for Do Chu as it can be observed from the flood maps in **Chapter 4**, there are no risk of flooding from a 25-year return period storm event. Similarly, sections for downstream of Pa Chu i.e from the Do Chu confluence point past the Airport and further downstream are adequate to pass a 25-year flow. Also there is no resection proposed between the bridge point (way to tiger nest), as this portion was found to be adequate. As such primary immediate measures consist of protection works along the right bank of the u/s Pa Chu reach via gabion (CC blocks as alternative) with wired net. Immediate measures include:

- Protection works in right bank (RB) of Pa Chu u/s;
- Alternate cases of protection through gabion mesh and with CC revetment considered (details in Chapter 7);
- Bank protection via 1:3 sloping of river bank; and
- Provisions are kept for toe-wall for added stability of bank.

Figure 6.3 presents a map with immediate measures for Pa Chu and **Table 6.2** presets the location for measures.

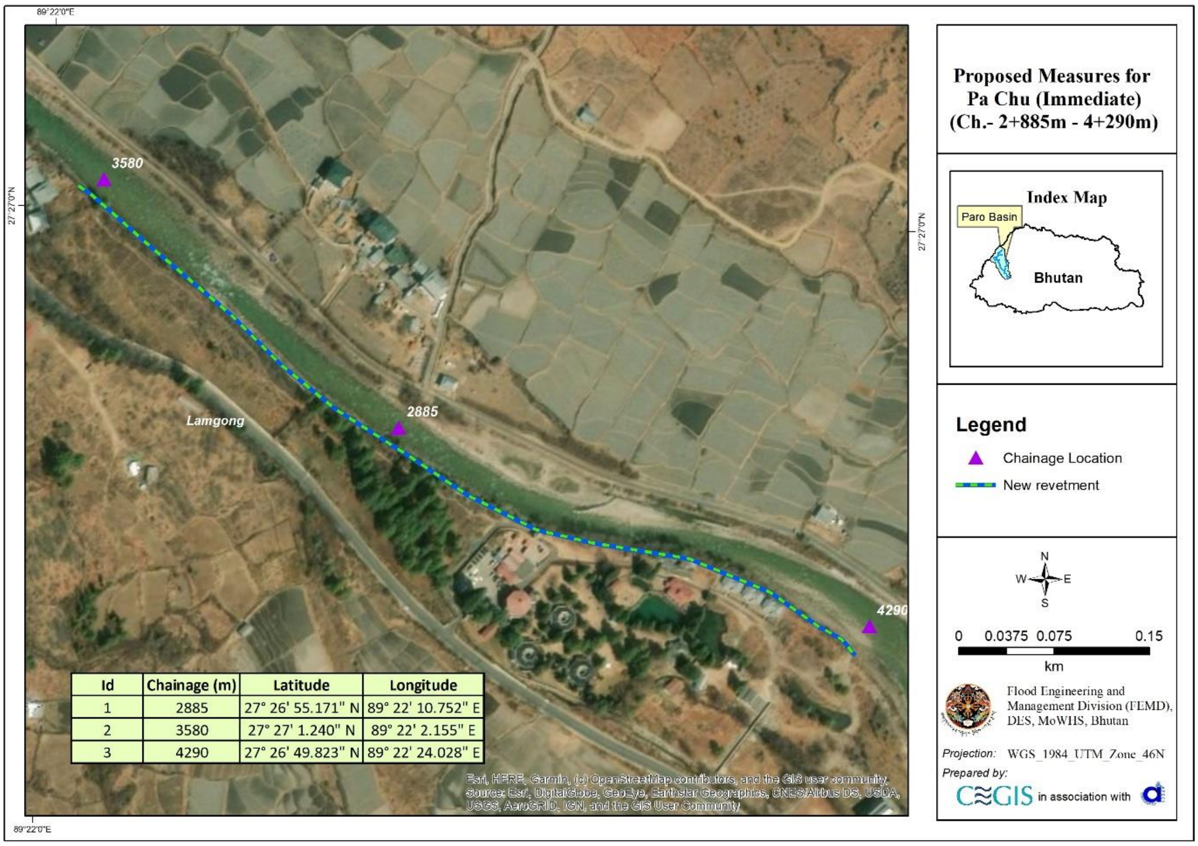


Figure 6.3: Proposed immediate engineering measure for flood management of Pa Chu

Table 6.2: Intervention section chainage and locations for Pa Chu (immediate)

Section Id	Chainage (m)	Lat	Long
1	2300	27° 27' 27.512" N	89° 21' 29.047" E
2	2400	27° 27' 27.551" N	89° 21' 32.668" E
3	2885	27° 26' 55.171" N	89° 22' 10.752" E
4	3580	27° 27' 1.240" N	89° 22' 2.155" E
5	4290	27° 26' 49.823" N	89° 22' 24.028" E
6	7280	27° 26' 21.173" N	89° 24' 4.228" E
7	7410	27° 26' 18.501" N	89° 24' 8.037" E
8	7500	27° 26' 16.100" N	89° 24' 10.261" E
9	7690	27° 26' 12.153" N	89° 24' 15.525" E
10	7860	27° 26' 9.101" N	89° 24' 20.261" E
11	8380	27° 25' 59.383" N	89° 24' 35.581" E
12	8660	27° 25' 55.325" N	89° 24' 44.472" E
13	9000	27° 25' 50.743" N	89° 24' 54.742" E
14	9380	27° 25' 46.297" N	89° 25' 6.546" E

*** Zero chainage starts from the bridge on the way to Tiger nest (lat: 27°28'20.35"N, long: 89°20'44.27"E)*

Figure 6.4 illustrates a section for immediate measures for Pa Chu right bank.

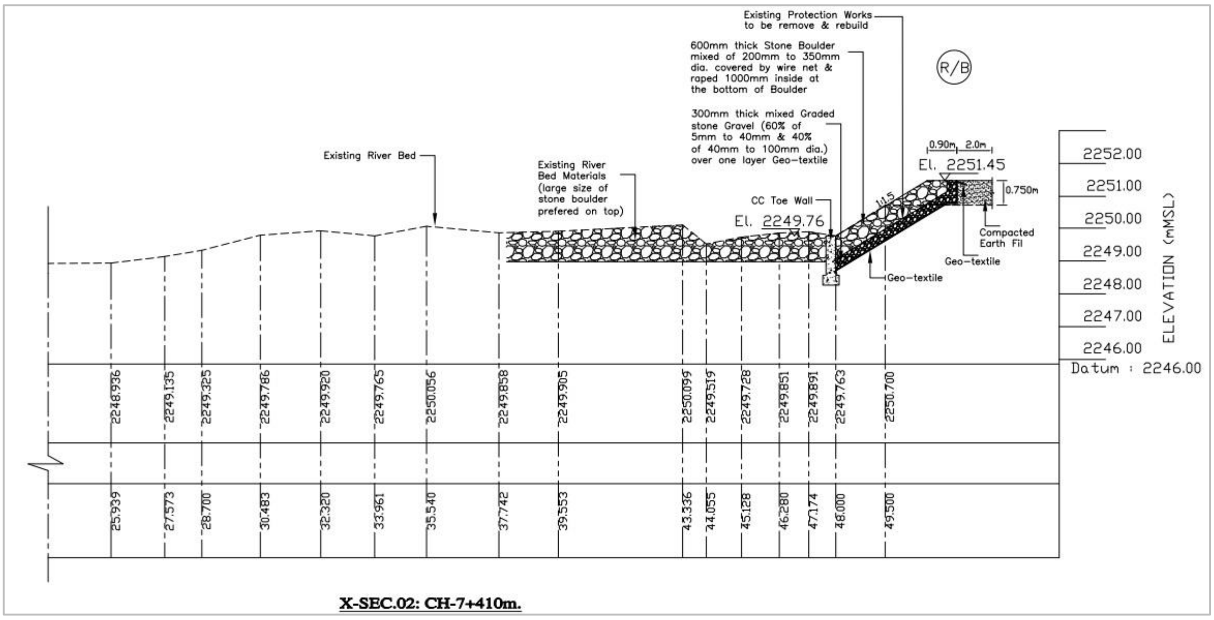
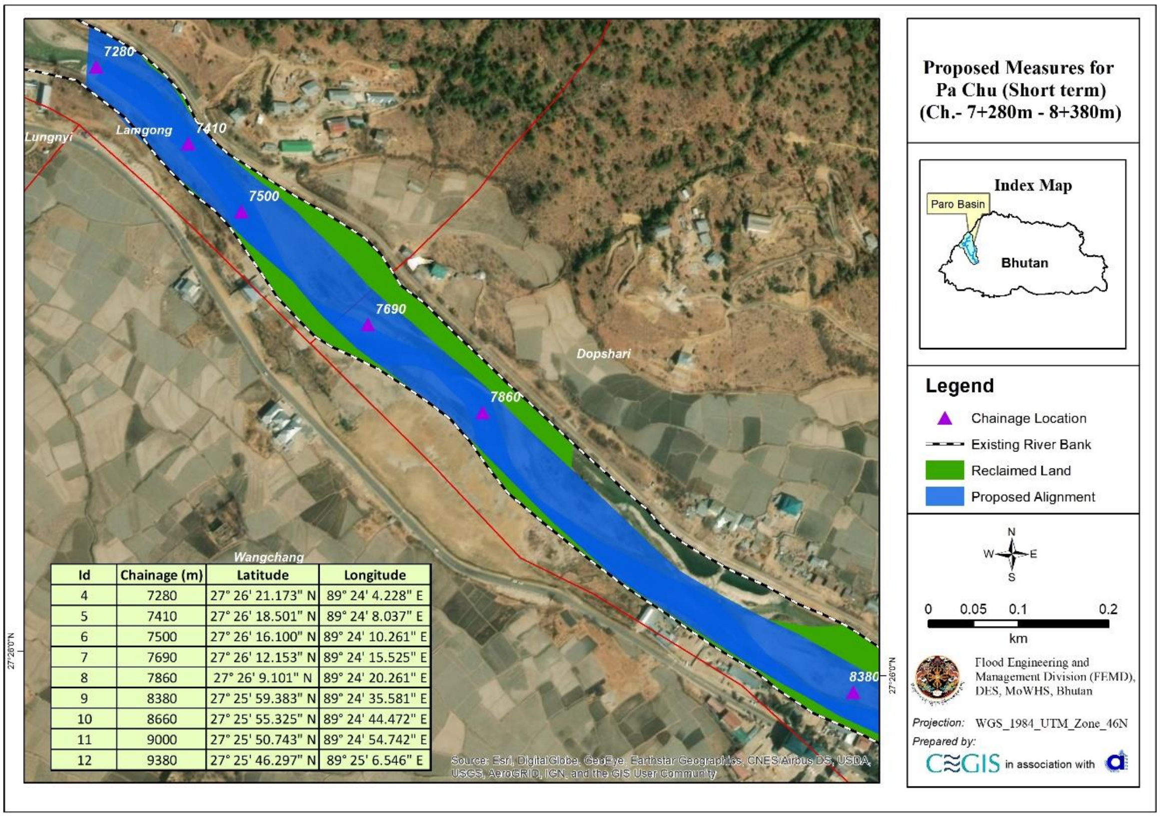


Figure 6.4: Pa Chu immediate-term option with right bank protection

Short-term measures are focused on a 2.1 km reach of Pa Chu upstream up to approximately its confluence with Do Chu as can be seen from the map in **Figure 6.5**. A composite set of measures have been proposed for this reach which consist of the following –

- Revised river sections as the existing sections are risk of flooding to high intensity events;
- Channelized river alignment where the previous braided nature of the river has been controlled into a more defined channel within this short reach for maximizing flood protection for a very high risk zone;
- Bank protection via 1:3 sloping of river bank
- Provisions are kept for toe-wall for added stability of bank; and
- Alternatives are provided via provisions of CC blocks laid in the banks for protection.



Id	Chainage (m)	Latitude	Longitude
4	7280	27° 26' 21.173" N	89° 24' 4.228" E
5	7410	27° 26' 18.501" N	89° 24' 8.037" E
6	7500	27° 26' 16.100" N	89° 24' 10.261" E
7	7690	27° 26' 12.153" N	89° 24' 15.525" E
8	7860	27° 26' 9.101" N	89° 24' 20.261" E
9	8380	27° 25' 59.383" N	89° 24' 35.581" E
10	8660	27° 25' 55.325" N	89° 24' 44.472" E
11	9000	27° 25' 50.743" N	89° 24' 54.742" E
12	9380	27° 25' 46.297" N	89° 25' 6.546" E

Figure 6.5: Proposed short-term engineering measure for flood management of Pa Chu

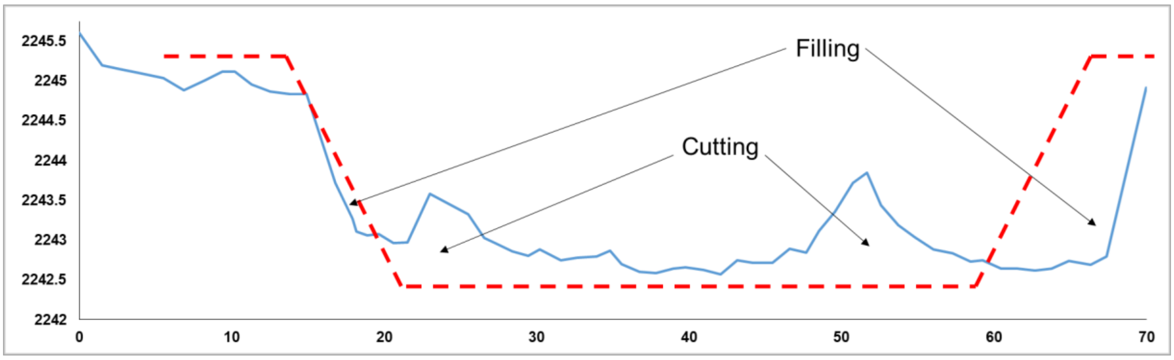


Figure 6.6: Representative schematic of a river section for proposed short-term measure for Pa Chu

It can be observed from the above figure that the proposed section is fitted within the existing river section therefore, there is no additional requirement of bank area. As per design sections presented in **vol. 4**, the proposed bed level is 200-300 mm below the existing bed level. This serves two purpose. Firstly, this increases channel section which serves the two-fold purpose of not only allowing smooth passage of 25 year return period flow, but also allows for providing ample freeboard to pass out even higher return period flood flow (50/ 100 year return period). Secondly, this allows provision for using the excavated bed material to be graded and laid as fill material for establishing channel banks which drastically reduces both cost and effort of having to bring in material from outside for filling purposes. As can be seen from alternate section options presented in **Figures 6.7-6.9**, provisions for 1:3 natural banks laid with graded bed material both with and without toe wall have been proposed with an alternative option of 1:3 bank slope with CC blocks for additional protection.

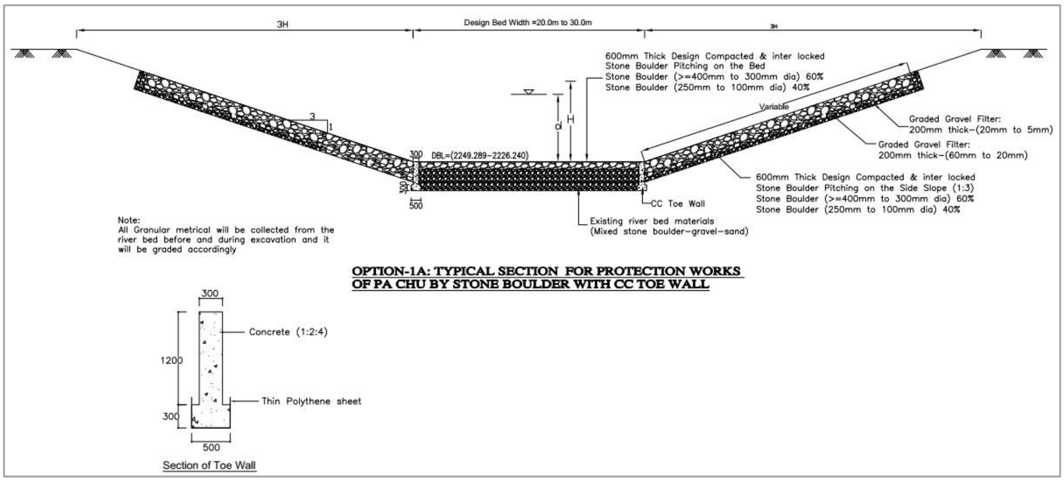


Figure 6.7: Pa Chu short-term option with 1:3 side slope and toe-wall

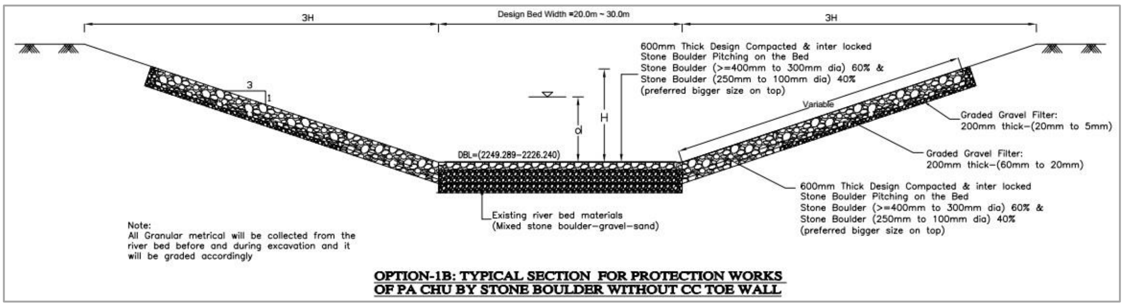


Figure 6.8: Pa Chu short-term option with 1:3 side slope and without toe-wall

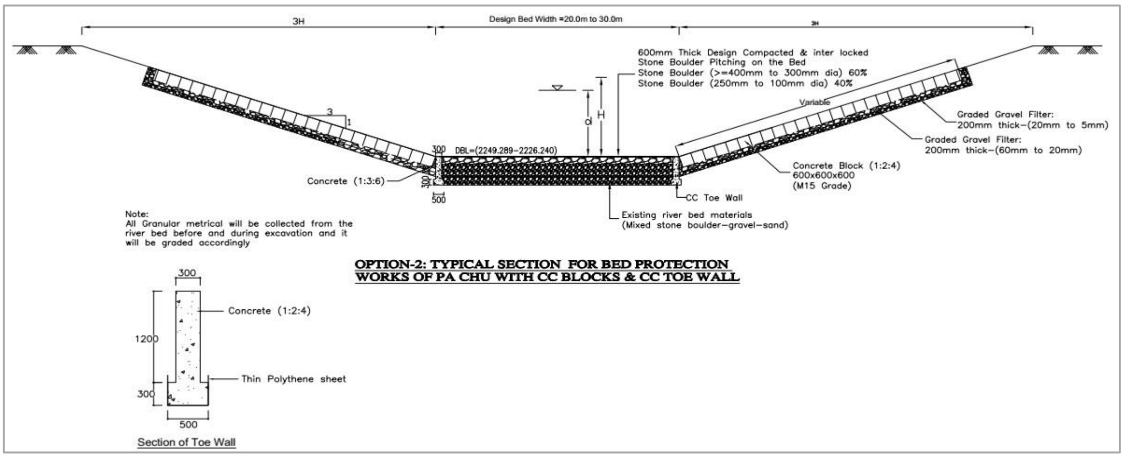


Figure 6.9: Pa Chu short-term option with 1:3 side slope with CC block and toe-wall

Table 6.3 presents the location of the upstream reach of Pa Chu for the proposed interventions.

Table 6.3: Intervention section chainage and locations for Pa Chu (short-term)

Section Id	Chainage (m)	Lat	Long
1	7280	27° 26' 21.1" N	89° 24' 4.2" E
2	7410	27° 26' 18.5" N	89° 24' 8.0" E
3	7500	27° 26' 16.1" N	89° 24' 10.2" E
4	7690	27° 26' 12.1" N	89° 24' 15.5" E

Section Id	Chainage (m)	Lat	Long
5	7860	27° 26' 9.1" N	89° 24' 20.2" E
6	8380	27° 25' 59.3" N	89° 24' 35.5" E
7	8660	27° 25' 55.3" N	89° 24' 44.4" E
8	9000	27° 25' 50.7" N	89° 24' 54.7" E
9	9380	27° 25' 46.2" N	89° 25' 6.5" E

*** Zero chainage starts from the bridge on the way to Tiger nest (lat: 27°28'20.35"N, long: 89°20'44.27"E)*

For long-term flood management, measures have been proposed for both Pa Chu and Do Chu in the form of channel re-sectioning and bank protection. This has been done keeping in mind a flood flow management window of 50-100 years during which, it is more than likely that one or multiple catastrophic events may occur. Under long-term measures for Pa Chu and Do Chu, re-sectioning of existing flow sections have been proposed to increase conveyance as well as administer proper channelization of flow to allow smooth passage. This has been presented in **Figure 6.10**. These re-sectioned designs have been done with a 25 year return period storm event generated runoff. But enough freeboard has been kept to enable a 50 year flow to pass through the channel, should it occur. **Figure 6.10** presents the map of the portion of Paro Basin for which re-sectioning of rivers is to be done. **Figures 6.11 to 6.14** present the alternate section options for Pa Chu and Do Chu. It is to be mentioned here that, survey data was available for said portion only, based on which designs have been done. Provisions should be made to accommodate future additional survey works and associated design for especially the downstream of Pa Chu up to its outfall. **Table 6.4** presents the respective chainage locations.

Table 6.4: Intervention section chainage and locations for Pa Chu and Do Chu (long-term)

ID	X	Y	Chainage (m)	ID	X	Y	Chainage (m)
Pachu_01	251426	537779	+.00	Pachu_24	257207	532060	9+792.31
Pachu_02	251700	537519	+377.92	Pachu_25	257567	531441	10+507.75
Pachu_03	251940	537329	+683.57	Pachu_26	257951	530951	11+130.41
Pachu_04	252307	537175	1+081.82	Pachu_27	258322	530451	11+752.79
Pachu_05	252631	536915	1+496.60	Pachu_28	258772	530263	12+239.86
Pachu_06	252983	536702	1+908.30	Pachu_29	259400	530343	12+873.31
Pachu_07	254065	536476	3+012.73	Pachu_30	260217	529589	13+984.52
Pachu_08	254668	536435	3+616.85	Pachu_31	260488	529010	14+623.45
Pachu_09	255229	536157	4+242.90	Pachu_32	260617	528393	15+253.33
Pachu_10	255509	535941	4+596.13	Pachu_33	261264	527041	16+751.71
Pachu_11	256002	535593	5+199.27	Pachu_34	262009	525671	18+310.44
Pachu_12	256447	535372	5+696.39	**Do Chu**			
Pachu_13	256770	535230	6+049.28	Dochu_01	258196	541564	+.00
Pachu_14	256915	535221	6+194.41	Dochu_02	257897	541133	+524.75
Pachu_15	257049	535161	6+340.81	Dochu_03	257826	540674	+988.33
Pachu_16	257118	535050	6+471.65	Dochu_04	257590	540170	1+545.31
Pachu_17	257124	534877	6+644.94	Dochu_05	257543	539699	2+018.55
Pachu_18	257108	534699	6+823.52	Dochu_06	257358	538979	2+760.95
Pachu_19	257196	533996	7+531.05	Dochu_07	257149	537904	3+855.37
Pachu_20	256900	533657	7+981.22	Dochu_08	257000	537215	4+560.68
Pachu_21	256692	533386	8+322.95	Dochu_09	256932	536648	5+130.88
Pachu_22	256747	532850	8+861.47	Dochu_10	256670	535862	5+959.56
Pachu_23	256903	532406	9+331.49	Dochu_11	256896	535330	6+537.59

*** Zero chainage starts from Drukgyel Dzong (lat: 27°28'20.35"N, long: 89°20'44.27"E)*

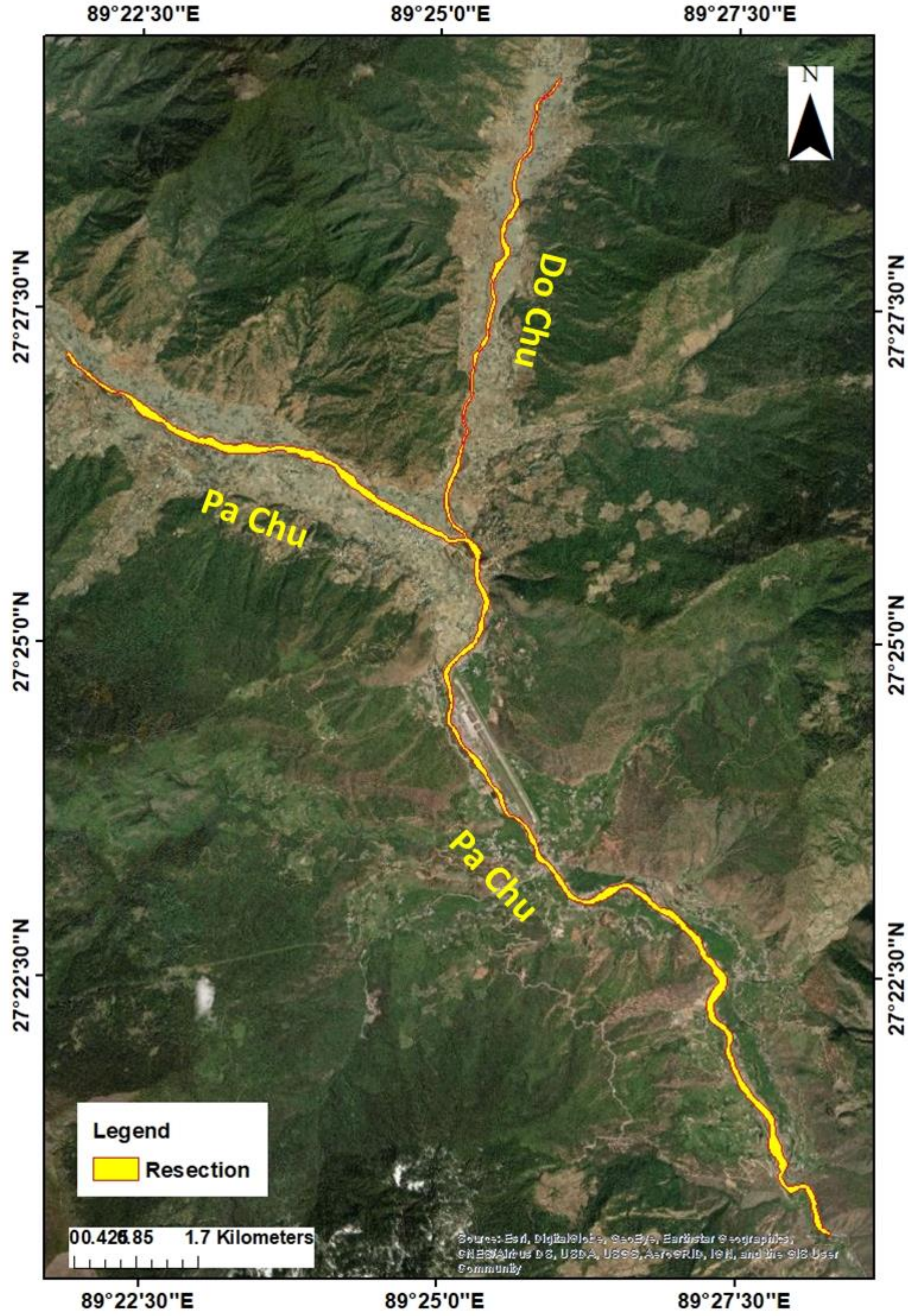


Figure 6.10: Map with extent of proposed long-term measures for Pa Chu and Do Chu

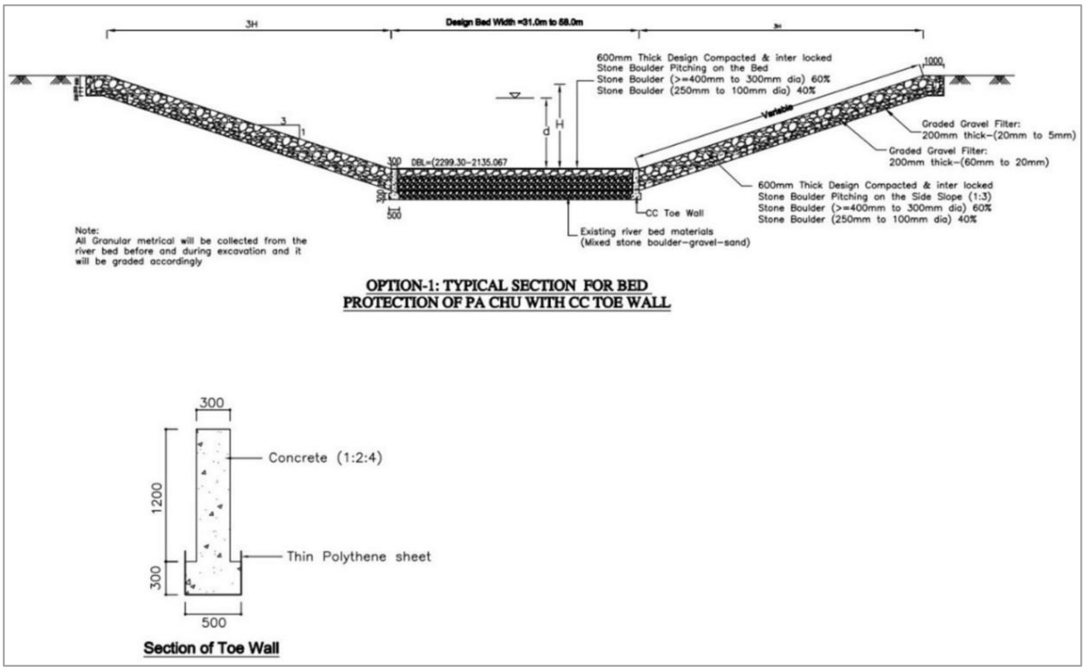


Figure 6.11: Option with toe wall for Pa Chu long-term measure

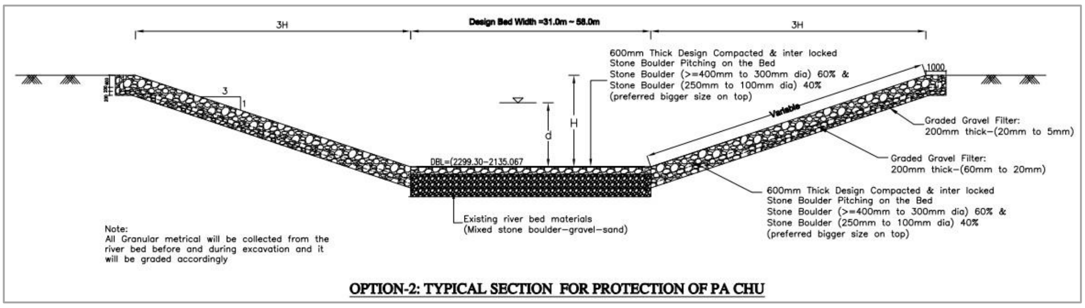


Figure 6.12: Option without toe wall for Pa Chu long-term measure

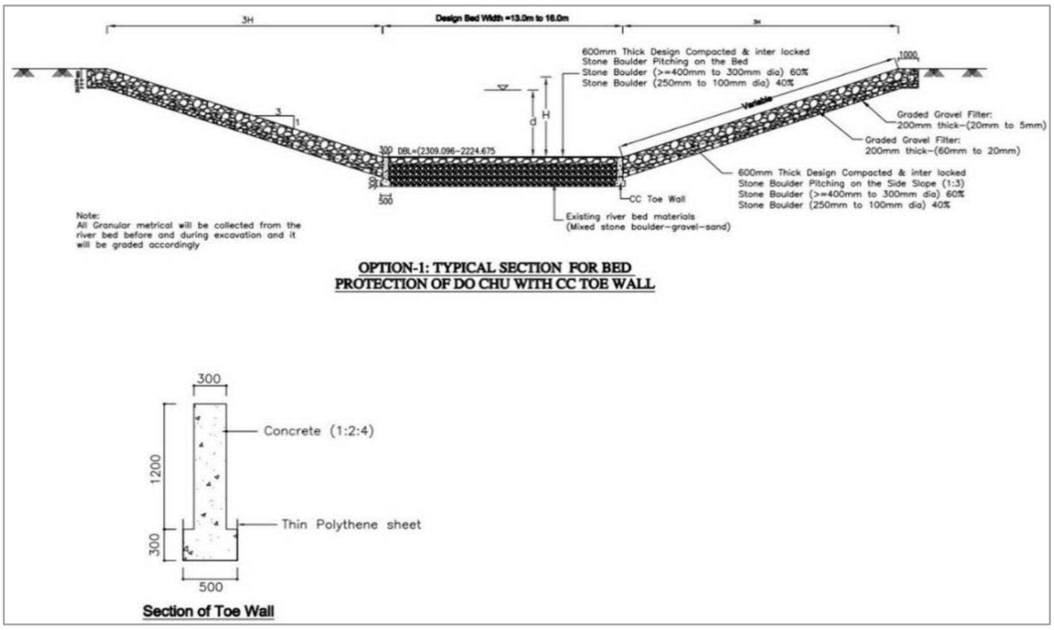


Figure 6.13: Option with toe wall for Do Chu long-term measure

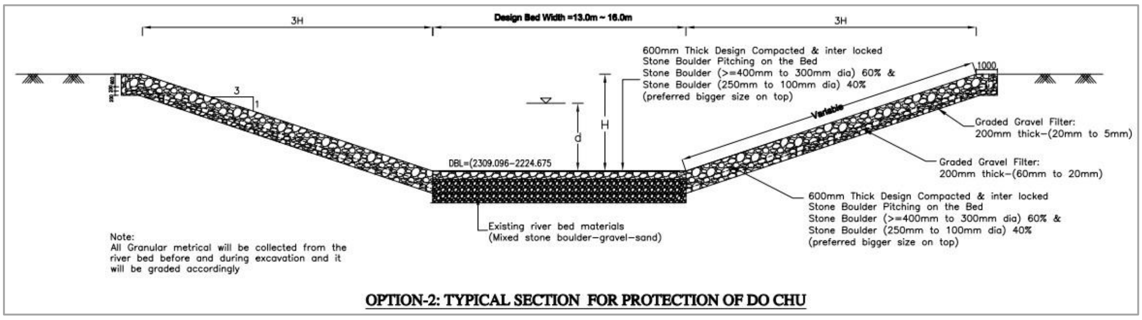


Figure 6.14: Option without toe wall for Pa Chu long-term measure

6.3.2 Streams

For the streams a singular set of measures have been provided for both short- and long-terms as such this terminology is not used for the 8 smaller streams. These include the one or mixing of the following.

- Trapezoidal sections;
- Rectangular sections (brick masonry); and
- Cross-drainage structures.

These have been elaborated below with relevant maps and tables for each stream.

Nephu Chu

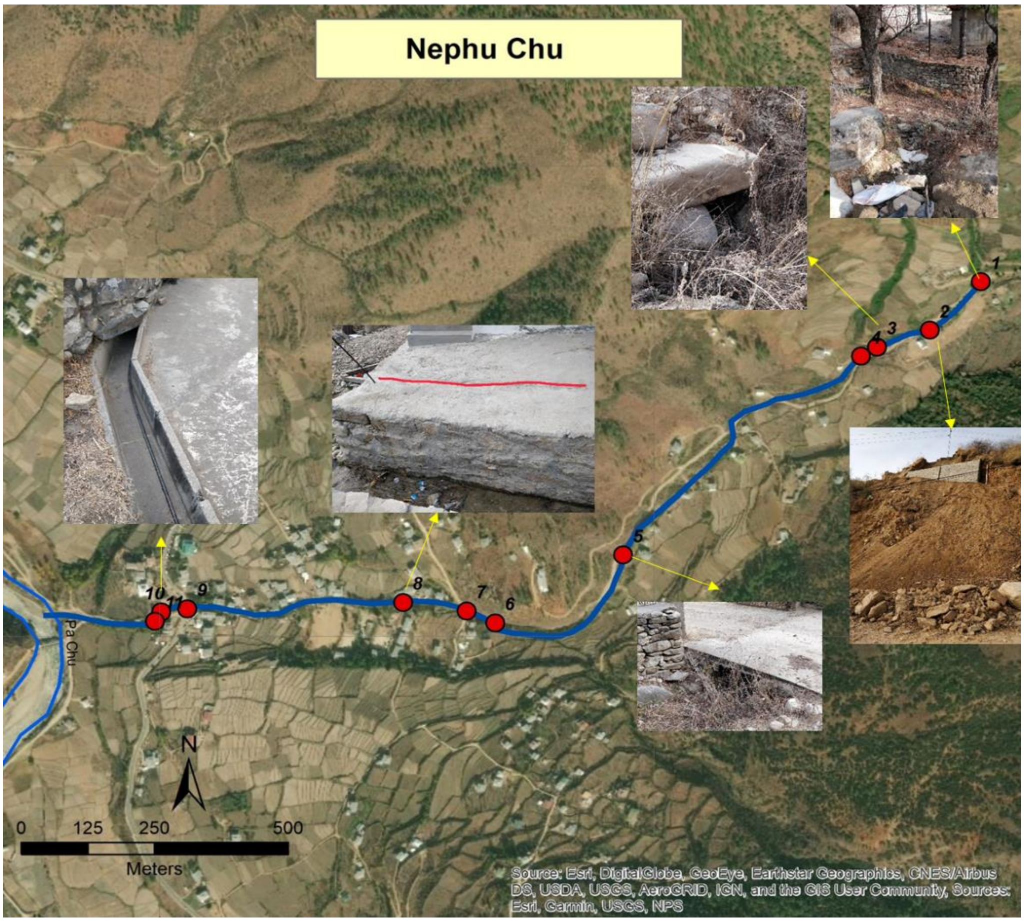


Figure 6.15: Map of concerned critical locations along Nephu Chu and corresponding flow constrictions

For Nephu Chu, two particular options have been considered.

- Trapezoidal section all throughout with culverts in designated locations; and
- A mix of trapezoidal section with rectangular sections in downstream to reduce top-width of stream section along with culverts in designated locations.

Table 6.5: Location-wise proposed measures for Nephu Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
2	275	Pipe culvert	900 mm dia	Need to clean the flow path. Landslide risk.	Culvert designed (Ground elevation: 2349.5)
3	370	Pipe culvert	600 mm dia	2m x 1.5 m box culvert.	Culvert designed (Ground elevation: 2339.9)
4	405	Pipe culvert	900 mm dia	2m x 1.5 m box culvert.	Culvert designed (Ground elevation: 2335.9)
5	990	Box culvert	1 .0x 0.75 m	Opening size checked via design discharge.	Culvert designed (Ground elevation: 2285.6)
6	1305	Pipe culvert	600 mm dia	Opening size checked via design discharge.	Culvert designed (Ground elevation: 2258.2)
7	1360	Pipe culvert	2 x 450 mm	Opening size checked via design discharge.	Culvert designed (Ground elevation: 2252.8)
8	1470	Box culvert		Opening size checked via design discharge. Approx. 1m encroachment on channel.	Section designed (Ground elevation: 2243.8)
9	1830	Bridge		Opening is adequate.	
10	1880	Pipe culvert	4 x 120 mm dia	Opening size checked via design discharge.	adequate
11	1900	Box culvert		Opening is adequate.	

Locations for re-sectioning culvert placements are presented in **Tables 6.6 and 6.7** respectively and maps for both measure sets are presented in **Figures 6.16 and 6.17**.

Table 6.6: Location of re-sectioning for Nephu Chu

Chainage	Lat	Long
Ch. 0.0 m	27° 22' 54.5" N	89° 28' 24.5" E
Ch. 472.0 m	27° 22' 46.4" N	89° 28' 11.6" E
Ch. 841.0 m	27° 22' 39.9" N	89° 28' 1.60" E
Ch. 1165.0 m	27° 22' 31.1" N	89° 27' 55.9" E
Ch. 1302.0 m	27° 22' 30.5" N	89° 27' 51.4" E
Ch. 1653.0 m	27° 22' 32.3" N	89° 27' 39.1" E
Ch. 1986.0 m	27° 22' 30.6" N	89° 27' 28.3" E

Table 6.7: Proposed box culvert locations for Nephu Chu

Chainage	Lat	Long
Ch. 275.0 m	27° 22' 49.512" N	89° 28' 16.752" E
Ch. 370.0 m	27° 22' 48.432" N	89° 28' 13.548" E
Ch. 405.0 m	27° 22' 47.856" N	89° 28' 12.576" E
Ch. 990.0 m	27° 22' 35.184" N	89° 27' 58.140" E
Ch. 1305 m	27° 22' 30.864" N	89° 27' 50.364" E
Ch. 1360 m	27° 22' 31.620" N	89° 27' 48.636" E
Ch. 1470 m	27° 22' 32.160" N	89° 27' 44.784" E

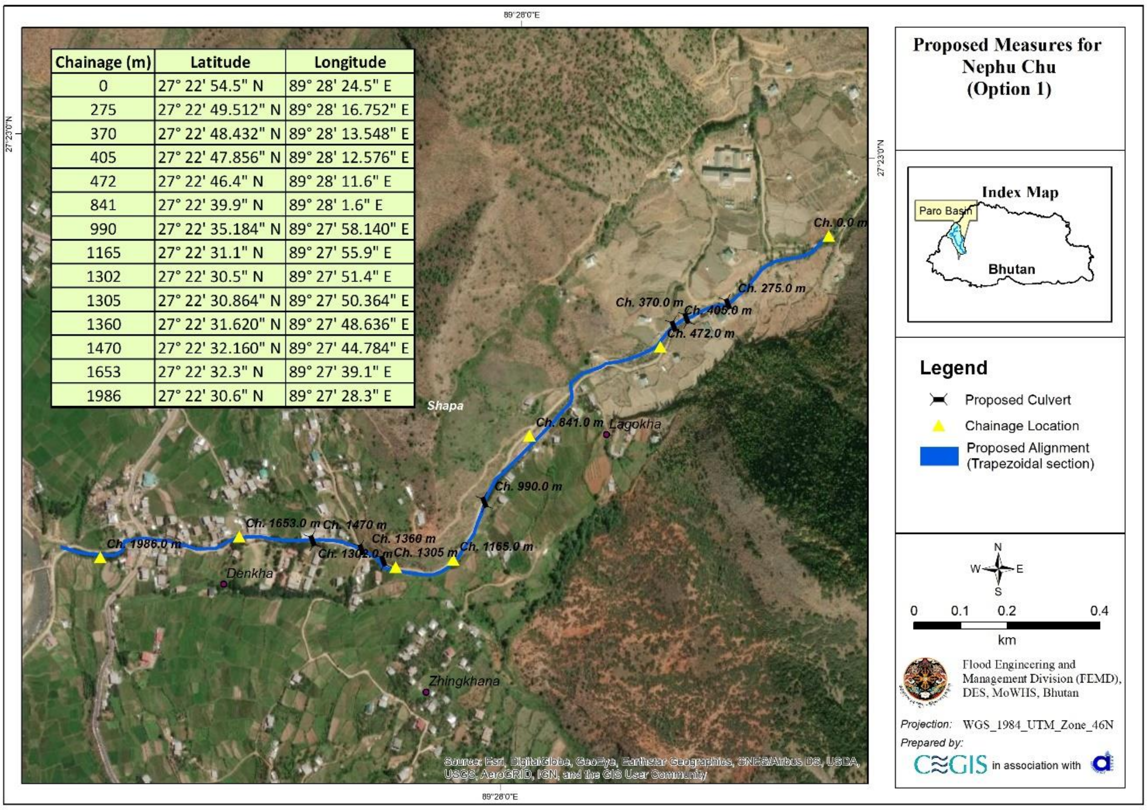


Figure 6.16: Proposed option for Nephu Chu with trapezoidal section all throughout

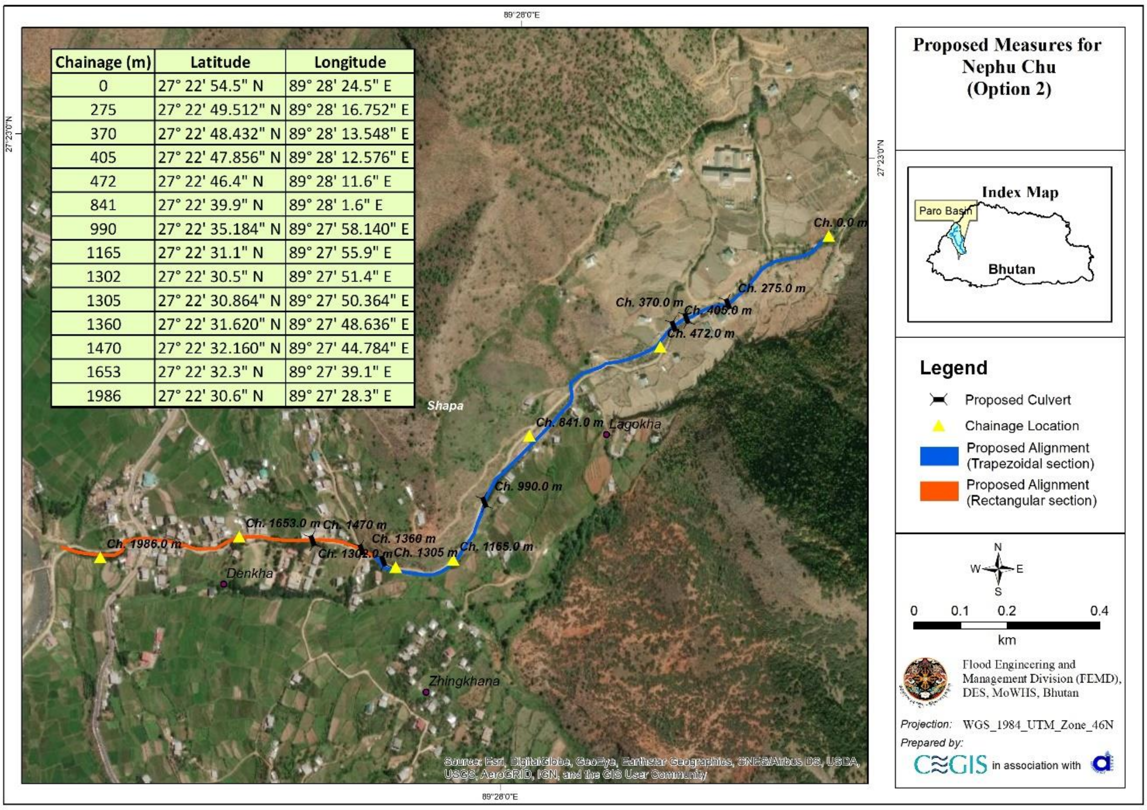


Figure 6.17: Proposed option for Nephu Chu with A mix of trapezoidal section with rectangular sections in downstream reach

Ngoborong Chu

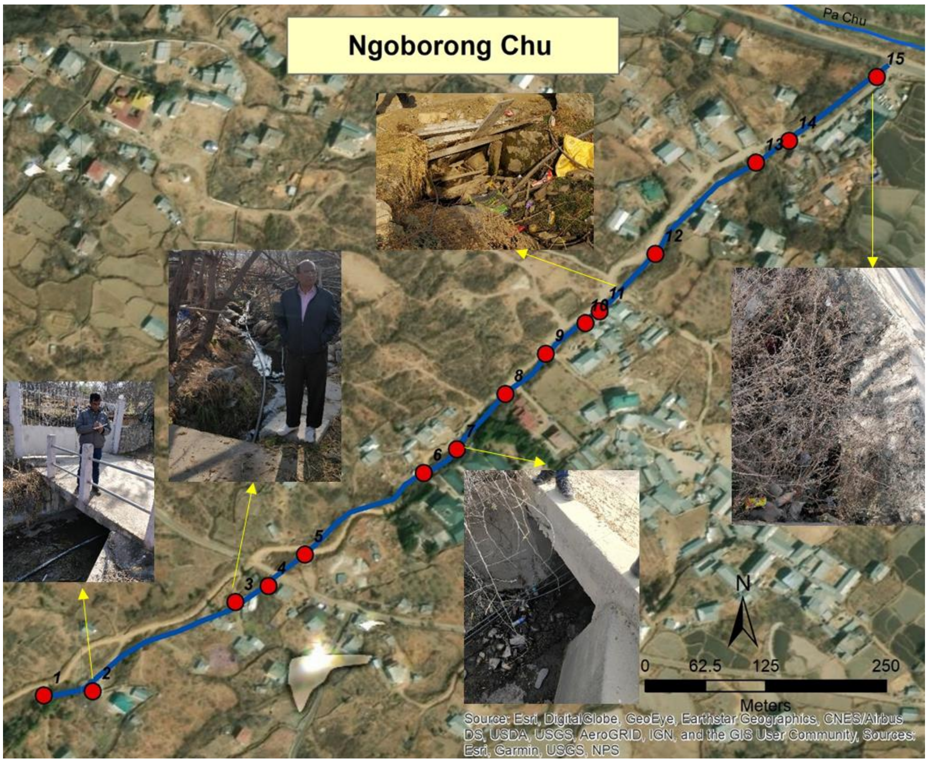


Figure 6.18: Map of concerned critical locations along Ngoborong Chu and corresponding flow constrictions

For Ngoborong Chu, the full stream is proposed to be of rectangular stone masonry sections with two possible options –

- No additional top slab cover; and
- Construction of additional top slab cover for smooth passage of road traffic.

Table 6.8 presents the location-wise proposed measures for Ngoborong Chu and **Figures 6.19 and 6.20** present the maps for both options.

Table 6.8: Location-wise proposed measures for Ngoborong Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommendation	Remarks
1	0	Box culvert	2 x 0.8 m	Slight Bed scouring at d/s of culvert. Masonry wall at bottom section is recommended. Adequacy of the culvert has been checked.	Adequate
2	45	Box culvert	2 x 0.9 m	Functional. Adequacy of the culvert has been checked.	Adequate
3	205	Box culvert	1.5 x 1.0 m	During Summer it overflows. Re-sectioning and build 75m masonry guide wall both side.	Adequate
4	245	Box culvert	2.8 x 1.25 m	Adequacy of the culvert has been checked.	Adequate
5	290	Box culvert	1.9 x 1.25 m	Adequacy of the culvert has been checked.	Adequate
6	430	Box culvert	1.6 x 1.0 m	No flow during dry season.	Adequate
7	470	Box culvert	2 x 0.7 m	Adequacy of the culvert has been checked.	Adequate
8	545	Box culvert	1.25 x 0.9 m	Near Pinewood hotel. Adequacy of the culvert has been checked.	Adequate
9	600	Box culvert	2.0 x 1.2 m	Need to clean garbage and clear flow path by replacing boulder.	Adequate
10	650	Box culvert	1.4 x 1.25 m	Near Kay ARR restaurant.	Adequate
11	670	Box culvert		Non-functional & Need to replace.	Culvert designed
12	745	Box culvert	2.0 x 1.55 m	Adequacy of the culvert has been checked.	Adequate
13	880	Irrigation		Need drop structure to pass the stream.	Adjusted with the irrigation pipe bottom level with stream top level
14	920	Box culvert	1.6 x 1.2 m	Adequacy of the culvert has been checked.	Adequate
15	1025	Pipe culvert	2 x 900 mm	Need to rehabilitate and re-design.	Culvert designed

Table 6.9: Chainage-wise coordinates for proposed culverts for option 2

Sl	Chainage	Lat	Long
1	0	27° 26' 8.484" N	89° 22' 28.740" E
2	45	27° 26' 8.628" N	89° 22' 30.396" E
3	205	27° 26' 11.580" N	89° 22' 35.184" E
4	245	27° 26' 12.120" N	89° 22' 36.300" E
5	290	27° 26' 13.164" N	89° 22' 37.524" E
6	430	27° 26' 15.864" N	89° 22' 41.520" E
7	470	27° 26' 16.656" N	89° 22' 42.636" E
8	545	27° 26' 18.492" N	89° 22' 44.256" E
9	600	27° 26' 19.824" N	89° 22' 45.624" E
10	650	27° 26' 20.832" N	89° 22' 46.956" E
11	670	27° 26' 21.228" N	89° 22' 47.424" E
12	745	27° 26' 23.136" N	89° 22' 49.296" E
13	880	27° 26' 26.160" N	89° 22' 52.680" E
14	920	27° 26' 26.880" N	89° 22' 53.796" E
15	1025	27° 26' 29.004" N	89° 22' 56.748" E

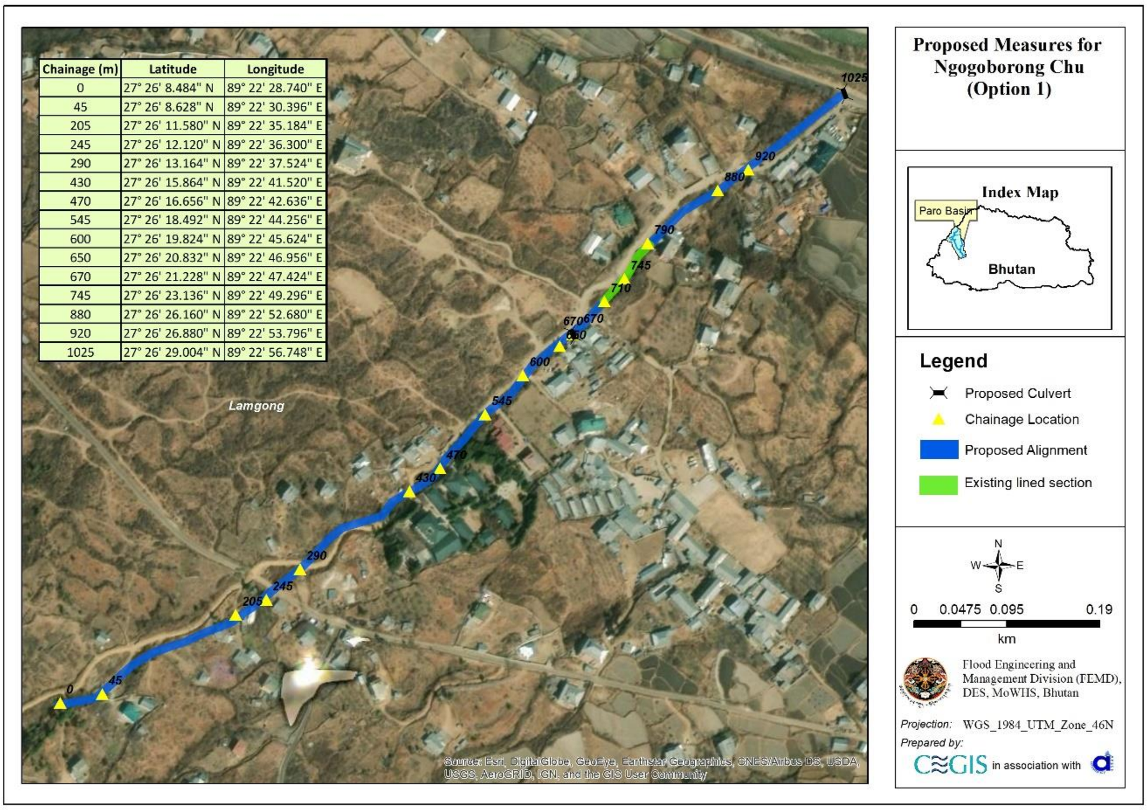


Figure 6.19: Proposed option for Ngoborong Chu with no additional box culvert

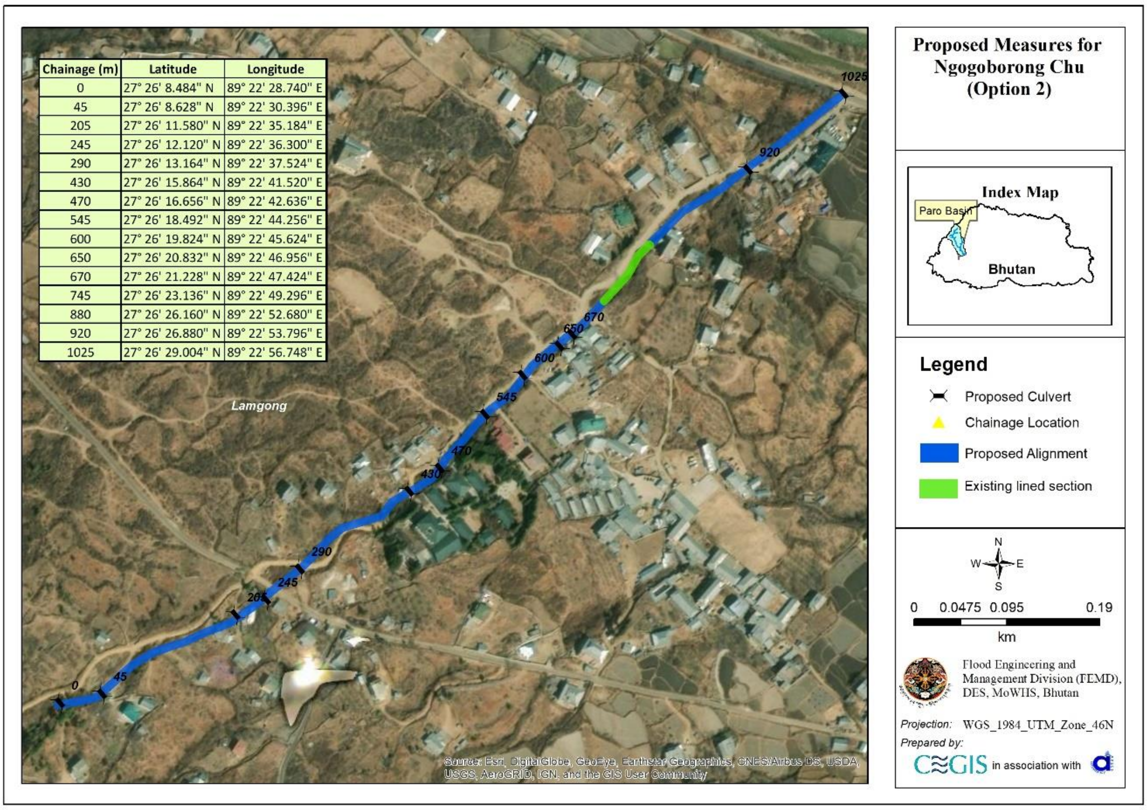


Figure 6.20: Proposed option for Ngoborong Chu with construction of additional box culverts

Dakhorong Chu

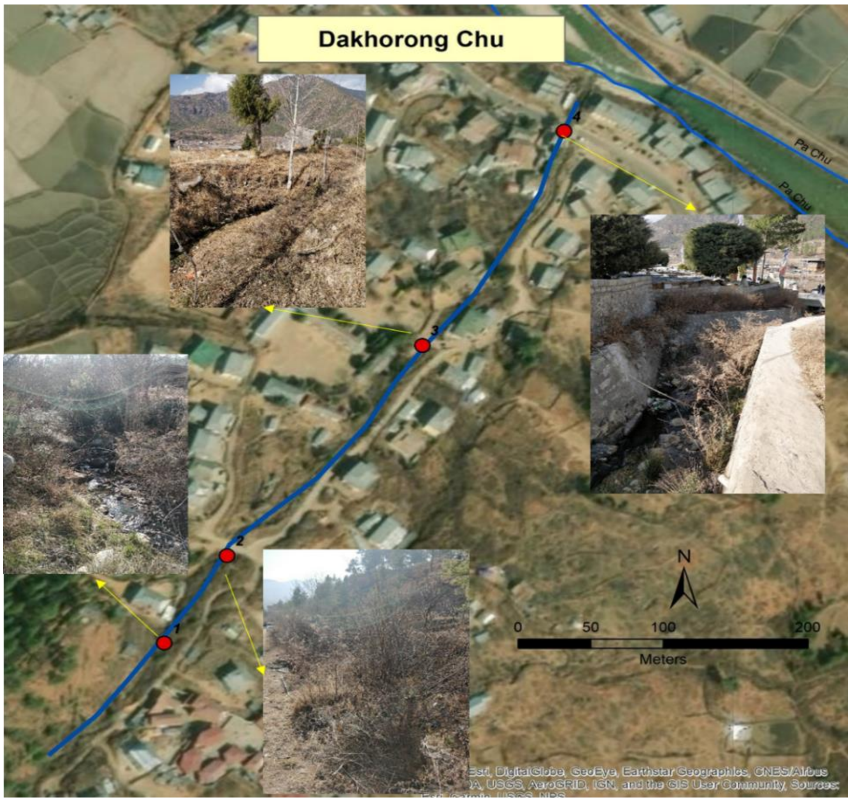


Figure 6.21: Map of concerned critical locations along Dakhorong Chu and corresponding flow constrictions

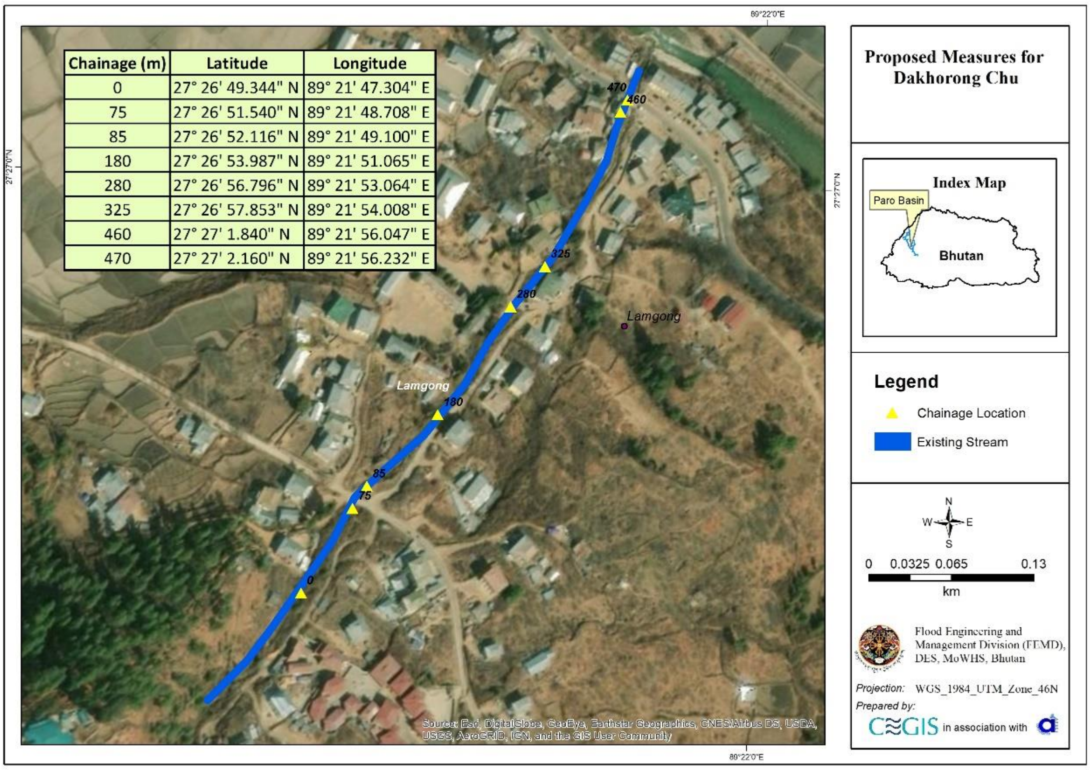
For Dakhorong Chu, sections are seen to be adequate as per hydrodynamic modeling as such no additional section area is required. However, local solutions in the form of cross-drainage structures will still be required, details of which are given below.

Table 6.10: Location-wise proposed measures for Dakhorong Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
1	0	Narrow stream section		Need re-sectioning of 100m river reach (30 m upstream to 80 downstream).	The cross-section was checked using design discharge and found adequate
2	75	Pipe culvert	3 x 900 mm	Need to clean flow path. Stream is inside the school boundary.	Culvert is found adequate
3	280	Pipe culvert	2 x 900 mm	Encroachment at the d/s of culvert at the right bank, need to protect with retaining wall.	Found adequate for design discharge
4	470	Box culvert	5 m x 1.5 m	Outfall condition is good. Adequacy checked using design discharge.	Adequate

Table 6.11: Chainage locations for Dakhorong Chu

Chainage	Lat	Long
0	27° 26' 49.344" N	89° 21' 47.304" E
75	27° 26' 51.540" N	89° 21' 48.708" E
85	27° 26' 52.116" N	89° 21' 49.100" E
180	27° 26' 53.987" N	89° 21' 51.065" E
280	27° 26' 56.796" N	89° 21' 53.064" E
325	27° 26' 57.853" N	89° 21' 54.008" E
460	27° 27' 1.840" N	89° 21' 56.047" E
470	27° 27' 2.160" N	89° 21' 56.232" E



Chainage (m)	Latitude	Longitude
0	27° 26' 49.344" N	89° 21' 47.304" E
75	27° 26' 51.540" N	89° 21' 48.708" E
85	27° 26' 52.116" N	89° 21' 49.100" E
180	27° 26' 53.987" N	89° 21' 51.065" E
280	27° 26' 56.796" N	89° 21' 53.064" E
325	27° 26' 57.853" N	89° 21' 54.008" E
460	27° 27' 1.840" N	89° 21' 56.047" E
470	27° 27' 2.160" N	89° 21' 56.232" E

Figure 6.22: Proposed measure locations for Dakhorong Chu with construction of additional box culverts

Satsam Chu North

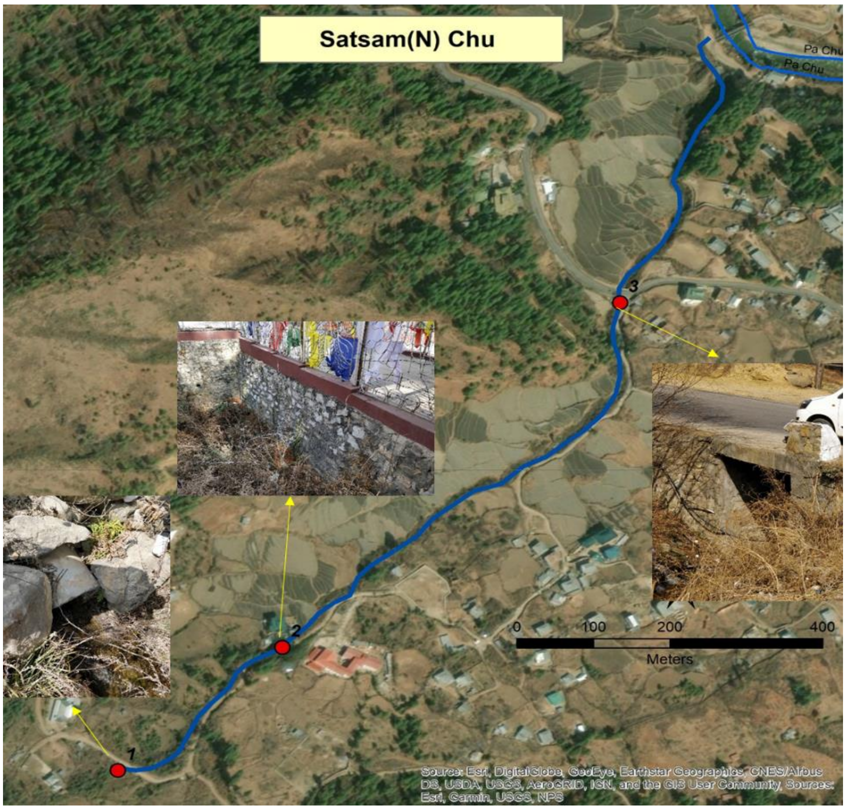


Figure 6.23: Map of concerned critical locations along Satsam Chu North and corresponding flow constrictions

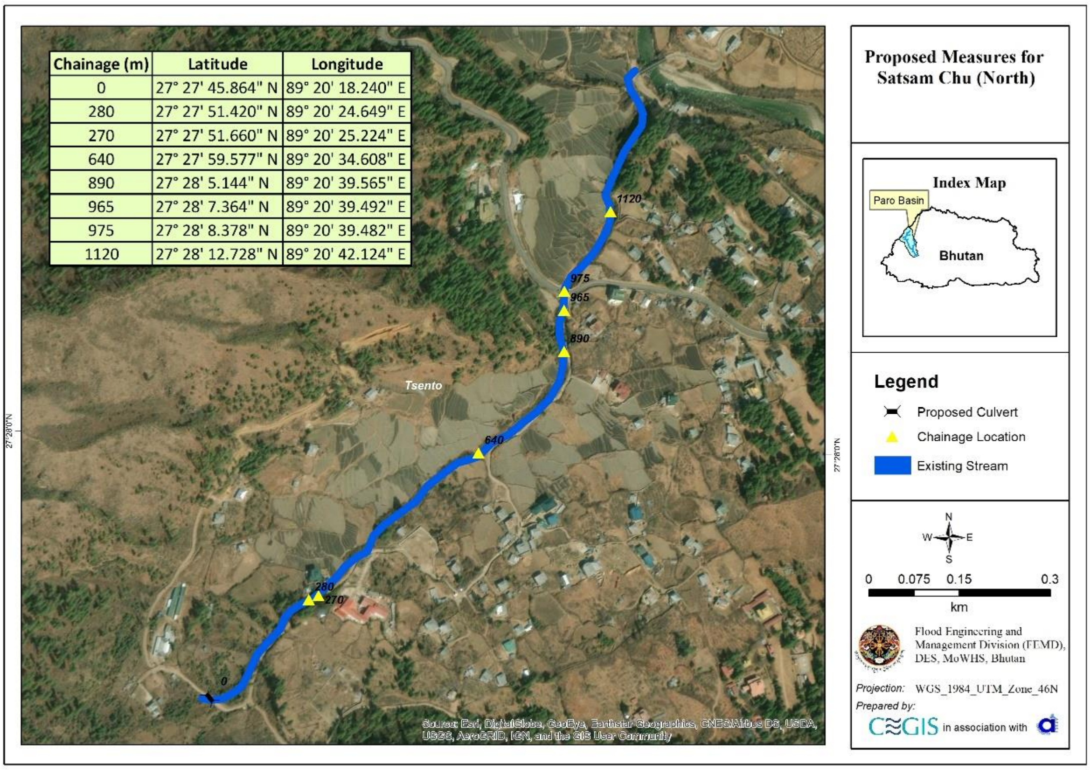
For Satsam Chu North, sections are seen to be adequate as per hydrodynamic modeling as such no additional section area is required. However, local solutions in the form of cross-drainage structures will still be required, details of which are given below.

Table 6.12: Location-wise proposed measures for Satsam Chu North

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
1	0	Pipe culvert	600 mm dia	Replace with 2m x 1.5 m box culvert with 5m length.	Culvert designed
2	280	Pipe culvert	2/3 x 1.2 m dia	Blocked by resort entrance. Adequacy has been checked. Encroachment into channel.	Adequate
3	975	Box culvert	2 m x 3.5 m	Depth of box culvert is okay. Width can be increased slightly. Need to clean bush throughout the length of the stream.	Adequate

Table 6.13: Chainage locations for Satsam Chu North

Chainage	Lat	Long
0	27° 27' 45.864" N	89° 20' 18.240" E
280	27° 27' 51.420" N	89° 20' 24.649" E
270	27° 27' 51.660" N	89° 20' 25.224" E
640	27° 27' 59.577" N	89° 20' 34.608" E
890	27° 28' 5.144" N	89° 20' 39.565" E
965	27° 28' 7.364" N	89° 20' 39.492" E
975	27° 28' 8.378" N	89° 20' 39.482" E
1120	27° 28' 12.728" N	89° 20' 42.124" E



Chainage (m)	Latitude	Longitude
0	27° 27' 45.864" N	89° 20' 18.240" E
280	27° 27' 51.420" N	89° 20' 24.649" E
270	27° 27' 51.660" N	89° 20' 25.224" E
640	27° 27' 59.577" N	89° 20' 34.608" E
890	27° 28' 5.144" N	89° 20' 39.565" E
965	27° 28' 7.364" N	89° 20' 39.492" E
975	27° 28' 8.378" N	89° 20' 39.482" E
1120	27° 28' 12.728" N	89° 20' 42.124" E

Figure 6.24: Proposed measure locations for Satsam Chu North with construction of additional box culverts

Satsam Chu South

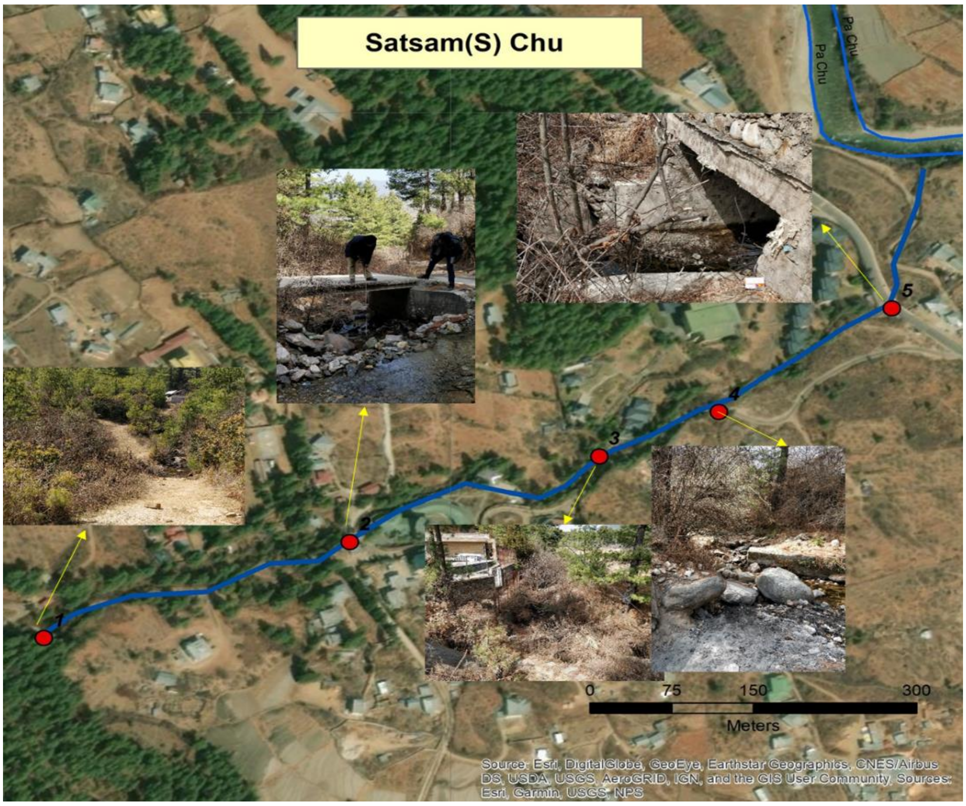


Figure 6.25: Map of concerned critical locations along Satsam Chu South and corresponding flow constrictions

For Satsam Chu South, sections are seen to be adequate as per hydrodynamic modeling as such no additional section area is required. However, local solutions in the form of cross-drainage structures will still be required, details of which are given below.

Table 6.14: Location-wise proposed measures for Satsam Chu South

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
1	0	Box culvert		Replace with a bridge of 5m length and 6m width. Need bank protection from the bridge to 30m d/s of the bridge to protect the road.	Culvert has been designed, capacity of the stream is adequate, no need flood wall
2	280	Box culvert	1.9 x 1.1 m	Replace with a bridge of 5m length and 6m width. Need bank protection at the left bank around 60 m length.	Culvert designed
3	520	Box culvert	4.7 x 1.8 m	Structure on the river just upstream of the bridge to divert water to local resort. Need to demolish the diversion structure.	Not mandatory, thus excluded from the mitigation measures.
5	800	Box culvert (2 nos)	3.15 x 1.85 m and 2 x 1 m	Two different sill levels. Previously constructed culvert has lower sill. Constriction at the down of the culvert. On-field recommendation: Replace the previous box culvert with a lower sill level. Width 3m & Depth 2m.	The capacity of two culverts were found adequate.

Table 6.15: Chainage locations for Satsam Chu South

Chainage	Lat	Long
0	27° 27' 42.084" N	89° 20' 47.904" E
10	27° 27' 42.467" N	89° 20' 48.234" E
270	27° 27' 45.142" N	89° 20' 56.565" E
280	27° 27' 45.360" N	89° 20' 57.012" E
330	27° 27' 46.310" N	89° 20' 58.257" E
520	27° 27' 48.276" N	89° 21' 4.428" E
630	27° 27' 49.788" N	89° 21' 7.992" E
800	27° 27' 53.316" N	89° 21' 13.140" E
485	27° 27' 47.466" N	89° 21' 3.530" E
770	27° 27' 52.739" N	89° 21' 11.933" E
710	27° 27' 51.568" N	89° 21' 10.083" E

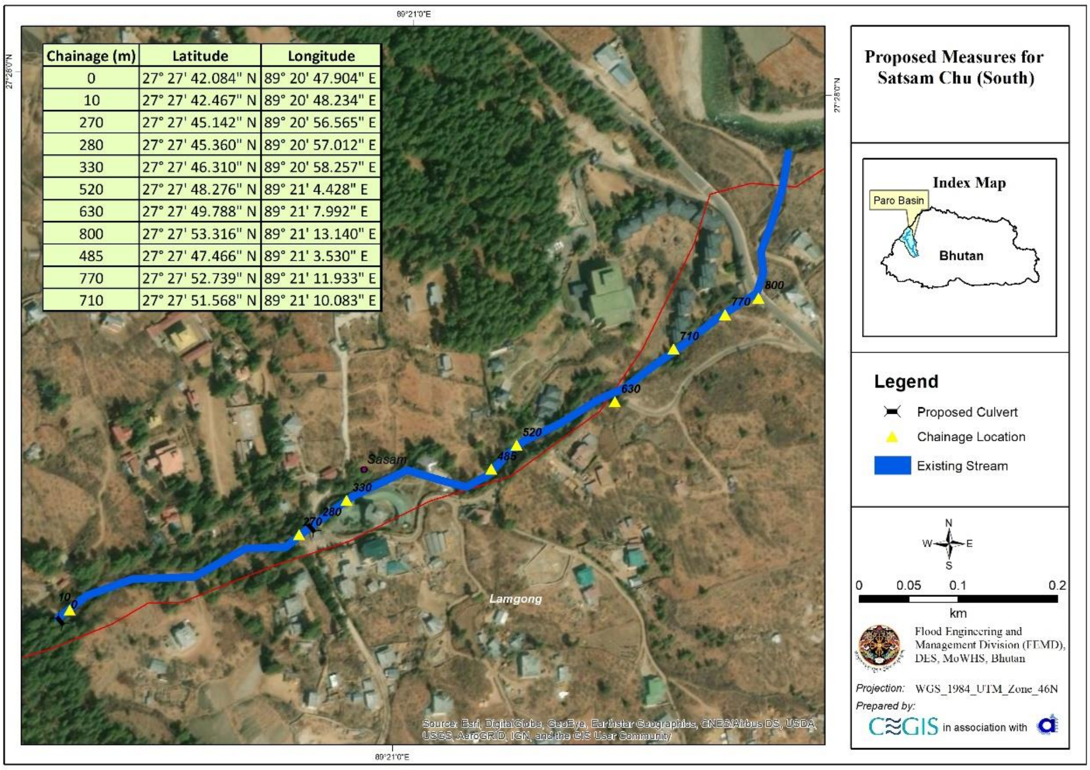


Figure 6.26: Proposed measure locations for Satsam Chu South with construction of additional box culverts

Jew Chu

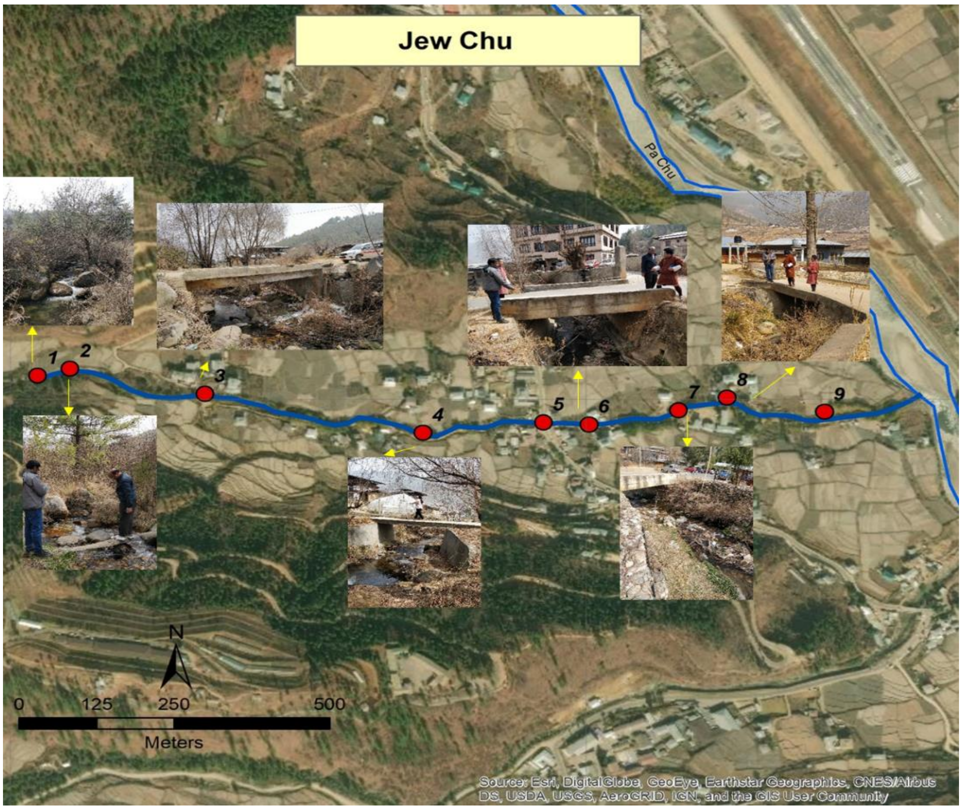


Figure 6.27: Map of concerned critical locations along Jew Chu and corresponding flow constrictions

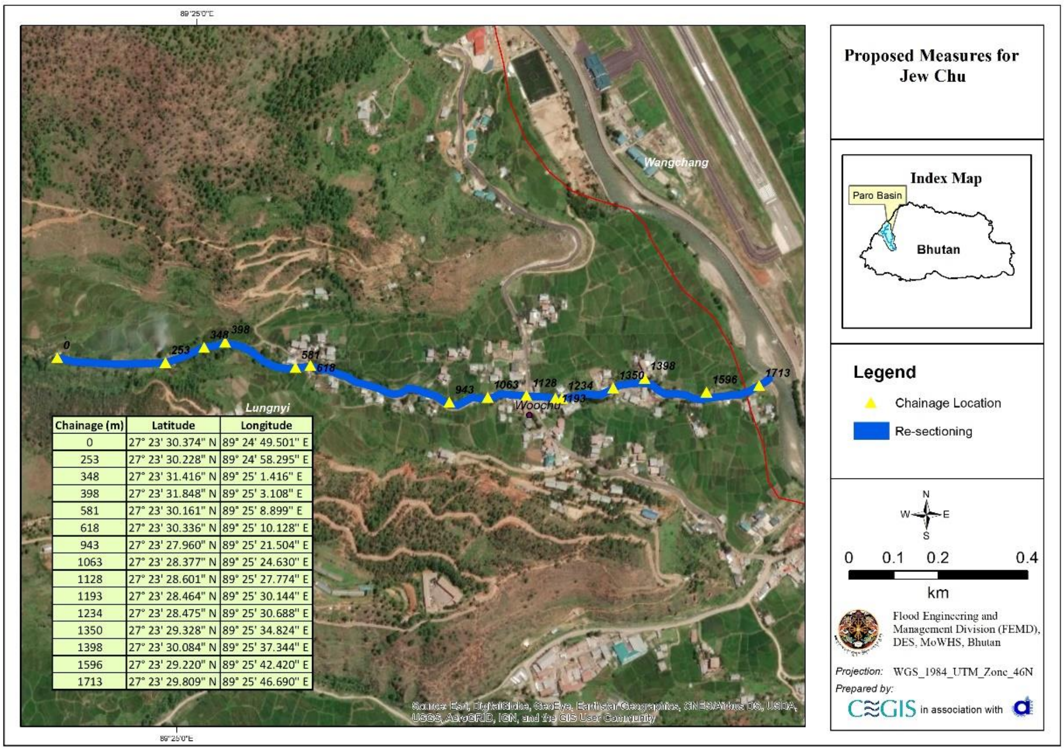
For Jew Chu, additional section area is required to pass out the flood flow as per hydrodynamic modeling. For this purpose, two alternate options are being considered initially. One is where sections will remain trapezoidal and natural. The other is that sections will be rectangular throughout the channel with RCC lining, making it a U-shaped channel. Also, local solutions in the form of cross-drainage structures will still be required, details of which are given below.

Table 6.16: Location-wise proposed measures for Jew Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measures	Remarks
1	348	u/s of Jewchu		Need to clear the flow path along the river.	
2	398	Cross submerged road		Clear the boulders at inner bend of the river. A road for pedestrian movement can be provided. Brick wall and RCC slab over it.	Suggestion
3	618	Box culvert	5.2 x 1.8 m	The opening is full during monsoon. There is a stone wall at the up at the left bank. In 1968, the river flooded.	Adequate for 25 year design discharge
4	943	Box culvert	3 x 1.5 m	Remove boulder under the culvert.	Clear the flow path
5	1128	Bridge		The Bridge has sufficient opening.	
6	1193	Box culvert	3.65 x 1.82 m	Section checked using design discharge.	Adequate
7	1350	Box culvert	4.7 x 1.6 m	Erosion just up of the culvert. Right bank gabion failed just down of the culvert.	Need to clear the flow path
8	1398	Box culvert	3.35 x 2.25 m	Section checked using design discharge.	Adequate
9	1596	Narrow section		Re-sectioning and recommend guide wall in both section with box culvert. 20-30m of length.	Re-sectioning of the stream designed to address the problem

Table 6.17: Chainage locations for Jew Chu

Chainage	Lat	Long
0	27° 23' 30.374" N	89° 24' 49.501" E
253	27° 23' 30.228" N	89° 24' 58.295" E
348	27° 23' 31.416" N	89° 25' 1.416" E
398	27° 23' 31.848" N	89° 25' 3.108" E
581	27° 23' 30.161" N	89° 25' 8.899" E
618	27° 23' 30.336" N	89° 25' 10.128" E
943	27° 23' 27.960" N	89° 25' 21.504" E
1063	27° 23' 28.377" N	89° 25' 24.630" E
1128	27° 23' 28.601" N	89° 25' 27.774" E
1193	27° 23' 28.464" N	89° 25' 30.144" E
1234	27° 23' 28.475" N	89° 25' 30.688" E
1350	27° 23' 29.328" N	89° 25' 34.824" E
1398	27° 23' 30.084" N	89° 25' 37.344" E
1596	27° 23' 29.220" N	89° 25' 42.420" E
1713	27° 23' 29.809" N	89° 25' 46.690" E



Chainage (m)	Latitude	Longitude
0	27° 23' 30.374" N	89° 24' 49.501" E
253	27° 23' 30.228" N	89° 24' 58.295" E
348	27° 23' 31.416" N	89° 25' 1.416" E
398	27° 23' 31.848" N	89° 25' 3.108" E
581	27° 23' 30.161" N	89° 25' 8.899" E
618	27° 23' 30.336" N	89° 25' 10.128" E
943	27° 23' 27.960" N	89° 25' 21.504" E
1063	27° 23' 28.377" N	89° 25' 24.630" E
1128	27° 23' 28.601" N	89° 25' 27.774" E
1193	27° 23' 28.464" N	89° 25' 30.144" E
1234	27° 23' 28.475" N	89° 25' 30.688" E
1350	27° 23' 29.328" N	89° 25' 34.824" E
1398	27° 23' 30.084" N	89° 25' 37.344" E
1596	27° 23' 29.220" N	89° 25' 42.420" E
1713	27° 23' 29.809" N	89° 25' 46.690" E

Figure 6.28: Proposed measure locations for Jew Chu with construction of additional box culverts

Gatanarong Chu

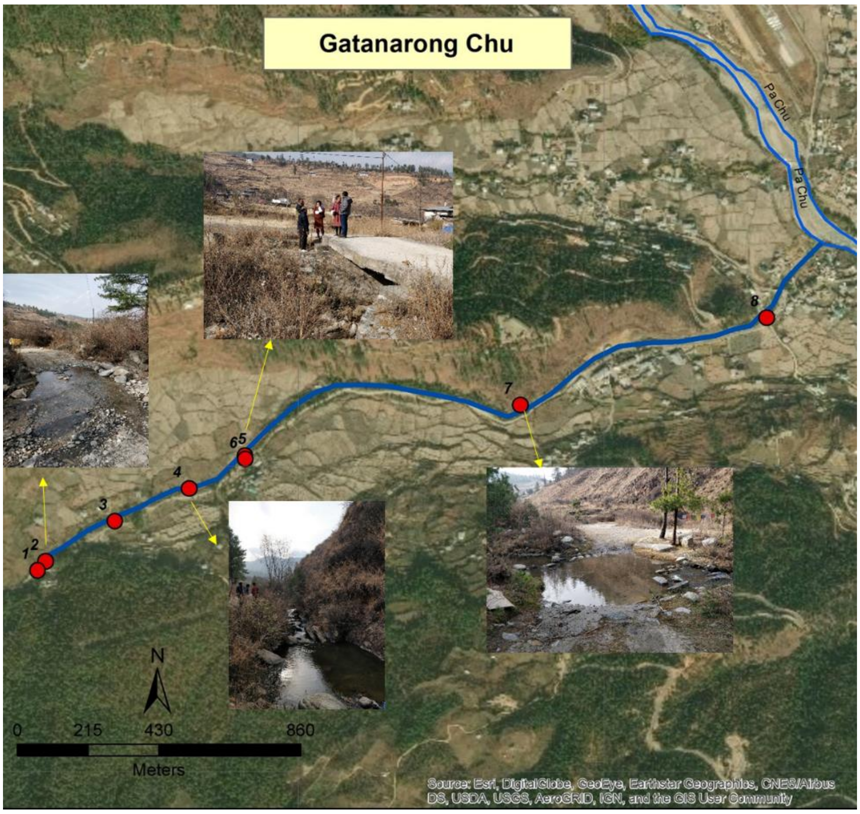


Figure 6.29: Map of concerned critical locations along Jew Chu and corresponding flow constrictions

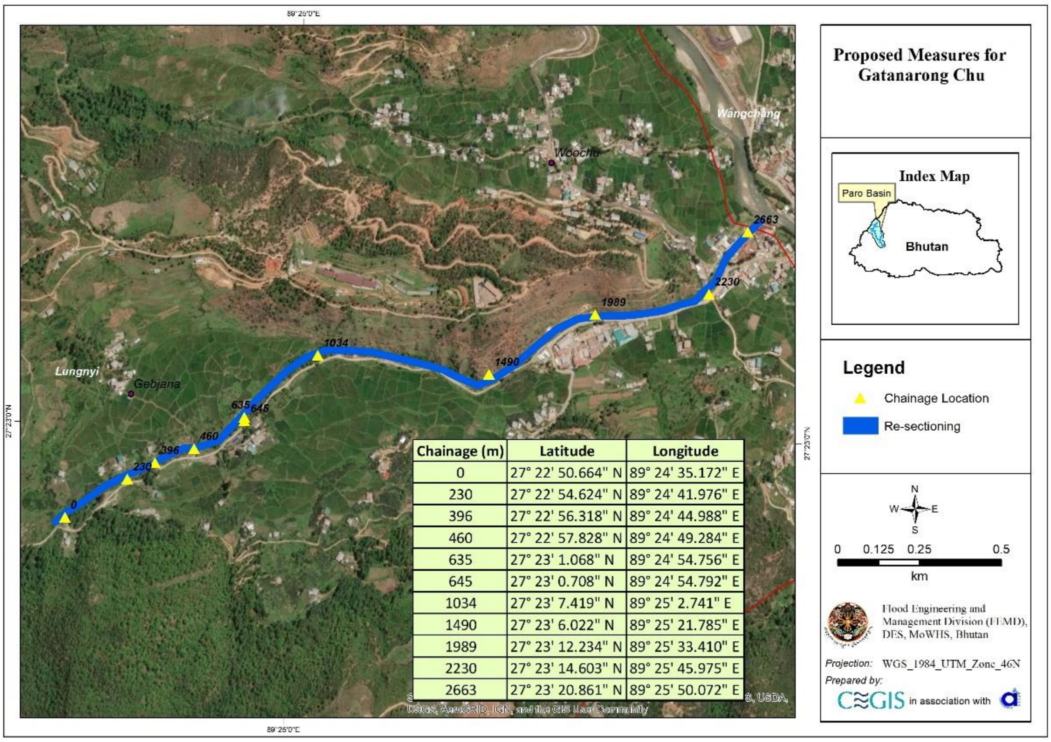
For Gatanarong Chu, additional section area is required to pass out the flood flow as per hydrodynamic modeling. For this purpose, two alternate options are being considered initially. One is where sections will remain trapezoidal and natural. The other is that sections will be rectangular throughout the channel with RCC lining, making it a U-shaped channel. Also, local solutions in the form of cross-drainage structures will still be required, details of which are given below.

Table 6.18: Location-wise proposed measures for Gatanarong Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
2	0	Cross submerged road		Stream filled up to allow vehicle and pedestrian passage. Rectify immediately via box culvert and allowance of clear flow path (2V x 3m x 4m depth).	Re-sectioning of the stream designed to address the problem.
3	230	Box culvert	4.7 x 2.25 m	No railing. Bending stream. Culvert needs to be re-constructed. Stream filled to make the road, need to clear the temporary cross road.	Suggestion given
4	460	Box culvert	5.8 x 2.6 m	Section checked using design discharge.	Adequate
5	635	Temporary cross passage		Re-sectioning required. Need Culvert of 6m span.	Re-sectioning of the stream designed to address the problem.
6	645	Another gully join		2m x 2m box culvert required across the road.	
7	1490	Pipe culvert	450 mm dia	Cross drainage.	
8	2230	Bridge		The bridge opening is adequate to pass the flow.	Opening is adequate

Table 6.19: Chainage locations for Gatanarong Chu

Chainage	Lat	Long
0	27° 22' 50.664" N	89° 24' 35.172" E
230	27° 22' 54.624" N	89° 24' 41.976" E
396	27° 22' 56.318" N	89° 24' 44.988" E
460	27° 22' 57.828" N	89° 24' 49.284" E
635	27° 23' 1.068" N	89° 24' 54.756" E
645	27° 23' 0.708" N	89° 24' 54.792" E
1034	27° 23' 7.419" N	89° 25' 2.741" E
1490	27° 23' 6.022" N	89° 25' 21.785" E
1989	27° 23' 12.234" N	89° 25' 33.410" E
2230	27° 23' 14.603" N	89° 25' 45.975" E
2663	27° 23' 20.861" N	89° 25' 50.072" E



Chainage (m)	Latitude	Longitude
0	27° 22' 50.664" N	89° 24' 35.172" E
230	27° 22' 54.624" N	89° 24' 41.976" E
396	27° 22' 56.318" N	89° 24' 44.988" E
460	27° 22' 57.828" N	89° 24' 49.284" E
635	27° 23' 1.068" N	89° 24' 54.756" E
645	27° 23' 0.708" N	89° 24' 54.792" E
1034	27° 23' 7.419" N	89° 25' 2.741" E
1490	27° 23' 6.022" N	89° 25' 21.785" E
1989	27° 23' 12.234" N	89° 25' 33.410" E
2230	27° 23' 14.603" N	89° 25' 45.975" E
2663	27° 23' 20.861" N	89° 25' 50.072" E

Figure 6.30: Proposed measure locations for Gatanarong Chu with construction of additional box culverts

Ri Chu

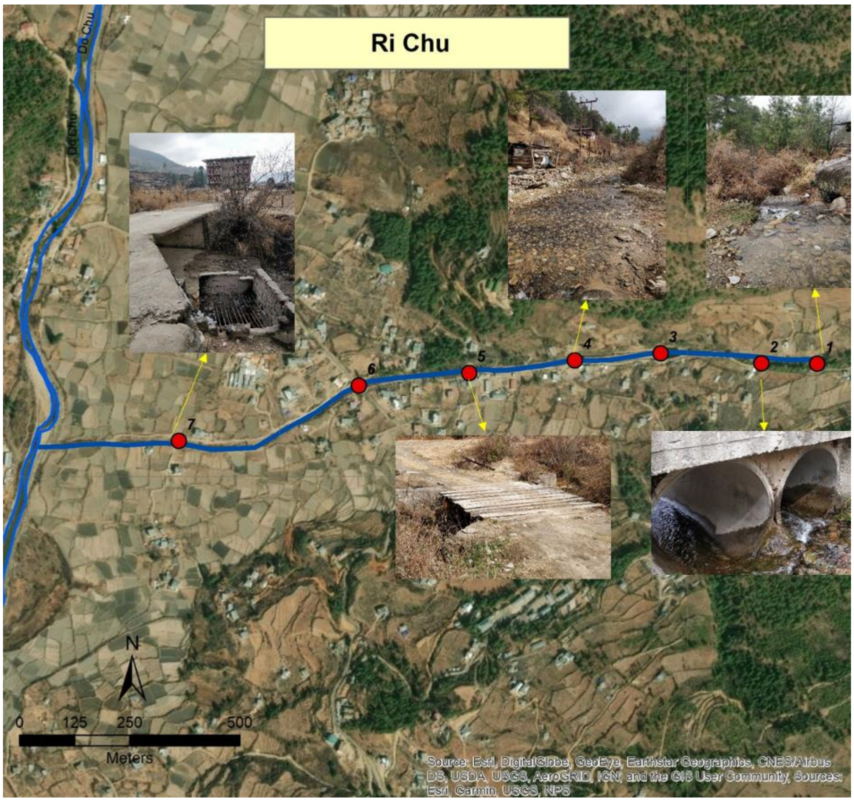


Figure 6.31: Map of concerned critical locations along Ri Chu and corresponding flow constrictions

For Ri Chu, additional section area is required to pass out the flood flow as per hydrodynamic modeling. For this purpose, two alternate options are being considered initially. One is where sections will remain trapezoidal and natural. The other is that sections will be rectangular throughout the channel with RCC lining, making it a U-shaped channel. Also, local solutions in the form of cross-drainage structures will still be required. An additional recommendation for Ri Chu is that the existing Ri Chu dam reservoir can be utilized to its full potential if the depth is increased as it will allow for additional storage, a trait that is not required for hydraulic purposes, rather more so as it will allow some form of fish culture possibilities. Details of measures for Ri Chu are given below.

Table 6.20: Location-wise proposed measures for Ri Chu

Id.	Chainage (m)	Existing Measure	Dimensions	Recommended Measure	Remarks
1	904	Cross submerged road		Temporary submerged road across the river. Box culvert is suggested.	Not mandatory, it a suggestion. thus excluded from measures
2	1014	Pipe culvert	2 x 900 mm dia	Pipe Culvert is okay. 50m guide wall (20m up + 30m down from culvert) at right bank is required.	Pipe culvert is adequate. Channel was re-sectioned to accommodate the design water
3	1219	Ri Chu dam		No contribution to flooding.	The Ri Chu dam is not functioning and its storage reservoir is silted up. But it does not cause any adverse effect of flooding
4	1389	Cross submerged road		Temporary submerged road that cross the river. Need box culvert with wing wall.	Not mandatory, it a suggestion. thus excluded from measures
5	1609	Wooden culvert	3.5 x 1.3 m	Wooden culvert can be replaced with box culvert.	It's an optional suggestion
6	1834	Box culvert	5 x 1.3 m	Stream crosses the main road. Opening size checked for design discharge	Culvert is adequate
7	2239	Box culvert		Opening size seems adequate.	Culvert is adequate

Table 6.21: Chainage locations for Ri Chu

Chainage	Lat	Long
0	27° 26' 47.580" N	89° 26' 39.014" E
904	27° 26' 38.328" N	89° 26' 9.528" E
1014	27° 26' 38.364" N	89° 26' 5.424" E
1093	27° 26' 38.976" N	89° 26' 2.874" E
1151	27° 26' 39.117" N	89° 26' 0.769" E
1219	27° 26' 39.084" N	89° 25' 58.008" E
1291	27° 26' 38.942" N	89° 25' 55.728" E
1389	27° 26' 38.580" N	89° 25' 51.708" E
1513	27° 26' 37.819" N	89° 25' 47.878" E
1609	27° 26' 37.644" N	89° 25' 43.932" E
1834	27° 26' 36.708" N	89° 25' 35.832" E
2135	27° 26' 32.205" N	89° 25' 26.989" E
2239	27° 26' 32.640" N	89° 25' 22.584" E
2411	27° 26' 32.354" N	89° 25' 17.592" E
2521	27° 26' 32.189" N	89° 25' 13.656" E

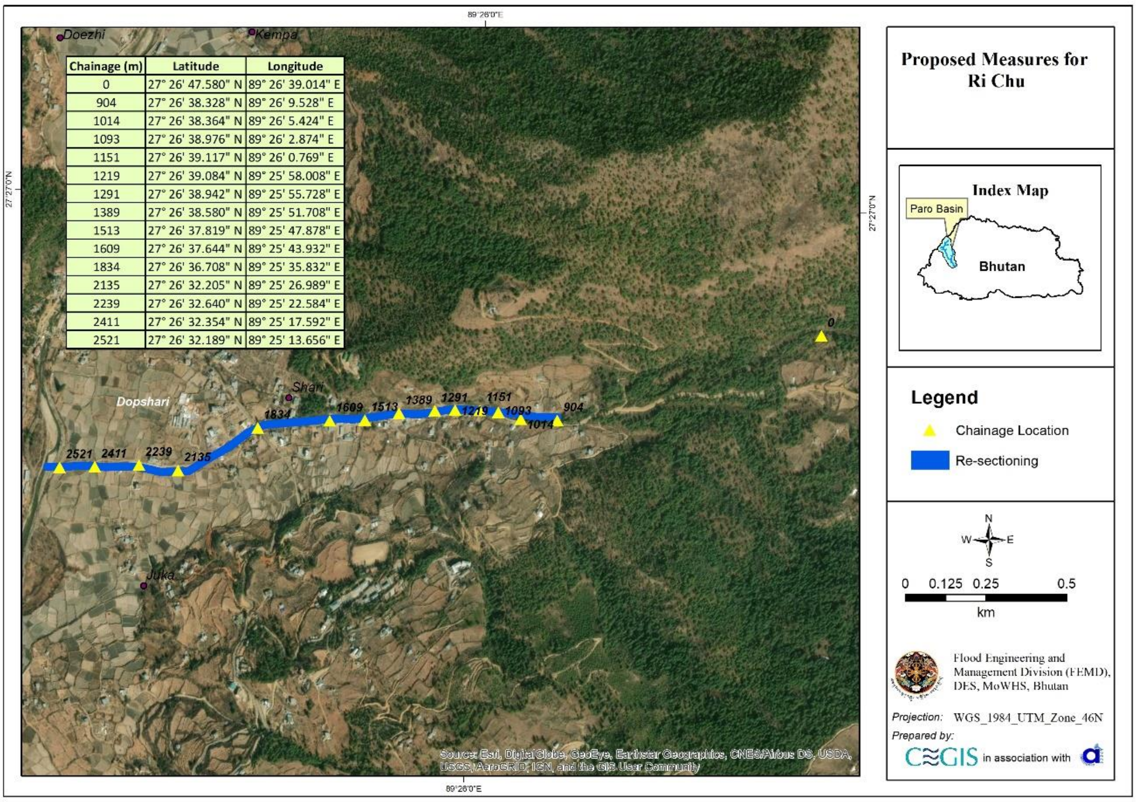


Figure 6.32: Proposed measure locations for Ri Chu with construction of additional box culverts

6.4 Non-structural Measures

In addition to the structural measures discussed above, a number non-structural measures have been recommended for flood mitigation in Paro Basin to enhance the effectiveness of climate resilient measures and make all of the stakeholders as opportunist of structural measures. Non-structural measures have been recommended in general and as a whole for both the river and stream catchments within the Paro Basin. Recommended non-structural measures include –

- Floodplain Zoning
- Flood Early Warning System
- Preservation and/or restoration of natural wetlands
- Capacity development of relevant stakeholders

These key non-structural measures are more elaborately discussed within the following detailed section.

6.4.1 Floodplain Zoning

A comprehensive Floodplain Zoning for the entire Paro Basin floodplain will have to be implemented. This is to be done from results generated via hydrodynamic modeling whereby flood depths for different portions of the floodplain area are to be determined. This data will undergo a detailed comparison and matching with historical flood depth data for the region via field studies to device separate flood zones. The probable flood zones in conjunction with model generated climate change considerate flood maps for 25/ 50/ 100 years flood events are as follows –

- **Zone A:** This zone has flood depth range equal to or exceeding 2.0 meters and represents the flowing channels such as rivers and associated steams. As the prime bearers of flood flow from the Paro basin, these represent the pinnacle of flood management and will have to be maintained rigorously as per designed sections with ample bank protection measures.

- **Zone B:** This zone consists of the locations immediate to the flowing water bodies and represent the region that is at high risk should a substantial flood event occurs. As per flood maps, the corresponding depths can be from 1.0-2.0 m.
- **Zone C:** This zone consists of the locations with relative higher average elevation than high risk flood zones and represent the region that is at moderate risk should a substantial flood event occurs. As per flood maps, the corresponding depths can be from 0.5-1.0 m.
- **Zone D:** This zone consists of the locations relatively near the upper echelon of the floodplain in comparison to the flood risk zones and represent the region that is at low risk should a substantial flood event occurs. As per flood maps, the corresponding depths can be from 0.0-0.5 m.

Figure 6.33 illustrates a basic exemplary concept schematic section of flood plain zoning for Paro Basin.

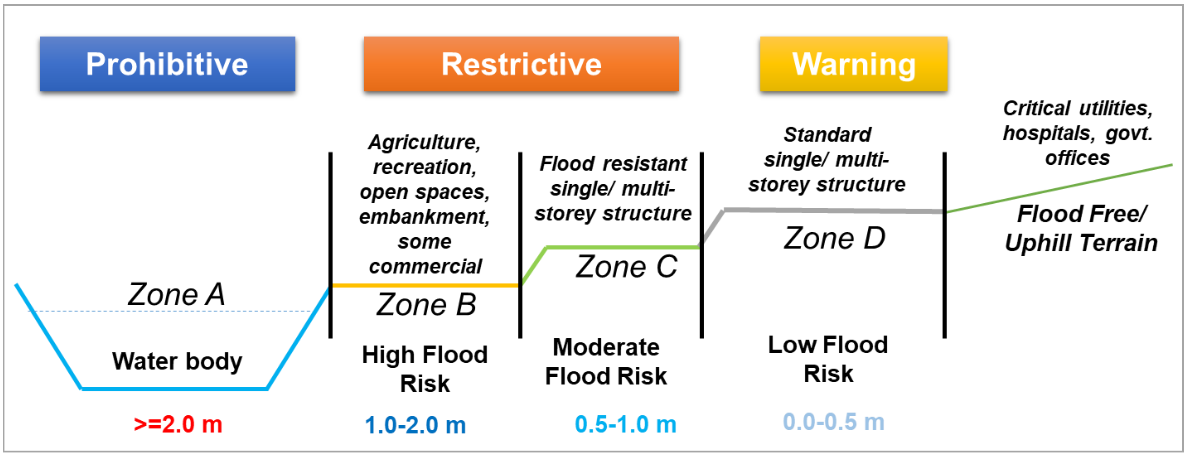


Figure 6.33: Generic exemplary schematic section of floodplain zoning for Paro Basin

The Floodplain Zoning concept will include and ensure the following –

- Categorical zoning of designated floodplain area within the Paro Basin for 25, 50, 100 year flood extent area and associated depths;
- Since Paro is undergoing rigorous development phase with development of essential engineering structures for tourism and urbanization; strict guidelines can be developed that can regulate the building of structures within high risk floodplain zones;
- Floodplain zoning would enable the future proofing of urban development of Paro Dzongkhag which would minimize potential damage to structures due to high intensity flooding thereby reduce damages;
- Floodplain zoning would allow provision for more green space to be blended within open spaces in urban development, via enforcing if need be. This would allow natural flow retardation, allow more space for infiltration and would automatically enforce plantation within development zone for maximum reduction to flow accumulation into channels;
- As the Paro valley is dominated by agricultural practices, this would be a win-win situation as floodplain zoning will ultimately enable provisions for more controlled agricultural practices within designated floodplain definitions for boosting productions as well as natural flow retardation. Zoning measures will ensure regulatory controlled inundation of

agricultural lands within the floodplain to maximize profits and minimize harmful flood extents;

- Floodplain zoning will also allow the designated agricultural lands to be treated as additional temporary flood flow reservoirs during times of catastrophic events based on lowest elevation lands. In such cases, flow during times of such events will have to regulated into these zones for maximum reduction of flood damage;
- In conjunction with the aforementioned "in-urban" infiltration pockets, floodplain zoning enables the provisions for implementing designated infiltration zones within the greater floodplain portion of the basin and enact a provision of "controlled flooding"; and
- The hypsometric curve in **Figure 6.2** means that in relevance, there are steep slope and mild slope within the basin and little "medium" slope in between which causes for unwarranted increase in surface runoff velocity and reducing time of concentrations. As such, provisions such as these will greatly help in increasing time of concentration through phased retardation of flow.

Challenges in Implementation of Floodplain Zoning

- Administration has to arrive a solid consensus regarding the stipulated flood event return period for design of protection measures, land development measures and building construction;
- Implementation of comprehensive land development schemes such as floodplain zoning is comparatively difficult on land area that has already been developed and it has to be tailor-made to fit the type of land development already prevalent;
- Close integration has to exist and be maintained in between disaster management and landuse planning divisions and inter-agency coordination has to be maintained between the technical and local administrative organizations;
- Strictly regulated future development plans, especially on regions where there is pre-existing landuse development;
- Climate projections have to be constantly taken into account and have to be comprehensively incorporated into devising floodplain zoning;
- Careful overall techno-economic and administrative consideration on delineating floodplain zones and subsequently development zones as otherwise there might arise necessity for altering zone areas which will cause unnecessary cost incursions; and
- For hybrid regions i.e., where there exists both developed and barren lands such as Paro, special emphasis has to be given to the future development possibilities of the barren lands in question so that they may, at times of necessity act as sustainable compensatory flood management/ storage facilities.

6.4.2 Flood Early Warning System

Flood Early Warning System (EWS) has to be implemented for the rivers and high flowing streams of Paro Basin. This will have to include the following –

- Calculation of flood discharge and water levels for varying return periods (25/ 50/ 100 years) via hydrodynamic modeling and incorporating climate projection scenarios into modeling exercises;

- Device suitable warning concept in conjunction with existing and perceived structural measures. From aforementioned considerations and the resultant data from modeling, designate appropriate flood water levels throughout the river/ stream reach;
- Establish water level measurement gages in the upstream reaches of the rivers and high risk streams and develop warning mechanism for designated flood levels, incorporating and factoring in a suitable lead-time;
- Devise proper community driven and gender sensitive flood warning response mechanism for designated flood zones and entitle appropriate authorities responsible for carrying out flood response strategies; and
- Ensure timely collection, accumulation and dissemination of flood data and knowledge to achieve most effective and sustainable warning broadcasting and response mechanism to attain full-fledged disaster preparedness.

Figure 6.32 illustrates a basic schematic of an early warning mechanism.

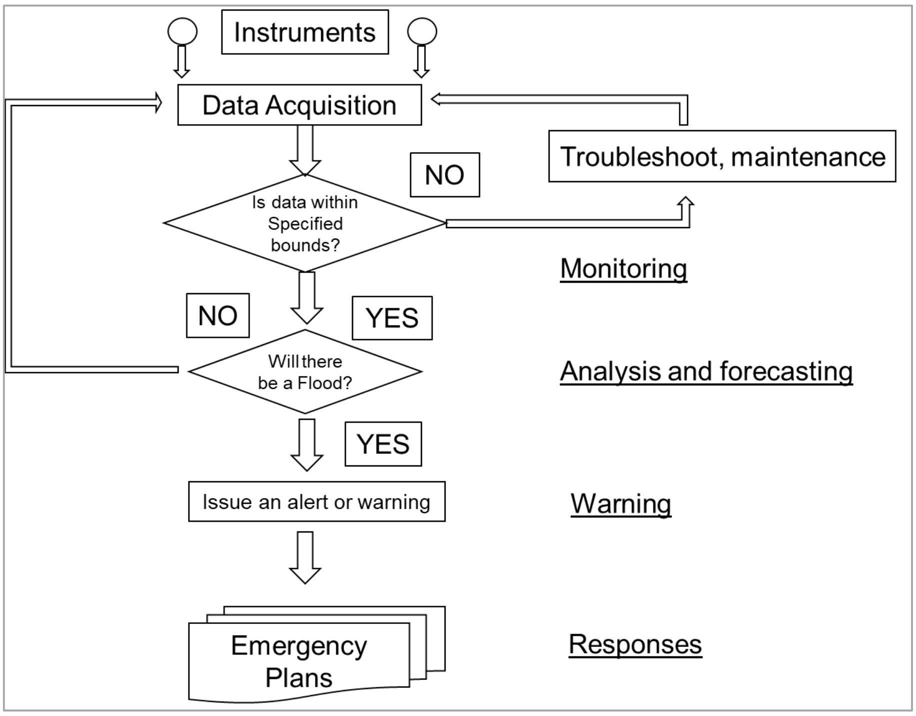


Figure 6.34: Generic technical mechanism of flood early warning system

Challenges in Implementation of Early Warning System

- Low lead times i.e., less time for taking precautionary measures due to short travel times of flood water coupled with steep slope;
- Inaccessible upstream catchment locations due to mountainous terrain and dense forest vegetation which can make installment of water gage or other equipment difficult;
- High capacity computational power requirements for data processing and flood forecasting;
- Challenges exist regarding utilization of satellite based rainfall data, particularly ground level measurements, with the actual rainfall using estimates from radar measurements or observation gauges;

- Development and operation of basin wide flood forecasting modeling framework requires adequate historical and current short duration as well as daily data; and
- Deteriorating hydrological services, particularly in carrying discharge measurements, maintenance and servicing of the gauging stations is also a challenge which can create further limitations to data quality assurance for forecasting purposes.

6.4.3 Preservation and/or Restoration of Natural Wetlands

As can be seen from **Table 2.10**, approximately one-tenth of the Paro Basin consists of marshy wetlands that are natural contributors to flood management. These wetlands, especially the ones falling within the upstream portion of river/ stream catchments have to be properly accounted for and maintained for natural water retention and thereby reducing flow accumulation through enforcing retardation of flood flow. Wetlands preservation is to include the following –

- Existing wetlands will be zoned and classified according to the flood vulnerability as well as levels of ecological, utilitarian, national and local significance, and managed sustainably on the basis of appropriate flood management mechanisms;
- Restoration of degraded wetlands will be given priority;
- Privately owned wetlands will be brought under appropriate management systems, if necessary through legal reforms;
- Integration of wetland management into water/ flood management policies, land use plans at all levels;
- Sustainable use and equitable benefit sharing, habitat conservation and integrated management at all stages involving participatory and collaborative processes;
- Active and informed participation of civil society in the conservation of wetlands will be encouraged; and
- Sustainable financing mechanisms through local and foreign sources will be developed for the management and wise use of wetlands.

6.4.4 Capacity Development of Relevant Stakeholders

All the above discussed flood management intervention both structural and non-structural share common requirement such as –

- Knowledge on underlying technical development;
- Construction/ implement supervision;
- Operation and maintenance;
- Formulation/ development criteria and mechanism; and
- Incentive for further research.

On that note, it is imperative that the existing capacity of the local stakeholders are maximized. The local stakeholders include –

- Dzongkhag/ Gewog Officials;
- Field officials; and
- Local inhabitants.

This can be achieved through capacity development sessions for –

- Knowledge on flood management on a basin-scale including proper envisioning of problems in both upstream and downstream of a channel and all other associated environmental and socio-economic factors;
- Attain necessary knowledge on hydrological and hydrological analyses for determining design parameters and design criteria for development of flood management/ mitigation measures;
- Knowledge on the requirement of and thereby establishment of necessary institutional arrangement for hydrological and sediment data collection and monitoring;
- Strengthening of existing institution for implementation and monitoring of engineering activities ;
- Capacity development of local engineers and awareness raising among local residents and stakeholders; and
- Incentives and mode of research activities should be performed for geotechnical stabilities of sources and bank of streams with bio-engineering.

7. Finalization of Measures

7.1 Development of Potential Options

As from discussions in chapter 6 regarding flood management measures, the major measures regarding both river and stream network lie in both location specific bank protection as well as re-sectioning of existing flow passage sections to allow smooth conveyance of flood flow with additional provisions for box culverts in selected stream(s). Techno economic analysis was performed for choosing the most suitable option from among the potential options. As both environmental and social aspects were also taken under consideration, the Multi-Criteria Decision Analysis (MCDA) tool has been used in order to assess all available options analytically, combining environmental and social aspects and linking them with techno economic factors in providing a holistic coherent picture scenario to aid decision making.

Separate MCDA analyses were performed for the rivers and streams within the study region. Three separate MCDA have been performed for the river namely, one for the immediate right bank protection measures for Pa Chu upstream, one for Pa Chu for short-term measures and one for Pa Chu and Do Chu long-term measures. Three separate MCDA have also been performed for the streams; one for Nephu Chu, one for Ngoborong Chu and one for the 3 streams Jew Chu, Gatanarong Chu and Ri Chu. No alternative option selection via MCDA have been done for the 3 streams Satsam Chu North, Satsam Chu South and Dakhorong Chu as flow sections for these streams have been found to be adequate. Development of relevant options for each MCDA has been presented in **Table 7.1** below.

Table 7.1: Potential design options for flood management measures for rivers and streams

MCDA 1: Potential Immediate Options for Pa Chu

- **Option 1: RB protection in vulnerable locations via gabion mesh**

  This option presents the protection for Pa Chu upstream portion and for the right bank only. It consists of bank protection measures via gabion mesh. Toe-wall is provided as per requirement.

- **Option 2: RB protection in vulnerable locations via CC revetment**

  This option presents the protection for Pa Chu upstream portion and for the right bank only. It consists of bank protection measures via CC revetment. Toe-wall is provided as per requirement.

MCDA 2: Potential Short-term Options for Pa Chu

- **Option 1: Designed river sections with gabion mesh without toe wall**

  This option presents the re-sectioning of Pa Chu River upstream sections with excavated bed and/ or bank material graded and used for filling material for bank and bed. Banks are filled with 1:3 slope with graded materials with provisions for design without toe wall at bank and bed connections.

- **Option 2: Designed river sections with gabion mesh with toe wall**

  Pa Chu River upstream sections with excavated bed and/ or bank material graded and used for filling material for bank and bed. Banks are filled with 1:3 slope with graded materials with provisions for design with toe wall at bank and bed connections where toe walls providing more mutual stability with little added cost incursion.

- **Option 3: Designed river sections with CC revetment and toe wall**

  This option considers bank protection in the form of CC revetment along with the designed river sections with 1:3 side slope and toe walls installed. Bed is filled with graded cut material.

MCDA 3: Potential Long-term Options for Pa Chu and Do Chu

- **Option 1: Designed river sections with gabion mesh without toe wall**

In this option, the river banks and bed have been filled with graded cut materials with provisions for design without toe wall at bank and bed connections.

- **Option 2: Designed river sections with gabion mesh with toe wall**

  In this option, the river banks and bed have been filled with graded cut materials with toe wall at bank and bed connections where toe walls providing more mutual stability with little added cost incursion.

MCDA 4: Potential Options for Nephu Chu

- **Option 1: Trapezoidal stream section**

  This option presents the simplest state with the stream sections designed to convey flood flow downstream. The sections are kept in its current natural state in that no concrete lining is recommended.

- **Option 2: Mix of Trapezoidal and Rectangular stream section**

  This option considers trapezoidal sections in the upstream portion and rectangular RCC lined sections in the downstream portion.

MCDA 5: Potential Options for Ngoborong Chu

- **Option 1: Rectangular section without renovation of existing culverts**

  As much of Ngoborong Chu is already rectangular shaped, both option envisages the entire stream as a rectangular brick masonry channel. Having said that, this first option does so with keeping the existing culverts intact as they have been found sufficiently adequate in terms of allowing flow passage.

- **Option 2: Rectangular section with renovated culverts**

  This option considers similar rectangular brick masonry channel but now with the existing culverts demolished and reconstructed. This has been considered to even further smoothen out the flow passage and providing additional gaps within each culvert openings to negate any potential future bottleneck due to waste dumping and/or sedimentation.

MCDA 6: Potential Options for the 3 Streams (Jew Chu, Gatanarong Chu, Ri Chu)

- **Option 1: Trapezoidal stream section**

  This option presents the simplest state with the stream sections designed to convey flood flow downstream. The sections are kept in its current natural state in that no concrete lining is recommended.

- **Option 2: Rectangular stream section**

  This option considers rectangular RCC lined streams for flow passage.

The techno-economic analysis and subsequent selection of best suitable options for both the rivers and streams are described in the following sections.

7.2 Techno-economic Analysis

MCDA aims at providing an overall ordering of alternatives from the most to least preferred, based on several objectives or criteria characterized by any mixture of monetary and non-monetary objectives in breaking the problem into more manageable pieces.

All considered options have some inherent advantages/ disadvantages regarding conveyance of flow and final decision has been taken after extensive comparative analysis, taking all factors under consideration. For the immediate options for Pa Chu, option 1 presents the protection of right bank at selected locations via gabion mesh while option 2 presents protection at similar locations via CC revetment. In case of short term measure selection for Pa Chu, option 1 presents the simpler solution in the technical sense, and would involve the least implementation and maintenance costs. But this option may be subject to relative bank erosion as well as bed scouring and erosion in the long run from recurring high velocity flows. Option 2 has a bit of additional protection due to installment of toe wall, it is cheaper than option 3 but also has potentiality to succumb to long term erosion. Option 3 has more reinforced river banks through CC block protection that not only allow smooth flow passage and less friction, but also cancels and bank erosion possibilities. But river beds are still prone to erosion, more so due to additional flow velocity gained from decreased bank friction. Also, the CC block works would incur a substantial increase in implementation costs. For case of long-term solution for both rivers, option 1 presents the simpler solution in the technical sense, and would involve the least implementation and maintenance costs. But this option may be subject to relative bank erosion as well as bed scouring and erosion in the long run from recurring high velocity flows. Option 2 has a bit of additional protection due to installment of toe wall, but also has potentiality to succumb to long term erosion.

For Nephu Chu, both options 1 & 2 would be costly to a certain extent as option 1 although has provisions or natural trapezoidal sections, will require land acquisitions as more top width will be required. On the other hand, option 2 will be costly as rectangular RCC sections will instill an increased capital cost. Thus for this stream, ultimate verdict depends on which cost is less overall, conclusions of which are ultimately drawn based on field experiences associated with existing land costs. For Ngoborong Chu both options 1 and 2 consist of brick masonry rectangular structures. However, as the existing culverts are deemed to be satisfactorily adequate, option 1 aims to keep them which would minimize costs. Option 2 aims to reconstruct them with additional opening. This is beneficial in terms that as the stream will anyhow be subjected to flow constriction from waste dumping and/or boulder blockage from sedimentation, allowing additional opening helps in keeping satisfactory passage available during such times. This however, incurs additional cost both for construction and for probable land acquisitions. For the 3 streams (Jew Chu, Gatanarong Chu and Ri Chu), alternates are sought in between keeping natural sections and rectangular RCC sections.

The techno-economic analysis have been done on four broad categories namely, technical, economic, environmental and social grounds. Criteria for evaluating flood flow management have been selected based on the expected impacts that various relevant factors might exert upon the construction, long term operation and maintenance of the river sections. A total of seven criteria have been selected and they have been grouped into the aforementioned four categories. These criteria and their respective categories are illustrated in **Figure 7.1**. Two criteria under technical analysis are the ability of the intervention to convey flow as smoothly i.e. with minimal energy dissipation and the amount of bank and bed erosion and bed scouring the intervention might face in the long run. Two criteria under economic analysis include cost of construction and O&M costs. Two criteria under environmental analysis include sedimentation of river bed and water quality degradation. Finally, the sole criteria for evaluating social acceptability is land acquisition. Evaluation categories and criteria remain the same for both rivers and streams.

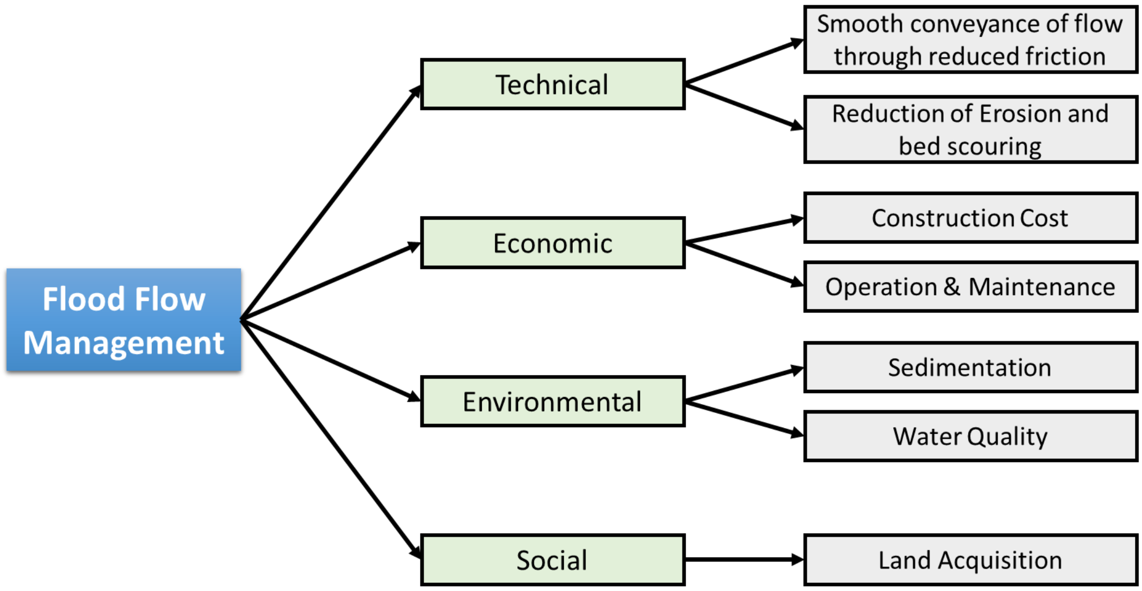


Figure 7.1: Selected criteria used for evaluating alternative options of flood flow management

Expert judgment was used in assigning individual scores to each criteria based on the present and/ or future state of the respective criteria. Weight factor for each group have been fixed based on their relative importance in selecting the best possible option. **Table 7.2** shows the scoring process followed for each criteria and **Tables 7.3 to 7.8** shows the scores assigned for each criteria along with the assigned weightage for the categories for river and streams respectively. The total score for both cases of the alternatives is calculated based on the weighted sum method given in the following equation (Chowdhury and Rahman, 2008):

$V(A) = \sum * w_i * v_i(a_i)$

where,

w_i = weight of criterion i

$v_i(a_i)$ = score of the alternative with respect to criterion i

$V(A)$ = value of the alternative A

As can be seen from **Table 7.2**, evaluation for each of the seven (7) criteria have been done through assigning a scoring mechanism of 1.0 to 5.0. Balance has been kept for the sake of easily decipherable analysis results in the form that 5.0 has been kept as the score for most beneficial and 1.0 as the least beneficial. An increment of 0.5 has been used to assign individual scores. Whereas there is an intrinsic end-cost issue built-in into all of the four broad categories, for simplicity, we are considering the qualitative aspects for technical, environmental and social categories. For the economic category, high cost is less beneficial and low cost is highly beneficial and scoring has been done accordingly.

Table 7.2: Scoring process followed for each criteria

Category	Criteria	Basis	Assigned Score
Technical	Smooth conveyance of flow through reduced friction	Very High to Very Low	5.0 – 1.0
	Reduction of erosion of bed scouring	Very High to Very Low	5.0 – 1.0

Category	Criteria	Basis	Assigned Score
Economic	Construction cost	Relatively Low to Relatively High	5.0 – 1.0
	O & M cost	Relatively Low to Relatively High	5.0 – 1.0
Environmental	Sedimentation	Very Low to Very High	5.0 – 1.0
	Water quality	Preferable to Not Preferable	5.0 – 1.0
Social	Land acquisition	Low Requirement to High Requirement	5.0 – 1.0

****Note: Values assigned during MCDA analyses incorporates a 0.5 increment while individual score assignments, based entirely on the technical judgment of the consultant.*

Table 7.3: Techno-economic analysis for MCDA 1 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2	
			Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	3.5	Relatively low due to gabion mesh having comparatively higher friction	4.0	Relatively high due to use of CC blocks as bank protection
		Reduction of erosion of bed scouring	3.5	Relatively lower reduction to erosion due to gabion mesh being slightly susceptible to erosion in the long run	4.0	Higher reduction due to both toe wall, graded bed and CC bocks at bank
Economic	0.9	Construction cost	5.0	Relative low due to availability of materials on site	2.0	Relatively high due separate construction of CC block, site management etc.
		O & M cost	3.5	Relatively high to cope with possible erosion and bed scouring through periodic dredging	4.5	Relatively low due to increased stability
Environmental	0.7	Sedimentation	4.0	Some probability as lower compaction due to absence of toe wall	4.5	Lowest probability due to CC block in bank and toe wall
		Water quality	4.0	Some probability in relevance to sedimentation	4.5	Lowest probability as CC block cancels sedimentation of banks and toe wall provides bed stability
Social	0.6	Land acquisition	4.5	Little to no land acquisition required	2.0	Relatively high requirement on a temporary basis for construction

Table 7.4: Techno-economic analysis for MCDA 2 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2		Option 3	
			Score	Remarks	Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	3.5	Lowest among the three options with graded bed and bank and no toe wall	3.5	Similar to option 1 with graded bed and bank and toe wall installed	4.0	Relatively high due to use of CC blocks as bank protection
		Reduction of erosion of bed scouring	3.5	Relatively lower reduction to erosion as although bed and bank graded, no toe wall	4.0	Relatively higher reduction than option 1 due to toe wall	4.5	Highest reduction among the three due to both toe wall, graded bed and CC bocks at bank
Economic	0.9	Construction cost	5.0	Lowest among the three	4.5	Relatively high due to installation of toe wall	2.0	Highest among the three
		O & M cost	3.0	Relatively high to cope with possible erosion and bed scouring through periodic dredging	3.5	Relatively moderate to high; periodic dredging required	4.5	Lowest among the three
Environmental	0.7	Sedimentation	3.0	Some probability as lower compaction due to absence of toe wall	4.0	Lower probability due to some form of compaction from toe wall	4.5	Lowest probability due to CC block in bank and toe wall
		Water quality	3.0	Some probability in relevance to sedimentation	4.0	Lower probability due to lower sedimentation rate due to stability from toe wall	4.5	Lowest probability as CC block cancels sedimentation of banks and toe wall provides bed stability
Social	0.6	Land acquisition	4.5	Little to no land acquisition required	4.5	Little to no land acquisition required	3.0	Relatively high requirement on a temporary basis for construction

Table 7.5: Techno-economic analysis for MCDA 3 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2	
			Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	3.5	Lowest among the three options with graded bed and bank and no toe wall	3.5	Similar to option 1 with graded bed and bank and toe wall installed
		Reduction of erosion of bed scouring	3.5	Relatively lower reduction to erosion as although bed and bank graded, no toe wall	4.0	Relatively higher reduction than option 1 due to toe wall
Economic	0.9	Construction cost	5.0	Lowest among the three	4.5	Relatively high due to installation of toe wall
		O & M cost	3.0	Relatively high to cope with possible erosion and bed scouring through periodic dredging	3.5	Relatively moderate to high; periodic dredging required
Environmental	0.7	Sedimentation	3.0	Some probability as lower compaction due to absence of toe wall	4.0	Lower probability due to some form of compaction from toe wall
		Water quality	3.0	Some probability in relevance to sedimentation	4.0	Lower probability due to lower sedimentation rate due to stability from toe wall
Social	0.6	Land acquisition	4.5	Little to no land acquisition required	4.5	Little to no land acquisition required

Table 7.6: Techno-economic analysis for MCDA 4 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2	
			Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	3.5	Relatively moderate	4.0	Relatively high due to RCC rectangular section downstream
		Reduction of erosion of bed scouring	3.5	Relatively moderate	4.0	Relatively high due to RCC rectangular section downstream
Economic	0.9	Construction cost	4.5	Relatively low	3.5	Relatively high as CC lining of stream reach downstream
		O & M cost	3.0	Relatively high as cost of sediment removal and bush cleaning will be required on some level	4.0	Relatively on the lower side as minimal cleaning of debris will be required
Environmental	0.7	Sedimentation	3.0	Relatively high due to full trapezoidal channel	3.5	Relatively low as portion of channel will be RCC lined
		Water quality	3.0	Relatively higher due to sedimentation	3.5	Relatively lower due to RCC lining on downstream portion
Social	0.8	Land acquisition	2.0	High land acquisition requirements downstream due added top width from trapezoidal channel	4.0	Land acquisition requirements relatively low to moderate

Table 7.7: Techno-economic analysis for MCDA 5 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2	
			Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	4.0	Relatively slightly low	4.5	Relatively slightly high
		Reduction of erosion of bed scouring	4.5	Little to none as brick masonry all throughout	4.5	Little to none as brick masonry all throughout
Economic	0.9	Construction cost	5.0	Relatively low as much of existing channel is already rectangular with brick masonry	3.0	Relatively high as existing culverts will be demolished and re-constructed
		O & M cost	3.5	Relatively high as increased possibility of debris	4.5	Relatively on the lower side as minimal cleaning of debris will be required due to added width in culvert locations
Environmental	0.7	Sedimentation	4.5	Little to none as brick masonry all throughout	4.5	Little to none as brick masonry all throughout
		Water quality	4.0	Minimal probability remains if by anyhow culvert locations are constricted due to solid waste dumping	4.5	Little to none as minimal sedimentation due to bed/ bank erosion
Social	0.8	Land acquisition	4.5	Minimal requirement	3.0	Some land acquisition will be required both due to probable expansion of culvert length and during construction

Table 7.8: Techno-economic analysis for MCDA 6 – Assigned scores for each criteria and assigned weightage for categories

Categories	Wt.	Criteria	Option 1		Option 2	
			Score	Remarks	Score	Remarks
Technical	1.0	Smooth conveyance of flow through reduced friction	3.5	Relatively moderate	4.5	Relatively high
		Reduction of erosion of bed scouring	3.5	Relatively moderate	4.5	Relatively high
Economic	0.9	Construction cost	5.0	Relatively low	1.0	Relatively very high as entire section will be RCC lined in comparison to trapezoidal natural section
		O & M cost	3.5	Relatively moderate as bush cleaning will be required	4.5	Relatively on the lower side as cleaning of debris will be required
Environmental	0.7	Sedimentation	3.5	Relatively moderate as channels will remain natural trapezoidal	4.5	Minimal as due to RCC lining
		Water quality	3.5	Relatively moderate due to sedimentation	4.5	Minimal
Social	0.8	Land acquisition	4.0	Relatively low	2.0	Land acquisition requirements relatively low to moderate

7.3 CAPEX-OPEX Analysis

A tentative CAPEX & OPEX analysis was performed in order to get an idea about the relative expenditure for both construction (Capital) as well as O&M. The approximate "ballpark" values are presented in **Tables 7.9-7.14**.

Table 7.9: Total score of alternative options for MCDA 1

Categories	Criteria	Option 1	Option 3
Technical	Smooth conveyance of flow through reduced friction	3.50	4.00
	Reduction of erosion of bed scouring	3.50	4.00
Economic	Construction cost	4.50	1.80
	O & M cost	3.15	4.05
Environmental	Sedimentation	2.80	3.15
	Water quality	2.80	3.15
Social	Land acquisition	2.70	1.20
	Total	**22.95**	**21.35**

Table 7.10: Total score of alternative options for MCDA 2

Categories	Criteria	Option 1	Option 2	Option 3
Technical	Smooth conveyance of flow through reduced friction	3.50	3.50	4.00
	Reduction of erosion of bed scouring	3.50	4.00	4.50
Economic	Construction cost	4.50	4.05	1.80
	O & M cost	2.70	3.15	4.05
Environmental	Sedimentation	2.10	2.80	3.15
	Water quality	2.10	2.80	3.15
Social	Land acquisition	2.70	2.70	1.80
	Total	**21.10**	**23.00**	**22.45**

Table 7.11: Total score of alternative options for MCDA 3

Categories	Criteria	Option 1	Option 2
Technical	Smooth conveyance of flow through reduced friction	3.50	3.50
	Reduction of erosion of bed scouring	3.50	4.00
Economic	Construction cost	4.50	4.05
	O & M cost	2.70	3.15
Environmental	Sedimentation	2.10	2.80
	Water quality	2.10	2.80
Social	Land acquisition	2.70	2.70
	Total	**21.10**	**23.00**

Table 7.12: Total score of alternative options for MCDA 4

Categories	Criteria	Option 1	Option 2
Technical	Smooth conveyance of flow through reduced friction	3.5	4
	Reduction of erosion of bed scouring	3.5	4
Economic	Construction cost	4.05	3.15
	O & M cost	2.7	3.6
Environmental	Sedimentation	2.1	2.45
	Water quality	2.1	2.45
Social	Land acquisition	1.6	3.2
	Total	**19.55**	**22.85**

Table 7.13: Total score of alternative options for MCDA 5

Categories	Criteria	Option 1	Option 2
Technical	Smooth conveyance of flow through reduced friction	4.00	4.50
	Reduction of erosion of bed scouring	4.50	4.50
Economic	Construction cost	4.50	2.70
	O & M cost	3.15	4.05
Environmental	Sedimentation	3.15	3.15
	Water quality	2.80	3.15
Social	Land acquisition	3.60	2.40
	Total	**25.70**	**24.45**

Table 7.14: Total score of alternative options for MCDA 6

Categories	Criteria	Option 1	Option 2
Technical	Smooth conveyance of flow through reduced friction	3.50	4.50
	Reduction of erosion of bed scouring	3.50	4.50
Economic	Construction cost	4.50	0.90
	O & M cost	3.15	4.05
Environmental	Sedimentation	2.45	3.15
	Water quality	2.45	3.15
Social	Land acquisition	3.20	1.60
	Total	**22.75**	**21.85**

7.4 Selection of Suitable Option

Table 7.15 below summarizes all the selected measures.

Table 7.15: Selected measures as per MCDA analyses

Channel	Term	MCDA Serial	MCDA Score	Selected Option
River (Pa Chu - Upstream)	Immediate	MCDA 1	22.95	**Option 1: RB protection in vulnerable locations via gabion mesh** This option presents the protection for Pa Chu upstream portion and for the right bank only. It consists of bank protection measures via gabion mesh. Toe-wall is provided as per requirement.
River (Pa Chu - Upstream)	Short	MCDA 2	23.00	**Option 2: Designed river sections with graded banks with toe wall** Pa Chu River upstream sections with excavated bed and/ or bank material graded and used for filling material for bank and bed. Banks are filled with 1:3 slope with graded materials with provisions for design with toe wall at bank and bed connections where toe walls providing more mutual stability with little added cost incursion.
River (Pa Chu + Do Chu)	Long	MCDA 3	23.00	**Option 2: Designed river sections with graded banks with toe wall** In this option, the river banks and bed have been filled with graded cut materials with toe wall at bank and bed connections where toe walls providing more mutual stability with little added cost incursion.
Stream (Nephu Chu)	Short	MCDA 4	22.85	**Option 2: Mix of Trapezoidal and Rectangular stream section** This option considers trapezoidal sections in the upstream portion and rectangular RCC lined sections in the downstream portion.
Stream (Ngoborong Chu)	Short	MCDA 5	25.70	**Option 1: Rectangular section without renovation of existing culverts** As much of Ngoborong Chu is already rectangular shaped, both option envisages the entire stream as a rectangular brick masonry channel. Having said that, this first option does so with keeping the existing culverts intact as they have been found sufficiently adequate in terms of allowing flow passage.
Stream (Jew Chu, Gatanarong Chu, Ri Chu)	Short	MCDA 6	22.75	**Option 1: Trapezoidal stream section** This option presents the simplest state with the stream sections designed to convey flood flow downstream. The sections are kept in its current natural state in that no concrete lining is recommended.

Additional Notes:

- **Immediate** measures are akin to only vulnerable locations i.e., locations of overtopping along the right bank of Pa Chu river upstream.
- No measure is required for the short-term for Do Chu as, as per flood maps, river sections have been found to be adequate.
- For short-term, measures are only given at Pa Chu upstream as this ~2.1 km reach is highly vulnerable to flooding and also houses both the Pa Chu tow and the Pa Chu-Do Chu confluence.
- For long-term flood protection, re-sectioning for Pa Chu and Do Chu is required as if we consider a period of 50-100 years in the future, catastrophic events are likely to occur, and for which additional flow section will be required. This option however, is of low priority.
- For Nephu Chu, a mix of both trapezoidal section for u/s and rectangular section for urban d/s has been deemed as most efficient.
- For Ngoborong Chu, brick masonry section without the provision for additional slab or box-culverts have been deemed as most suitable for the time being. Option 2 in this case however, can be considered for long-term, but is not recommended.
- For Jew Chu, Gatanarong Chu and Ri Chu, full trapezoidal section is the clear choice as a full scale rectangular section would incur unrealistic implementation costs. No additional cross-drainage culvert would be required for these 3 streams.
- For Dakharong Chu and Satsam Chu North and South, no MCDA has been done as as per hydrodynamic model results, flow sections for these 3 streams have been found to be sufficiently adequate. Design for any culverts that may be required for these streams, have been provided.

7.5 Performance Evaluation

The performance of the measures was evaluated in terms of reduction of flooding extent. The developed hydro-dynamic model for the rivers were used for this purpose. The model cross sections were adjusted and proposed immediate interventions for Pa Chu were included into the model. The model then simulated using the design discharge and flood extent maps were extracted. The flood extent maps for Pa Chu considering the short terms measures are given from **Figure 7.2-7.4**. It was found that the flood extent reduced and the flow is only confined into the river for post project condition while it overspill the right bank during pre-project condition and caused flooding.

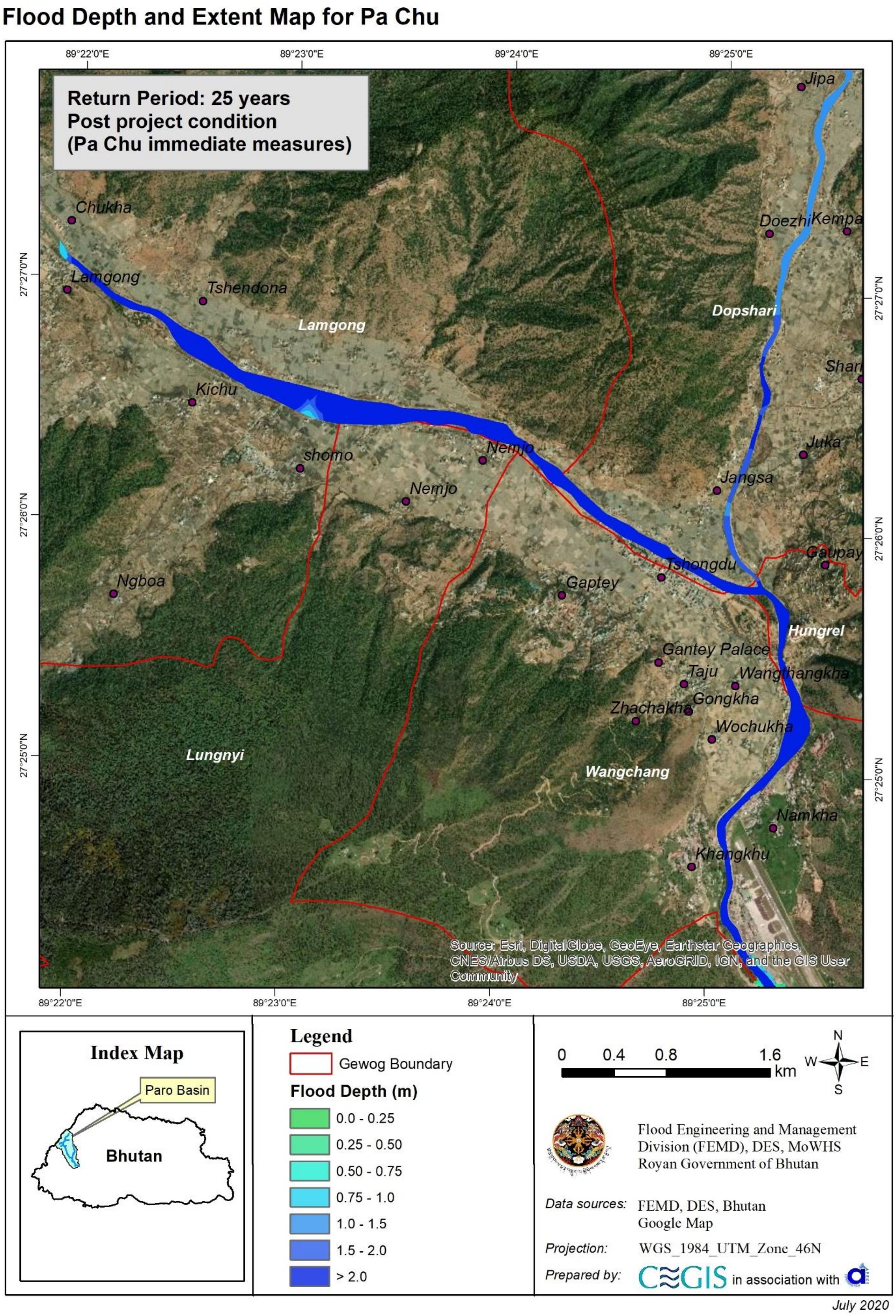


Figure 7.2: Flood depth and extent map of Pa Chu with proposed immediate measures

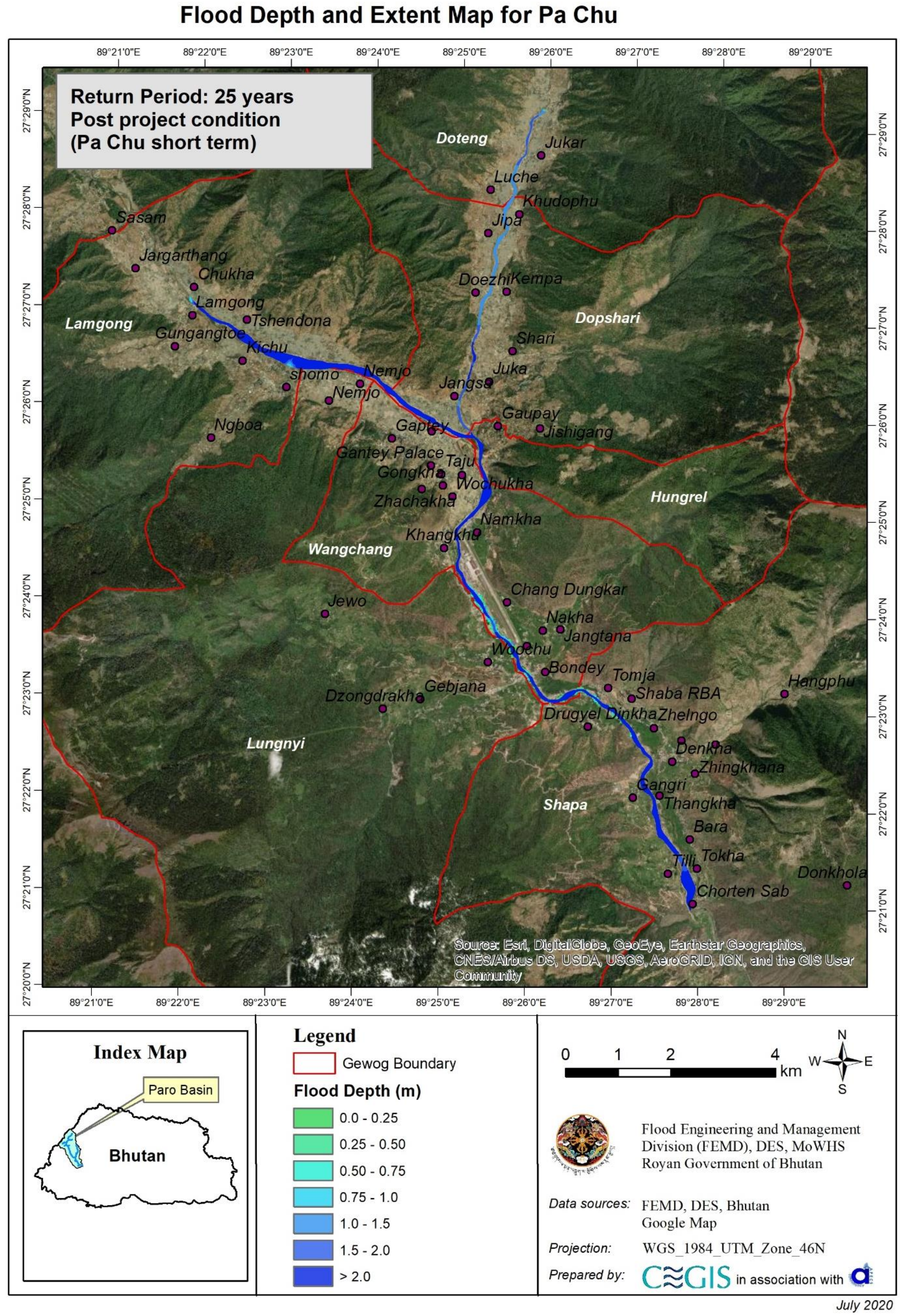


Figure 7.3: Flood depth and extent map of Pa Chu with proposed short-term measures

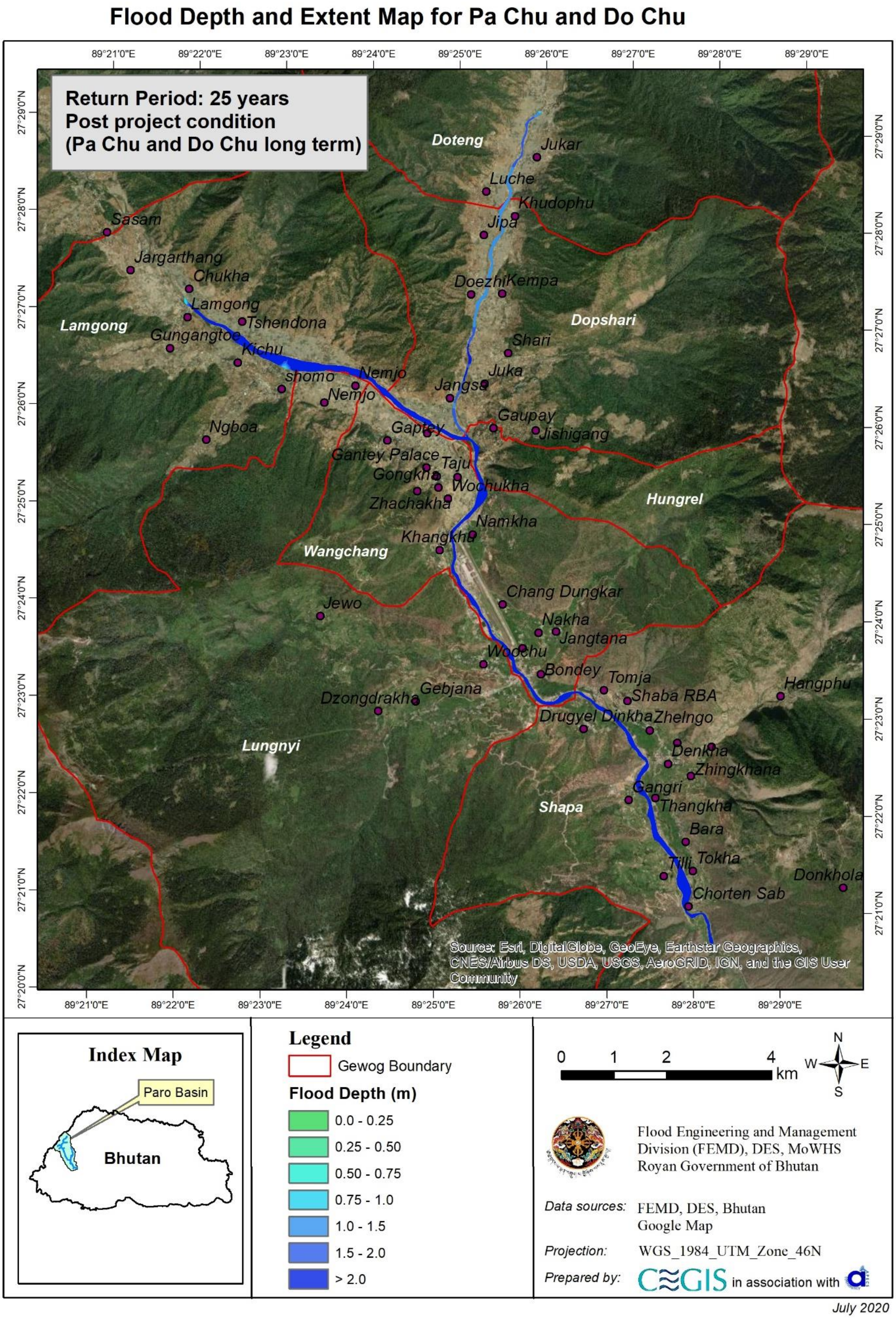


Figure 7.4: Flood depth and extent map of Pa Chu with proposed immediate measures

8. Detailed Engineering Design

8.1 Design Considerations

Hardcore engineering measures that were designed for the study include –

- Bank Protection
- River sections
- Stream sections
- Culverts etc.

The hydrological or hydraulic aspects of designing these components involve calculation of design discharge and water level values, designated from a selected or agreed upon design storm event of suitable return period, in this case which is a 25 year precipitation event. On the other hand, the structural aspect of design would have to be satisfied via survey of river and streams which is to include–

- A detailed topographic survey of the entire river stretch from as upstream as is accessible, to river outfall downstream;
- Detailed cross-section survey of this designated reach of river at suitable locations with emphasis given at locations of sharp bends and flow passage increase/ decreases;
- Longitudinal section survey which is to portray the long slope of the river at appropriate scale and as accurately as possible.

Having said that, design works have been done based on the limited data and information received during the course of the study and thus the following points have to be taken under consideration –

- There was no detailed topographic survey for the rivers which shows locations of existing structures as well as river width along its flow path thus design was difficult as it was difficult to ascertain what to expect if river width is to be increased for a certain stretch of the reach.
- Survey was not done for the complete river length. This is understandable to the point that upstream portion of most of these mountainous rivers cannot be surveyed due to inaccessibility reasons. However, survey for Pa Chu has to be done from the visit point of the study team namely the Drukgyel Dzong and it has to continue downstream up till the outfall of the river. This will enable for adjustments in the longitudinal bed slope and provide for smooth passage of flow.
- There were no bed level elevation given for stream discharge points along both Pa Chu and Do Chu. This is especially required if adjustments in longitudinal stream bed has to be done to accommodate flow. The stream bed at outfall has to always be higher to a controlled point from the river bed. This was not verified due to lack of said data.
- Survey data was available scarcely for only 4 out of the concerned streams, making the design of the latter difficult. Moreover, section survey of critical locations namely at junction points and at locations where cross-drainage structures would be required are not made and thus hand measurements were taken at said locations which would imply some loss of accuracy. Also, some of the streams exhibited substantial unplanned encroachment at varying levels that were absent from the survey data.

- Significant portion of some streams were lined with masonry or RCC which was not represented in the surveyed sections drawings. Also, in some instances, there were relatively recent development in the form of narrow culverts and lined sections that is also not present in the survey data. These make the design of the already narrow channels carrying critical flow rather difficult and also imparts certain level of inaccuracy.
- Full scale implementation of design of structures will have to be accompanied by thorough pre-works survey of all streams and rivers which is to include topographic, cross- and long-section surveys.

8.2 Design of Measures

Detailed design and drawing of structural measures have been done in the form of bank protection measures as well as river and stream re-sectioning. Besides this, provisions for cross-drainage structures will be suggested for each critical location along the flow path of each individual stream. Design has been done based on hydrological and hydrodynamic model results and using available survey data. Maximum peak discharges have been estimated for varying return period and values of flow pertaining to a return period of 25 years have been selected for designing the river and stream sections. However, for the rivers, enough freeboard have been sanctioned so as to accommodate flow levels representing that of 50 year return period event. Design flow at outlet of Pa Chu and Do Chu rivers are 401.3 and 81.6 cumec respectively. On the other hand, maximum scour depth has been found 1.6 m on an average from HFL among the two rivers using Lacey's formula. Detailed design, drawing and technical specification for structural measures of the rivers and streams are presented in **Volume – 4**.

8.3 Operation and Maintenance

After successful completion of the project a complete operational and maintenance measures shall be prioritized by maintenance personnel. These include maintenance of re-excavated rivers and streams, cleaning and maintenance of storm water RCC portions, operation and maintenance of culverts and other narrow flow passages, repair of stream side road and protection walls.

For streams uncontrolled discharge of industrial Waste, garbage dumping and illegal encroachment should be discouraged by direct man power appointment i.e watch man hired by Dzongkhag and/ or local Gweog authorities. Routine maintenance work i.e. removal of sediment/ boulder, garbage and mud consist of re-excavation by excavator and transportation of excavated material by dump track to an approved off-site land fill or disposal site. For this purpose excavator and dump truck hired by authorities shall have to be engaged for each and every channel.

For ensuring connectivity among storm water drainage network (streams), all streams are to be cleaned under periodic maintenance work adopted by respective Gewog authorities. All debris and solid waste has been transported to an off-site land-fill or disposal site. Solid waste management shall be carried out by Gewog authorities.

Illegal encroachment besides the stream by local resort authorities is a bad practice. This shall be stopped by appropriate authority. Proper provisions have to be made for rehabilitation of existing mud roads along streams for future maintenance purposes as well as to minimize encroachment and reduce probable landslide/ sedimentation of stream bed.

8.4 Cost Estimations

This section presents the cost estimations of design components. These are presented in tabular format below.

Table 8.1: Cost summary of measures

Channel	Measure	BOQ Cost (Nu)
Pa Chu	RB protection in vulnerable locations via gabion mesh	26,759,221
Nephu Chu	Trapezoidal re-section for ~1400m u/s reach and rectangular section for ~500m d/s reach	23,727,079
Ngoborong Chu	Brick masonry rectangular channel re-section without top slab	9,769,390
Jew Chu	Trapezoidal re-section	1,672,671
Gatanarong Chu	Trapezoidal re-section	2,226,249
Ri Chu	Trapezoidal re-section	4,213,778
Dakhorong Chu	Culvert construction	2,874,728
Satsam Chu North	Culvert construction	2,521,403
Satsam Chu South	Culvert construction	2,731,979
	Total	**76,496,498**

9. Environmental Code of Practice

9.1 Hard Measures

9.1.1 ECoP-1: Bank Revetment Works

Locations have been identified for protection of river bank (**Figure 9.1**) in the project area of Paru and Docu for protection of schools, roads, settlements, airport of the Paro Dzogkhag of Bhutan. These sites of the rivers are severe erosion prone area due to flash flood. Most of the village peoples have been located near the river bank sides. People reported that these sites should be protected by stones around settlement and some sites would be protected by adding linear trees plantation along the river banks.

Figure 9.1: Erosion prone area

The following Environmental Code or Practice should be followed during implementation of the bank revetment works.

Pre-Construction phase

- Design should be prepared on the basis of modeling outputs. Collect all design documents for execution and prepare a plan accordingly which should be submitted to the Department of engineering Services, Ministry of Works and Human Settlement, Royal Government of Bhutan.
- Plan should include all activities starting from mobilization of stone materials and equipment to handover of the revetment works to the property authority for operation and maintenance.
- Site office and labor shed with provision of hygienic toilet and pure drinking water facility for all must be ensured during implementation of the civil works.
- Effluent from washroom/ labor shed toilets must not be disposed into the near streams (Chu) and should be handled properly.
- All vegetation or debris and wastes (**Figure 9.2**) should be cleaned up before removing the stones along the deepest point of the rivers/streams (Chu).

Figure 9.2: Debris and wastes at streams

- Netting quality along the bank side of the rivers should be ensured by the staff with specified laboratory test and it must comply with specification.
- Stone size must comply with the specifications.

Construction Phase

- All movement of stone works should be executed in accordance with design and plan and these are to be displayed at site office so that local stakeholders can see and understand them.
- Safety measures should be taken up in every activity for the construction labor, students near the school during school time and also for the dwellers of the settlement.
- First Aid box should be at hand so that it is readily available or can be used when needed.
- Implementation work should be monitored properly and regularly by project engineer so that the work can be completed in accordance with design specification and plan.
- All the Stone works should be placed as per specification.
- All the nests of the trees along the bank should be kept as it is. No nests should be destroyed during project works.
- All the stone works should be implemented to keep the trees as it is.

Post-Construction Phase

- Monitor completed work by government staff.
- Any type of movement and activity such as children playing on the protected portion should be prohibited.
- Agricultural /vegetable gardening practices on the bank should be prohibited.

9.1.2 ECoP-2: Re-excavation of Rivers and Streams

River reach have been identified for river re-excavation of Pa Chu, Do Chu and streams for flood protection in the areas of schools, roads, settlements, airport of the Paro Dzogkhag of Bhutan. Most of the village peoples have been located near the river bank sides. People reported that these sites should be re-excavated by appropriate machineries without creation of noise around settlement and some sites would be protected by adding linear trees plantation along the river banks.

Pre-Construction phase

- Re-excavation alignment should be prepared on the basis of modeling output. Collect all design documents for execution and prepare a plan accordingly which should be submitted to the proper authority.
- Plan should include all activities starting from mobilization of labors, materials and equipment to handover of the project works.
- Site office and labor shed with provision of hygienic toilet and pure drinking water facility for all must be ensured.
- Effluent from toilet must not be disposed into the near water bodies or any other streams and should be handled properly.
- Tree felling from the project sites should be avoided to the possible extent.
- Formed WMOs for performing participatory management of the food management plan.

Construction Phase

- All works should be executed in accordance with design and plan and are to be displayed at site office so that stakeholders would be able to understand them.
- Safety measure should be taken up for all activities during construction period.
- First Aid box should be at hand so that it is readily available or can be used as and when needed.
- Construction work should be monitored properly and regularly by concern authority so that the work can be completed in accordance with design specification and plan.
- While dumping excavated stones, care should be taken to minimize all kind of vegetation loss.

Figure 9.3: Re-excavation sites at Jewchu

Post-Construction Phase

- Encourage stake- holders for long rooted tree plantation along both side of the bank, but discourage people for vegetable cultivations along the project works.
- Plantation should be made on both side of the river bank with suggested species of plant (e.g: Blue Pine and Cypress etc.). Monitor planted saplings through proper responsible authority till they are matured.
- WMOs should be formed as per policy of Bhutan and follow up training to the executive committee members of WMOs for refreshing their activities regarding O&M should be ensured by the proper authority.

- Engage concerned WMOs for performing regular O&M activities of important project works to ensure proper functioning.
- Ensure regular meeting of WMOs.

9.1.3 ECoP-3: Plantation of Blue Pine and Cypress Trees

Planting should be done in both bank of the rivers to enhance river ecosystem and also wildlife of the project area.

Pre-Construction phase

All the plantation program (**Figure 9.4**) should be displayed on a notice in board in the project site for public awareness.

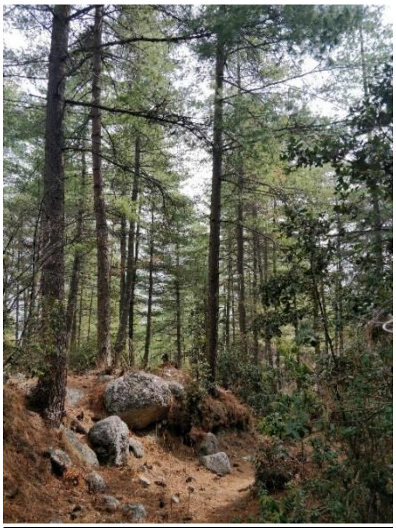


Figure 9.4: Plantation program at Jewchu Site

Construction Phase

- Trees should be planted in such a way that the agriculture field can get adequate sunlight.
- Native plants should be given priority as they are part of the local ecosystem.
- Trees which provide fruit as well as timber should be given more importance. These also act as financial security of vulnerable peoples near the rivers.
- Plantation programs should be implemented before wet season.

Post-Construction Phase

- Monitoring growth of plantation by local stakeholders through group formation.

9.2 Concluding remarks

- A WMGs should be formed to ensure maintenance and operation works of the project;
- For smoothing of early warning system WMGs should be formed before starting the works;

A detailed EIA should be conducted before implementation the project works for minimizing the ecosystem loss in the project area.

10. Financial Analysis

10.1 Introduction

Cost benefit analysis measures the investment worth of the Project. Financial and Economic analysis govern the main criteria in the decision making process for taking up of the Project. Financial cost benefits are considered as primary indicators of the study and reflect private profitability from the Project. On the other hand, economic cost benefit analysis is the appraisal technique used to decide whether this Project will make contribution towards reaching national plan objectives. On economic feasibility of the Project, climate resilient flood mitigation measures have been evaluated with respect to economic benefits of the Project.

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 economic viability of the Project.

10.2 Approach of the Analysis

Discounted method of Project assessment has been used in cost benefit analysis. Benefits are accrued to the protective measures avoiding damages infrastructures (Residential and non-residential property) crops, and other resources from floods. In this regard, data obtained from the engineering analysis (model result[5]) of the Project. In this regards, climate resilient flood hazard mitigation and maintenance costs were analyzed for assessing economic viability of the Project. Project investment cost data has been taken from the engineering assessment done by the consultants of the Project.

Regarding Net benefit of the Project, it has been estimated comparing the changes between With project (W) and Without Project conditions. With Project benefits are the save values of flood damage occurred in Without Project condition taking assumption of annual development at a rate of 2.9% in FY20[6]. Annual damage value is estimated at *Nu.* 30.46 million based on 25 year return period. After

[5] Data taken from CEGIS engineering study team of the Project.

[6] http://www.bhutannewsnetwork.com/2020/04/world-bank-cuts-growth-forecast-for-bhutan/ **World Bank** has **projected** that real **GDP growth of Bhutan** is **expected** to decelerate to 2.9 percent in FY20 due to significant disruptions from COVID-19 to domestic production, tourism, and services. ... The **growth outlook** is likely to remain subdued in FY21 with some recovery **expected** in FY22.Apr 12, 2020

multiplying the estimated damage value by the factor representing annual development in the "without" case, the discounted value of the flow annual benefits generated from the preventing floods is calculated. On the above mentioned increase in annual development, the discount rate is 12% and the lifetime of the project is 30 years[7] for cost benefit comparison.

Financial costs and benefits are adjusted to their economic values for economic cost benefit analysis. On Conversion Method of Economic valuation of non-traded items that has been calculated using Standard Conversion Factor (SCF)[8] to reflect boarder price equivalent.

Two working seasons of two consecutive years are considered for implementation of the physical work.

10.3 Financial and Economic Parameters

The following parameters are used to derive economic costs 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 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;
- Labour cost adjusted to economic cost using conversion factor 1, it reflects scarcity of local labour) labour deficit in construction sector;
- Economic benefits and costs of the project are worked out based on the standard conversion factor (SCF) of 0.902 would be sued to convert the price of non-traded goods into economic values.

10.4 Engineering Measures and Economic Issues

Heavy Monsoon rainfall and flash floods, it causes damage to agriculture, human settlement, and private and public infrastructures. Ultimately these recurrent damages turn into economic loses to both household at the vicinity of the streams and national level. Consequently, the level of GDP of Bhutan could be reduced; if not any flood mitigation measures were put in place. The structural measures to prevent the flood damage, the measures and related costs are developed and presented in the following **Table 10.1**.

Table 10.1: Investment cost (Nu in millions)

Channel	Measures	Cost (rounded)
Pa Chu	RB protection in vulnerable locations via gabion mesh	27
Nephu Chu	Trapezoidal re-section for ~1400m u/s reach and	24

[7] Flood Planning Co-ordination Organization (in Bangladesh) Guidelines 1992 under Flood Action Plan has been followed.

[8] Updated SCF = 0.902 in Bangladesh is used.

Channel	Measures	Cost (rounded)
	rectangular section for ~500m d/s reach	
Ngoborong Chu	Brick masonry rectangular channel re-section without top slab	10
Dakhorong Chu	Trapezoidal re-section	2
Satsam Chu North	Trapezoidal re-section	2
Satsam Chu South	Trapezoidal re-section	4
Jew Chu	Culvert construction	3
Gatanarong Chu	Culvert construction	3
Ri Chu	Culvert construction	3
	Base cost	**76**
	Physical contingency	4
	Price contingency	4
	Total Cost	**84**

Source: Engineering study of the Project.

Moreover, Period maintenance after every five year period is estimated at 10%[9] of the cost of each of the measures has been considered and the amount is estimated to be nu 8.40 million.

10.5 Benefits of the Project

10.5.1 Direct benefits

The engineering analysis quantifies the flood threats, and it is very important to determine the frequency of occurrence of flood peaks of various levels. In this particular case, it is considered *4 percent flood*, reciprocal of the probability of occurrence, *25 year return period* that means certain volume of flood water flows per second in the streams. It causes damage to the physical assets. With the engineering measures, expected major economic benefits are to be flood damage save value of the assets and save damages from erosion protection of the project. The economic benefits are given in the following Table.

Table 10.2: Annual Flood Damage Save Value

Return Period	Frequency of non-exceedance	Frequency of exceedance (1/25)	Estimated annual damage value (in million nu)	
			Infrastructural	Crops
			Residential and Non-residential	
2	0.5	0.5	12.42	0.27
5	0.8	0.2	25.22	0.36
10	0.9	0.1	29.54	0.51
25	0.96	0.04	30.46	0.65

[9] FPCO, Guidelines, 1992. Dhaka Bangladesh

Return Period	Frequency of non-exceedance	Frequency of exceedance (1/25)	Estimated annual damage value (in million nu)	
50	0.98	0.02	53.29	0.72
100	0.99	0.01	40.16	0.94

Source: CEGIS engineering study

The Investment improves protective benefits to physical assets. As such, tourism facilities create indirect benefits (revenue) to the surrounding community members with occupations formal informal workers, tourist guides, etc for men and women.

During implementation of the Project will create employment opportunities to skilled and unskilled labour. The indirect effects play a significant role in poverty alleviation. After completion of the project, job opportunities for the local community people are expected to be generated at the tourism site. Both direct and indirect effects would generate employment opportunities and revenue in the country, and eventually it contributes to GDP of the country.

The estimated number of labour days during implementation of the Project is given in the following Table.

Table 10.3: Employment Opportunities in Construction Work

Number of skilled labour-day	Number of unskilled labour-day	Total
11,850	63,130	74,979

Source: Economic analysis

10.6 Cost Benefit Comparison and Economic Justification

The Project has been evaluated for measuring the investment worth of the Project. In this regard, economic values of investment costs and benefits have been adjusted based on the following assumptions. These are:

- Financial cost is segregated by material cost 66% of total (traded and non traded items), Labour 24% and Taxes 10%;
- No adjustment is made for the traded items (namely, cement and others materials if any);
- Non-traded items are adjusted using SCF of 0.902;
- Labour cost conversion factor is considered 1.00, because construction sector is experienced in labour deficit in the country;
- Taxes cost conversion factor is considered to be transfer payment and economic value is to be zero (0).

After valuation of the costs and benefits, the cost benefit comparison is carried out for calculating the value of the economic indicators.

10.6.1 Cost Benefit Comparison

Discounting method of Project evaluation is used for calculating the present value of cost and benefit streams. Financial and Economic indicators are computed for examining 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.

10.6.2 Benefit cost Ratio (B/C)

Present worth of benefit is divided by the present worth of 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 is for discount rate

n=number of years.

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

10.6.3 Net Present Value (NPV)

It measures the present value of future net incremental benefit of the project over 50 years, i.e., 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, higher positive value of NPV is more attractive to decision makers.

10.6.4 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) is zero (Gittenger, 1982). The equation is as follows:

IRR: the discount rate *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 more than the discount rate (12%) signifying opportunity cost of capital. The rate at which an investment breaks even level (discounted value of revenue minus discounted value of cost is equal to zero). As a rule, higher value of IRR is more attractive than the lower value provided it remains above the discount rate (12%). In this project, the estimated values of the indicators show viability of the project, because all the criteria follow the acceptance rules. The results are given in **Table 10.4**.

Table 10.4: Results of Cost-Benefit Analysis

Indicators	Financial	Economic	Acceptance Rules
B/C	3.18:1.00	3.49:1.00	>1.0
NPV (in million Nu)	167	157	Positive value
IRR	35%	37%	=>12%

10.7 Sensitivity Analysis

Sensitivity analysis has been carried out in both financial and economic perspectives. On economic perspective, the analysis shows the impact on the values the indicators due to change in the important variables, i.e., costs and benefits in uncertain situation. The values of the indicators in four scenarios are given **Table 10.5.**

Table 10.5: Sensitivity analysis

Indicator	Base case	Scenario 1: Benefit decrease by 10%	Scenario 2: Cost increased by 10%	Scenario 3: (best case) benefits increase by 10% and costs also decrease by 10%)	Scenario 4: (worst case) benefits decrease by 10% at the time cost increase by 10%
BCR	3.49	3.18	3.18	4.23	2.89
NPV (in million Nu)	157	137	151	185	131
IRR	37%	34%	34%	44%	32%

On the sensitivity analysis, the project seems to be consistent with the adverse situation as well.

10.8 Conclusions

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

11. Implementation Plan

11.1 Rationale of Implementation Plan

The Paro Valley i.e. Paro Basin have been susceptible to recurring flooding due to flood flows through the many streams and the two major rivers, Pa Chu and Do Chu. This has the potential to be further aggravated due to unwarranted landslides and GLOFs and consequent debris flow. As the study deals with a large area (Paro Dzonkhag), overall impact of climate change has been keenly taken under consideration in devising and designing flood management measures for the rivers and streams. Primary measures lie in the re-sectioning of existing river and streams sections for them to be able to convey flood flow. Flood and all associated hazards are creating havoc to life and properties, damaging farm lands and hampering education.

Frequency and intensity of these hazards will be increased in future due to climate change impact, so as the devastating nature, which needs to be reduced through climate resilient mitigation measures with other associated research, planning and implementation activities. Sporadic planning and initiatives by local government agencies did not bring any fruitful outcome due to lack of detailed scientific and technical studies. Moreover, lots of specific problem, issues and challenges have been identified throughout this study, especially for the streams. To address those issues, both structural and non-structural measures have been proposed with specific recommendations to bring out the effective outcome. Hence, need for an implementation plan is of essence, amalgamating all proposed structural, non-structural measures and recommendations to successfully implement the proposed interventions in an organized fashion.

11.2 Investment Priorities

This investment plan part of the Flood Management Plan comprises of 14 nos. priority investment projects (ID from 1-8) for immediate (2021-2023), short- (2023-2027) and long- (2027-2030) terms. Priorities have been given to select investment projects on the basis of the burning necessity in regards to requirement of flood management measures and how the project will address proposed structural, non-structural measures and recommendations of this study. The priority investment projects are as follows:

- Investment Project 1: Capacity Development of Professionals for Effective Flood Management in Paro Basin
- Investment Project 2a: Climate Resilient Flood Management for Nephu Chu
- Investment Project 2b: Climate Resilient Flood Management for Ngoborong Chu
- Investment Project 2c: Climate Resilient Flood Management for Pa Chu – 1
- Investment Project 3a: Climate Resilient Flood Management for Jew Chu
- Investment Project 3b: Climate Resilient Flood Management for Gatanarong Chu
- Investment Project 3c: Climate Resilient Flood Management for Ri Chu
- Investment Project 4a: Climate Resilient Flood Management for Dakhorong Chu
- Investment Project 4b: Climate Resilient Flood Management for Satsan Chu North
- Investment Project 4c: Climate Resilient Flood Management for Satsam Chu South

- Investment Project 5: Development of Early Warning System for Pa Chu and Do Chu
- Investment Project 6: Development of Floodplain Zoning for Paro Basin
- Investment Project 7: Climate Resilient Flood Management for Pa Chu – 2
- Investment Project 8: Climate Resilient Flood Management for Pa Chu and Do Chu

It is to be noted that, structural interventions required under major components of 11 investment projects (ID 2-4 and 7-8) are to be guided through proposed in this study **(see Volume 4: Design)**. Three investment projects (ID 1, 5 and 6) are non-structural measures aimed mostly at the long term of FMP implementation with exception of capacity development, and are actually to supplement the benefits of first four projects and make their outcome as desired one. As a whole, climate resilience of agriculture and local settlements will be enhanced, thus local inhabitants will be benefitted. **Table 11.1** presents a summary of the proposed projects.

11.3 Sources of Fund

Apart from the limited own resources of Royal Government of Bhutan, there are several types of available fund to become the potential financing sources of proposed investment project. The Government of India (GoI) can be a source of public funding. Green Climate Fund would be the best one among them, where Gross National Happiness Commission (GNHC) is the National Designated Authority (NDA). Recently, GCF started supporting the ambitious goal of Bhutan as a strategic partner through an investment of USD 26.6 million in the "Bhutan for Life" project, which has just begun implementation. Bhutan Climate Fund is under development with World Bank which is conceptualized in response to immediate investment need of USD 65 million through Strategic Program for Climate Resilience (SPCR) under Climate Investment Fund (CIF).

As a Least Developed Country (LDC), Bhutan is one of 13 LDCs or Small Island Developing States (SIDS) that make up a considerable share of the Adaptation Fund's NIEs (46%) under Direct Access. Bhutan Trust Fund for Environment Conservation (BTFEC) was accredited by the Adaptation Fund as Bhutan's first National Implementing Entity (NIE) under Direct Access on 25 January, 2018, which is also a potential source of fund. Last but not the least, another source of fund may be Global Environment Facility Trust Fund (GEF) or Least Developed Countries Trust Fund (LDCF) to implement investment projects. Besides these, the DRIVE Project can also be a source of funding.

11.4 Benefits of Investment

Lots of benefits will be achieved through implementing these proposed priority projects which are listed, but not necessarily remain limited, to the following:

- Bank protection will be ensured and bank erosion will be reduced or will be stopped in a sense
- Sediment flowing will be lessened drastically, consequently overtopping the banks and creating havoc to people and property
- Boost in agricultural production
- Bed scouring will be reduced
- Rivers and stream will get its own room for extreme flood passage
- Environment friendly and durable solution
- Huge life and property safe value will be gained

- One time investment will give protection for at least 50 years with some recurring maintenance costs
- Local administration will be able to invest for other development sectors
- Tourism sector will be developed and revenue will be added in Govt. budget
- Climate resilience of local of people of Paro Valley
- Knowledge base will be developed through research and scientific study
- Private investors will be attracted to invest in climate smart city
- Capacity and strength of local engineers will be enhanced

Table 11.1: Summary of Investment Projects

Cluster	Project ID	Tentative Title	Major Components	Focus Area	Responsible Agencies	Investment Priority	Implementation Schedule	Approx. Cost (Million Nu)
1	IP-1	Capacity Development of Professionals for Effective Flood Management in Paro Basin	▪ Training Programs ▪ Capacity Development Workshops	FEMD, NCHM, Dzongkhag, Gewog Officials	MoWHS	High	Immediate	10.00
2	IP-2a	Climate Resilient Flood Management for Nephu Chu	▪ Channel re-sectioning ▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Nephu Chu Catchment	MoWHS, Dzongkhag and Gewog	High	Immediate	23.73
	IP-2b	Climate Resilient Flood Management for Ngoborong Chu	▪ Construction of culverts ▪ Channel re-sectioning ▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Ngborong Chu Catchment	MoWHS, Dzongkhag and Gewog	High	Immediate	9.77
	IP-2c	Climate Resilient Flood Management for Pa Chu – 1	▪ Bank protection measures along vulnerable right bank of Pa Chu upstream portion ▪ Local capacity building workshops	Pa Chu u/s reach catchment, Paro Town	MoWHS, Dzongkhag and Gewog	High	Immediate	26.75
3	IP-3a	Climate Resilient Flood Management for Jew Chu	▪ Channel re-sectioning ▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Jew Chu Catchment	MoWHS, Dzongkhag and Gewog	High	Short	2.87
	IP-3b	Climate Resilient Flood Management for Gatanarong Chu	▪ Channel re-sectioning ▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Gatanarong Chu Catchment	MoWHS, Dzongkhag and Gewog	High	Short	2.52

Cluster	Project ID	Tentative Title	Major Components	Focus Area	Responsible Agencies	Investment Priority	Implementation Schedule	Approx. Cost (Million Nu)
	IP-3c	Climate Resilient Flood Management for Ri Chu	▪ Channel re-sectioning ▪ Bush clearing ▪ U/s wetlands conservation Local capacity building workshops	Ri Chu Catchment	MoWHS, Dzongkhag and Gewog	High	Short	2.73
4	IP-4a	Climate Resilient Flood Management for Dakhorong Chu	▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Dakhorong Chu Catchment	MoWHS, Dzongkhag and Gewog	Moderate	Short	1.67
	IP-4b	Climate Resilient Flood Management for Satsam Chu North	▪ Construction of culverts ▪ Bush clearing ▪ U/s wetlands conservation ▪ Local capacity building workshops	Satsam Chu North Catchment	MoWHS, Dzongkhag and Gewog	Moderate	Short	2.23
	IP-4c	Climate Resilient Flood Management for Satsam Chu South	▪ Construction of culverts ▪ Bush clearing ▪ U/s wetlands conservation Local capacity building workshops	Satsam Chu South Catchment	MoWHS, Dzongkhag and Gewog	Moderate	Short	4.21
5	IP-5	Development of Early Warning System for Pa Chu and Do Chu	▪ Installation of EWS ▪ Monitoring of System ▪ Data Analysis & Flood Forecasting ▪ Warning Mechanism ▪ Response Strategy	Paro Basin, Paro Town	MoWHS, Dzongkhag and Gewog	High	Long	n/a
6	IP-6	Development of Floodplain Zoning for Paro Basin	▪ Flood level determination ▪ Floodplain delineation ▪ Zone definition ▪ Zone management guidelines	Paro Basin, Paro Town	MoWHS, MoHCA, NCHM, Dzongkhag and other relevant agencies	Moderate	Long	n/a

Cluster	Project ID	Tentative Title	Major Components	Focus Area	Responsible Agencies	Investment Priority	Implementation Schedule	Approx. Cost (Million Nu)
7	IP-7	Climate Resilient Flood Management for Pa Chu – 2	▪ Channel re-sectioning ▪ Bank protection ▪ Land reclamation ▪ Local capacity building workshops	Paro Basin, Paro Town	MoWHS, Dzongkhag and Gewog	Low	Short	217.09
8	IP-8	Climate Resilient Flood Management for Pa Chu and Do Chu	▪ Channel re-sectioning ▪ Bank protection ▪ Land reclamation	Paro Basin, Paro Town	MoWHS, Dzongkhag and Gewog	Low	Long	1076.90

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Appendix I: Glacier Lake Inventory for the Paro Basin

Sl. No.	GLIMS_ID	Glacier_ID	Longitude	Latitude	Area_ sqkm	Elev_Max (msl)	Elev_Min (msl)	Elev_Mean (msl)	Slope_Max (degree)	Slope_Mean (degree)	Slope_Min (degree)	Aspect (degree)
1	G089322E27835N	WPagr16_33	89.322	27.835	9.246	6701	4342	5217	83	31	0	173
2	G089251E27798N	WPagr16_20	89.251	27.798	0.394	6087	5183	5544	71	39	3	144
3	G089281E27796N	WPagr16_24	89.281	27.796	1.577	5936	5059	5465	72	27	0	211
4	G089274E27818N	WPagr16_28	89.274	27.818	1.03	7051	5916	6465	69	37	1	153
5	G089284E27816N	WPagr16_30	89.284	27.816	1.191	6459	4864	5543	76	39	1	116
6	G089293E27829N	WPagr16_32	89.293	27.829	2.644	6409	5005	5521	82	36	0	143
7	G089303E27810N	WPagr16_31	89.303	27.81	1.121	4799	4385	4528	69	18	0	154
8	G089238E27800N	WPagr16_19	89.238	27.8	0.141	5962	5615	5756	67	33	1	214
9	G089267E27807N	WPagr16_22	89.267	27.807	2.657	7201	4842	5789	72	35	1	177
10	G089288E27793N	WPagr16_25	89.288	27.793	0.645	5654	5144	5439	58	22	1	178
11	G089274E27800N	WPagr16_23	89.274	27.8	0.065	5380	5179	5258	62	27	1	208
12	G089295E27792N	WPagr16_26	89.295	27.792	0.376	5618	5199	5381	66	26	1	159
13	G089416E27673N	WPagr16_8	89.416	27.673	0.375	5616	5037	5308	73	33	1	225
14	G089420E27675N	WPagr16_9	89.42	27.675	0.079	5533	5348	5447	63	32	2	220
15	G089405E27667N	WPagr16_7	89.405	27.667	0.134	5248	5019	5102	69	27	4	191
16	G089405E27707N	WPagr16_11	89.405	27.707	0.192	5325	4996	5100	58	25	1	292
17	G089407E27713N	WPagr16_12	89.407	27.713	0.127	5348	5055	5196	52	25	3	277
18	G089409E27732N	WPagr16_14	89.409	27.732	0.195	5672	5375	5540	68	30	1	218
19	G089406E27724N	WPagr16_13	89.406	27.724	0.506	5600	5000	5276	63	28	1	271
20	G089343E27836N	WPagr16_34	89.343	27.836	1.153	6333	5225	5776	79	37	0	158
21	G089229E27784N	WPagr16_15	89.229	27.784	0.352	5784	5237	5491	71	33	1	243
22	G089249E27775N	WPagr16_17	89.249	27.775	0.026	5373	5187	5301	62	34	4	191
23	G089242E27789N	WPagr16_18	89.242	27.789	2.271	6042	4878	5462	69	23	0	139

Sl. No.	GLIMS_ID	Glacier_ID	Longitude	Latitude	Area_ sqkm	Elev_Max (msl)	Elev_Min (msl)	Elev_Mean (msl)	Slope_Max (degree)	Slope_Mean (degree)	Slope_Min (degree)	Aspect (degree)
24	G089243E27778N	WPagr16_16	89.243	27.778	0.097	5457	5164	5362	60	31	3	213
25	G089269E27827N	WPagr16_29	89.269	27.827	0.289	7317	6862	7077	80	43	2	181
26	G089420E27679N	WPagr16_10	89.42	27.679	0.226	5570	5001	5237	64	31	1	259
27	G089251E27804N	WPagr16_21	89.251	27.804	0.118	6238	5937	6109	71	47	5	156
28	G089356E27605N	WPagr16_5	89.356	27.605	0.298	5544	5016	5300	61	31	2	277
29	G089289E27802N	WPagr16_27	89.289	27.802	0.606	5795	5081	5427	72	31	1	99
30	G089360E27605N	WPagr16_6	89.36	27.605	0.065	5530	5206	5331	69	41	11	116
31	G089169E27577N	WPagr16_4	89.169	27.577	0.191	5394	4934	5187	61	34	0	260

(Source: NCHM 2019a)

Appendix II: Detailed Field Visit

Introduction

As per work schedule, a detailed field visit was carried out by the Consultant Team to the concerned 8 stream catchments, and the two rivers namely, Pa Chu and Do Chu immediately after inception workshops were held. The visit took place from 20-23 February 2020. The team comprised of personnel from both consultant organizations namely, CEGIS and APECS as well as officials from the FEMD. The team visited the length of the concerning rivers, streams as well as in key locations along with Pa Chu and Do Chu rivers. During the visit, the team thoroughly observed the existing conditions, river/ stream banks, bed conditions, cross-channel structures, infrastructures along the stream and river banks and also, existing flood management structures. Details of the visit are elaborated in this chapter.

Visit Summary

Immediately upon completion of Inception Presentation Workshops, the study team set out to Paro for a 4-day detailed field visit, the team for which will specifically include the design engineer and members from the modeling team. The Consultant Team, during the detailed field visit, observed the entire lengths of the concerned eight streams as well as visit the critical locations of both Pa Chu and Do Chu Rivers. All concerning structural interventions such as gabion, guide walls, abutments, bridges, culverts, irrigation diversions, etc. have been identified along both banks of the streams. Measurements have been taken for bridges and culverts even culverts with piped layouts to note down dimensions. Measurements have been taken for existing irrigation diversion canals in different locations along the streams. GPS point locations have been taken in start and end locations of bank protection structures as well as for probable alignments for proposed protection and road, embankment level raising to calculate the probable length for proposed measures. Preliminary adequacy checking, as well as functionality of existing structures, have also been performed during this time via means of visual observation by the study team, from which ideas regarding preliminary solutions and measures will be perceived.

Visit Objectives

The primary purpose of the detailed field visit was to pick up where the reconnaissance visit has left off and done a detailed assessment of the surroundings as well as existing conditions and physical interventions of and along the streams and rivers of the study domain. More specifically, this visit was to fulfill the following key objectives:

- Detail visit along with Pa Chu, Do Chu and streams
- Investigate critical locations along rivers and observe existing structures
- Consultation with local people
- Identify site-specific solution
- Identification of key infrastructures

Detailed Visit Team

An expert team composed of Hydrologists, Engineers, and GIS Specialists both from Bhutan and Bangladesh was involved in the detailed visit. Particulars are listed below.

- Mr. Pema Cheda, Dy. Executive Engineer, FEMD, DES, MoWHS, Bhutan
- Mr. Md. Asaduzzaman, Design Engineer, CEGIS, Bangladesh
- Mr. Tanvir Ahmed, Hydrologist cum Team Leader of Paro FMP, CEGIS, Bangladesh
- Mr. Md. Monowar-ul Haq, Hydrologist & Climate Change Expert, CEGIS, Bangladesh
- Mr. H.N. Adhikari, Civil Engineer, APECS, Bhutan

Observations

Below is a brief chronological description of the study team's daily activities within the confinements of the study domain encompassing the lengths of the 8 streams and prominent areas within the Pa Chu and Do Chu catchments.

Day 1

Balakha Chu

At the beginning of the visit, the team went straight to Drukgyel Dzong at u/s of the Pa Chu River. There they observed the u/s surroundings and flow in the river which gets complimented further d/s via flow from various streams included in the study. The team was then joined by Mr. Pema from the FEMD and he then guided the team for the rest of the day's visits. From Drukgyel Dzong, the team moved downhill to a stream named Balakha. Although not included within the 8 streams of the study, this particular stream is significant in that it originated from relatively uphill terrain and traverses a rather steep slope downhill before discharging into the Pa Chu. At u/s most portion where the team started near a bridge in the highway, moving a bit further u/s, the team found a couple of small irrigation canals through which a bulk of the flow was being diverted from the stream. Although this is in a way an indirect method within itself for reducing flood flow during monsoon, peak discharges from heavy downpour would, however, still flood the banks, as the locals mentioned. Vegetation around both the banks included forest trees and bushes. Table 1 presents findings and Figure 1 illustrates Balakha Chu. This stream has been requested by the client-side to be included within the study bounds.

Table 1: Balakha Chu Findings

Balakha Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.49640	89.31910	Bridge on the road	Bridge opening is adequate. Old bridge constricts the flow during monsoon water comes to bridge-tunnel.
2	27.49590	89.31880	Irrigation diversion from the stream	
3	27.49730	89.32150	Need to remove the boulders from the flow path	Need to remove the boulders from the flow path.

Figure 1: Balakha Chu

Jew Chu

The team then moved some ways downstream along the Pa Chu River past Bondey where both Pa Chu and Do Chu meet and visited the Jew Chu stream. With a peak flow of 17 cumec (chapter 4) this is one of the more prominent contributors to the river flow among the 8 streams. The team started from the u/s most accessible portion of the stream and this notion of prominence faded somewhat in that the team witnessed constricted flow due to unplanned settlements, farming practices as well as heavy sediment depositions in certain places obstructing the smooth passage of flow. Another form of flow constriction came as a result of cross-structures such as small culverts, where the immediate section of flow passage under the structure was moderate to severely narrow out due to abutments and placement of pipes with inadequate diameter. The team observed locations of flow constriction and took measurements of cross-drainage structures including culverts and also any irrigation canals present. In the downstream portion, the stream seemed to have widened up substantially but again adequacy of the channel to be able to allow passage of peak discharge is yet to be fulfilled after a thorough evaluation of the hydrodynamic model. Banks from mid to d/s portion were covered by dense bushes which can be a significant contributor to flow reduction. The section narrows quite a bit d/s due to unplanned development. This is presented in Table 2 and portrayed in Figure 2.

Table 2: Jew Chu Findings

Jew Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.39206	89.41706	u/s of Jew Chu	Clear the boulders. Need to clear the flow path along the river.
2	27.39218	89.41753	Cross submerged road	Clear the boulders at the inner bend. A road for pedestrian movement can be provided. Brick wall and RCC slab over it.
3	27.39176	89.41948	Box culvert	The opening is full during monsoon. There is a stone wall at the up at the left bank. In 1968, the river flooded.
4	27.39132	89.42168	Low elevation road	Improve the road level. Sensitive area. (2-3 feet).
5	27.39127	89.42158	Start of road improvement	From this portion, road elevation needs to be raised at the right bank, to act as flood protection.
6	27.39144	89.42183	Join another small stream	Interim point of road improvement.
7	27.39134	89.42194	Box culvert	
8	27.39110	89.42264	Box culvert	Remove boulder under the culvert.
9	27.39112	89.42286	End of road improvement/	Start of right bank protection. Remove boulder to increase conveyance capacity.
10	27.39125	89.42342	Start of left bank protection	Gabion wall
11	27.39124	89.42504	Box culvert	
12	27.39125	89.42522	Scouring of right bank protection	During summer WL is 1m below road level and never crossed the road last 15 years. Constriction at the down of measurement structure.
13	27.39148	89.42634	Box culvert	Erosion just up of the culvert. Right bank gabion failed just down of the culvert.
14	27.39169	89.42704	Box culvert	
15	27.39145	89.42845	Narrow section	Recommend a guide wall in both sections with a box culvert. 20-30m of length.

Figure 2: Jew Chu

Gatanarong Chu

After Jew Chu, the team quickly moved a bit down the Pa Chu and came upon Gatanarong Chu. With an impressive 18 cumec discharge (chapter 4) into the combined Pa Chu, this is the most prominent among the 8 streams. This particular stream exhibited somewhat erratic visible flow passage in u/s position whereby flow is cutoff at places, partially due to the visit time being dry period, but mostly due to heavy siltation in the stream bed. This is however caused by random landslides but most, unfortunately, this is done intentionally at certain places to allow people to cross the stream. These locations have been immediately identified by the consultant team and have been marked for culvert design and placement, size of which will be in accordance with the catering transport load of both vehicular and pedestrian traffic. Moving from u/s to the d/s portion, the team came upon structures such as irrigation canals and a small water reservoir which was apparently filled through pipe flow from the stream. The stream did not, however, constrict further d/s as much as the Jew Chu but the presence of dense bushes was noticed and these will be recommended for clearing to allow smooth passage of flow during monsoon onset. The presence of bushes calls for an unwarranted increase in the roughness coefficient of the banks and restrains flow thereby reducing velocity and causing the same amount of flow to require a greater section to be able to pass, thus ultimately causing flooding. Table 3 presents and Figure 3 illustrates Gatanarong Chu findings.

Table 3: Gatanarong Chu Findings

Gatanarong Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.38074	89.40977	Cross submerged road	Stream filled up to allow vehicle and pedestrian passage. Needs to be rectified immediately via box culvert and allowance of the clear flow path. (2V x 3m x 4m depth)
2	27.38050	89.40955	Bridge	Railing is broken
3	27.38184	89.41166	Box culvert	No railing. Bending stream. Culvert needs to be reconstructed. Stream filled to make the road, need to clear the temporary crossroad.
4	27.38273	89.41369	Box culvert	
5	27.38363	89.41521	Temporary cross-passage	Re-sectioning required. Need Culvert of 6m span.
6	27.38353	89.41522	Natural gully and crosses the road	2m x 2m box culvert required
7	27.38541	89.41741	Need Box culvert/ Bridge	
8	27.38549	89.41805	Drinking water inlet	Constrict the flow path.
9	27.38528	89.42372	Stream constricted due to hill	Need to excavate 1m of the right bank.
10	27.38911	89.43049	Outfall to Pa Chu	Need to clear the flow path. Temporary crossroad.
11	27.37956	89.46995	Channel should be guided	Channel should be guided 150-200m of both sides of the retaining wall. It will also protect the encroachment.
12	27.37867	89.46795	Pipe culvert	Cross drainage.

Figure 3: Gatanarong Chu

Nephu Chu

With the setting sun in the background, the team visited the final stream for the day, Nephu Chu. This stream is unique in that with a hefty 16 cumec discharge, it is the third most contributing stream into the combined Pa Chu. However, as observations revealed, this stream is riddled with narrow passages that severely contradict the supposed flow at its outfall. The team had a hard time locating u/s sections of this stream due to a complex mix of wild vegetation and settlement causing severe narrowing of the flow passage. Moving along the downward slope which appeared to be a bit on the steep side as compared to the previous streams of the day, the team noticed marks of unplanned development with unsafe hill cuts for construction works are putting things at risk due to imminent landslides thereby further silting up of stream sections. Further downstream, the team found marks of unplanned settlements where people have build structures protruding into half of the stream section thus severely constricting flow passage. These have to be demolished even partially to increase conveyance. The stream sections widen up further d/s near the outfall into the combined Pa Chu where it traverses under a highway bridge and falls into the river. Sections along this portion have to be cleared from debris to allow for smooth conveyance. Table 4 presents findings and Figure 4 shows the observed conditions along with Nephu Chu.

Table 4: Nephu Chu Findings

Nephu Chu

Sl	Lat	Long	Observations	Remarks
1	27.38128	89.47218	Start of Nephu Chu	Need to clean the flow path.
2	27.38042	89.47132	Pipe culvert	Need to clean the flow path.
3	27.38034	89.47090	a channel filled with roadside soil	Need a clearly defined channel and guide wall. (25-30m of gravity wall)
4	27.38012	89.47043	Pipe culvert	Recommendation: 2m x 1.5 m box culvert
5	27.37996	89.47016	Pipe culvert	Recommendation: 2m x 1.5 m box culvert
6	27.37644	89.46615	Box culvert	
7	27.37565	89.46584	Join another stream	Join Nephu Chu at the left bank. Pipe culvert (200 mm diameter)
8	27.37524	89.46399	Pipe culvert	Left to right
9	27.37545	89.46351	Pipe culvert	Right to left
10	27.37560	89.46244	Box culvert	Left to right
11	27.37543	89.45836	Pipe culvert	
12	27.37527	89.45826	Box culvert	
13	27.46643	89.34288	Measurement of section	

Figure 4: Nephu Chu

Day 2

Satsam (North) Chu

The team started the second day early with a view to cover as much as possible with the then national holidays already in effect. The team moved to u/s of the Satsam Chu North and was immediately greeted with a scenic landscape. Nearby mountains converging into valley settlements were overlooked by distant snow-clad peaks of the Bhutanese Himalayan Range. The looming view of Taktsang Lhakhang or the Tiger Nest monastery in the not-so-distant mountain cliff gave a sense of serenity to the morning ambiance.

This stream discharges 6 cumec into the Pa Chu. U/s most accessible portion of the stream-side catchment housed a temporary stone grinding site which if left unchecked, has the potential to generate debris for the already narrow flow passage in the location. While moving further d/s on foot, the team witnessed the crisscrossing nature of the stream as it traversed both sides of the side-road through cross drainage piped culverts. These culverts were measured and initially deemed to be possessing a low diameter for flow passage. Flow passage naturally constricts a bit further d/s where the team came upon a construction site. This portion has to be widened via digging. Further d/s, the section widened up but along this passage, the flow path was severely constricted due to encroachment from a local resort named "Golden Roots". This resort took much of the adjacent flow path of the stream. This portion has to be demolished as soon as possible. Further d/s the section remains adequate apparently but accessibility is severely restricted due dense bushes. These have the potential to constrict flow substantially and thus have to be cleared. On a separate note, the presence of public restrooms along the bank will cause deterioration of stream thus river waters. The stream falls into Pa Chu after passing through a narrow highway culvert which will have to be widened. Table 5 presents findings and Figure 5 illustrates these observations.

Table 5: Satsam (North) Chu Findings

Satsam (North) Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.46274	89.33840	Pipe culvert	Recommendation: 2m x 1.5 ft box culvert with 5m length
2	27.46366	89.33958		Need box culvert and Re sectioning of the stream. 5m width of the stream.
3	27.46435	89.34034	Pipe culvert	Blocked by resort entry.
4	27.46810	89.34428	Section measurement	
5	27.46885	89.34432	Box culvert	The outfall of the stream. The depth of the box culvert is okay. The width can be increased slightly. Need to clean bush throughout the length of the stream.

Figure 5: Satsam (North) Chu

Satsam (South) Chu

The team then moved to the adjacent Satsam Chu (South) stream which is another small channel with a discharge of 3 cumec into the Pa Chu. The team started from u/s and was again welcomed with picturesque green mountain peaks. A substantial portion of u/s section of this channel is rather inaccessible due to dense vegetation and forest. When it did appear into vision though, it appeared a narrow creek which immediately upon the appearance, traverses across the hill-side road and then through a narrow culvert to the other side. This restricts flow passage as the bed on the road level is unwanted. A culvert will be proposed here to accommodate the immediate impact of high-velocity flow coming from the steep slope portion. Moving further d/s the team observed a septic tank along the left bank which has the potential to contaminate stream baseflow through leakage due to placements at such close quarters. Further d/s the team witnessed a huge dump of waste signifying unplanned disposal which again gets placed at the bed of the stream and obstructs flow passage. The stream then gets deeper as opposed to a relatively narrow width, barely visible due to dense bushes that have to be kept clear on a regular basis to reduce flow friction. Further d/s the team observed encroachment from another local resort and some small flow diversion structures. The d/s most portion of the channel passes under a highway culvert that has to be widened but is met with unfortunate narrowing through concrete channelization by locals. This will hamper flow passage to the Pa Chu and cause flooding during a heavy downpour. Table 6 presents and Figure 6 illustrates these findings.

Table 6: Satsam (South) Chu Findings

Satsam (South) Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.46129	89.33821	Starting of the stream	
2	27.46169	89.34664	Box culvert	Recommendation: 5m length and 6m width. Need protection 30m d/s of the bridge to save the road.
3	27.46260	89.34917	Box culvert	Flood problem. Raven's rest resort. Recommendation: 5m length and 6m width. Need 50-60m protection at left.
4	27.46341	89.35123	Box culvert	The structure on the river to divert water to a local resort. Need to demolish the diversion structure.
5	27.46383	89.35222	Encroachment	
6	27.46481	89.35365	Box culvert (2 nos)	Two different sill levels. The previously constructed culvert has a lower sill. Constriction at the down of the culvert. Recommendation: Replace the previous box culvert with a lower sill level. Width 3m & Depth 2m.

Figure 6: Satsam (South) Chu

Dakhorong Chu

In the latter half of the day, the team then moved to the Dakhorong Chu which is on the smaller to medium size in capacity among the streams with a peak discharge of 6 cumec into the Pa Chu. The channel sections seemed wide enough in u/s and d/s portions with some substantial narrowing in the middle portion. U/s has dense bush along both banks that have to be cleared. Boulders placed at random locations along the bed will also have to be cleared up to an acceptable extent to allow smooth passage for flow. Along the flow path, there is a culvert opening with a three piped layout for flow passage. This setup although might be adequate dimension-wise, but might still obstruct high-velocity flow. A mixture of dense shrubs and waste dumping as the stream nears its mid-section will have to be cleared to allow flow. In the mid-portion the stream is narrowed down due to encroachment and settlement to a point where a small wooden plank would suffice for taking one step to cross the stream (Figure 7). These portions have to widen sufficiently and crossings such as these will have to be accommodated via culverts, dimensions of which will be finalized after hydrodynamic simulations and consultation with the design engineer. There are gabions and protective works along the banks, a trait again, of human settlements. The stream widens as it moves further d/s with protective works along both banks. Near d/s outfall it traverses under a highway culvert which might have to be raised to maintain adequate flow section for discharge into Pa Chu. Table 7 presents and Figure 7 illustrates Dakhorong Chu observations.

Table 7: Dakhorong Chu Findings

Dakhorong Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.44620	89.36242	Undisturbed condition	
2	27.44704	89.36314	Narrow stream section	Need re-sectioning of 100m. 30up-80 down.
3	27.44765	89.36353	Pipe culvert	Need to clean the flow path. The stream is inside the school boundary.
4	27.44911	89.36474	Pipe culvert	Encroachment at the d/s of the culvert at the right bank, protect with retaining wall in future. Presently, no flooding and growth of the settlement.
5	27.44950	89.36521	Measurement of section	
6	27.44911	89.36538	Start of bank protection (both bank)	
7	27.45060	89.36562	Box culvert	Outfall condition is good.

Figure 7: Dakhorong Chu

Ngoborong Chu

In the afternoon, the team visited the Ngoborong Chu which a bit further d/s along with the Pa Chu. This is somewhat of a prominent stream with a peak discharge of 10 cumec . This stream follows a steep longitudinal slope in u/s region as it moves d/s, it has a number diversion canals for irrigation purposes. Moving towards the midsection, the stream is protected along both banks due to settlements, but considering its peak discharge, the resultant flow section might be up for a challenge. Adequacy checking of existing flow sections will be done via hydrological modeling exercises. There are a number of culverts along the channel, dimensions of which have been measured by the team members. Further d/s near the mid-portion the channel is narrowed down due to siltation from bank erosion and also due to unplanned rural settlement. These sections have to be widened with a clearing of large boulders at some key locations to accommodate smooth conveyance. This narrow portion extends for quite a length of the channel reach as it propagates d/s and is a cause for concern that has to be facilitated. Dense bushes and narrow culvers have to be cleared and reconstructed respectively for increased conveyance. The d/s portion is again regulated and guided with protection along both banks, adequacy of which will be checked. A series of culverts were found along this stretch of the reach which was all measured for placement in the hydrodynamic model. A flaw was located further d/s where landfilling without proper bank protection took place for some sort of construction works. This has serious implications in that any cave-in would cause the entirety of the flow channel to be obstructed. This has to be mitigated as soon as possible. Another serious flaw is that the stream enters under the highway via a two-pipe culvert but it does not exist on the other side. Small streams of water leach out of what appeared to be geobags protection placed over the pipe outlets and discharges into the Pa Chu. During peak flows, this is a recipe for a disaster. Table 8 presents and Figure 8 illustrates these major findings.

Table 8: Ngoborong Chu Findings

Ngoborong Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.43569	89.37465	Box culvert	The Channel section is the same as the culvert section. Slight Bed scouring at d/s of the culvert. Masonry wall at the bottom section is recommended.
2	27.43573	89.37511	Box culvert	Functional.
3	27.43655	89.37644	Box culvert	There is a small lake at the top of the hill. Channel section as the same as the culvert section. During Summer it overflows. Recommendation: Re-sectioning and build a 75m masonry guide wall on both sides.
4	27.43670	89.37675	Box culvert	
5	27.43699	89.37709	Box culvert	
6	27.43774	89.37820	Box culvert	No flow in the dry season.
7	27.43796	89.37851	Box culvert	A resort.
8	27.43847	89.37896	Box culvert	Near Pinewood hotel.
9	27.43884	89.37934	Box culvert	Need to clean garbage and clear flow path by replacing boulder.
10	27.43912	89.37971	Box culvert	Near Kay ARR restaurant.
11	27.43923	89.37984	Box culvert is non-functional	Need to replace.
12	27.43976	89.38036	Box culvert	Lined Channel with the same section around 30 m.
13	27.40060	89.38055	Box culvert	

Ngoborong Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
14	27.44060	89.38130	Irrigation channel, soil dumping u/s	Need drop structure to pass the stream, soil dumped recently so the channel is blocked.
15	27.44080	89.38161	Box culvert	
16	27.44139	89.38243	Pipe culvert	One side of the culvert fall in the river. Culvert not functional, riverside end of the pipe is blocked. An irrigational channel passes over the stream just u/s of the culvert. The channel dimension is 2m x 0.5m at the upper segment of the culvert. Recommendation: Re-sectioning required. Need section drop to pass the irrigational canal. Pipe culvert should be replaced with a box culvert. Condition of stream outfall at the river needs to be checked.


Figure 8: Ngoborong Chu

Day 3

Ri Chu

During the morning on day 3, the team visited Ri Chu, the last of the 8 streams. With a peak discharge of 11 cumec, it a prominent contributor to the flow of Do Chu which peaks at 60 cumec near outfall. It originates high in the mountains overlooking the Paro valley. U/s most portions are inaccessible by vehicle. The stream once visible appears narrow along with u/s segments with a very shallow bed level. This has to be re-sectioned to accommodate high-velocity flow during peak showers. Moving further d/s there is the Ri Chu Dam, a structure with u/s reservoir of insufficient depth as observed by the team members. A deeper reservoir would allow more storage as well as give incentives for fisheries practices. The stream section is significantly narrowed as we move d/s due to siltation and unplanned settlement. These have to be re-sectioned to allow flow. The team took measurements of the channel section as well as small culverts and other structures along the stream. The discharge point to Do Chu is the wide but proper connection has to be established via re-sectioning of u/s segments. Figure 9 illustrates this.

Table 9: Ri Chu Findings

Ri Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.44398	89.43598	Cross submerged road	The temporary submerged road across the river. Box culvert is recommended.
2	27.44399	89.43484	Pipe culvert	Pipe Culvert is okay. 50m guide wall (20m up + 30m down from culvert) at the right bank is required.
3	27.44419	89.43278	Ri Chu dam	No contribution to flooding.
4	27.44405	89.43103	Cross submerged road	The temporary submerged road that crosses the river. Need box culvert with wing wall.
5	27.44379	89.42887	Wooden culvert	The outfall of the stream near the main road (highway).
6	27.44353	89.42662	Box culvert	
7	27.44240	89.42294	Box culvert	Near the outfall.

Figure 9: Ri Chu

Pa Chu

With the observation of the streams completed, the team then moved along key locations along the Pa Chu River, marked from experience gained during reconnaissance visit. The team mainly observed the bank protection structures and assessed the necessity of further protective measures that might be required along designated stretches. The team also observed the flowing nature and made notes of the bed conditions so as to suggest necessary excavation works that might be required at certain portions. Table 10 presents and Figure 10 marks the Pa Chu observations.

Table 10: Pa Chu Findings

Pa Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.43400	89.40911	Erosion	Start of erosion at the right bank. Waterfall at the left bank.
2	27.43499	89.40738	Gabion failure	Gabion fails at the right bank. Input to water storage.
3	27.43573	89.40657	Start of gabion failure	Start of gabion failure at the right bank. Construction of new gabion is ongoing.
4	27.43630	89.40573	Gabion failure	
5	27.43674	89.40512	Start of right bank gabion failure	Soil dumps inside the river boundary.
6	27.43729	89.40441	Embankment	The embankment level is low around 50m.
7	27.43779	89.40344	Erosion	Start of erosion at the right bank.
8	27.46961	89.35065	Riverbank erosion	Riverbank erosion at the left bank due to the bending of the river. Around 100m down from this point.
9	27.45780	89.35925	Start of protection work	The right bank is new (multi-stage) and the left bank is old.

Figure 10: Pa Chu (Day 3)

Do Chu

The team ended visits on day 3 via visiting Do Chu. The team then moved along key locations along the Do Chu River, marked from experience gained during reconnaissance visit. The team mainly observed the bank protection structures and assessed the necessity of further protective measures that might be required along designated stretches. The team also observed cross-river structures as well as the flowing nature and took measurements and made notes of the bed conditions so as to suggest necessary excavation works that might be required at certain portions. Table 11 presents and Figure 11 marks the Da Chu observations.

Table 11: Do Chu Findings

Do Chu				
Sl	**Lat**	**Long**	**Observations**	**Remarks**
1	27.49279	89.43354	Bridge	Width is 6.5m and depth is 3.0m.
2	27.49246	89.43382	Erosion	Erosion at the left bank around 20 m. Protected by gabion. (old)
3	27.48892	89.43286	Bridge	Bank protection on both sides starts from this point.
4	27.48805	89.43311	Bridge	Submersible bridge. A 3m span bridge covering full length is recommended.
5	27.48497	89.43150	Bank slope measurement	

Figure 11: Do Chu

Day 4

The team visited key locations along with the Pa Chu on the final day of the visit. These visits included locations near the Tiger's Nest, along with mid to d/s segments of the stretch that meets Do Chu near Bondey and finally along with the combined Pa Chu near the Airport. Visit near the Tiger's Nest included observation of probable points of supercritical flow in coincidence with a sharp bend and subsequent high erosion probability at a large scale. Proper protection measures will have to be applied so that the energy of the flow is mitigated with as much ease as possible. This portion is highly prone to bank erosion. The next set of visits were concentrated along with the mid to d/s portion of the upper Pa Chu channel that meets Do Chu near Bondey. The team then moved along key locations along the section, and mainly observed the bank protection structures and assessed the necessity of further protective measures that might be required along designated stretches. The team also observed the flowing nature and made notes of the bed conditions so as to suggest necessary excavation works that might be required at certain portions. The final set of visits were made to the combined Pa Chu and Do Chu River near the international airport. The purpose of this segment of the visit was two folds. One was to observe and gather experience from the protection measures already in effect in that region and has been withholding flooding hazards for decades while simultaneously assess potential requirements of further measures. Figures 12 to 14 illustrate these observations and findings are presented in Table 11.

Figure 12: Pa Chu (Near Tiger's Nest)

Figure 13: Pa Chu (Upper Reach)

Figure 14: Combined Pa Chu (Near Paro Airport)

Consultations

The reconnaissance visit made in January 2020 covered stakeholder consultations at field level to a satisfactory extent. This along with the fact that national holidays were in effect during the detailed visit limited the scope of stakeholder consultations at government level. This was however overcome via meetings that took place in between the inception workshops prior to the detailed visit. Additionally, this allowed for more in-depth local level consultations at the field level. The root-level folks, ones who would be the direct beneficiary of the flood management plan were interviewed during the 4-day visits and their views were taken regarding the streams adjacent to which they lived and those whose day to day lives revolved around the surroundings of the stream catchments. It was found that the local level people harboured little knowledge about hydrological facts such as the necessity of maintaining a channel section and not narrowing at d/s locations so as to convey flow smoothly. However, when explained, they understood and even gave insights as to their requirements for ensuring a flood-free locality. Figure 15 highlights these consultations.

Figure 15: Field Consultations

Summary of Findings

General observations synthesized from the detailed field visit coincide with reconnaissance findings. However, the team took a wide array of data and information specific to each stream and critical location. Summary of generic findings are presented below –

- The main cause of the flooding is monsoon rainfall. The flow of the rivers and stream become very high after a storm event due to the high slope of the terrain, consequently causes flood;
- The velocity of the rivers is very high due to high river slope;
- Another potential cause of the flooding is glacier lake outbursts. Though this event is relatively rare but could cause tremendous flood damage;
- Both of the Bank of Pa Chu and Do Chu is protected using stone Gabion. At some location, especially at the bend of the river, the structure failed due to bed scouring at the outer bend;
- There are some large boulders at the upstream of the rivers which increase the friction of the river;
- For the streams, the width is comparatively higher at the upstream area while it gradually constricted at the downstream;
- The rivers and streams are constricted due to the construction of cross-drainage structures and other structures which reduces the conveyance capacity of the river and ultimately causes flooding;
- The downstream part of the Nephu Chu is converted into a small storm water drain;
- Lots of vegetation covers the stream which reduces the flow area and increases friction;

- At some location, the streams are filled to make some temporary road which causes flooding of the surrounding area;
- The outfall of the Ngoborong Chu is not functional;
- The Ri Chu dam, which was constructed for irrigation water diversion is silted up and not functional;
- The bridges, pipe and box culverts capture the debris during high flow and cause damage;
- There is no flood management plan for the Paro area;
- There is no disaster risk mitigation and preparedness program for the area;
- There is no land zoning plan to reduce the impact of major flooding; and
- There is no flood forecasting and early warning system.

The detailed summary of findings and remarks are presented in tabular form are given in Table 12.

Table 12: Summary of findings from detailed field visit

Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
1	27.49640	89.31910	Balakha Chu	Bridge on the road		Bridge opening is adequate. Old bridge constrict the flow during monsoon water comes to bridge tunnel.
2	27.49590	89.31880	Balakha Chu	Irrigation diversion from stream		
3	27.49730	89.32150	Balakha Chu	Need to remove the boulders from flow path		Need to remove the boulders from the flow path.
4	27.39206	89.41706	Jew Chu	u/s of Jewchu		Clear the boulders. Need to clear the flow path along the river.
5	27.39218	89.41753	Jew Chu	Cross submerged road		Clear the boulders at inner bend. A road for pedestrian movement can be provided. Brick wall and RCC slab over it.
6	27.39176	89.41948	Jew Chu	Box culvert	5.2 x 1.8 m	The opening is full during monsoon. There is a stone wall at the up at the left bank. In 1968, the river flooded.
7	27.39132	89.42168	Jew Chu	Low elevation road		Improve the road level. Sensitive area (2-3 feet).
8	27.39127	89.42158	Jew Chu	Start of road improvement		From this portion, road elevation needs to be raised at right bank, to act as flood protection.
9	27.39144	89.42183	Jew Chu	Join another small stream		Interim point of road improvement.
10	27.39134	89.42194	Jew Chu	Box culvert		
11	27.39110	89.42264	Jew Chu	Box culvert	3 x 1.5 m	Remove boulder under the culvert.
12	27.39112	89.42286	Jew Chu	End of road improvement/ Start of right bank protection		Remove boulder to increase conveyance capacity.
13	27.39125	89.42342	Jew Chu	Start of left bank protection		Gabion wall.
14	27.39124	89.42504	Jew Chu	Box culvert	3.65 x 1.82 m	
15	27.39125	89.42522	Jew Chu	Scouring of right bank protection		During summer WL is 1m below road level and never crossed the road last 15 years. Constriction at the down of measurement structure.
16	27.39148	89.42634	Jew Chu	Box culvert	4.7 x 1.6 m	Erosion just up of the culvert. Right bank gabion failed just down of the culvert.
17	27.39169	89.42704	Jew Chu	Box culvert	11 x 7.4 ft	

Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
18	27.39145	89.42845	Jew Chu	Narrow section		Recommend guide wall in both section with box culvert. 20-30m of length.
19	27.38074	89.40977	Gatanarong Chu	Cross submerged road		Stream filled up to allow vehicle and pedestrian passage. Needs to be rectified immediately via box culvert and allowance of clear flow path. **(2V x 3m x 4m depth)**
20	27.38050	89.40955	Gatanarong Chu	Bridge	15 x 7 ft	Railing broken.
21	27.38184	89.41166	Gatanarong Chu	Box culvert	15.4 x 7.4 ft	No railing. Bending stream. Culvert needs to be re-constructed. Stream filled to make the road, need to clear the temporary cross road.
22	27.38273	89.41369	Gatanarong Chu	Box culvert	19 x 8.5 ft	
23	27.38363	89.41521	Gatanarong Chu	Temporary cross passage		Re-sectioning required. Need Culvert of 6m span.
24	27.38353	89.41522	Gatanarong Chu	Natural gully and crosses the road		2m x 2m box culvert required
25	27.38541	89.41741	Gatanarong Chu	Need Box culvert/ Bridge		
26	27.38549	89.41805	Gatanarong Chu	Drinking water inlet		Constrict the flow path.
27	27.38528	89.42372	Gatanarong Chu	Stream constricted due to hill		Need to excavate 1m of the right bank.
28	27.38911	89.43049	Gatanarong Chu	Outfall to Pachu		Need to clear the flow path. Temporary cross road.
29	27.37956	89.46995	Gatanarong Chu	Channel should be guided		Channel should be guided 150-200m of both side of retaining wall. It will also protect the encroachment.
30	27.37867	89.46795	Gatanarong Chu	Pipe culvert	450 mm dia	Cross drainage.
31	27.38128	89.47218	Nephu Chu	Start of Nephu Chu		Need to clean the flow path.
32	27.38042	89.47132	Nephu Chu	Pipe culvert	900 mm dia	Need to clean the flow path.
33	27.38034	89.47090	Nephu Chu	channel filled with road side soil		Need clear defined channel and guide wall. (25-30m of gravity wall)
34	27.38012	89.47043	Nephu Chu	Pipe culvert	600 mm dia	Recommendation: 2m x 1.5 m box culvert
35	27.37996	89.47016	Nephu Chu	Pipe culvert	900 mm dia	Recommendation: 2m x 1.5 m box culvert
36	27.37644	89.46615	Nephu Chu	Box culvert	1 x .75 m	
37	27.37565	89.46584	Nephu Chu	Join another stream		Join Nephu Chu at left bank. Pipe culvert (200 mm diameter)
38	27.37524	89.46399	Nephu Chu	Pipe culvert	600 mm dia	Left to right

Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
39	27.37545	89.46351	Nephu Chu	Pipe culvert	2 x 450 mm dia	Right to left
40	27.37560	89.46244	Nephu Chu	Box culvert		Left to right
41	27.37543	89.45836	Nephu Chu	Pipe culvert	4 x 120 mm dia	
42	27.37527	89.45826	Nephu Chu	Box culvert		
43	27.46643	89.34288	Nephu Chu	Measurement of section		
44	27.46274	89.33840	Satsam (North) Chu	Pipe culvert	600 mm dia	Recommendation: 2m x 1.5 ft box culvert with 5m length
45	27.46366	89.33958	Satsam (North) Chu			Need box culvert and Re sectioning of the stream. 5m width of the stream.
46	27.46435	89.34034	Satsam (North) Chu	Pipe culvert	2/3 x 1.2 m dia	Blocked by resort entry.
47	27.46810	89.34428	Satsam (North) Chu	Section measurement	8.3 m x 3.75	
48	27.46885	89.34432	Satsam (North) Chu	Box culvert	2 x 3.5 m	Outfall of stream. Depth of box culvert is okay. Width can be increased slightly. Need to clean bush throughout the length of the stream.
49	27.46129	89.33821	Satsam (South) Chu	Starting of the stream		
50	27.46169	89.34664	Satsam (South) Chu	Box culvert		Recommendation: 5m length and 6m width. Need protection 30m d/s of the bridge to save the road.
51	27.46260	89.34917	Satsam (South) Chu	Box culvert	1.9 x 1.1 m	Flood problem. Raven's rest resort. Recommendation: 5m length and 6m width. Need 50-60m protection at left.
52	27.46341	89.35123	Satsam (South) Chu	Box culvert	4.7 x 1.8 m	Structure on the river to divert water to local resort. Need to demolish the diversion structure.
53	27.46383	89.35222	Satsam (South) Chu	Encroachment		
54	27.46481	89.35365	Satsam (South) Chu	Box culvert (2 nos)	3.15 x 1.85 m and 2 x 1 m	Two different sil levels. Previously constructed culvert has lower sill. Constriction at the down of the culvert. Recommendation: Replace the previous box culvert with a lower sill level. Width 3m & Depth 2m.
55	27.44620	89.36242	Dakhorong Chu	Undisturbed condition		

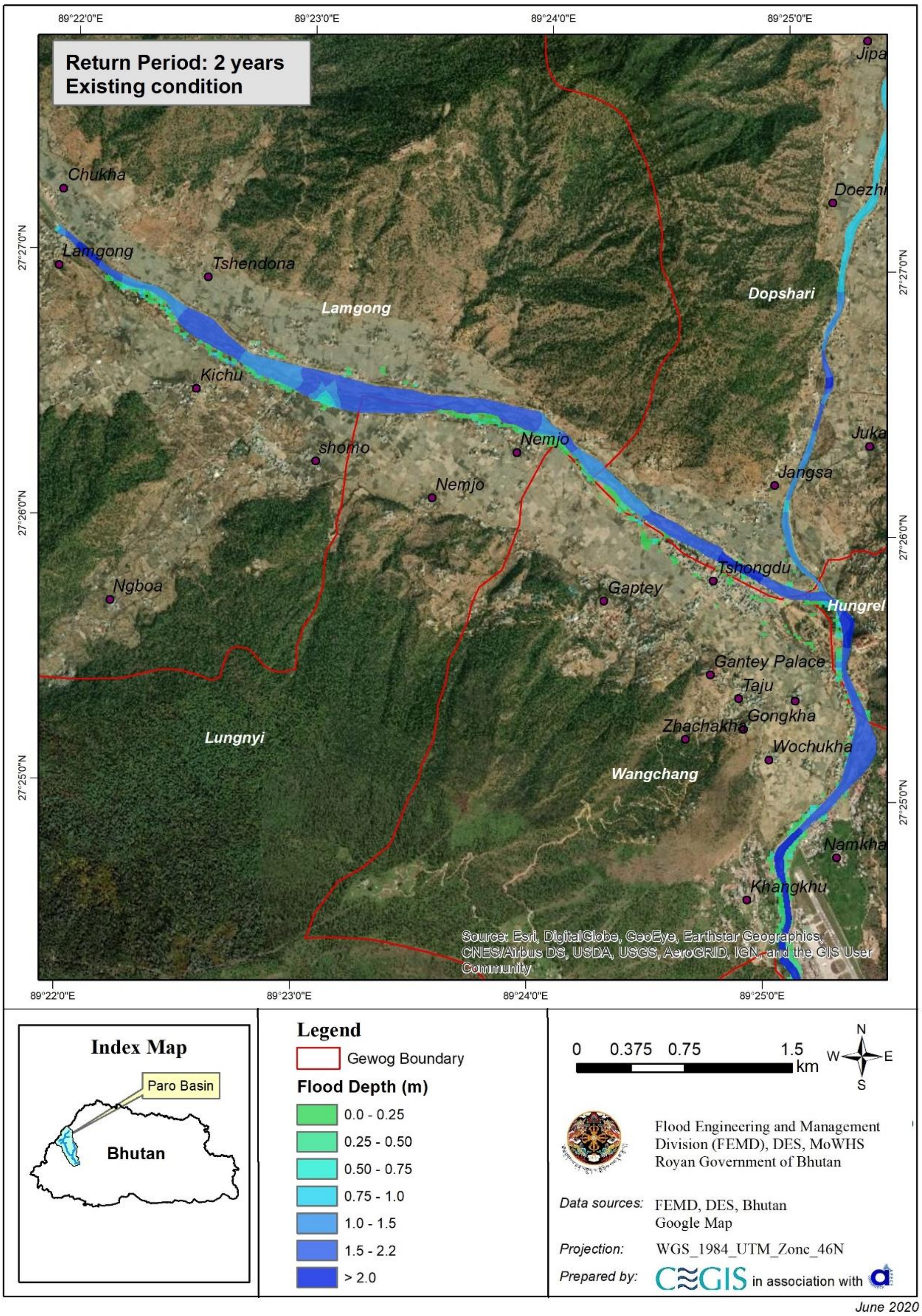
Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
56	27.44704	89.36314	Dakhorong Chu	Narrow stream section		Need sectioning of 100m. **30up-80 down.**
57	27.44765	89.36353	Dakhorong Chu	Pipe culvert	3 x 900 mm dia	Need to clean flow path. Stream is inside the school boundary.
58	27.44911	89.36474	Dakhorong Chu	Pipe culvert	2 x 900 mm dia	Encroachment at the d/s of culvert at the right bank, protect with retaining wall in future. Presently, no flooding and growth of settlement.
59	27.44950	89.36521	Dakhorong Chu	Measurement of section		
60	27.44911	89.36538	Dakhorong Chu	Start of bank protection (both bank)		
61	27.45060	89.36562	Dakhorong Chu	Box culvert	5 x 1.5 m	Outfall condition is good.
62	27.43569	89.37465	Ngoborong Chu	Box culvert	2 x 0.8 m	Channel section is same as culvert section. Slight Bed scouring at d/s of culvert. Masonry wall at bottom section is recommended.
63	27.43573	89.37511	Ngoborong Chu	Box culvert	2 x 0.9 m	Functional.
64	27.43655	89.37644	Ngoborong Chu	Box culvert	1.5 x 1.0 m	There is a small lake at the top of the hill. Channel section as same as culvert section. During Summer it overflows. Recommendation: Re-sectioning and build 75m masonry guide wall both side.
65	27.43670	89.37675	Ngoborong Chu	Box culvert	2.8 x 1.25 m	
66	27.43699	89.37709	Ngoborong Chu	Box culvert	1.9 x 1.25 m	
67	27.43774	89.37820	Ngoborong Chu	Box culvert	1.6 x 1.0 m	No flow in dry season.
68	27.43796	89.37851	Ngoborong Chu	Box culvert	2 x 0.7 m	A resort.
69	27.43847	89.37896	Ngoborong Chu	Box culvert	1.25 x 0.9 m	Near Pinewood hotel.
70	27.43884	89.37934	Ngoborong Chu	Box culvert	2.0 x 1.2 m	Need to clean garbage and clear flow path by replacing boulder.
71	27.43912	89.37971	Ngoborong Chu	Box culvert	1.4 x 1.25 m	Near Kay ARR restaurant.
72	27.43923	89.37984	Ngoborong Chu	Box culvert is non-functional		Need replace.
73	27.43976	89.38036	Ngoborong Chu	Box culvert	2.0 x 1.55 m	Lined Channel with the same section around 30 m.
74	27.40060	89.38055	Ngoborong Chu	Box culvert	1.5 x 1.5 m	
75	27.44060	89.38130	Ngoborong Chu	Irrigation channel pass and soil dumping u/s		Need drop structure to pass the stream, soil dumped recently so the channel is blocked.
76	27.44080	89.38161	Ngoborong Chu	Box culvert	1.6 x 1.2 m	

Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
77	27.44139	89.38243	Ngoborong Chu	Pipe culvert	2 x 900 mm dia	One side of the culvert fall in river. Culvert not functional, riverside end of the pipe is blocked. An irrigational channel pass over the stream just u/s of the culvert. The channel dimension is 2m x 0.5m at upper segment of the culvert. Recommendation: Re-sectioning required. Need section drop to pass the irrigational canal. Pipe culvert should be replaced with box culvert. Condition of stream outfall at river needs to be checked.
78	27.44398	89.43598	Ri Chu	Cross submerged road		Temporary submerged road across the river. Box culvert is recommended.
79	27.44399	89.43484	Ri Chu	Pipe culvert	2 x 900 mm dia	Pipe Culvert is okay. 50m guide wall (20m up + 30m down from culvert) at right bank is required.
80	27.44419	89.43278	Ri Chu	Ri Chu dam		Need box culvert with wing way.
81	27.44405	89.43103	Ri Chu	Cross submerged road		Temporary submerged road that cross the river. Need box culvert with wing wall.
82	27.44379	89.42887	Ri Chu	Wooden culvert	3.5 x 1.3 m	Out fall of stream near the main road (highway).
83	27.44353	89.42662	Ri Chu	Box culvert	5 x 1.3 m	
84	27.44240	89.42294	Ri Chu	Box culvert		Near the outfall.
85	27.43400	89.40911	Pa Chu (d/s to u/s)	Erosion		Start of erosion at the right bank. Waterfall at the left bank.
86	27.43499	89.40738	Pa Chu (d/s to u/s)	Gabion failure		Gabion fails at the right bank. Input to water storage.
87	27.43573	89.40657	Pa Chu (d/s to u/s)	Start of gabion failure		Start of gabion failure at right bank. Construction of new gabion is ongoing.
88	27.43630	89.40573	Pa Chu (d/s to u/s)	Gabion failure		
89	27.43674	89.40512	Pa Chu (d/s to u/s)	Start of right bank gabion failure		Soil dumps inside river boundary.
90	27.43729	89.40441	Pa Chu (d/s to u/s)	Embankment		Embankment level is low around 50m.
91	27.43779	89.40344	Pa Chu (d/s to u/s)	Erosion		Start of erosion at right bank.

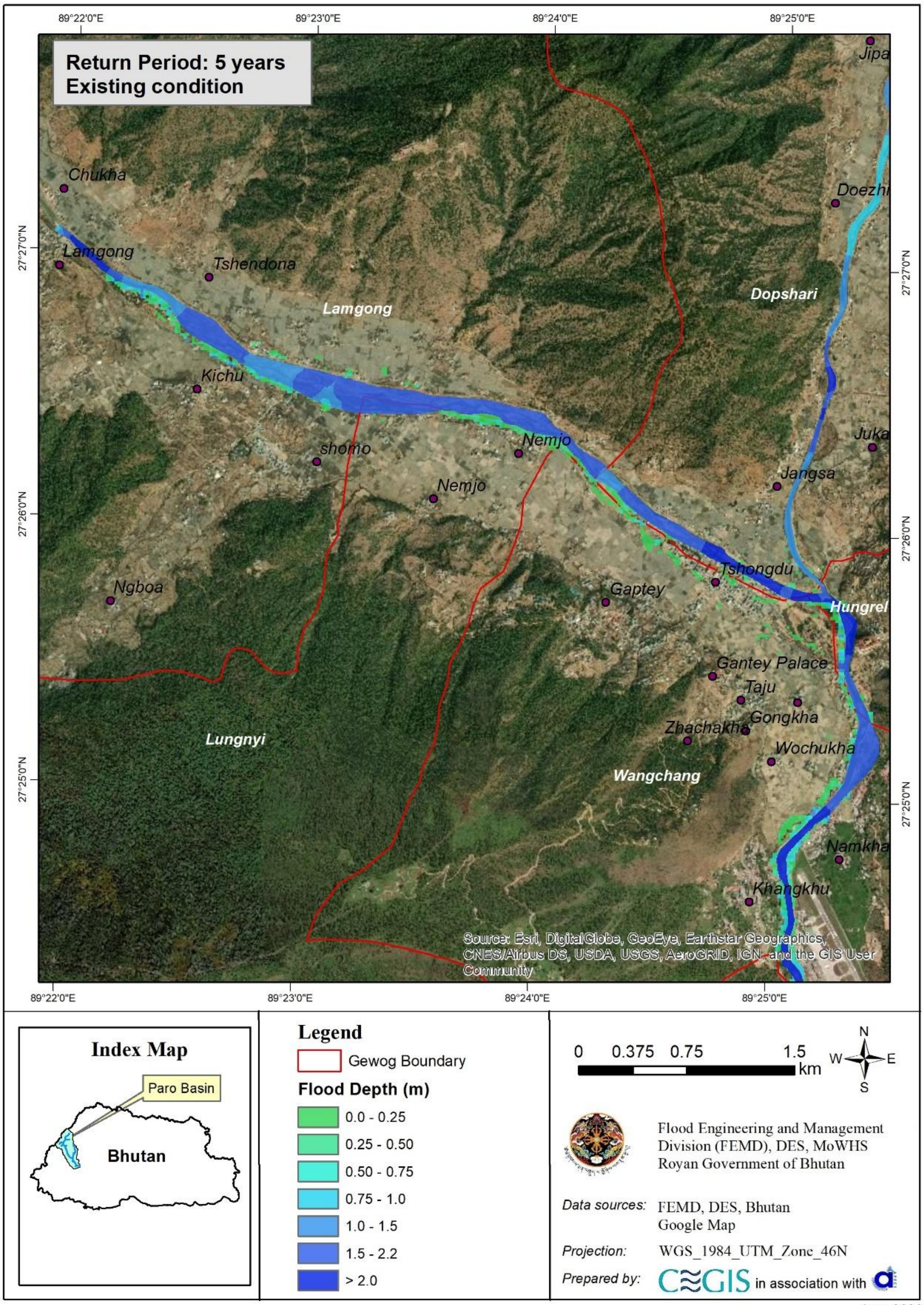
Sl	Lat	Long	Stream/River	Description	Dimensions	Remarks
92	27.49279	89.43354	Do Chu	Bridge		Width is 6.5m and depth is 3.0m.
93	27.49246	89.43382	Do Chu	Erosion		Erosion at the left bank around 20 m. Protected by gabion. (old)
94	27.48892	89.43286	Do Chu	Bridge	9.7 x 3.5 m	Bank protection on both side starts from this point.
95	27.48805	89.43311	Do Chu	Bridge	9 x 3.2 m	Submersible bridge. 3m span bridge covering full length is recommended.
96	27.48497	89.43150	Do Chu	Bank slope measurement	5H:1V	
97	27.46961	89.35065	Pa Chu	River bank erosion		River bank erosion at left bank due to bending of river. Around 100m down from this point.
98	27.45780	89.35925	Pa Chu	Start of protection work		Right bank is new (multi-stage) and left bank is old.

Appendix III: Flood Mapping for Existing and Climate Change Condition

Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)

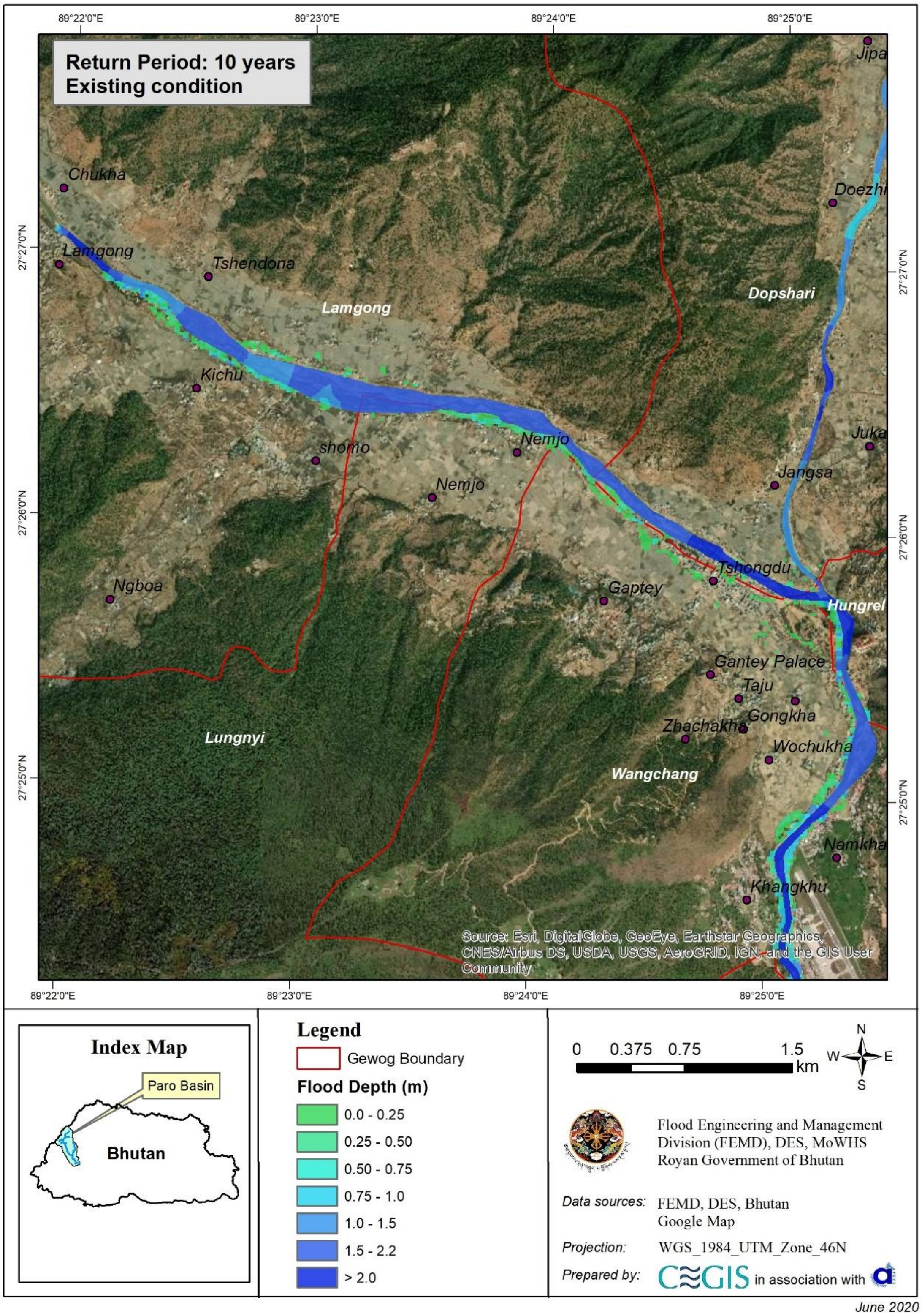


Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)

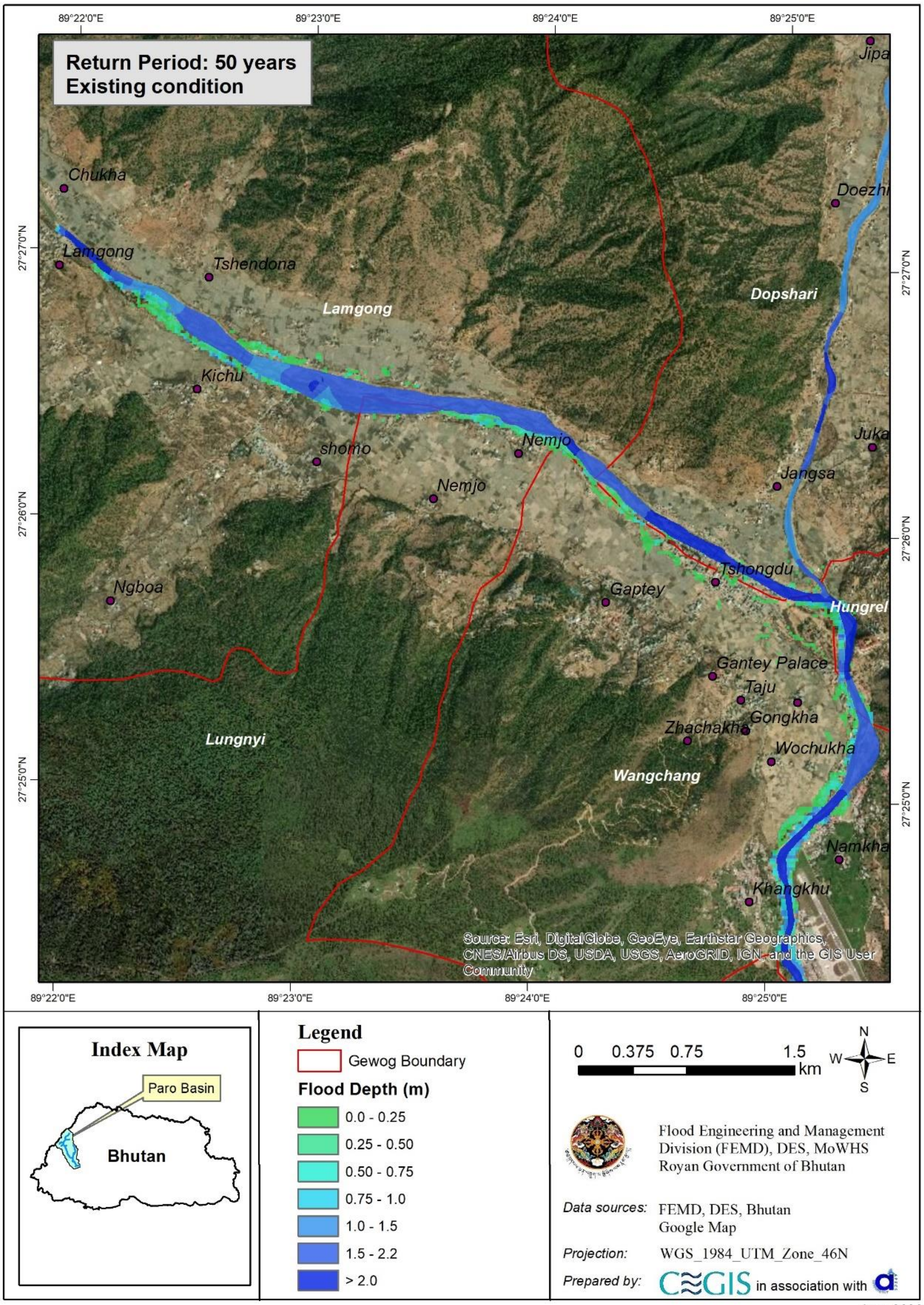


June 2020

Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



June 2020

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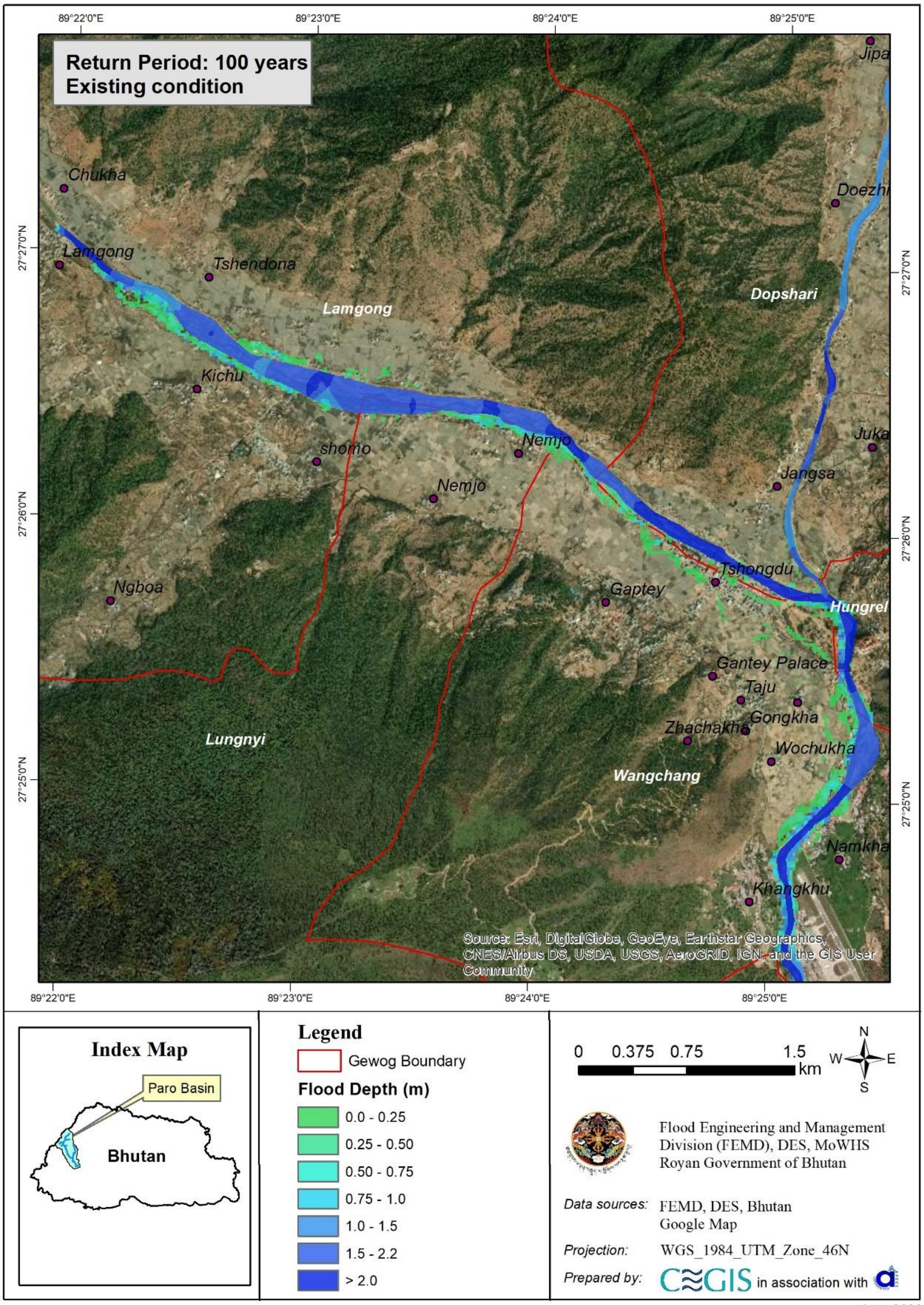
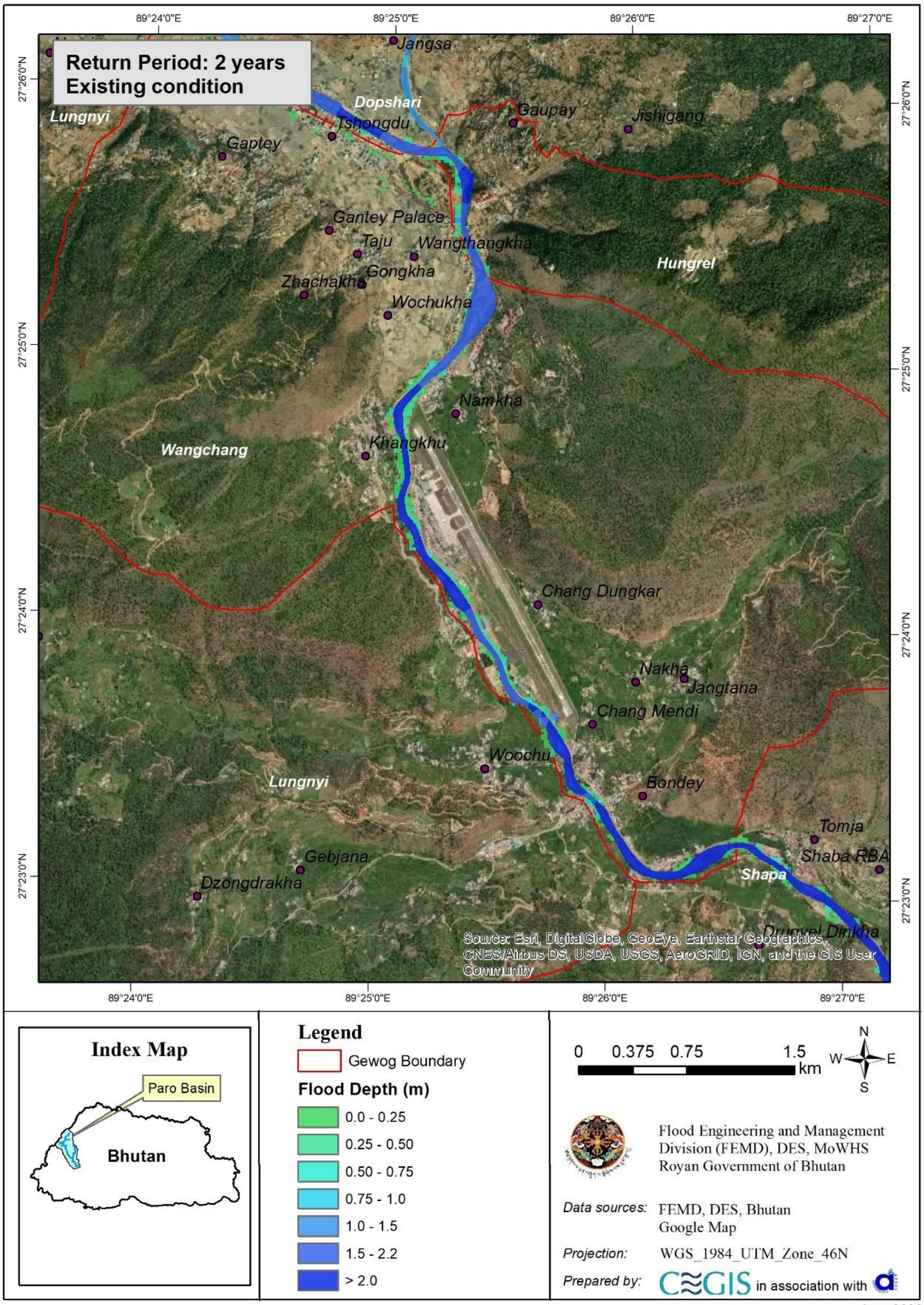


June 2020

Flood Depth and Extent Map for the Pa Chu (Hungrel - Shapa Gewog)



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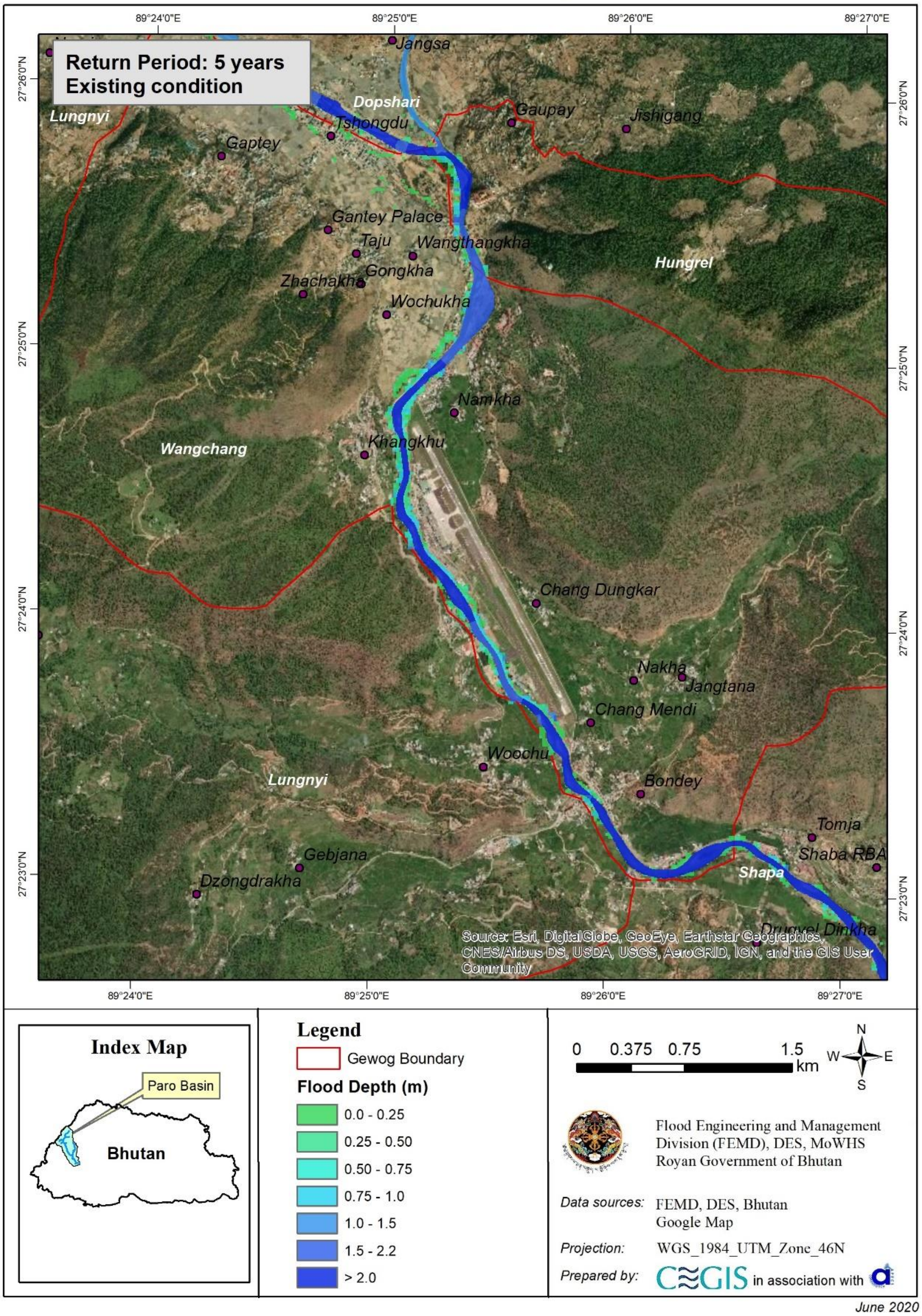

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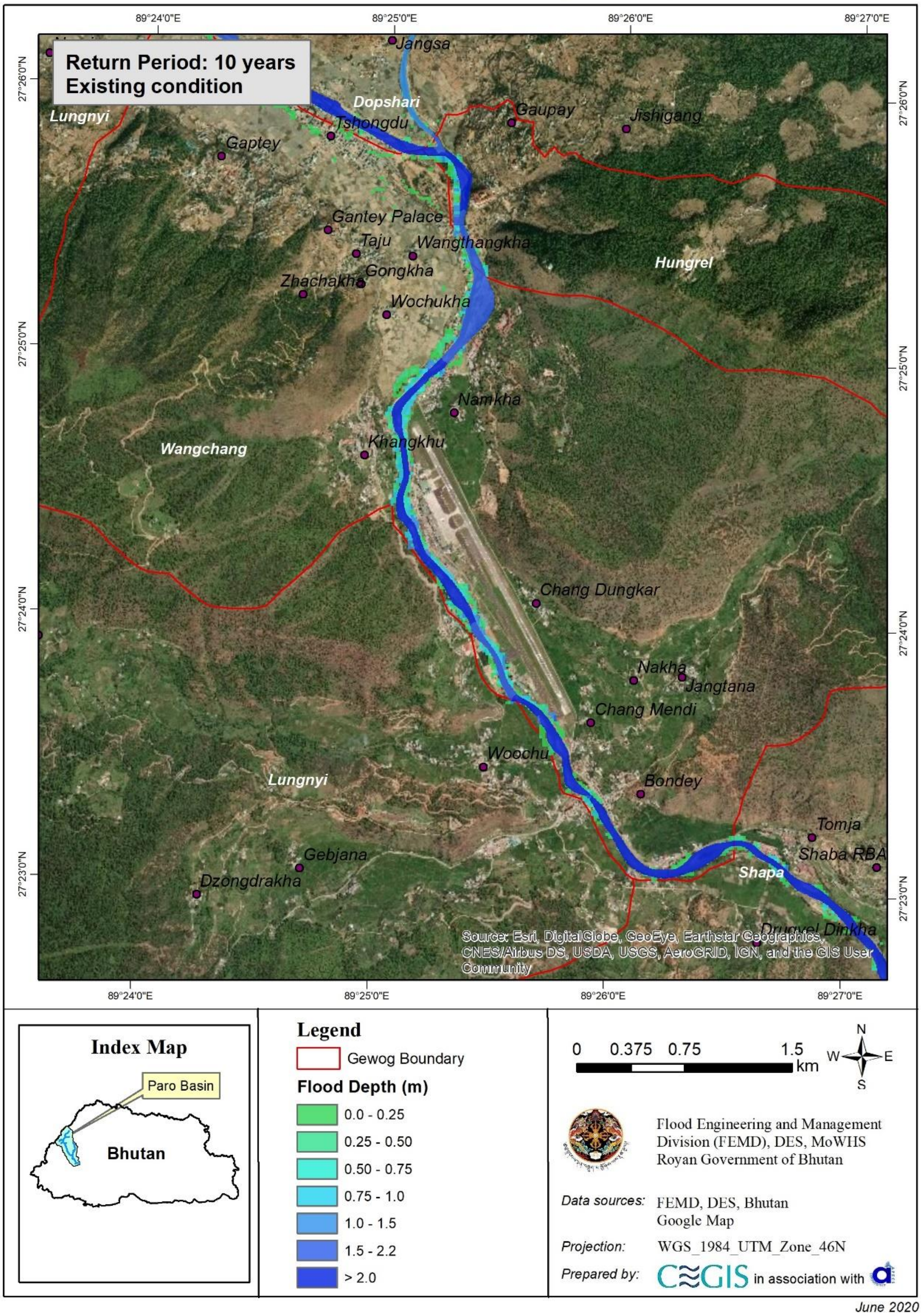

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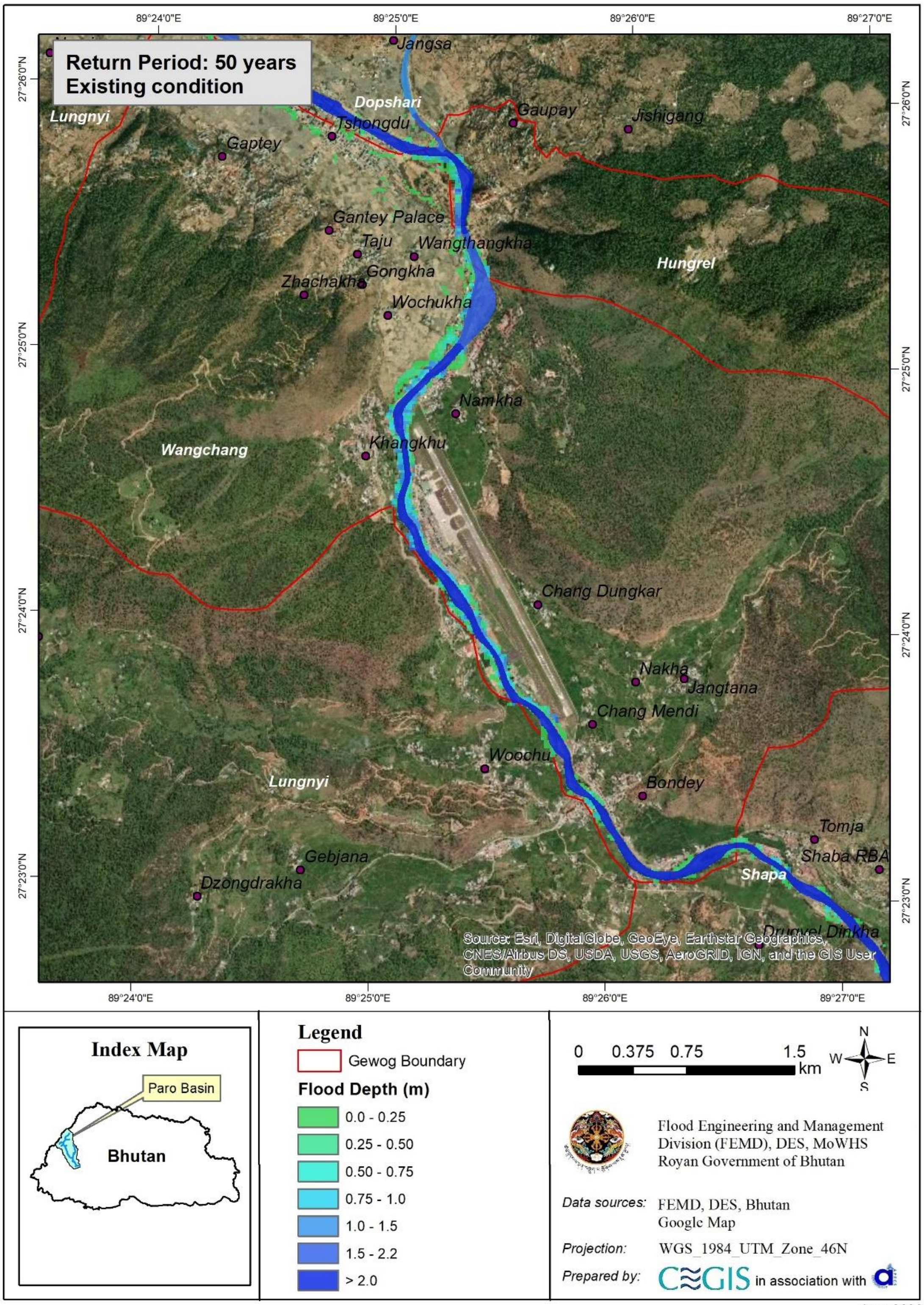

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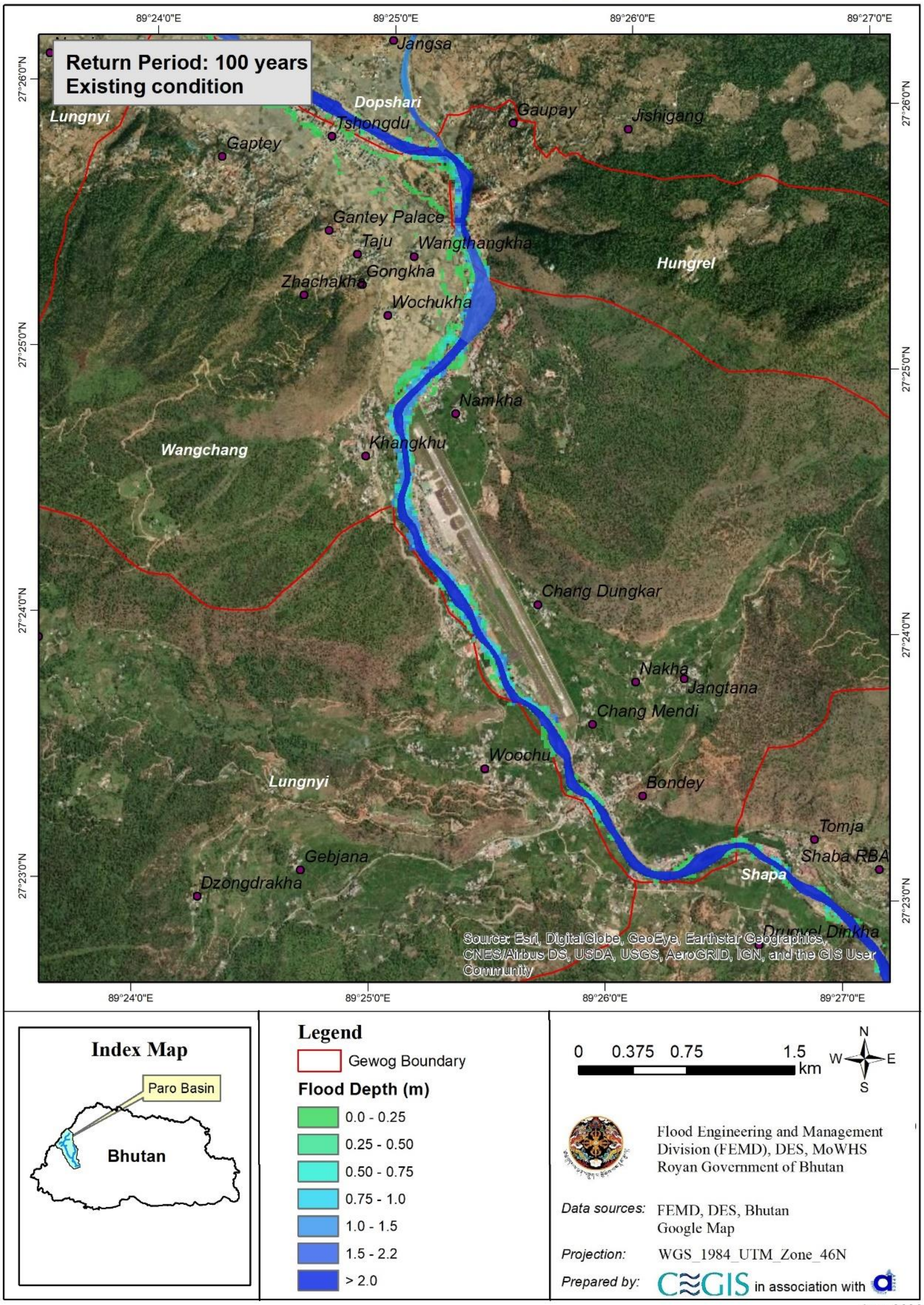

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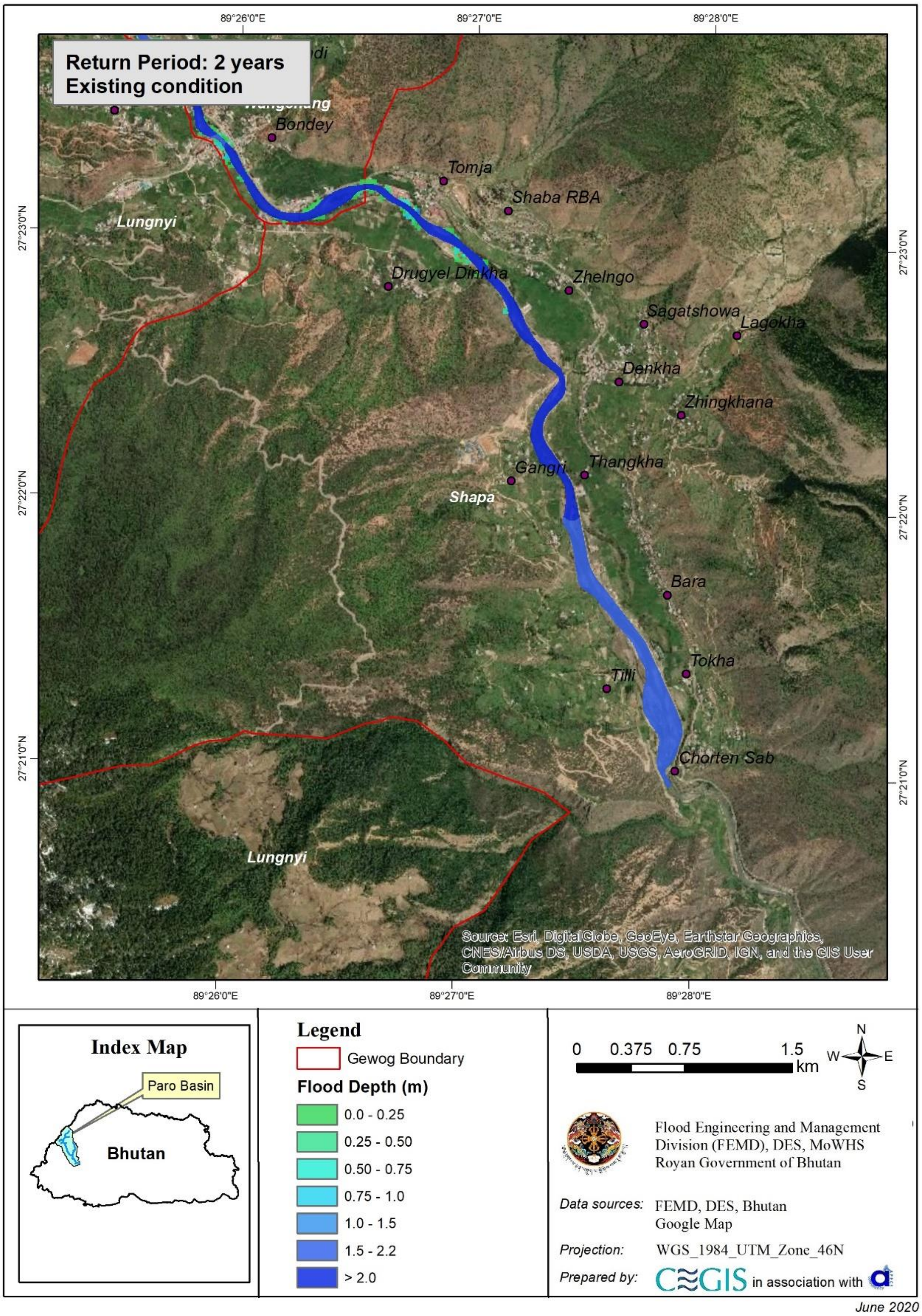
Flood Depth and Extent Map for the Pa Chu (Shapa Gewog)



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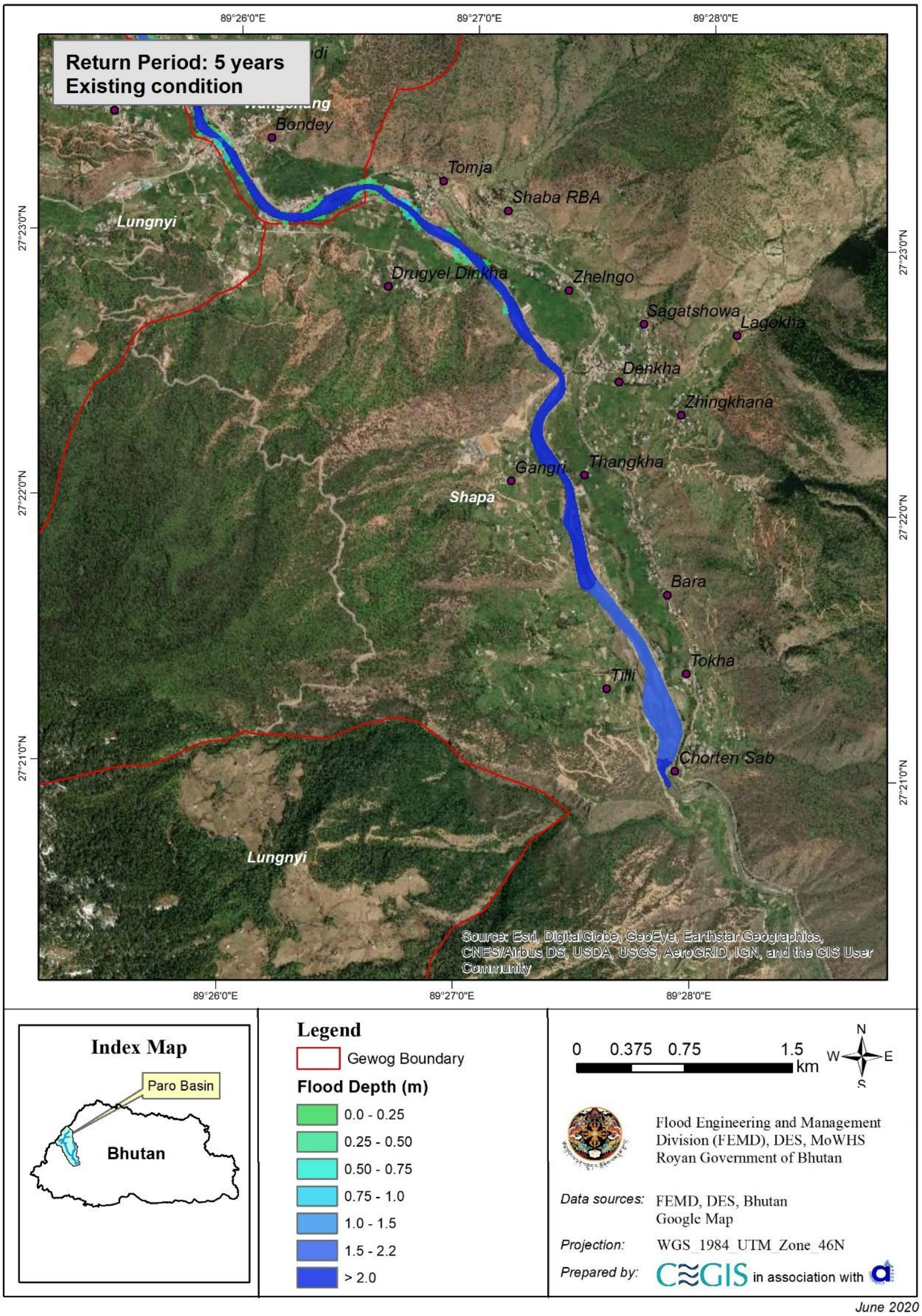

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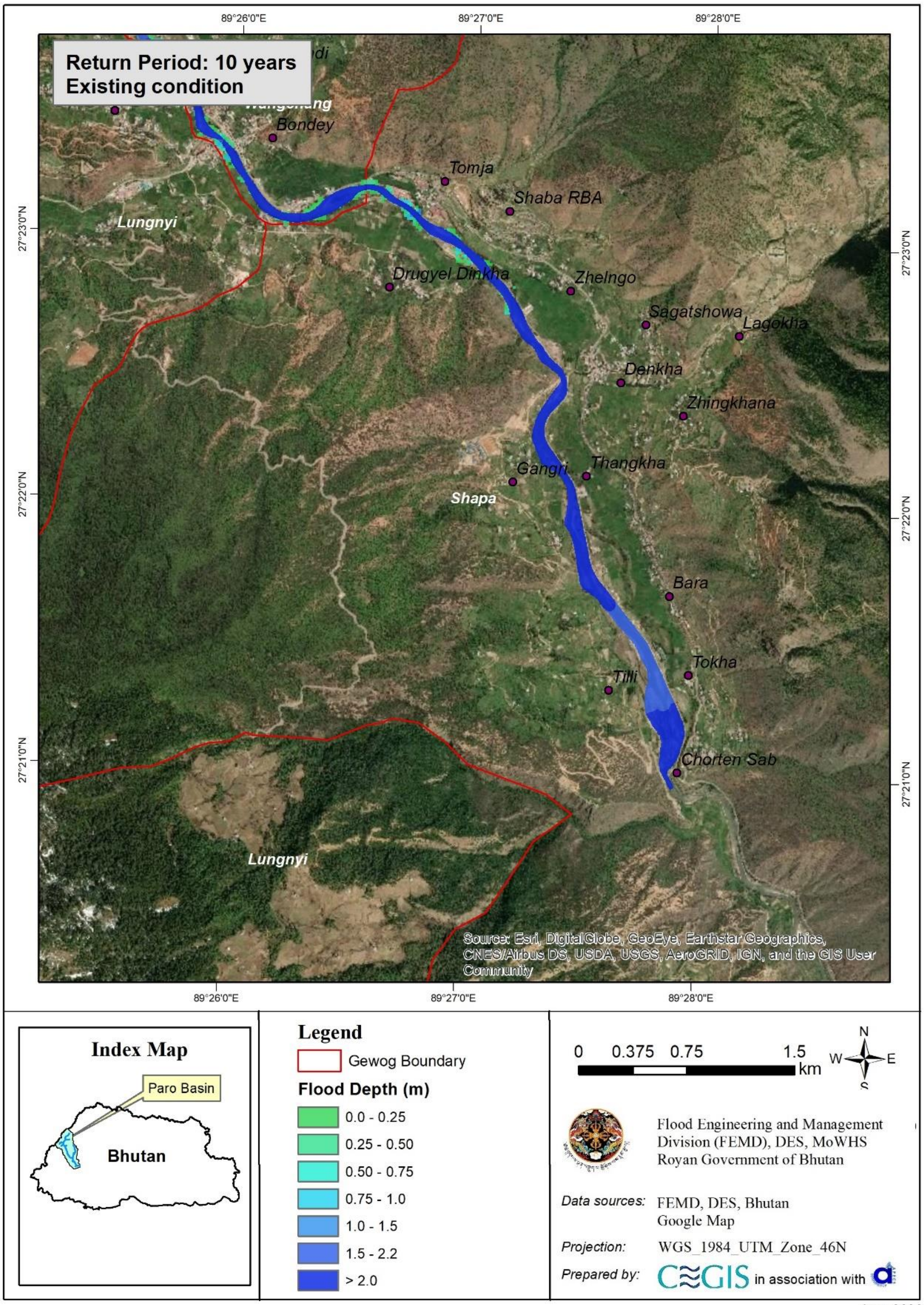

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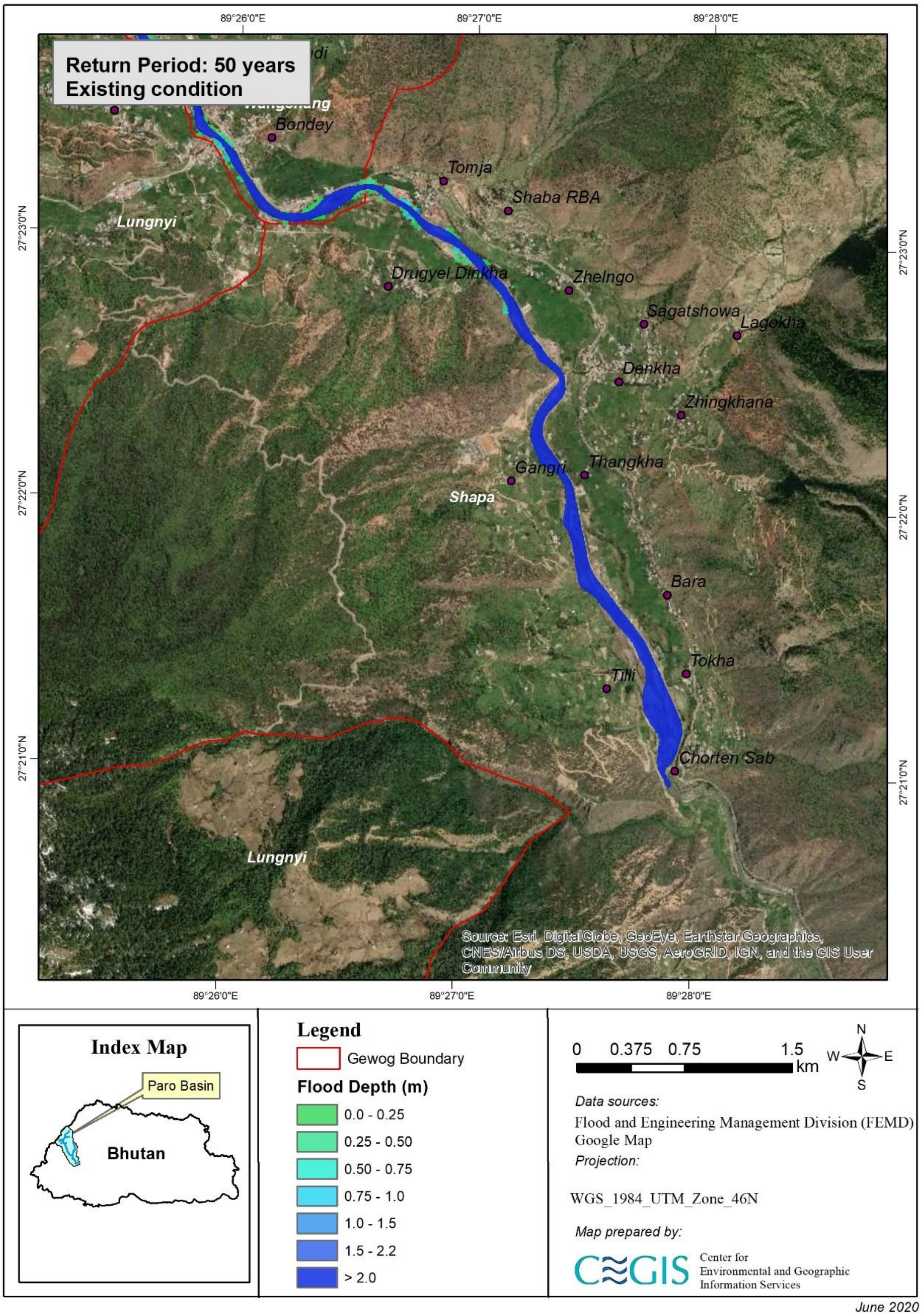

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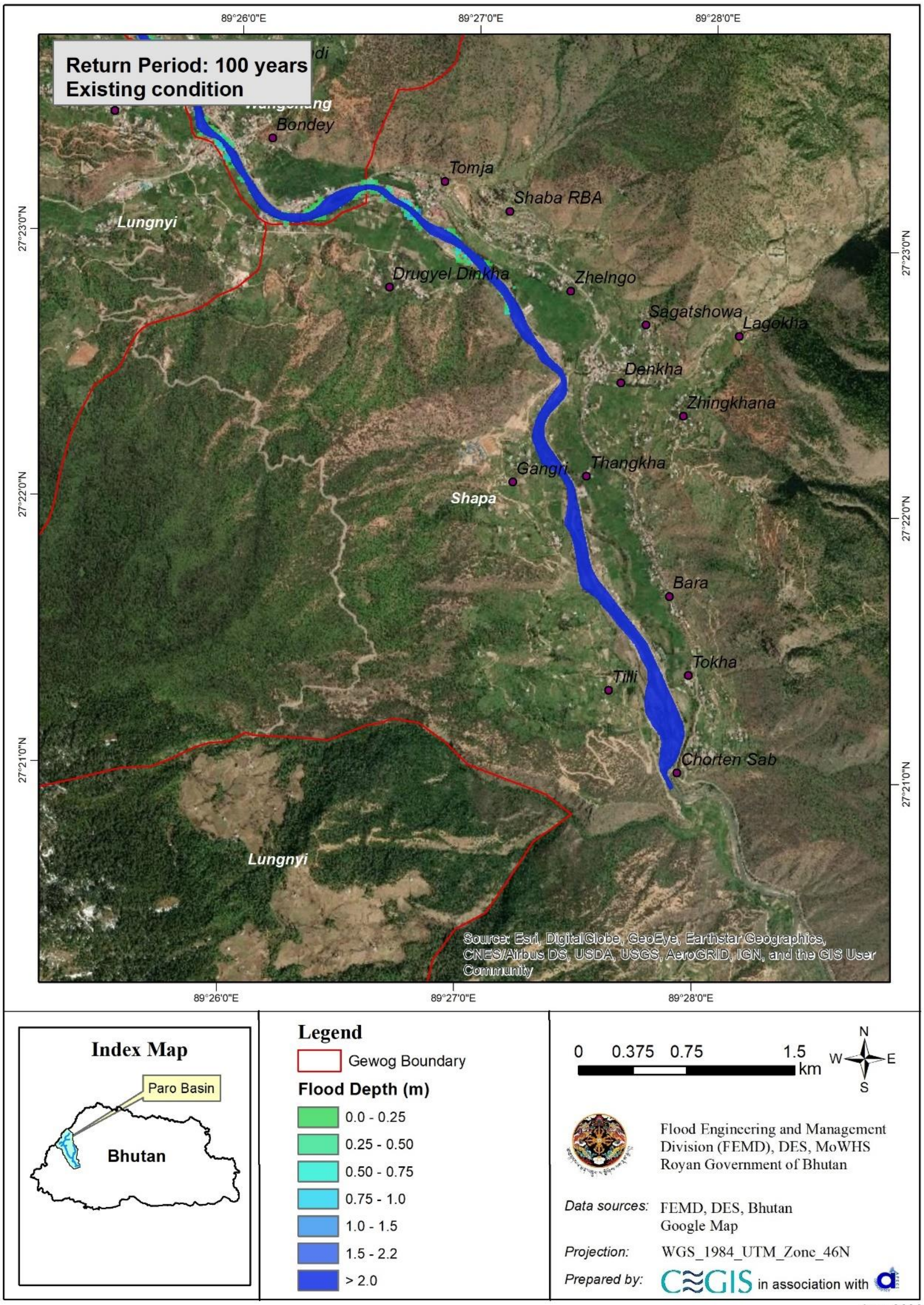
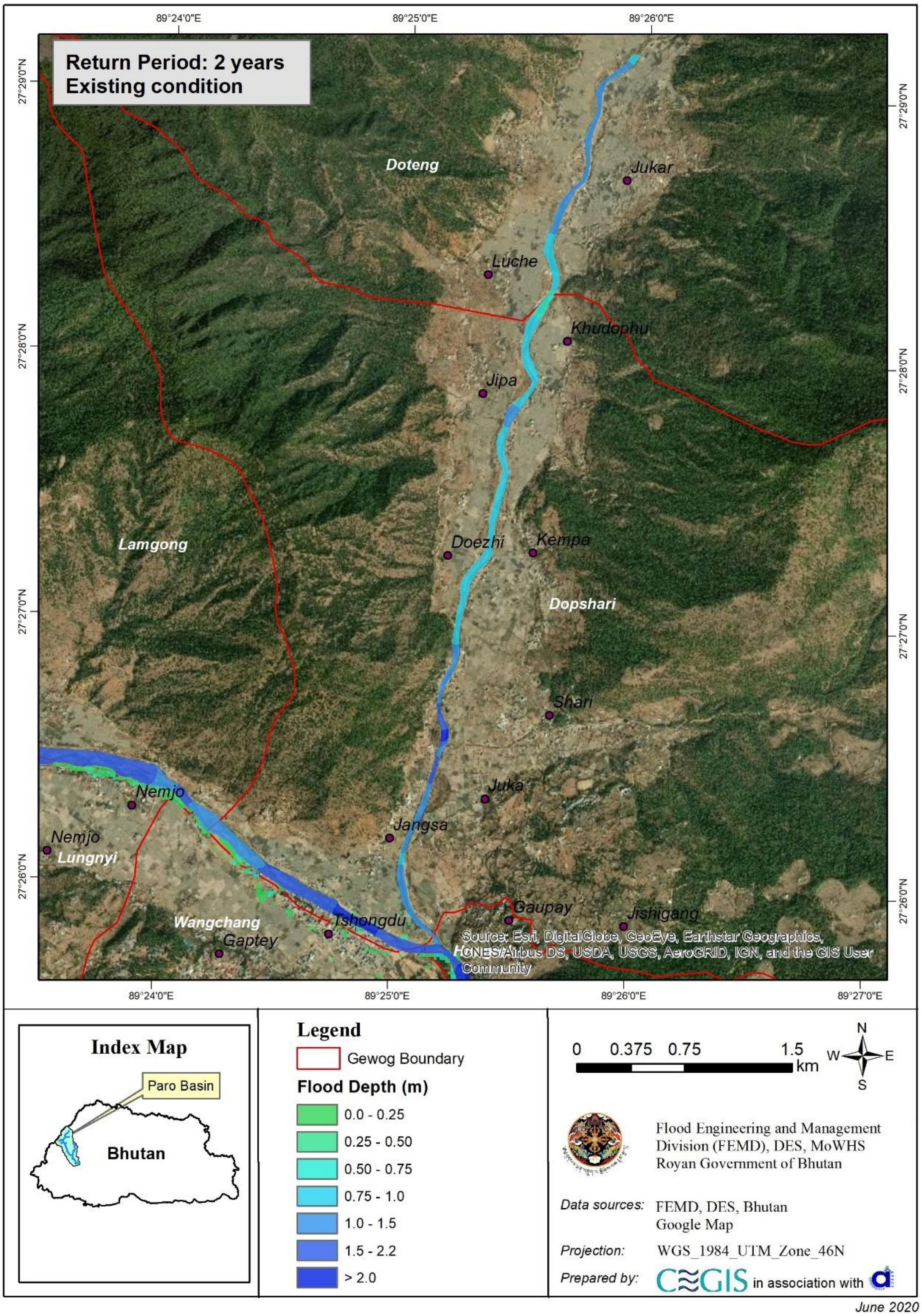
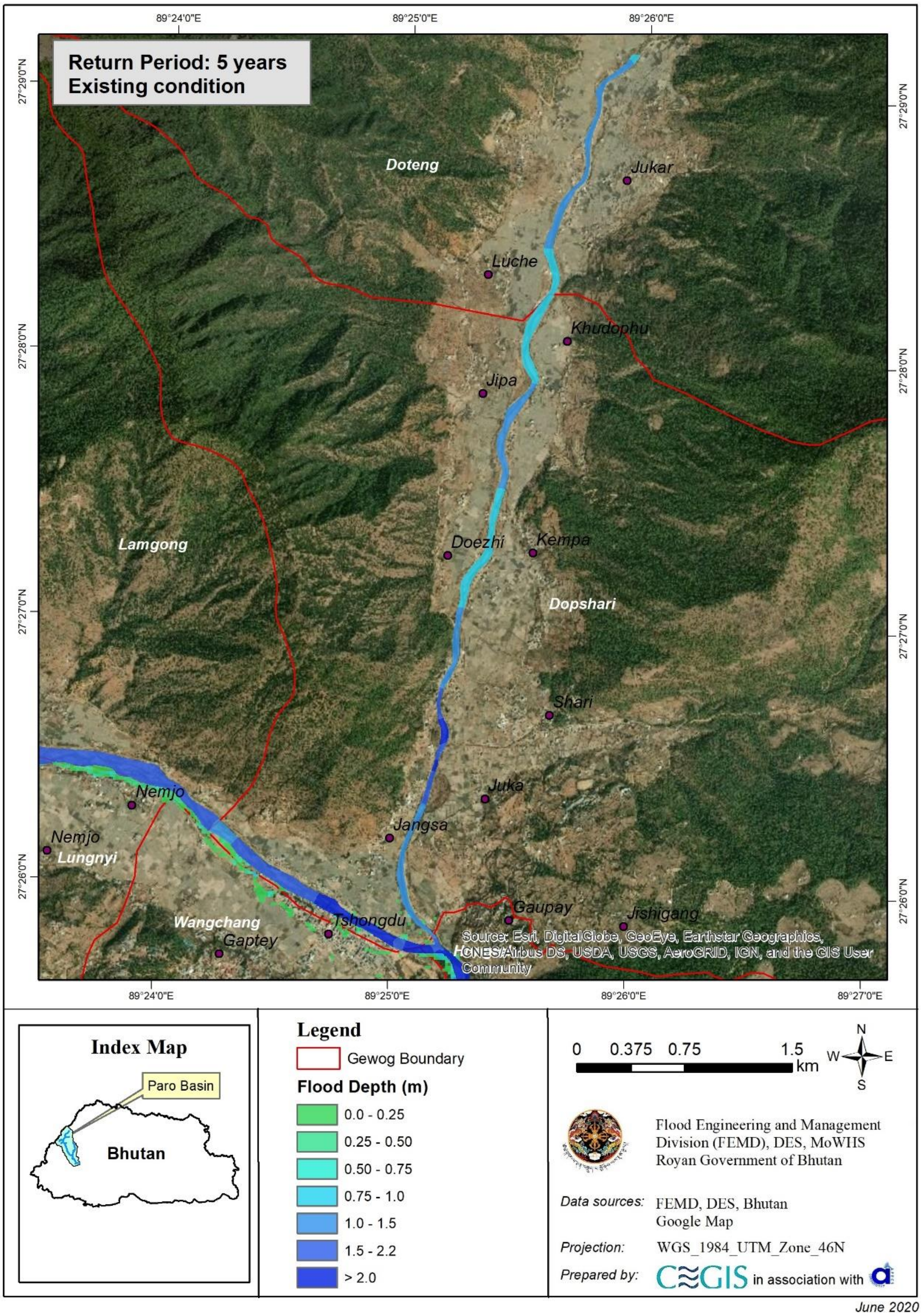


June 2020

Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



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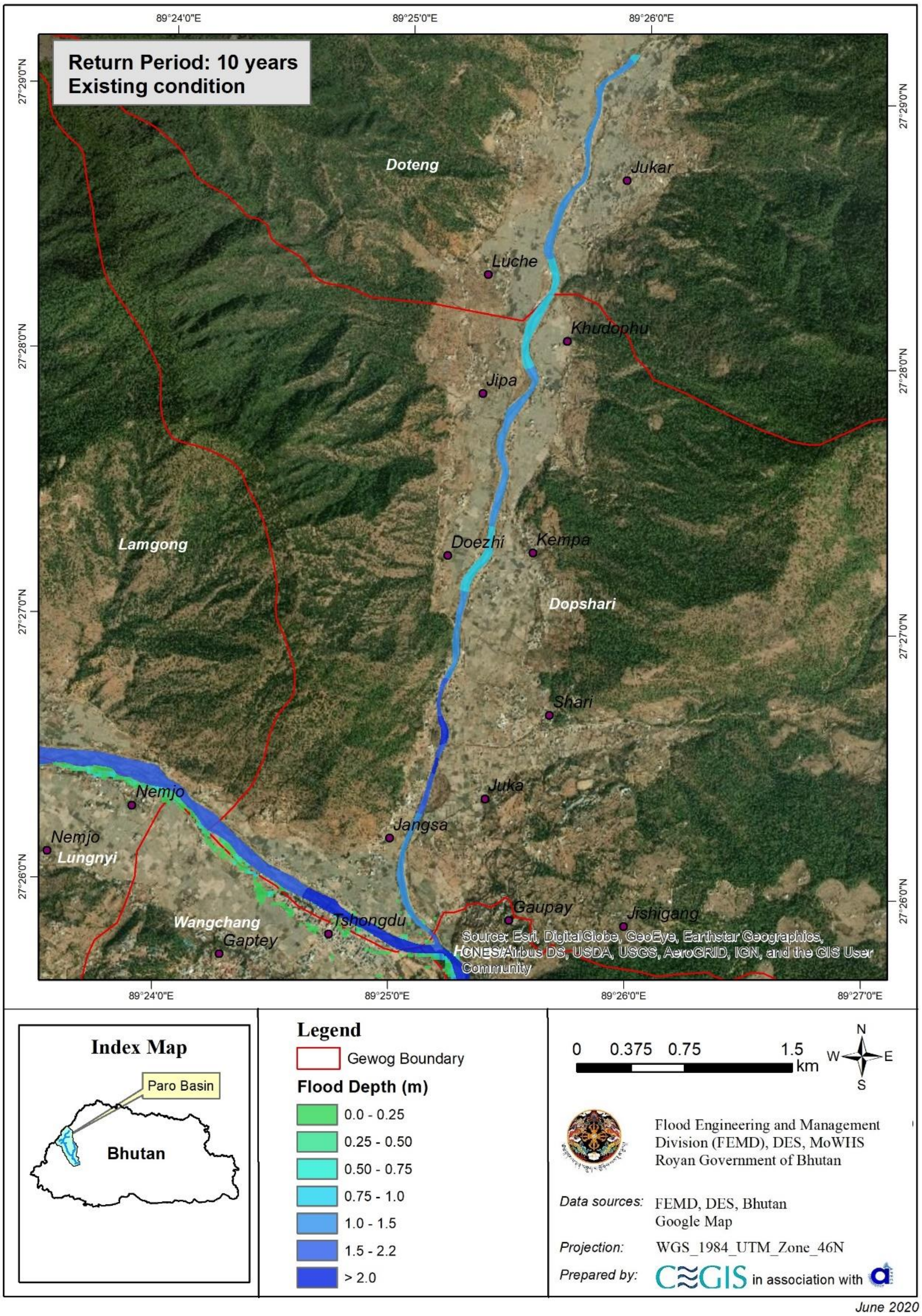

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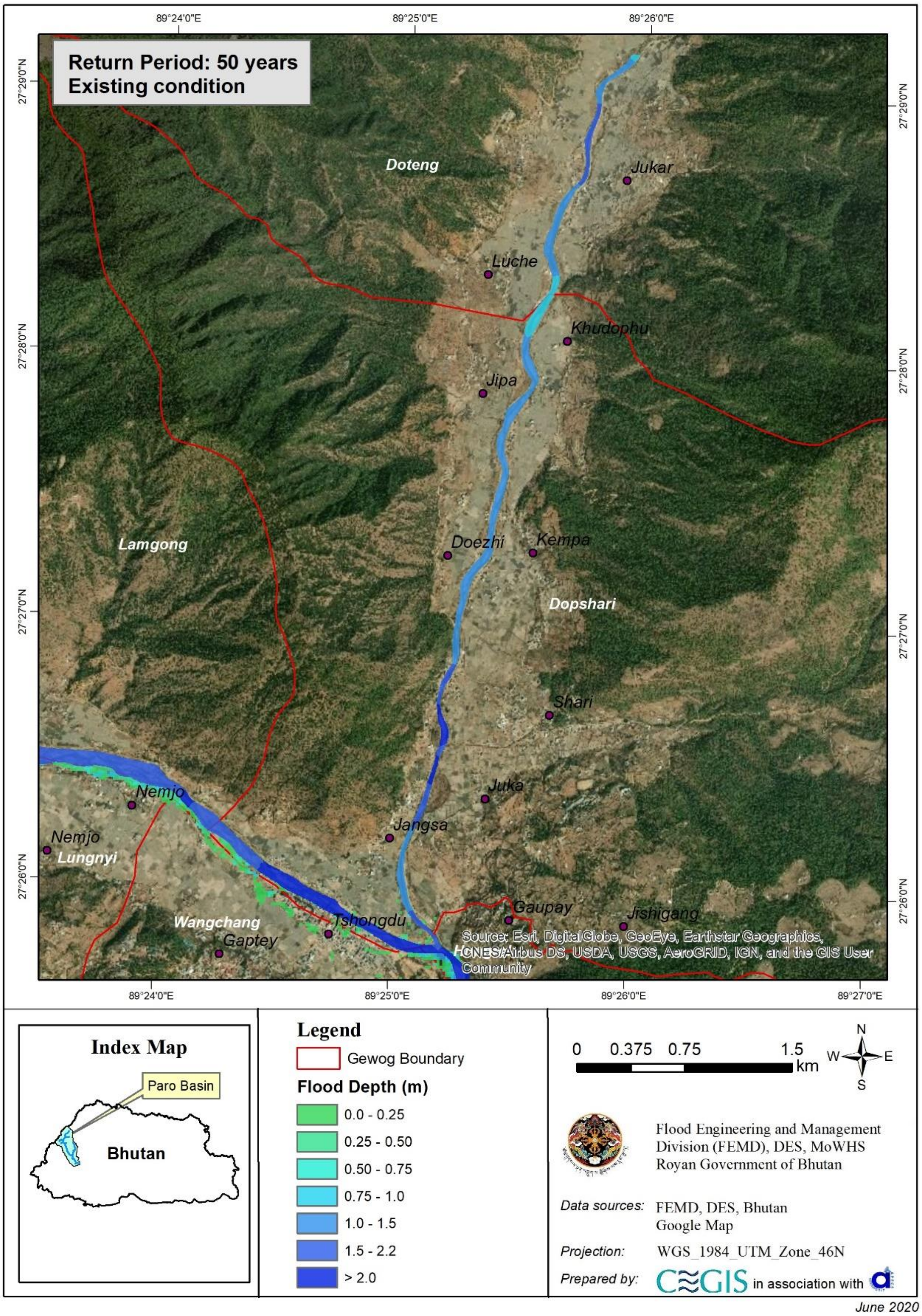

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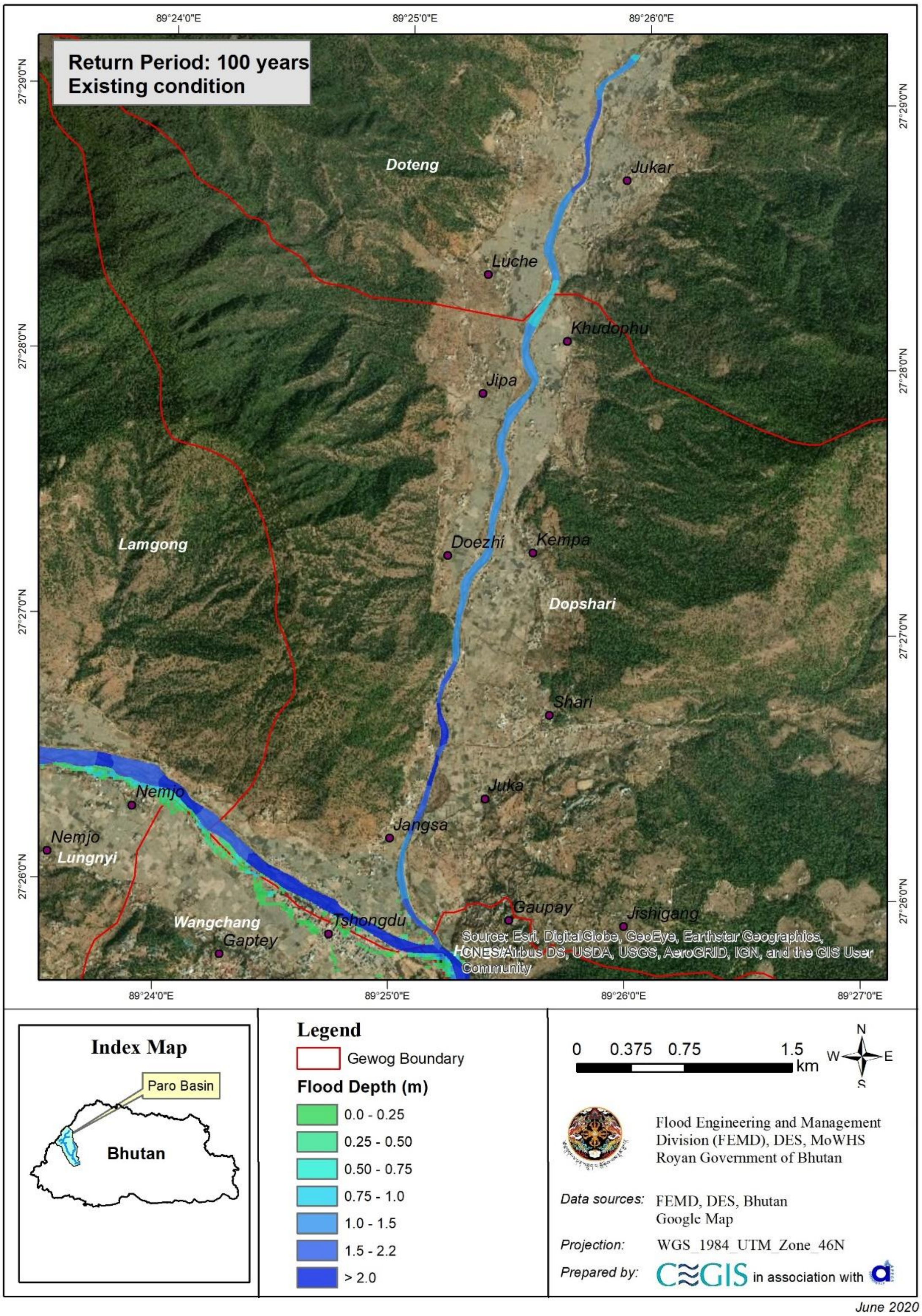
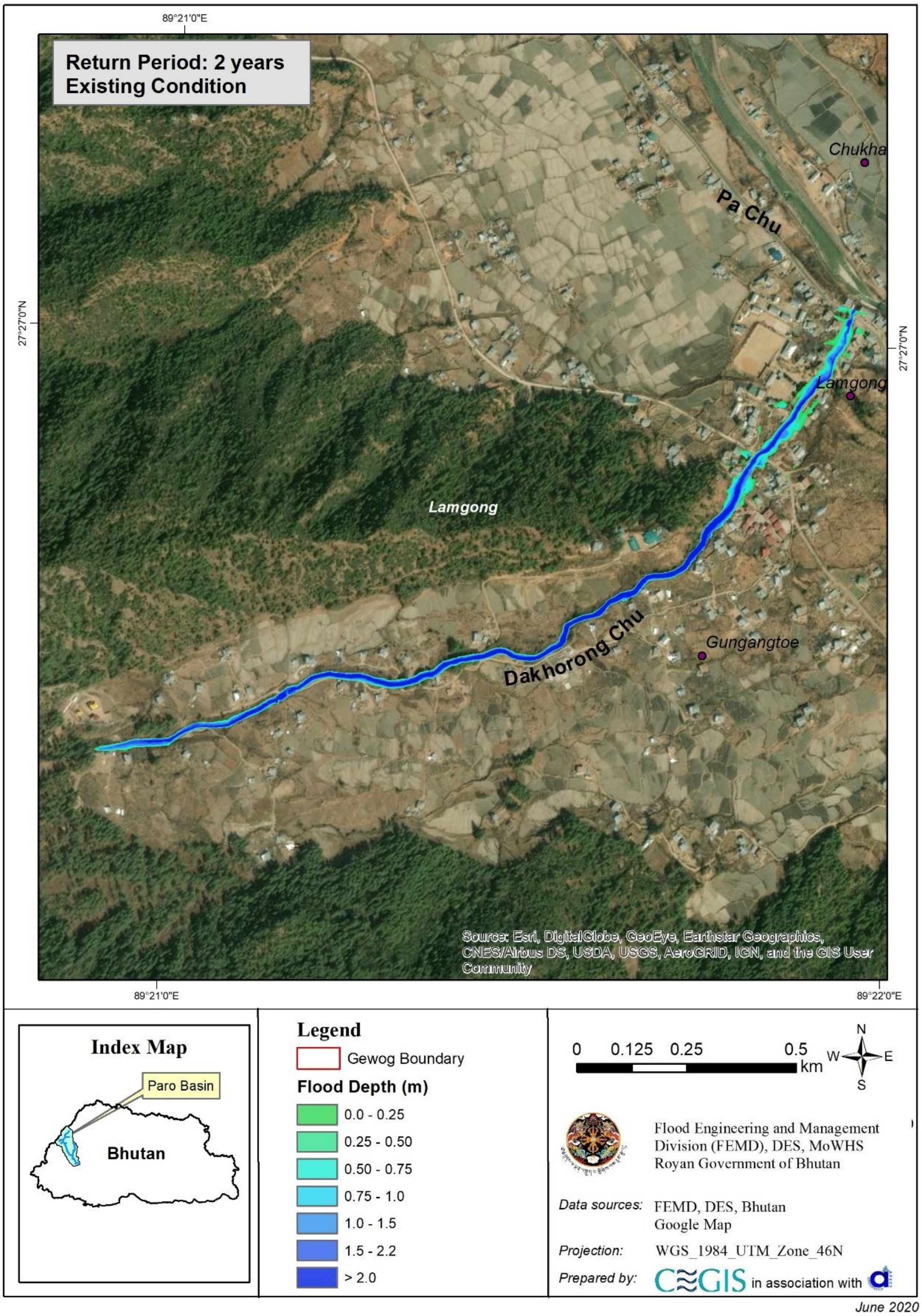
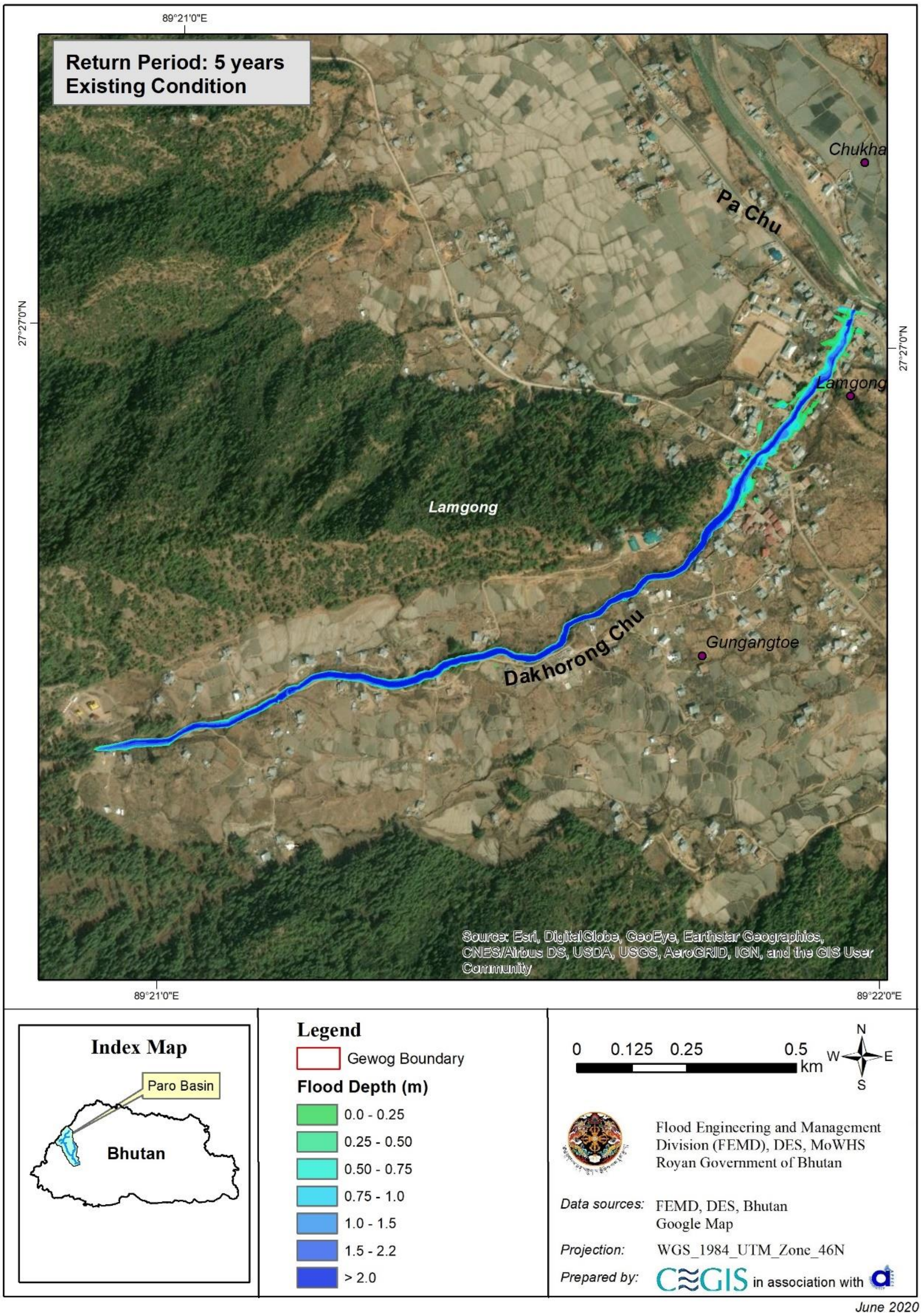


Flood Depth and Extent Map for Dakhorong Chu



Flood Depth and Extent Map for Dakhorong Chu



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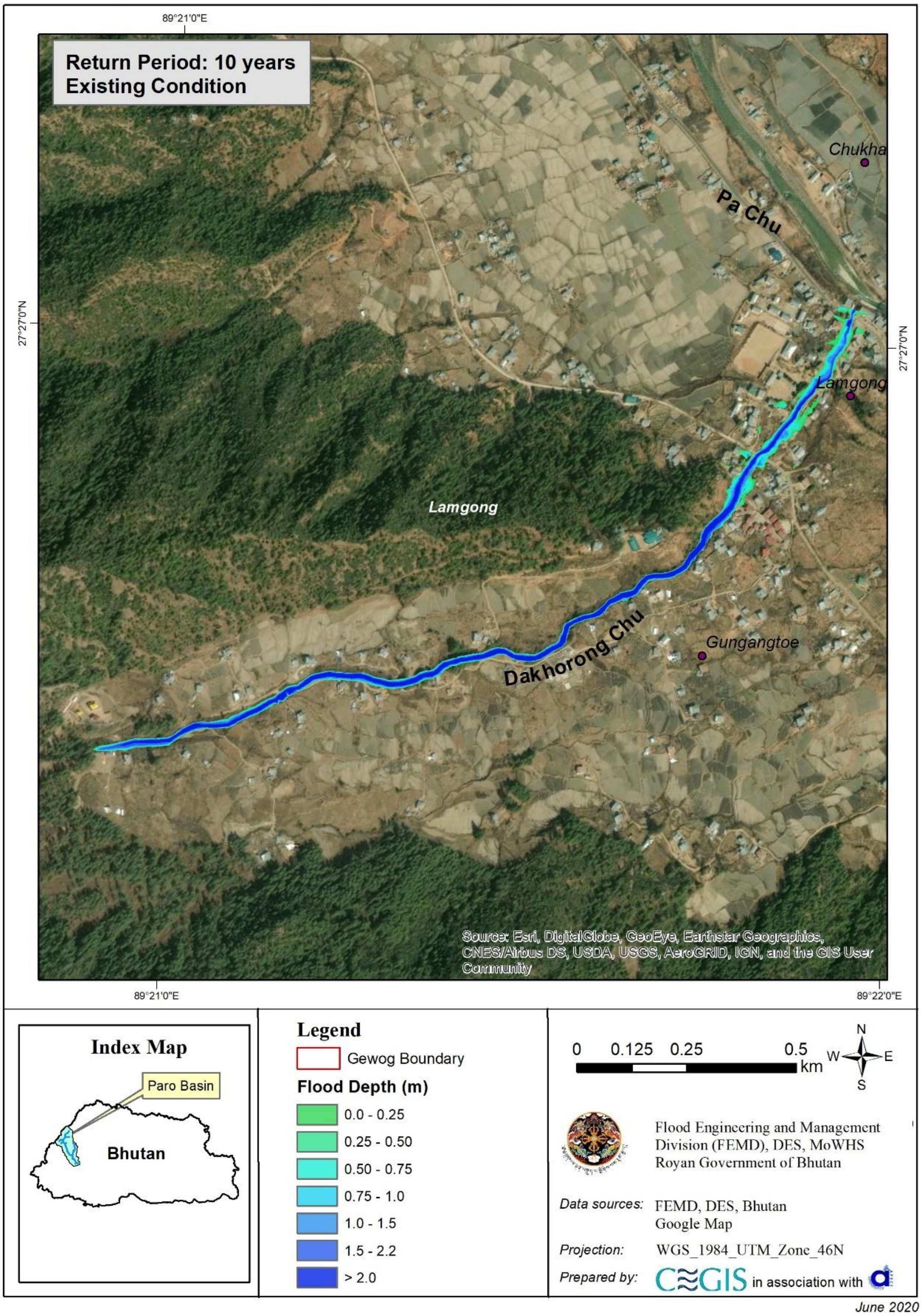
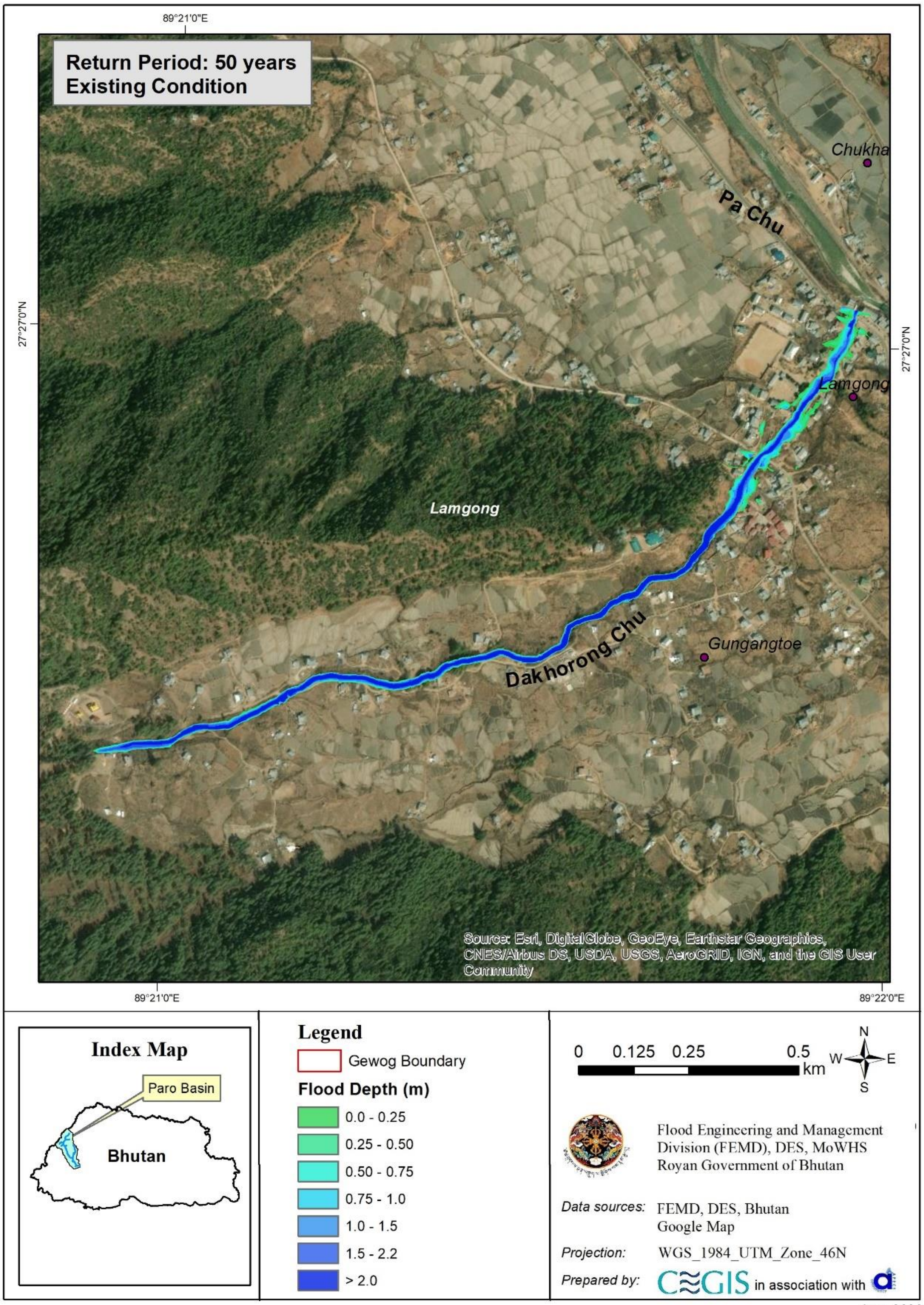


Flood Depth and Extent Map for Dakhorong Chu



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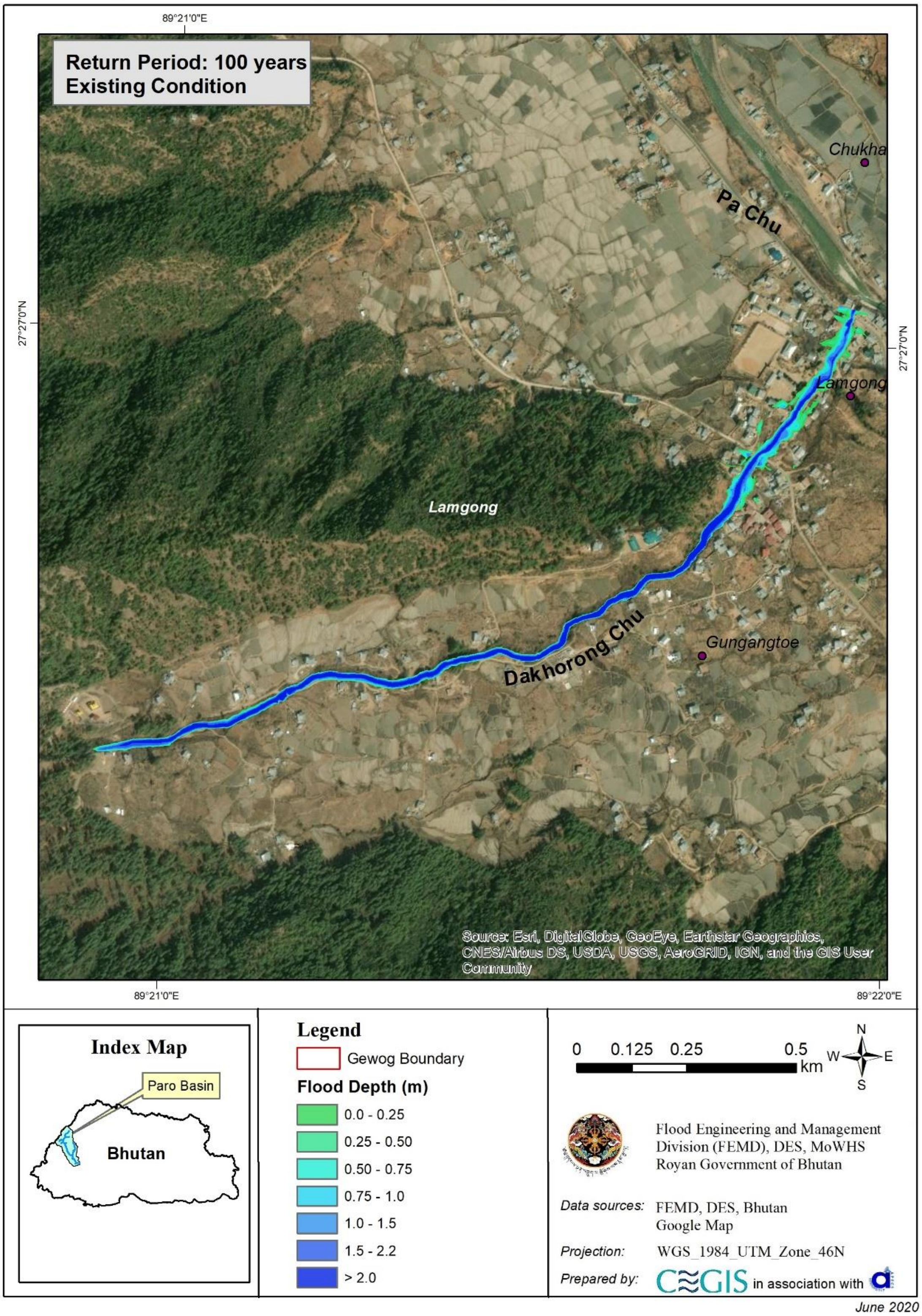

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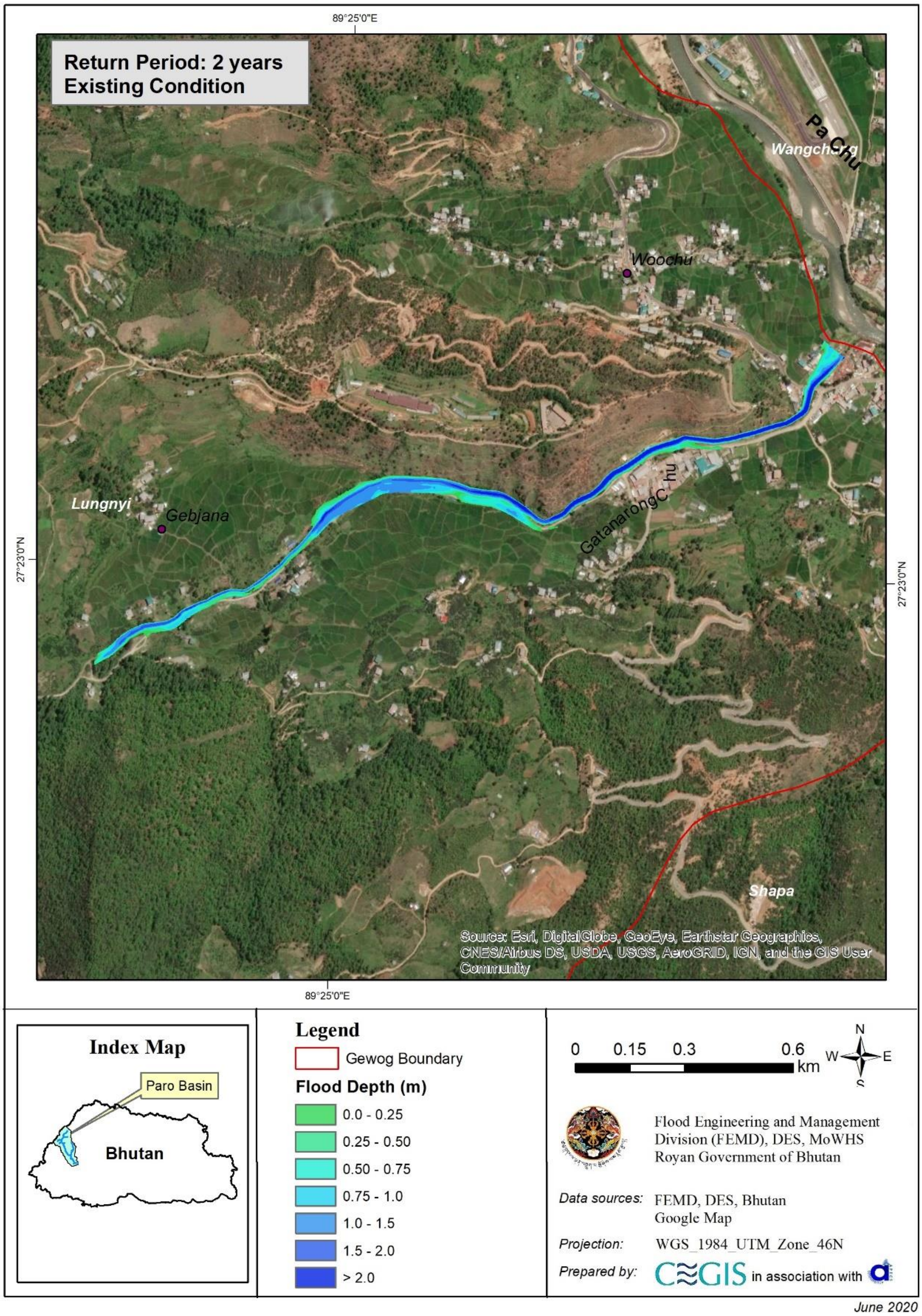

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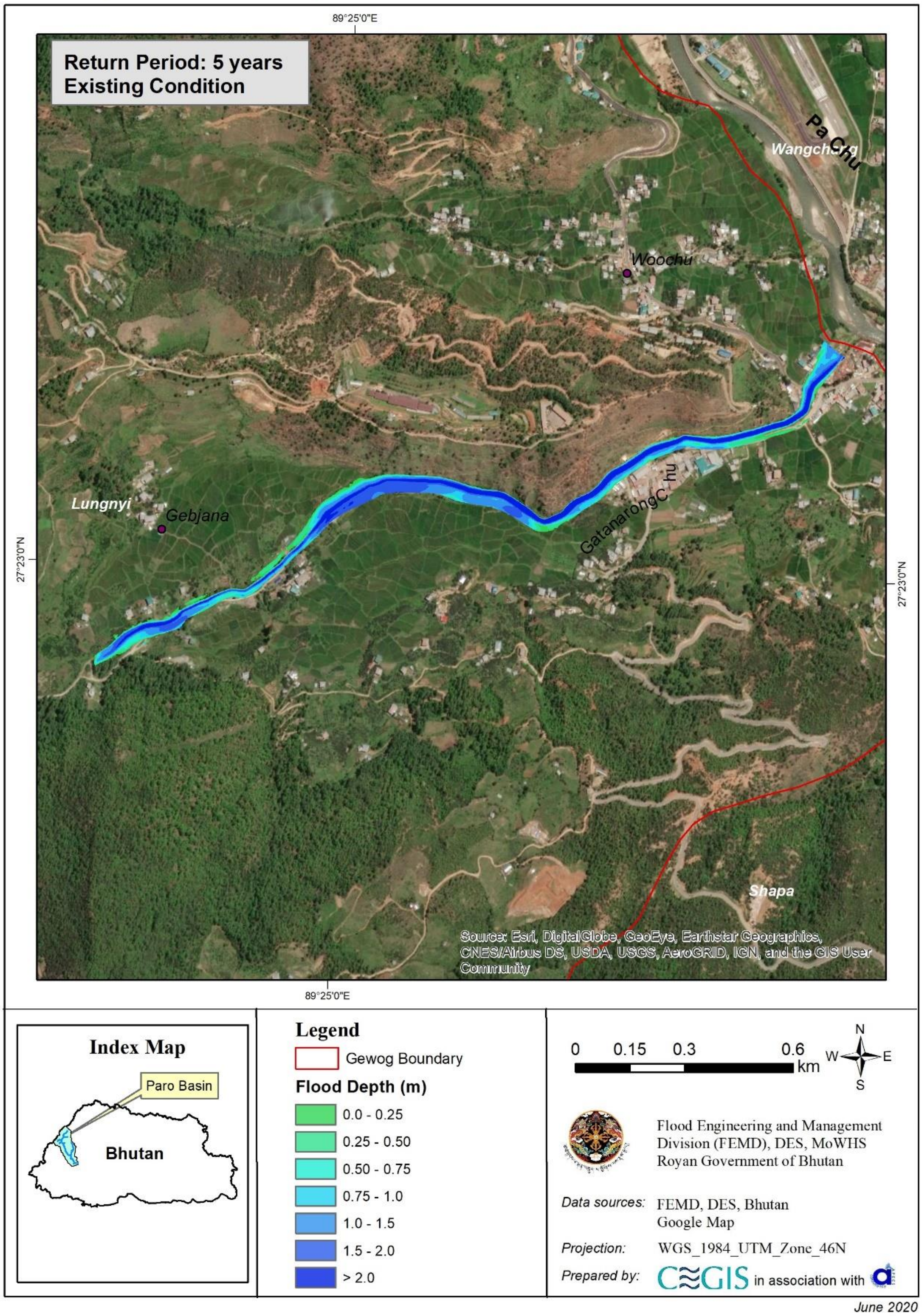

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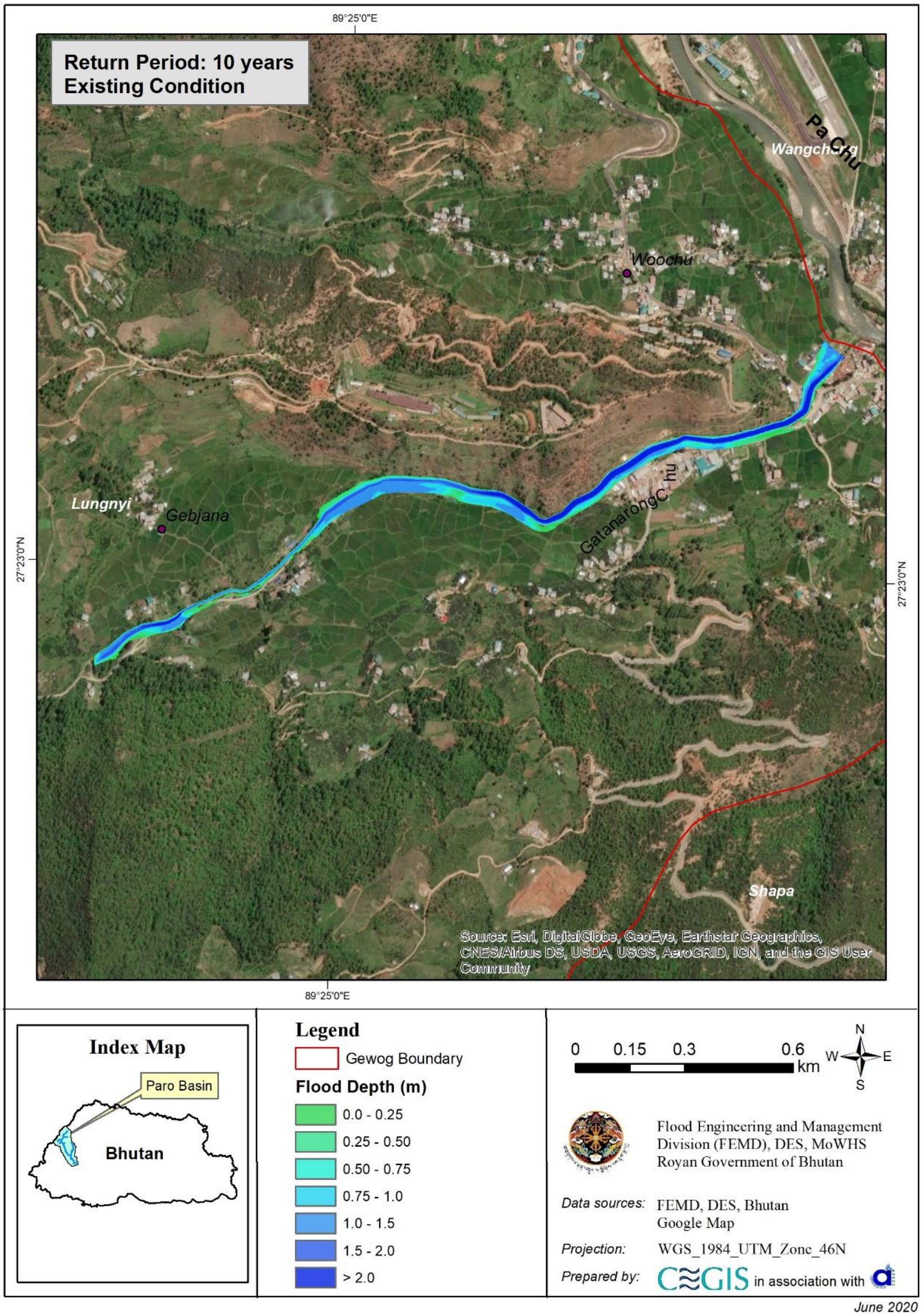

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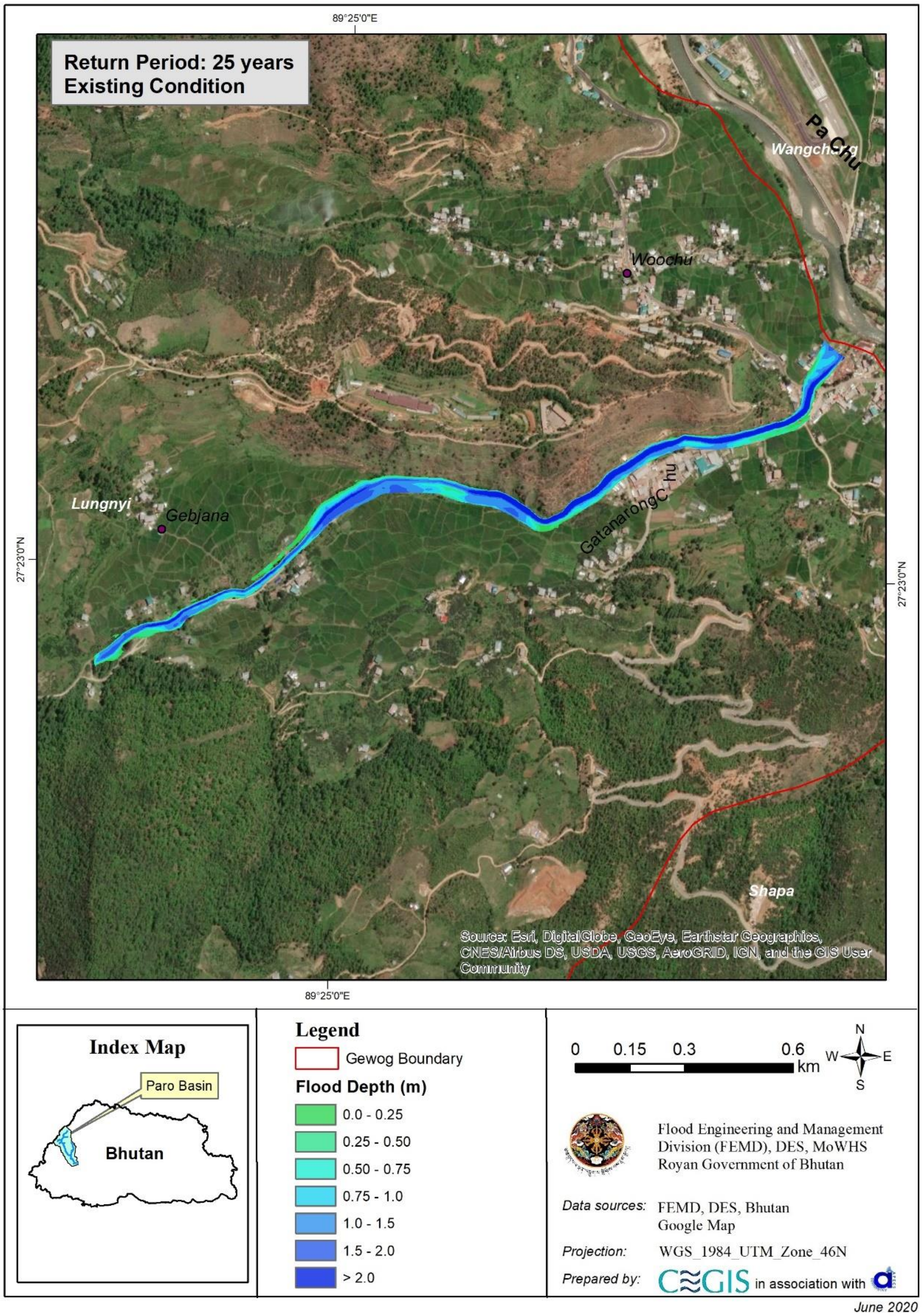

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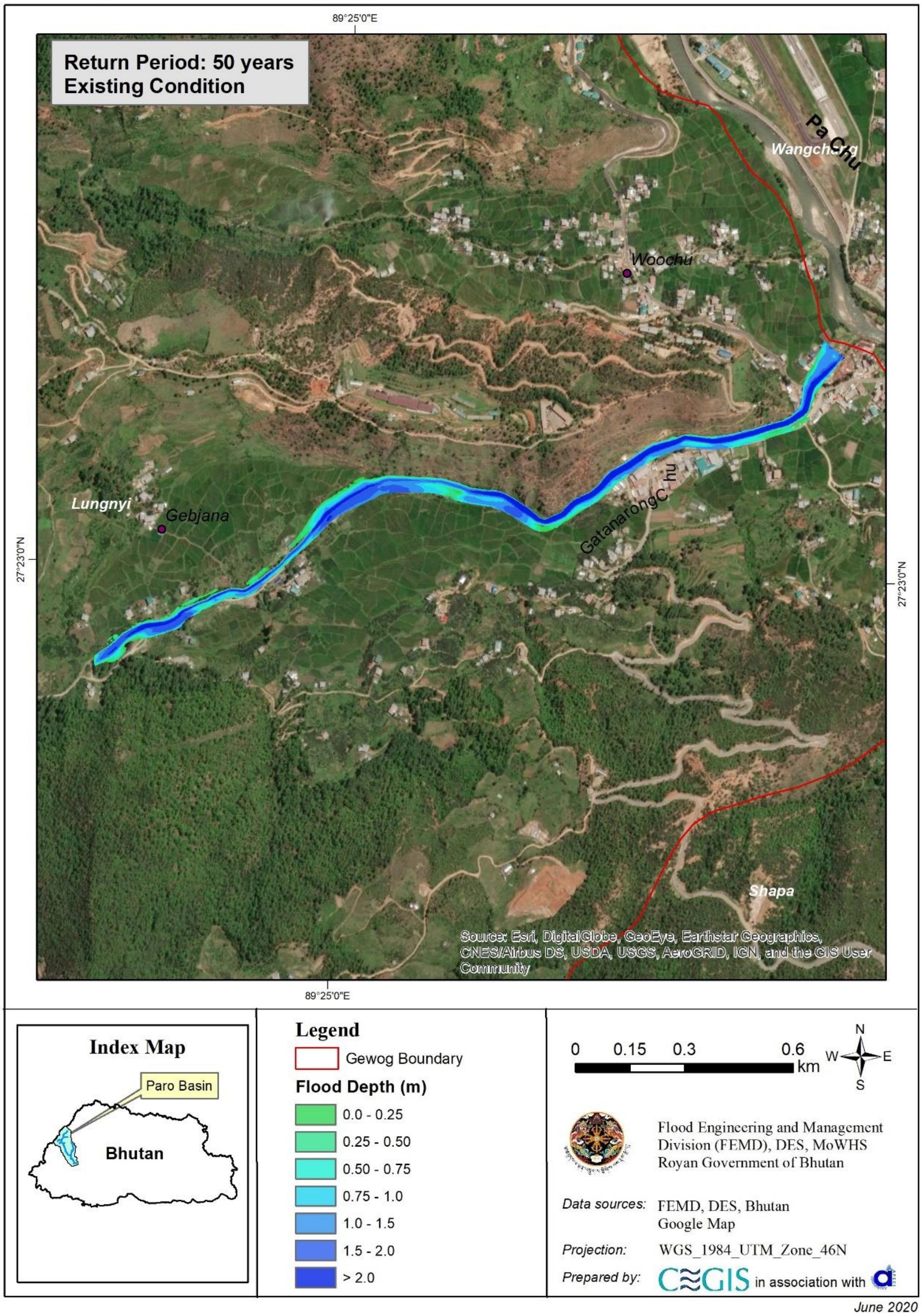

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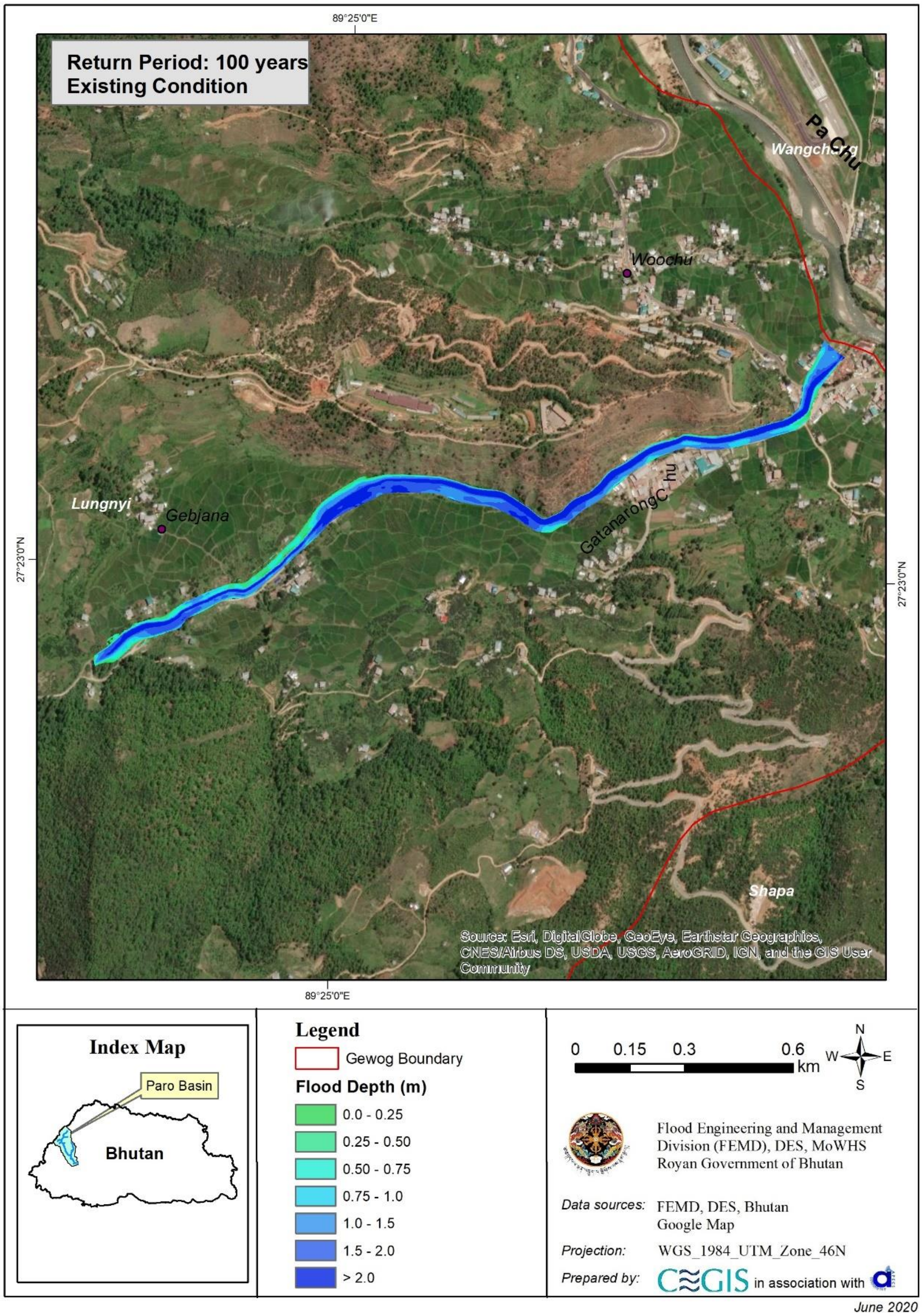
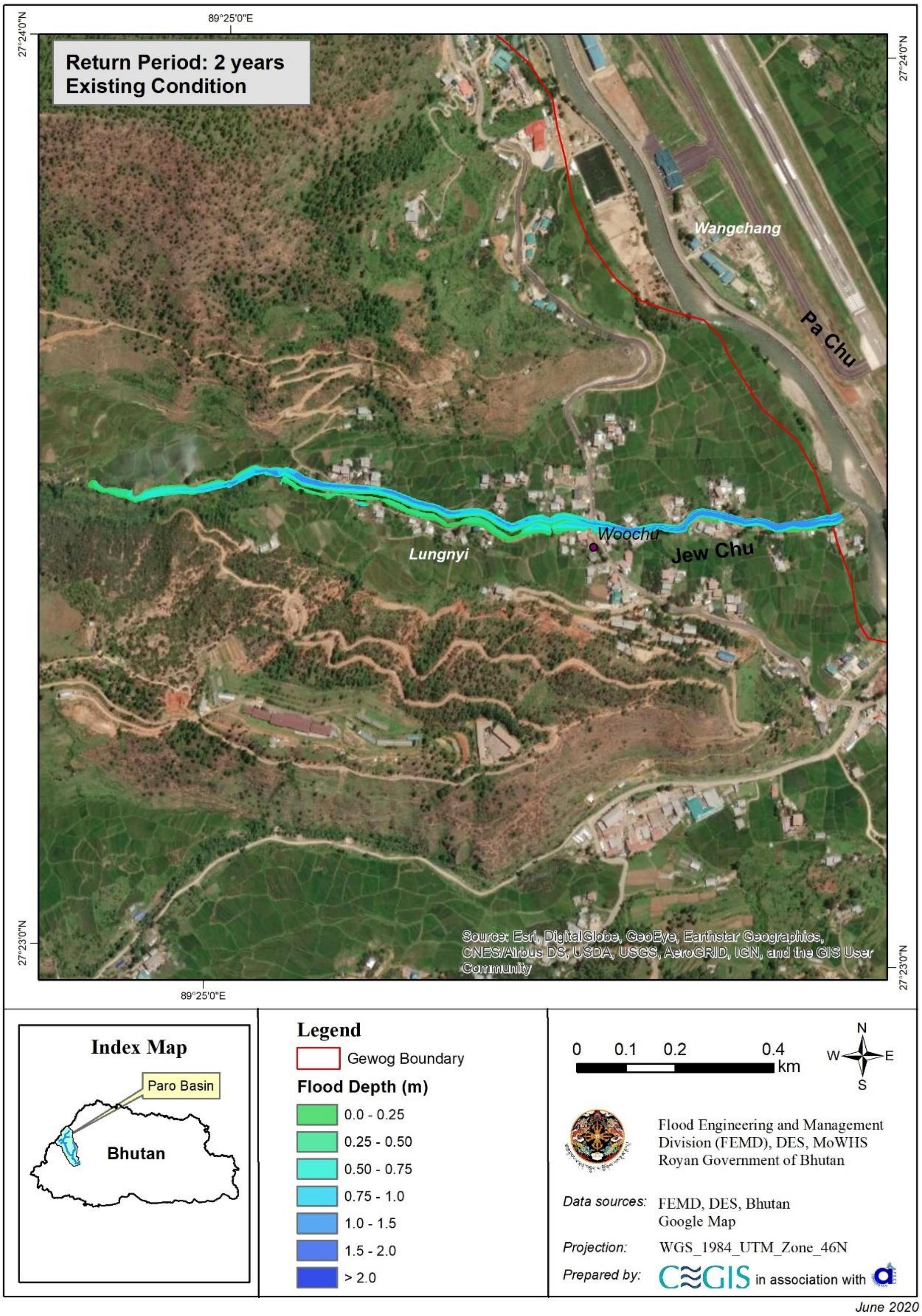
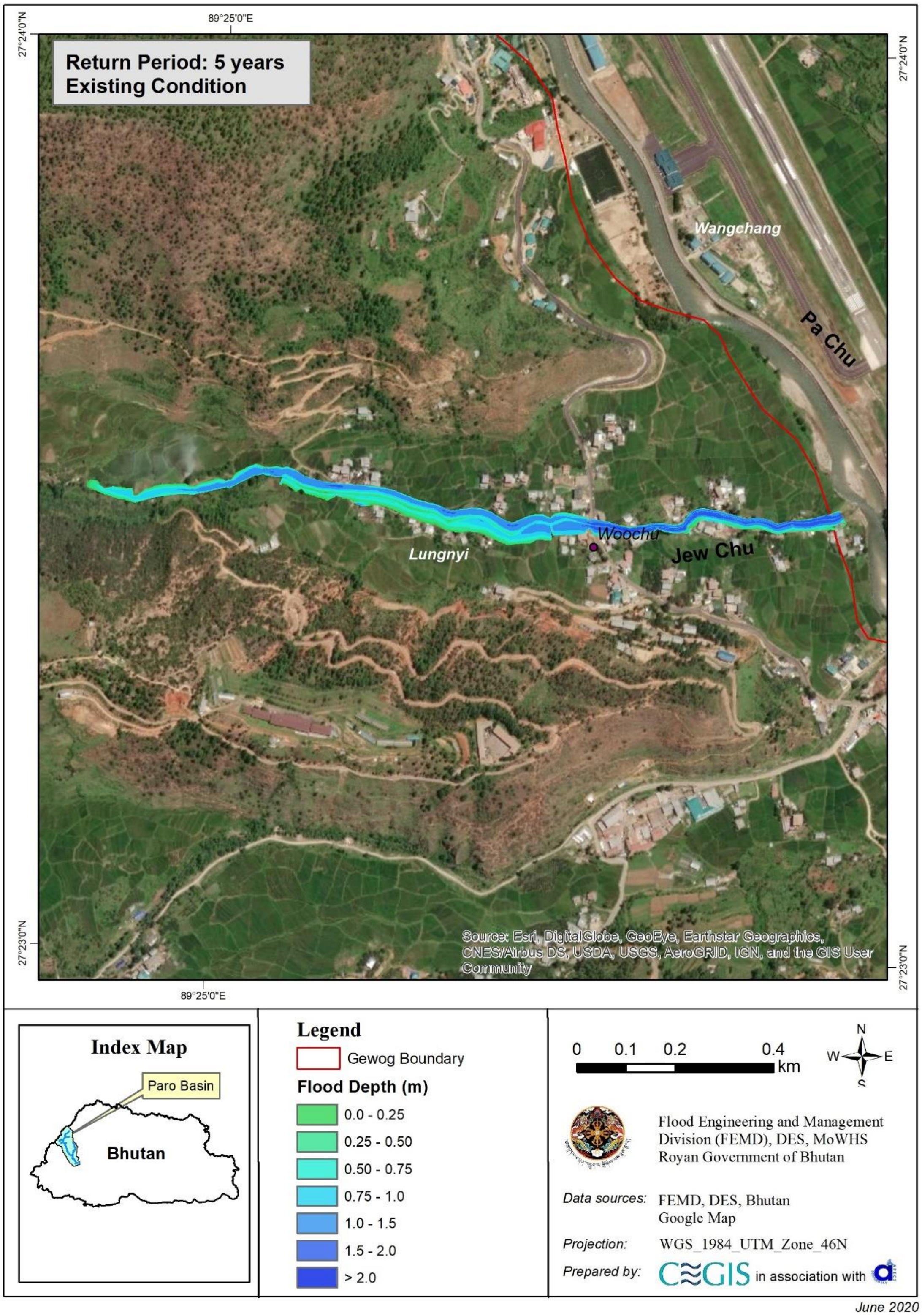


Flood Depth and Extent Map for Jew Chu



Flood Depth and Extent Map for Jew Chu



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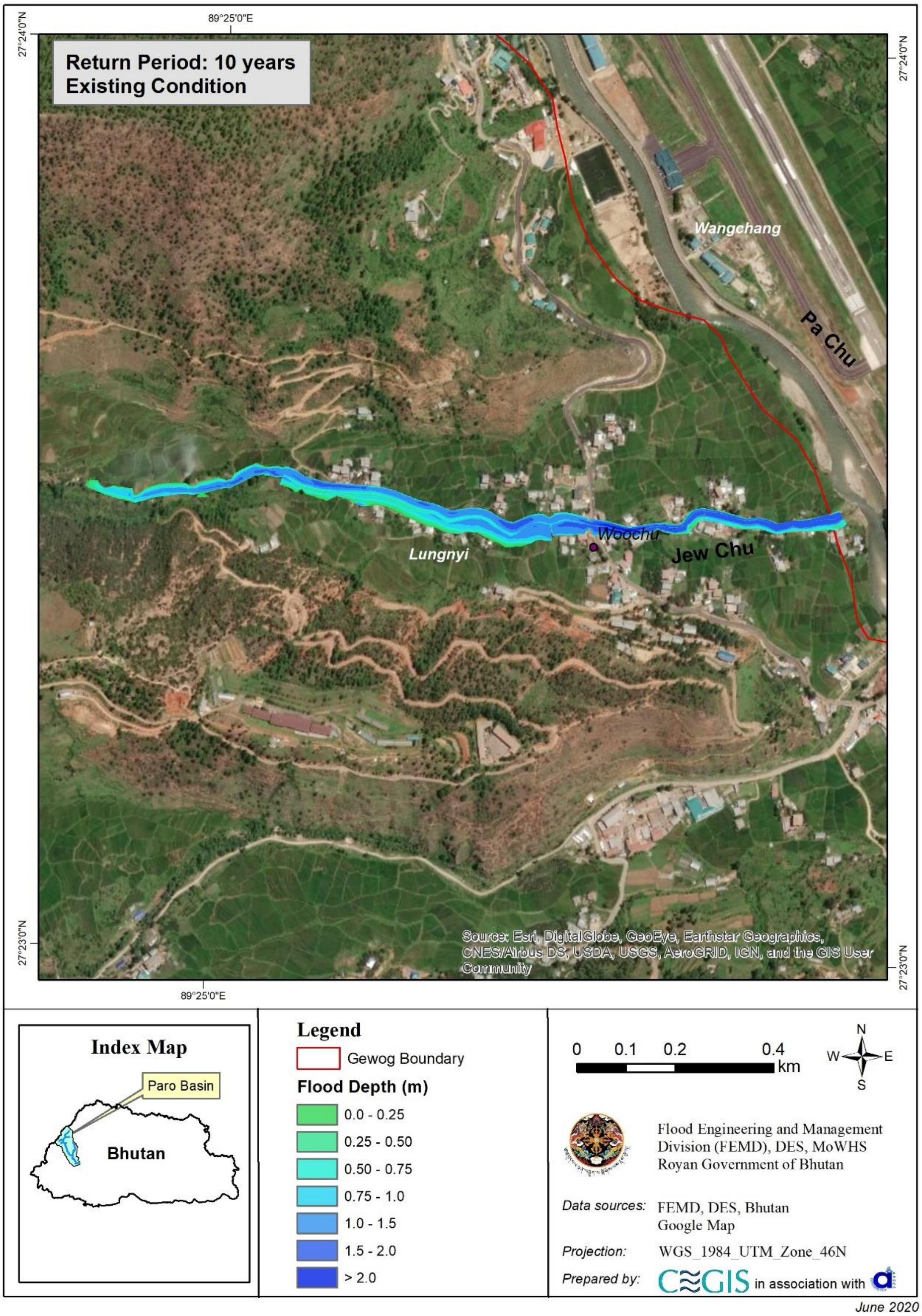

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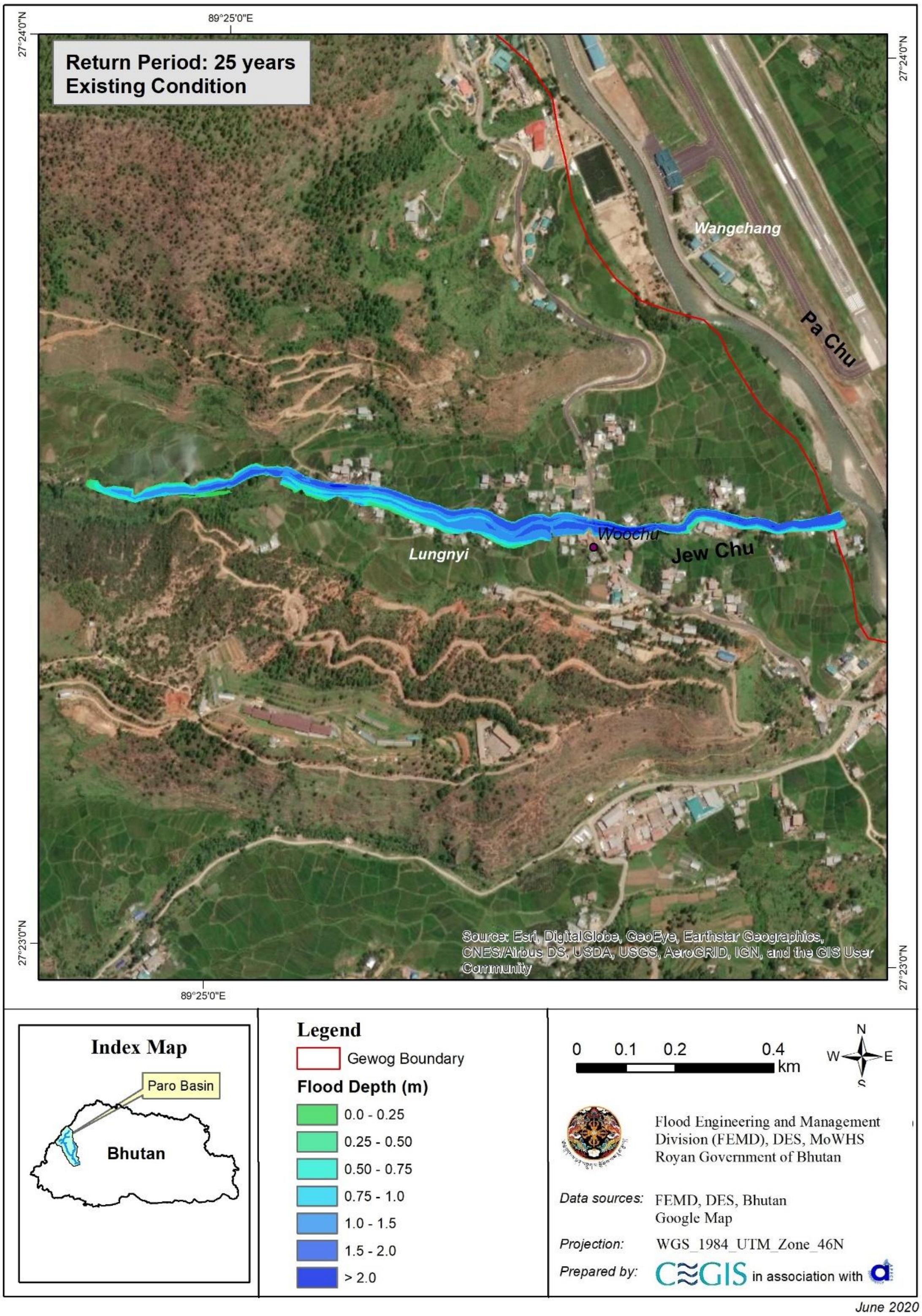

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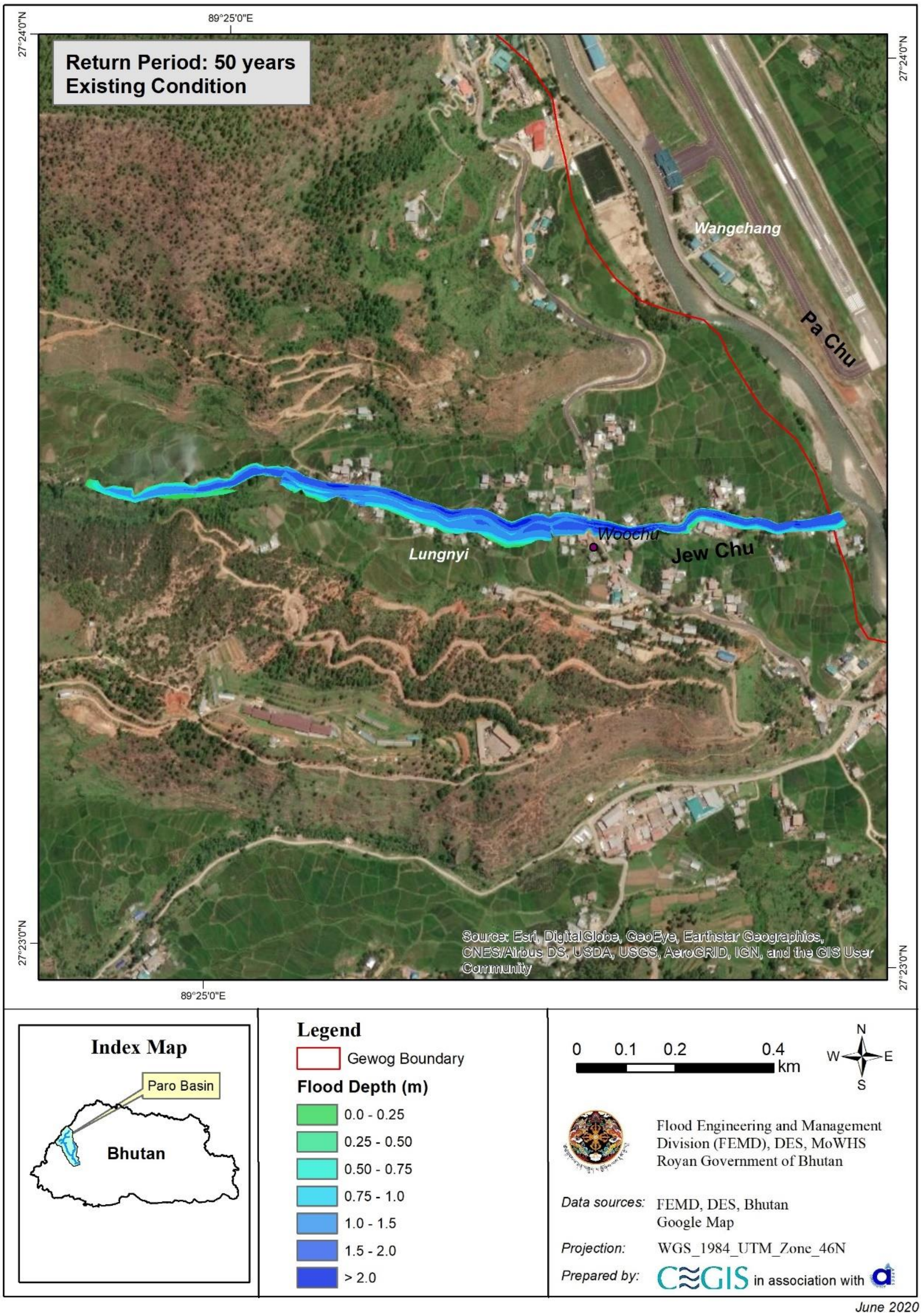

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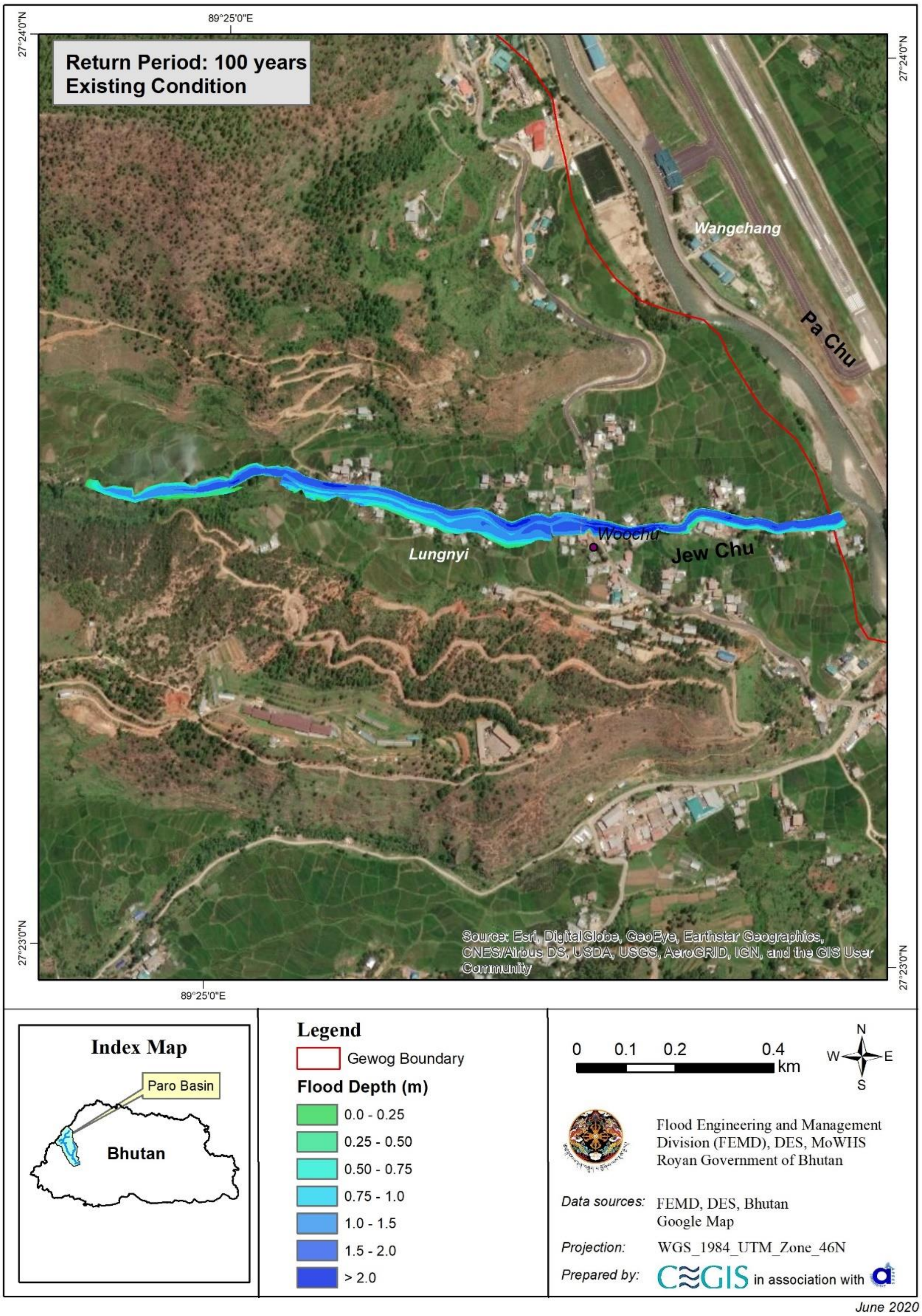
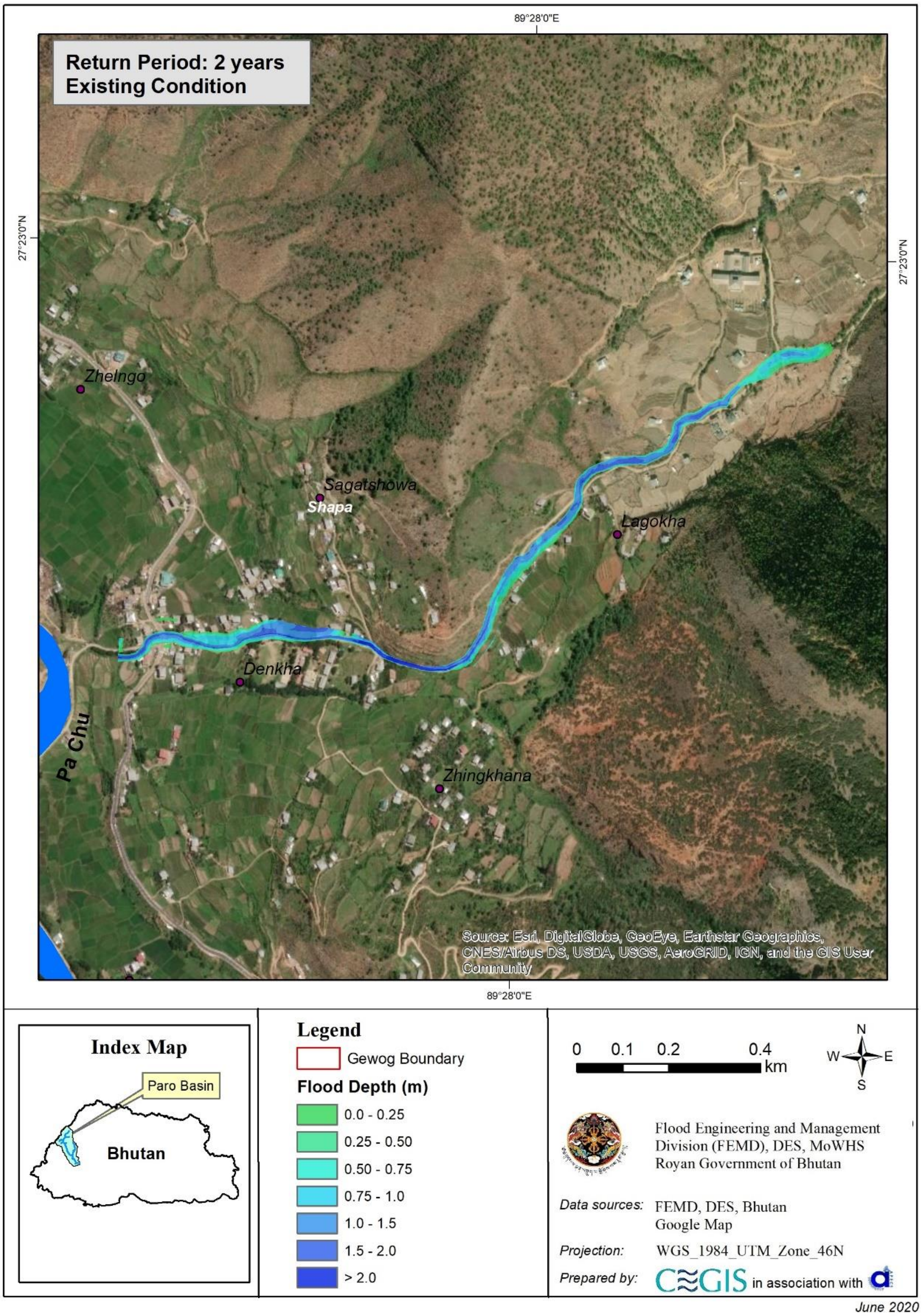
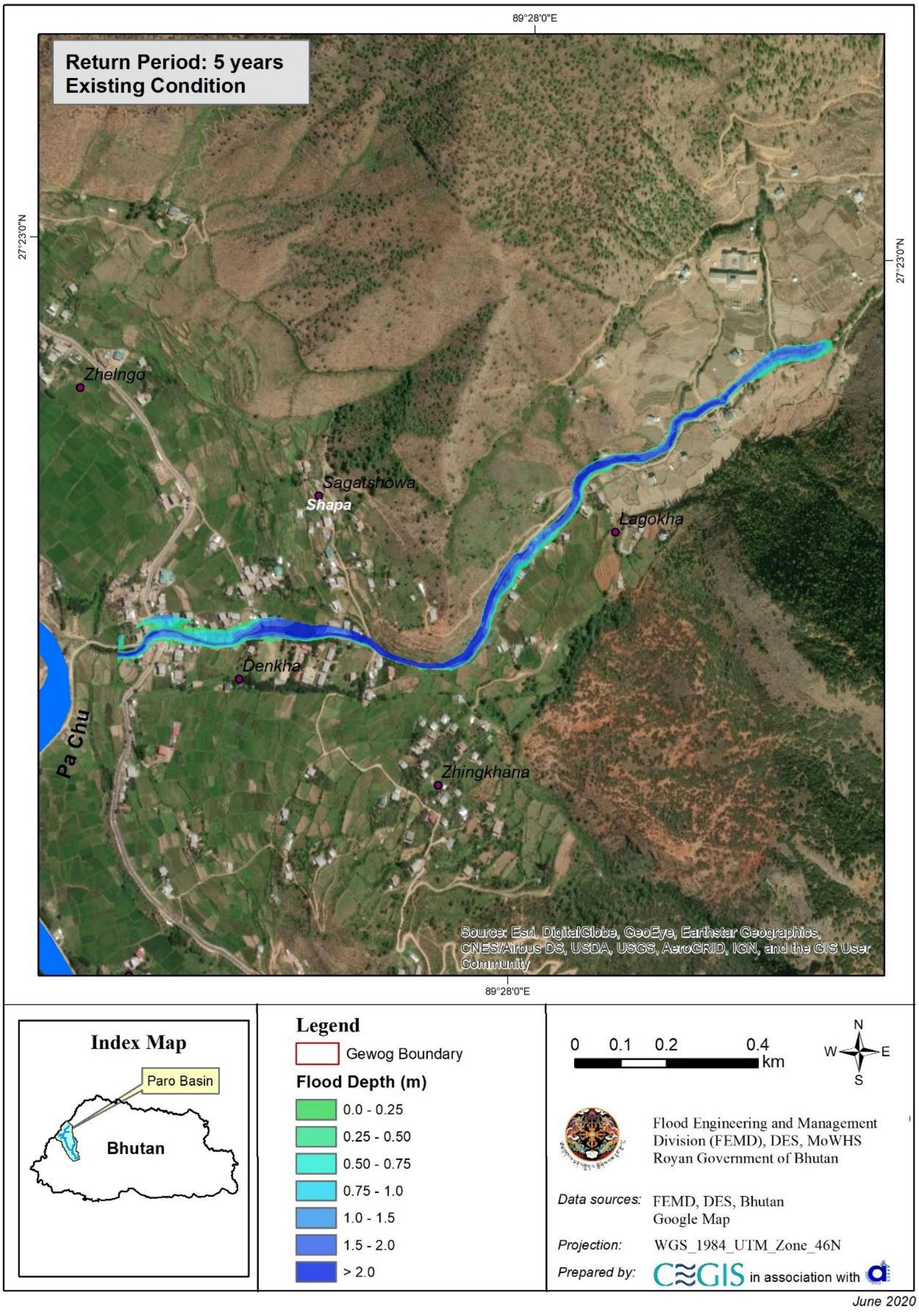


Flood Depth and Extent Map for Nephu Chu



Flood Depth and Extent Map for Nephu Chu



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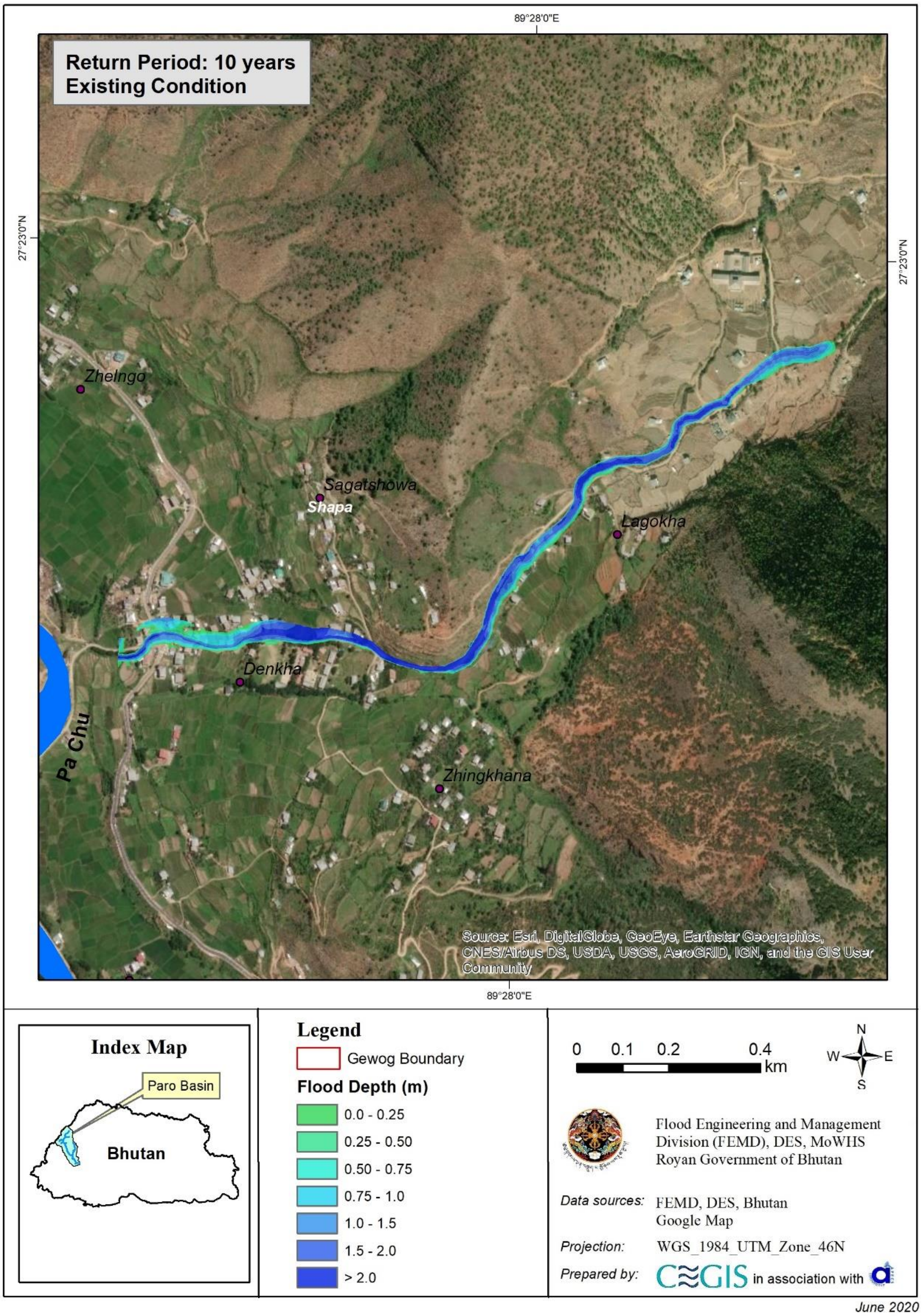

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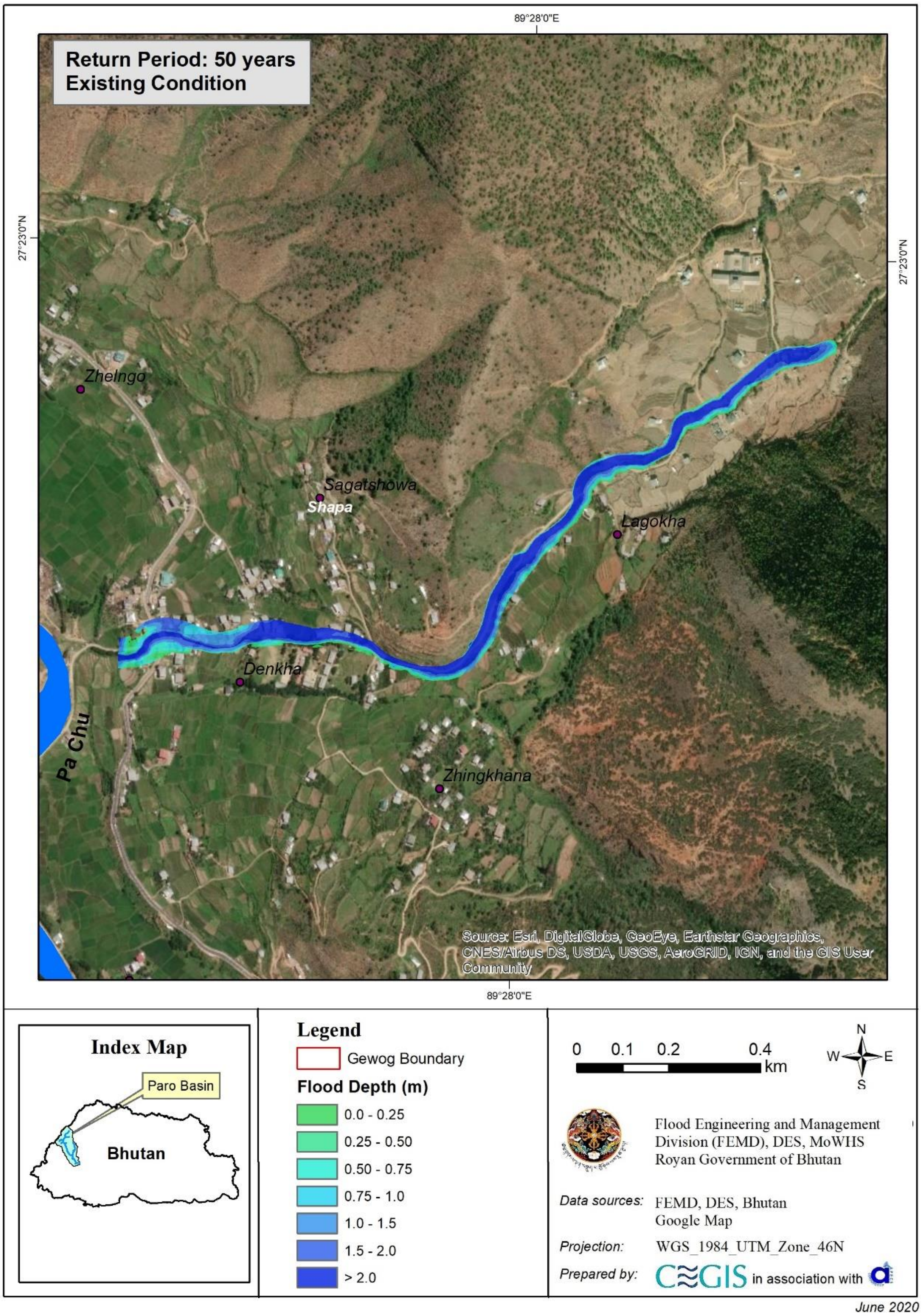

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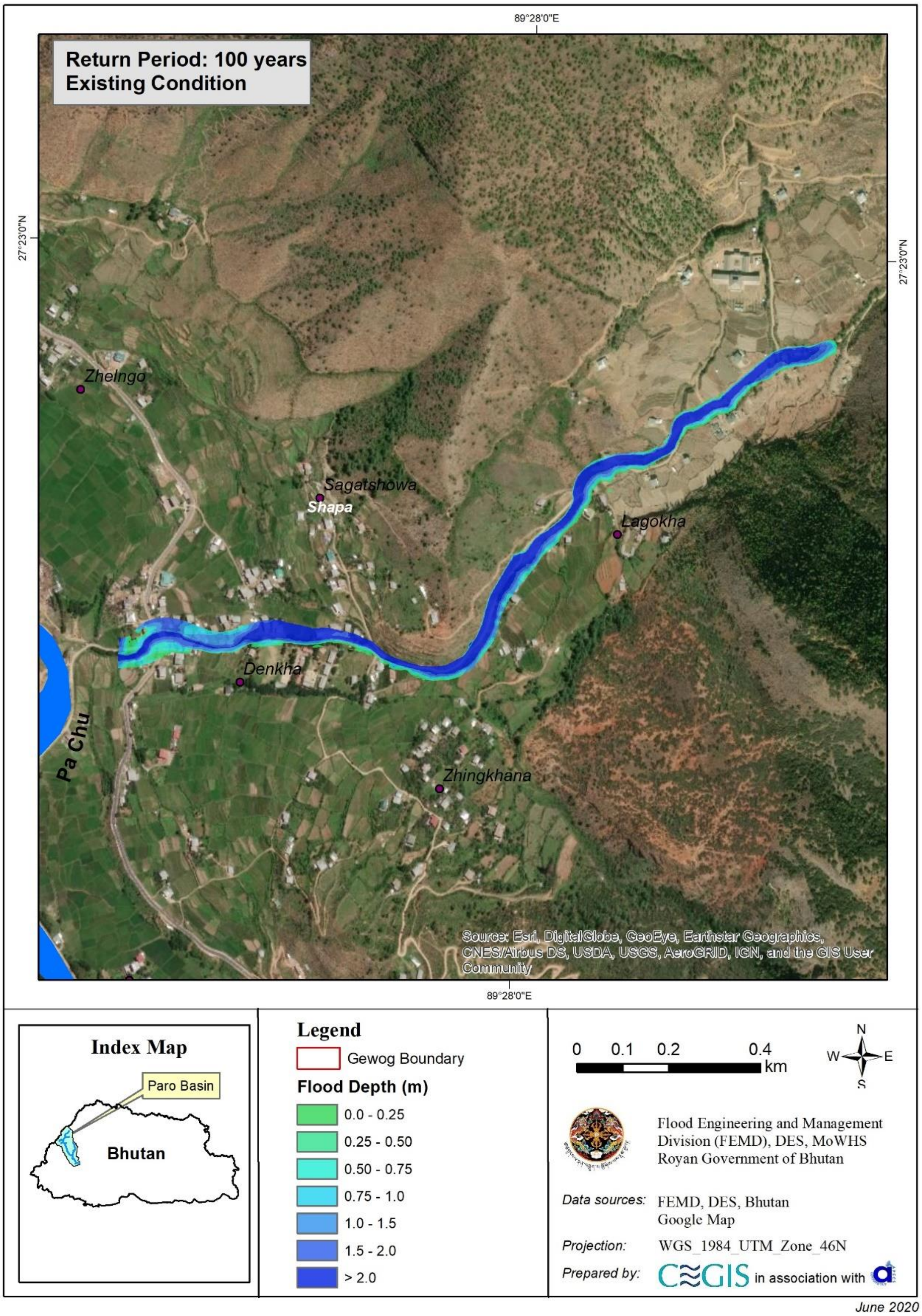
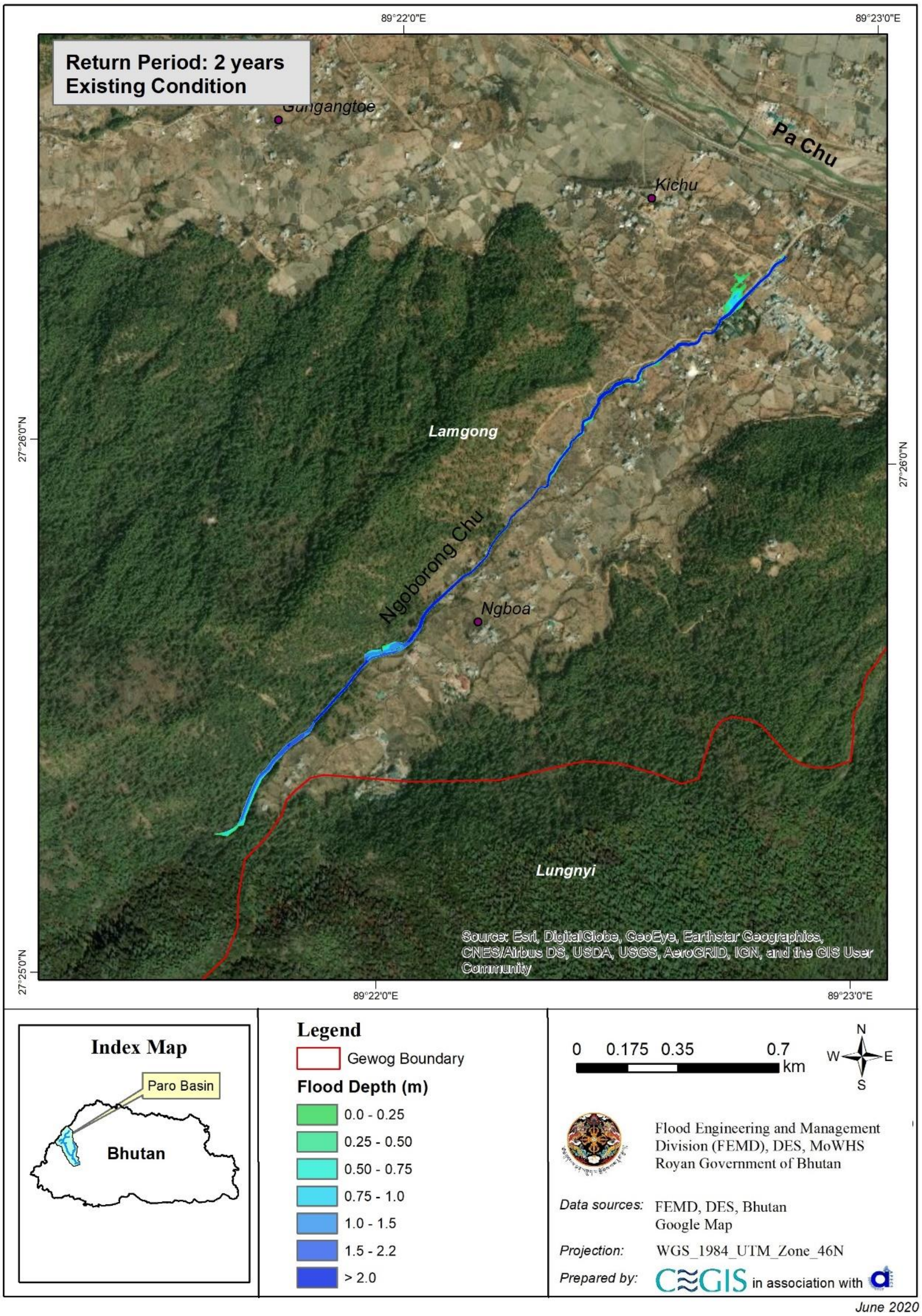
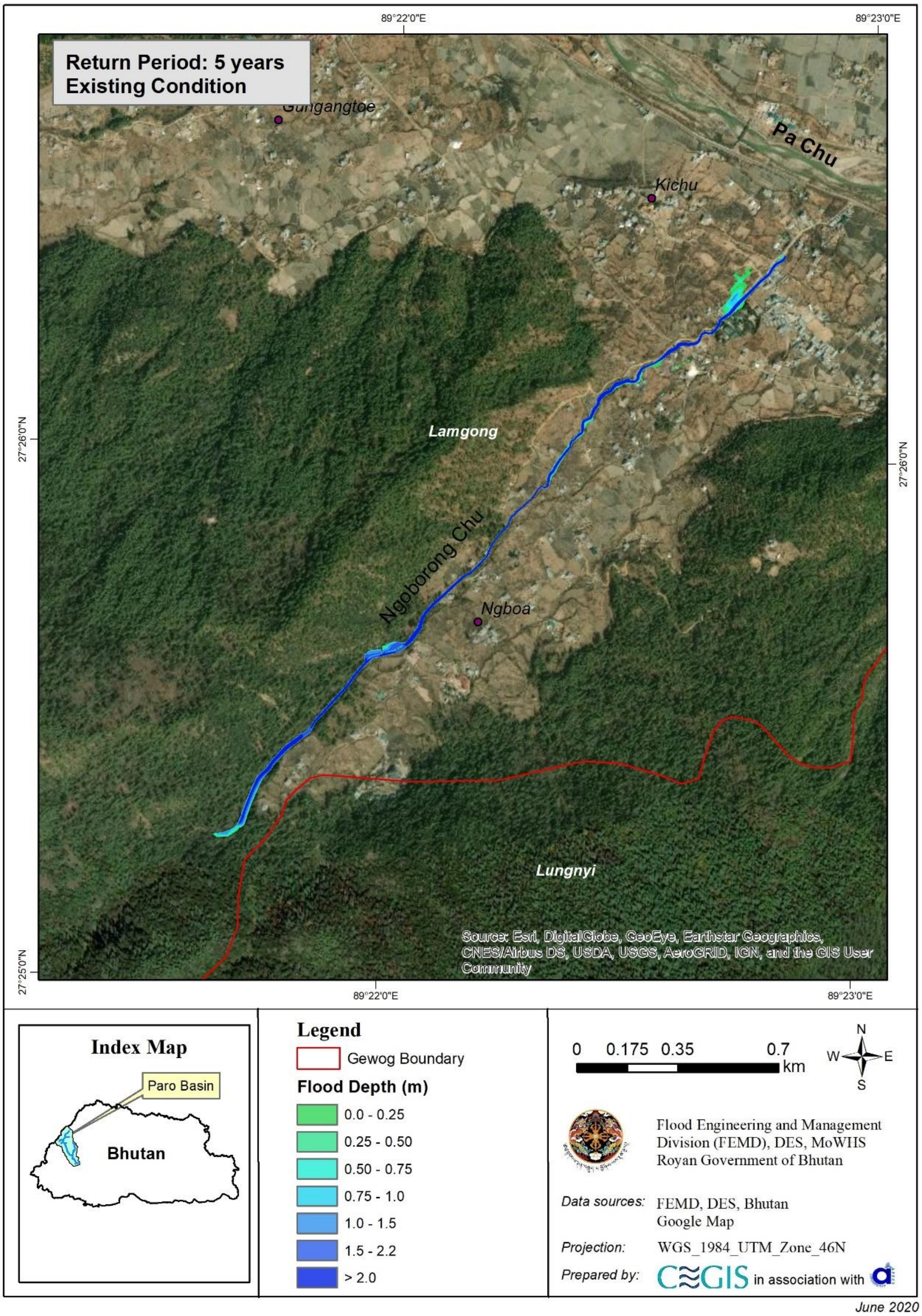


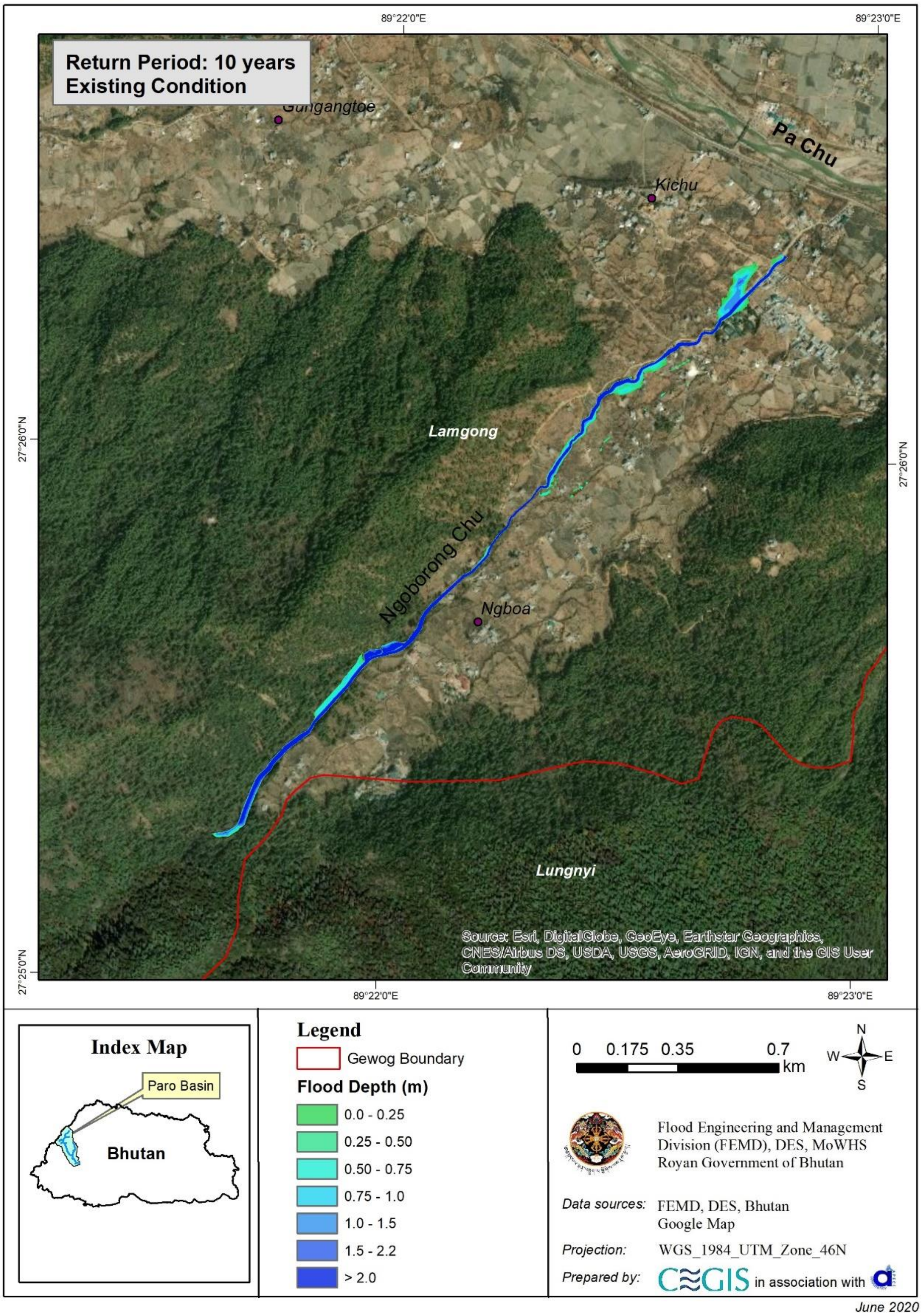
Flood Depth and Extent Map for Ngoborong Chu



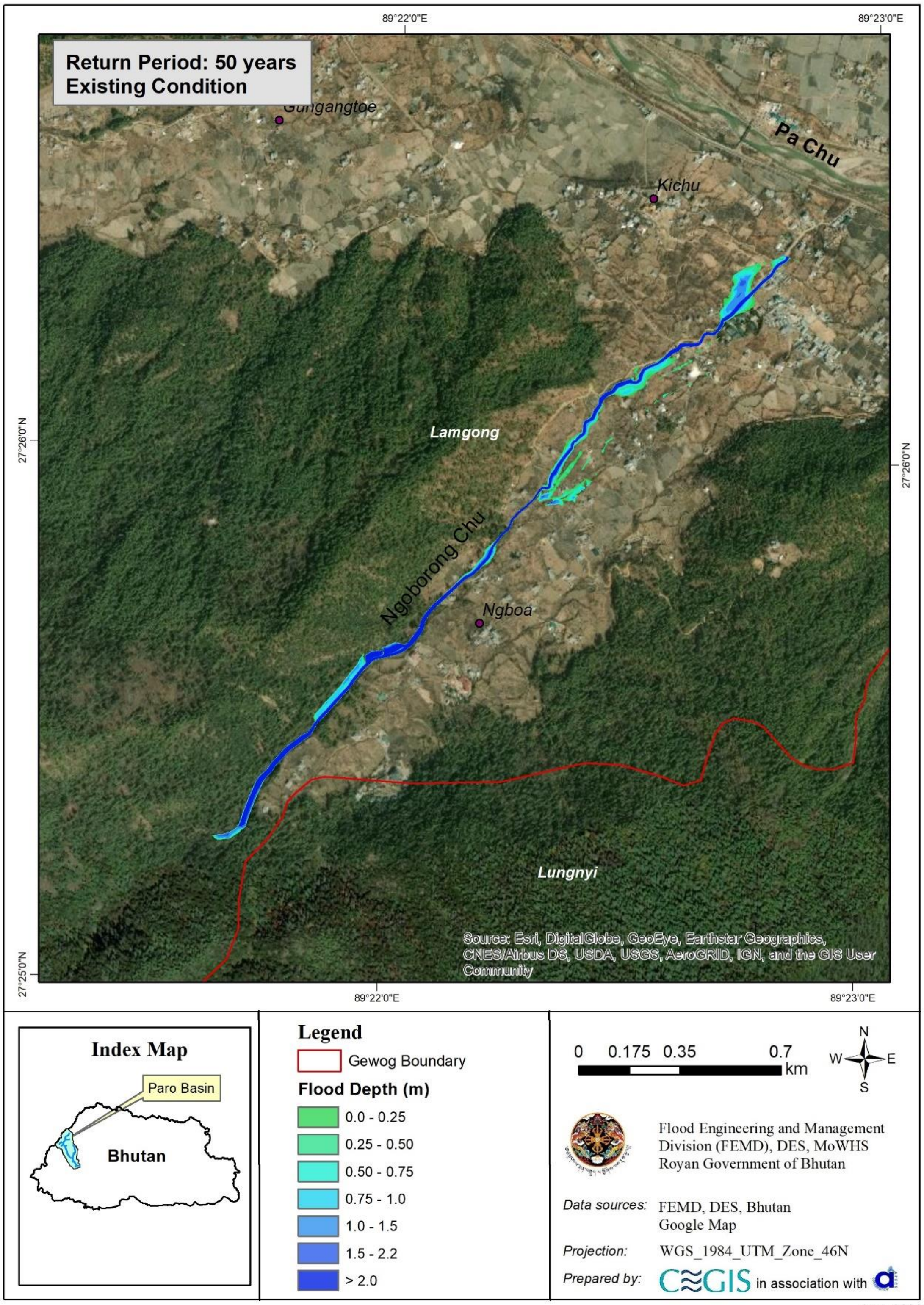
Flood Depth and Extent Map for Ngoborong Chu



Flood Depth and Extent Map for Ngoborong Chu



Flood Depth and Extent Map for Ngoborong Chu



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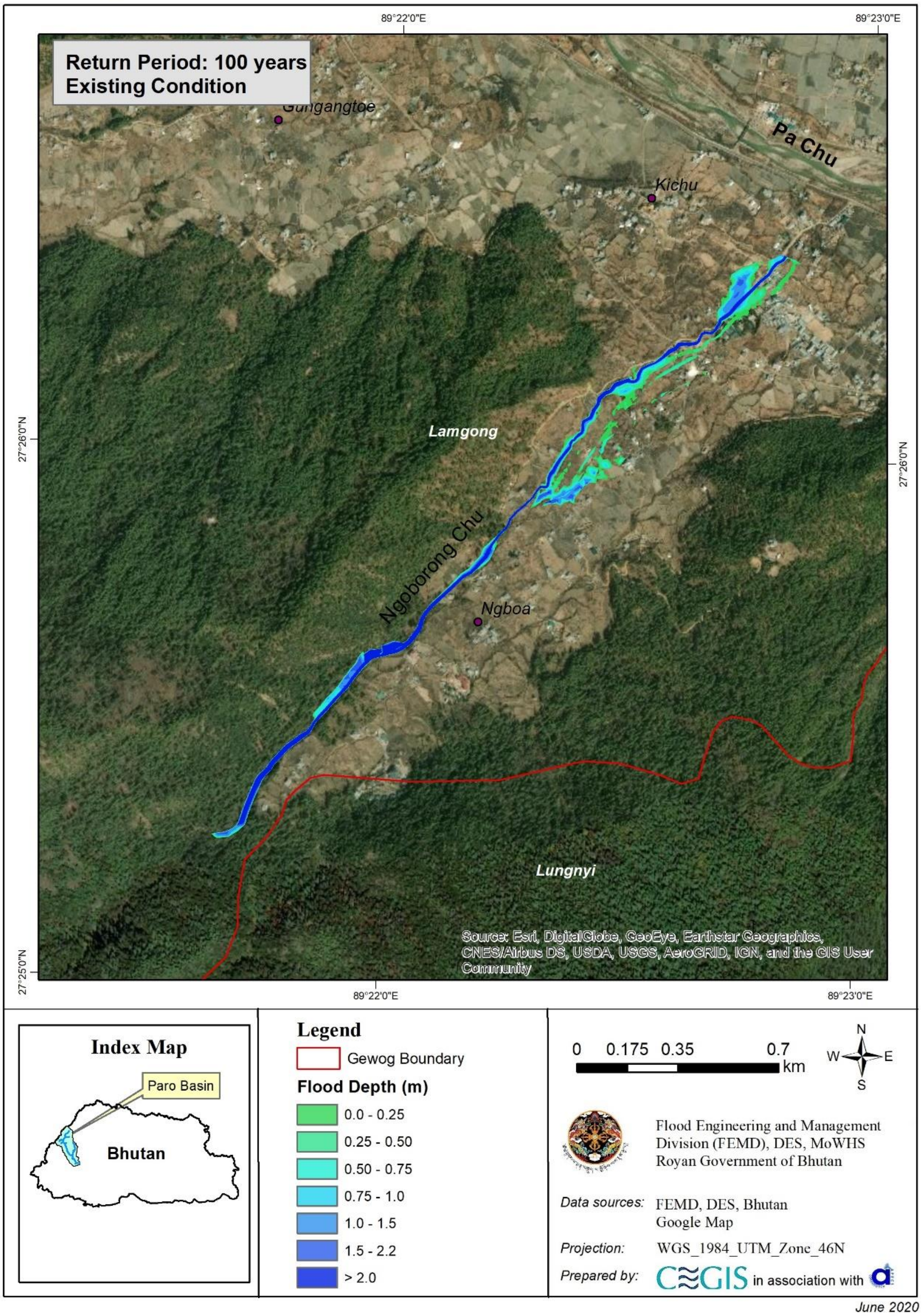
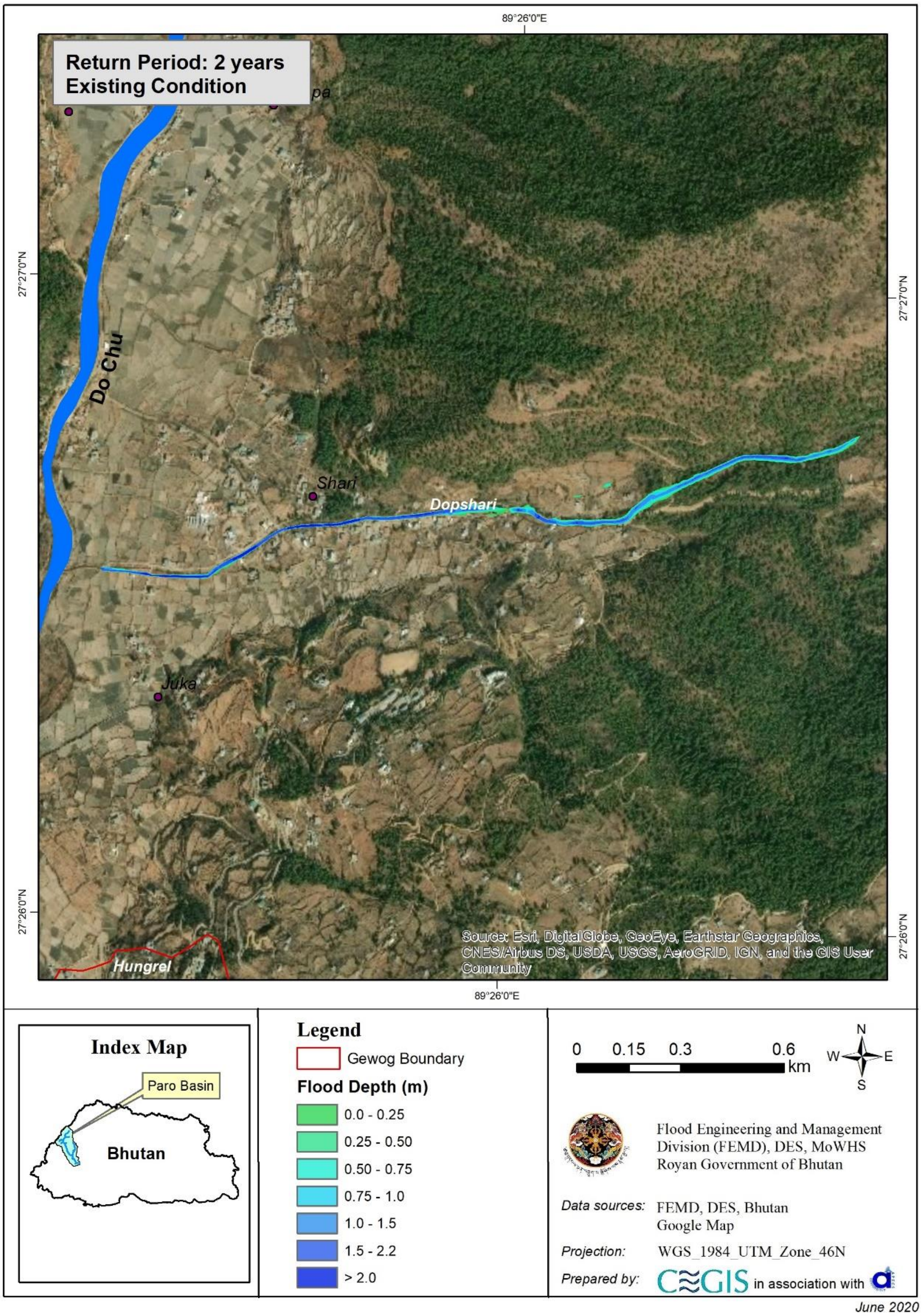
Flood Depth and Extent Map for Ngoborong Chu



Flood Depth and Extent Map for Ri Chu



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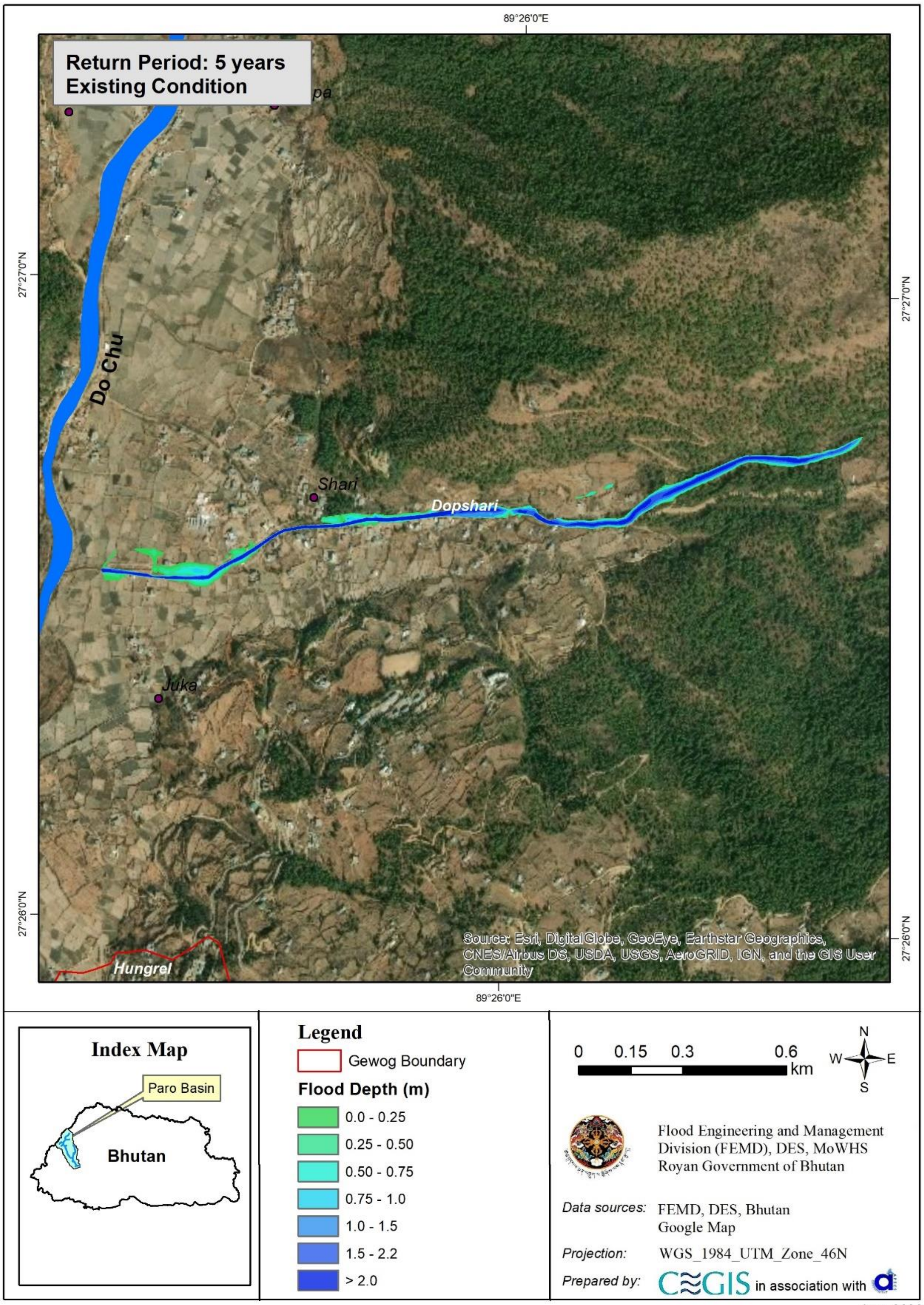

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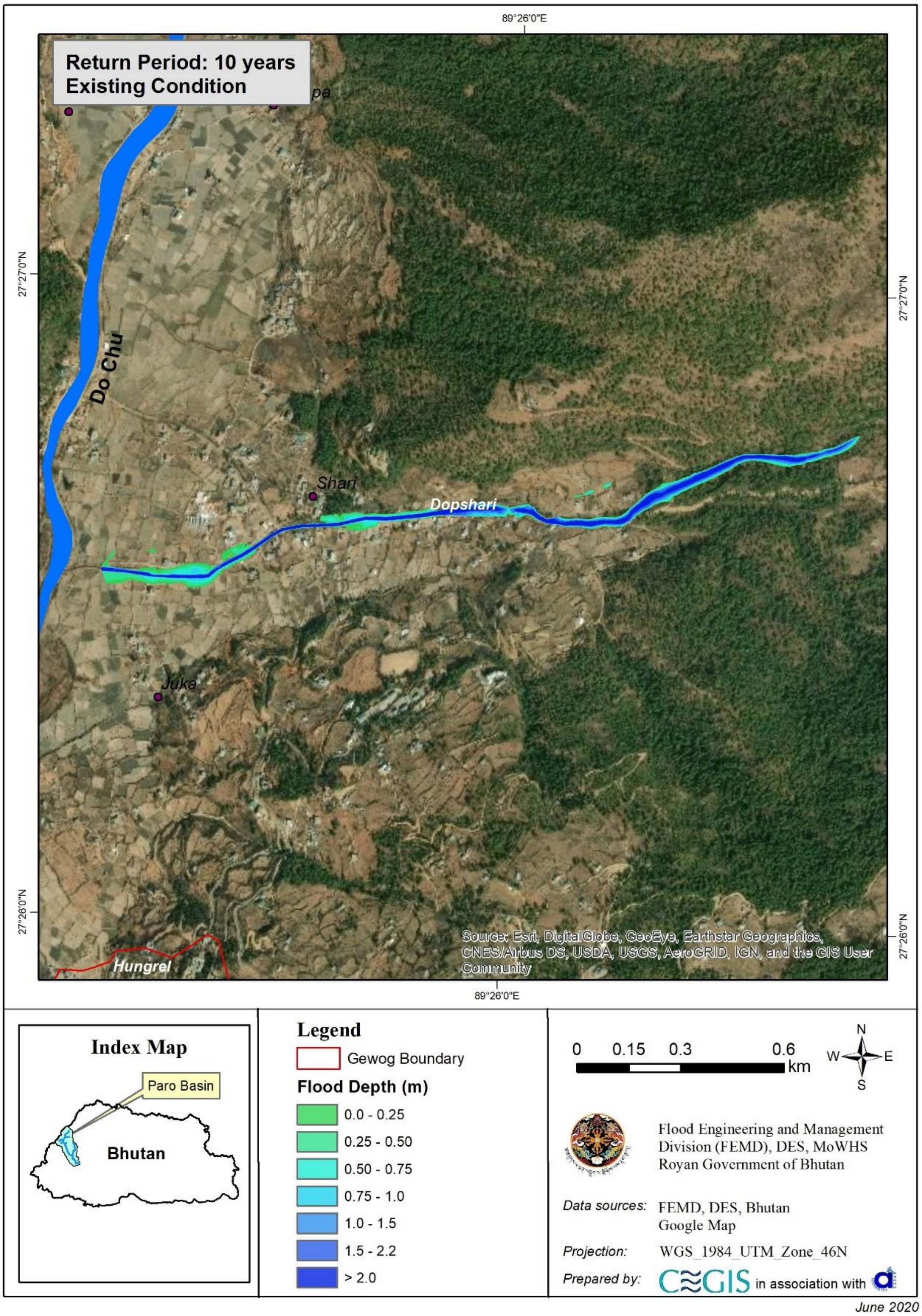
Flood Depth and Extent Map for Ri Chu



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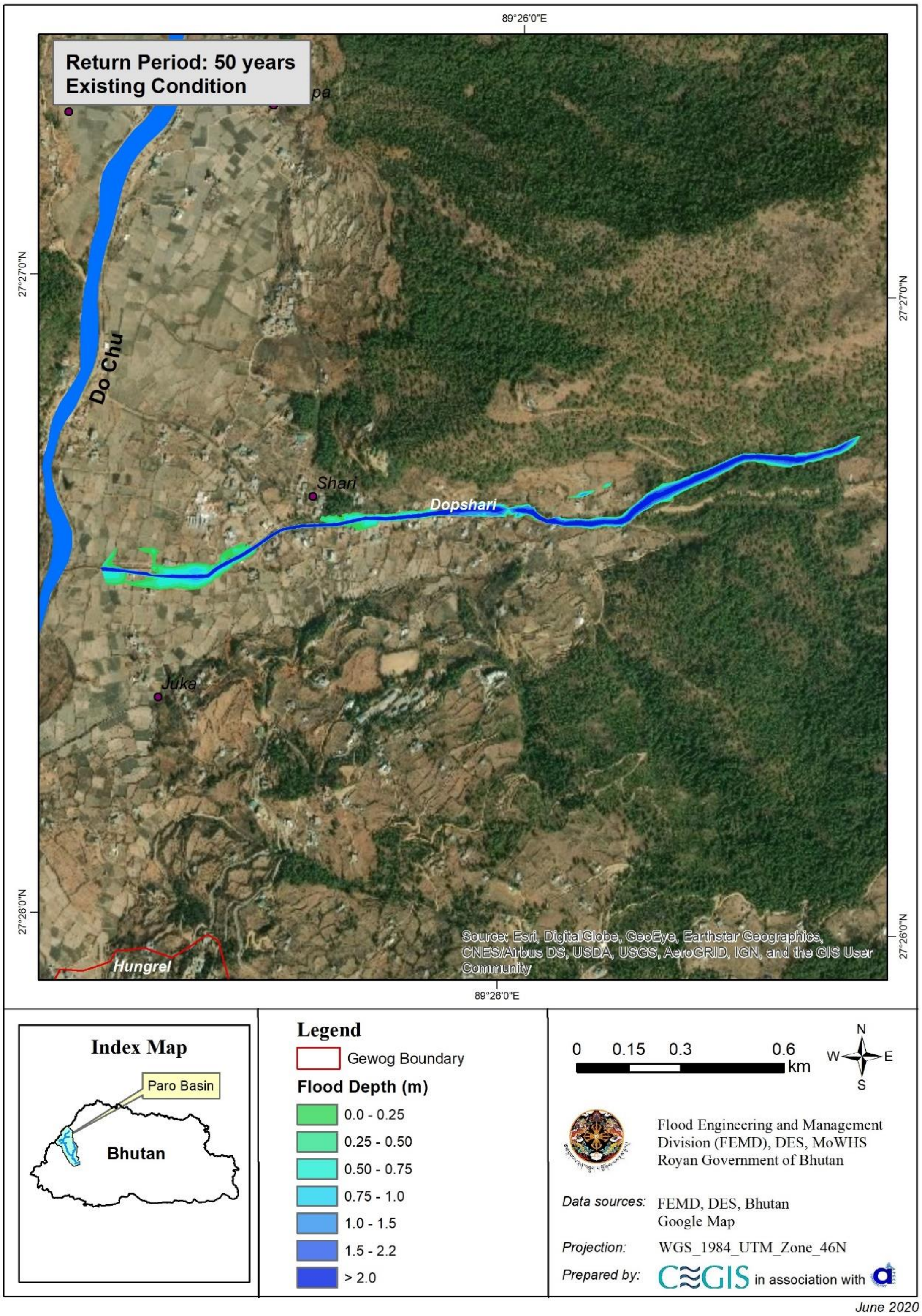

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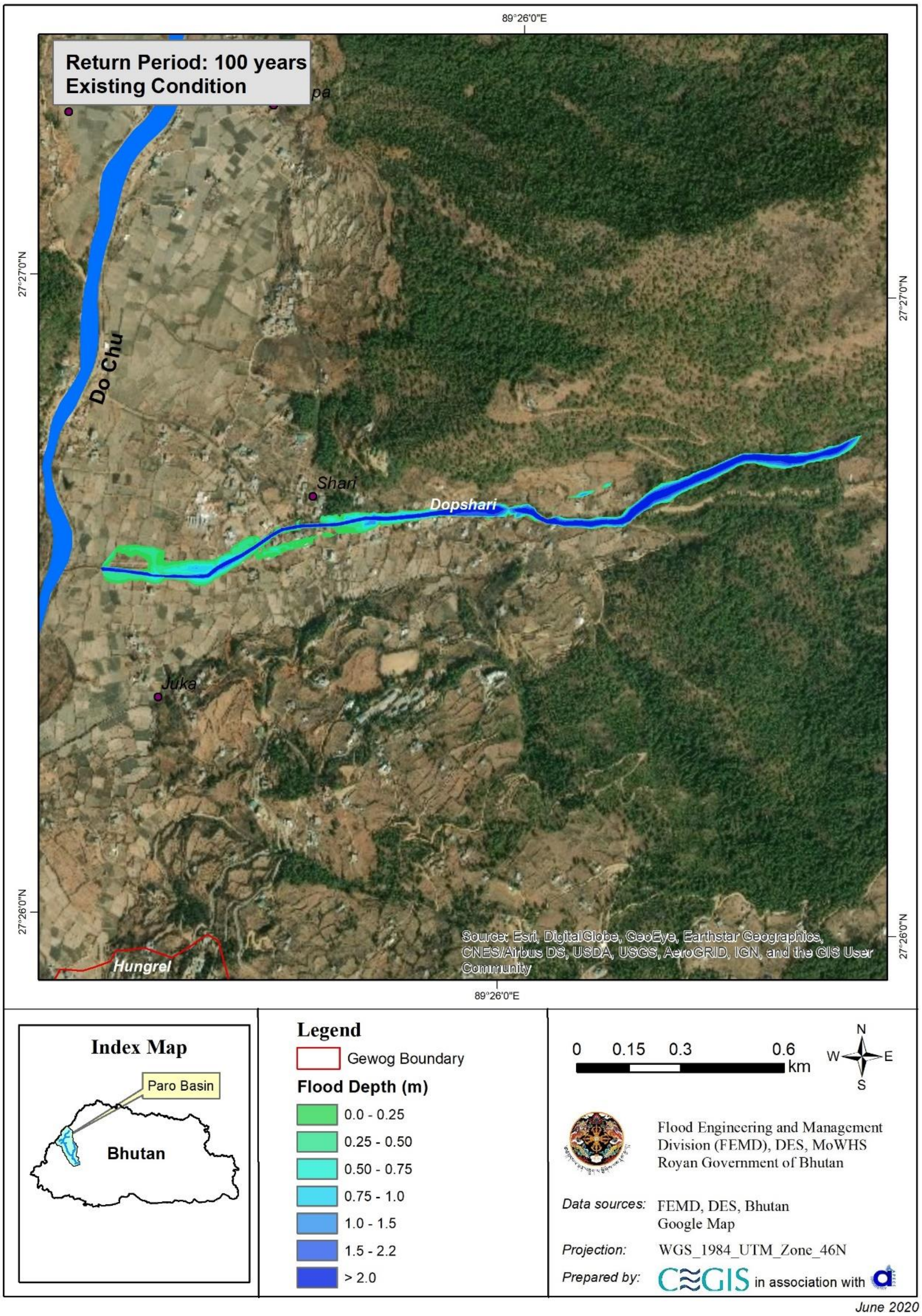
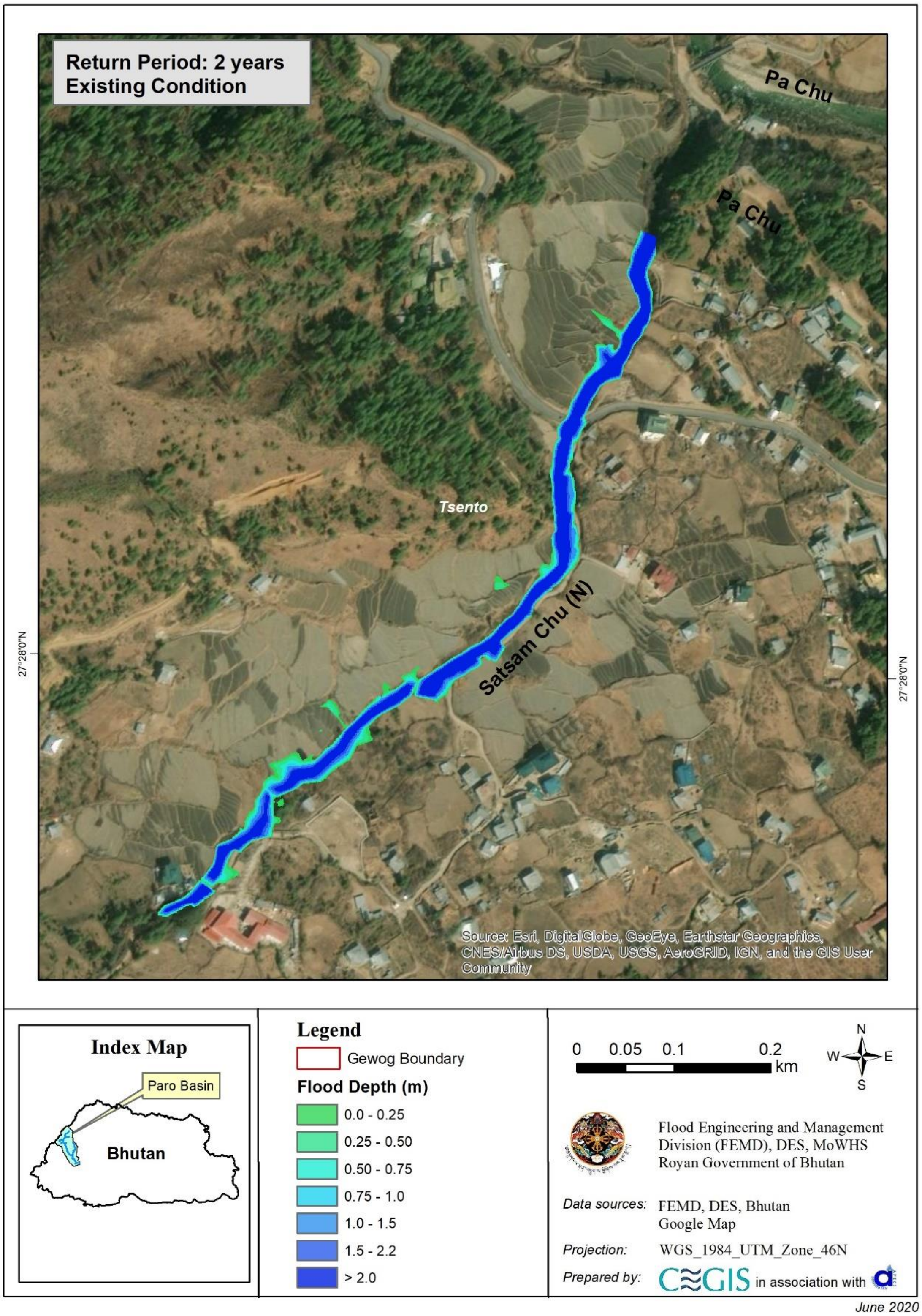


Flood Depth and Extent Map for Satsan Chu (N)



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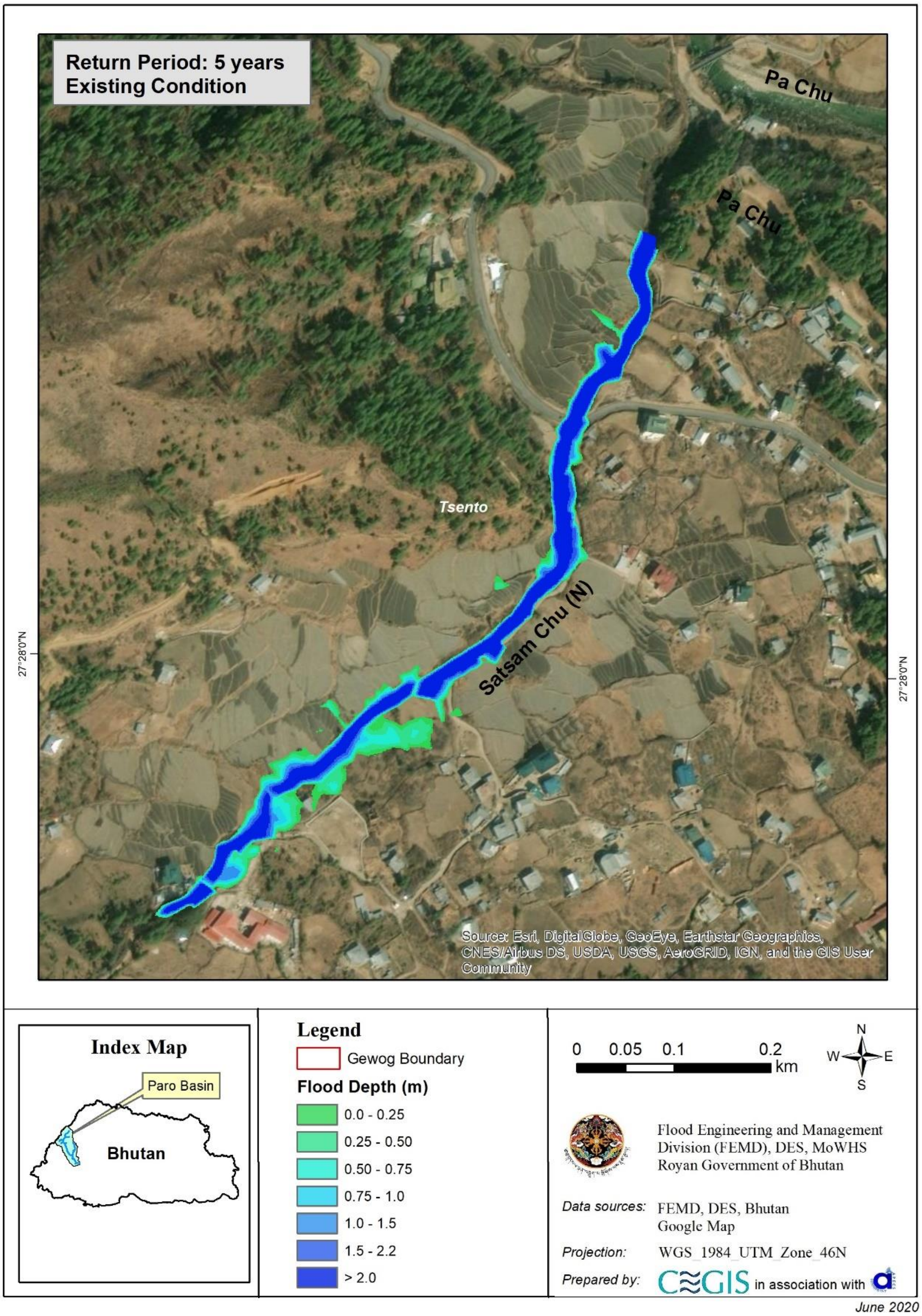

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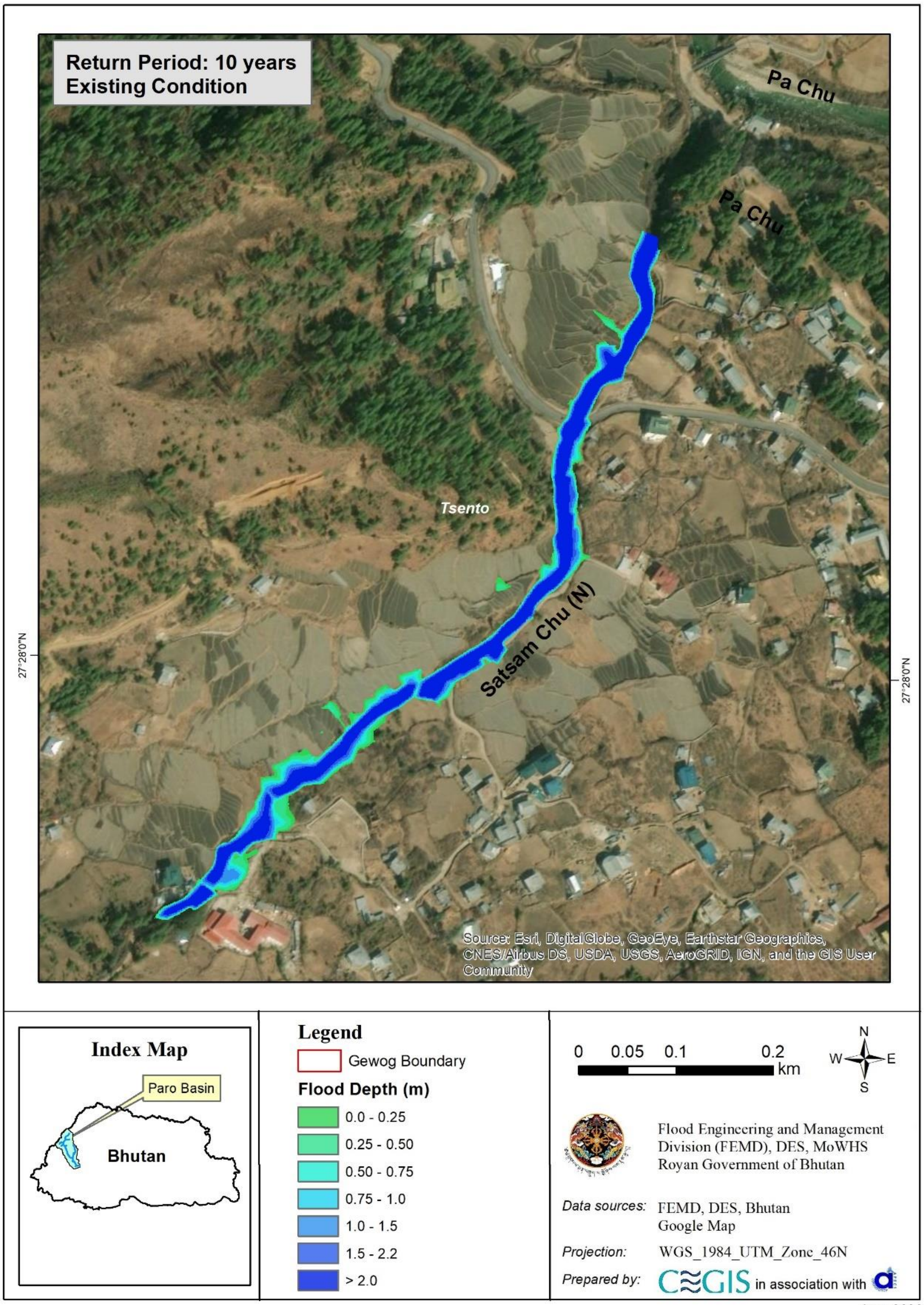

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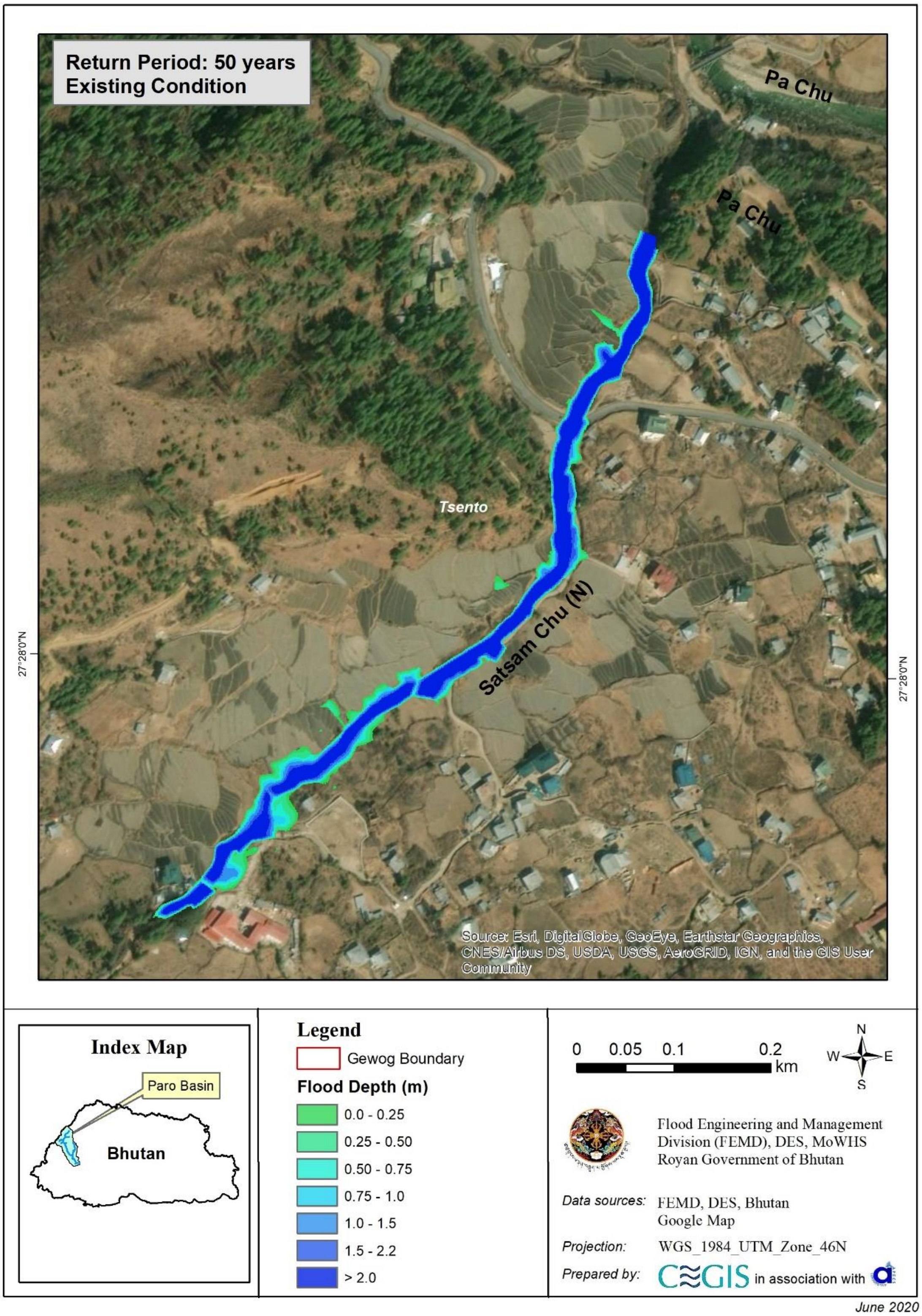
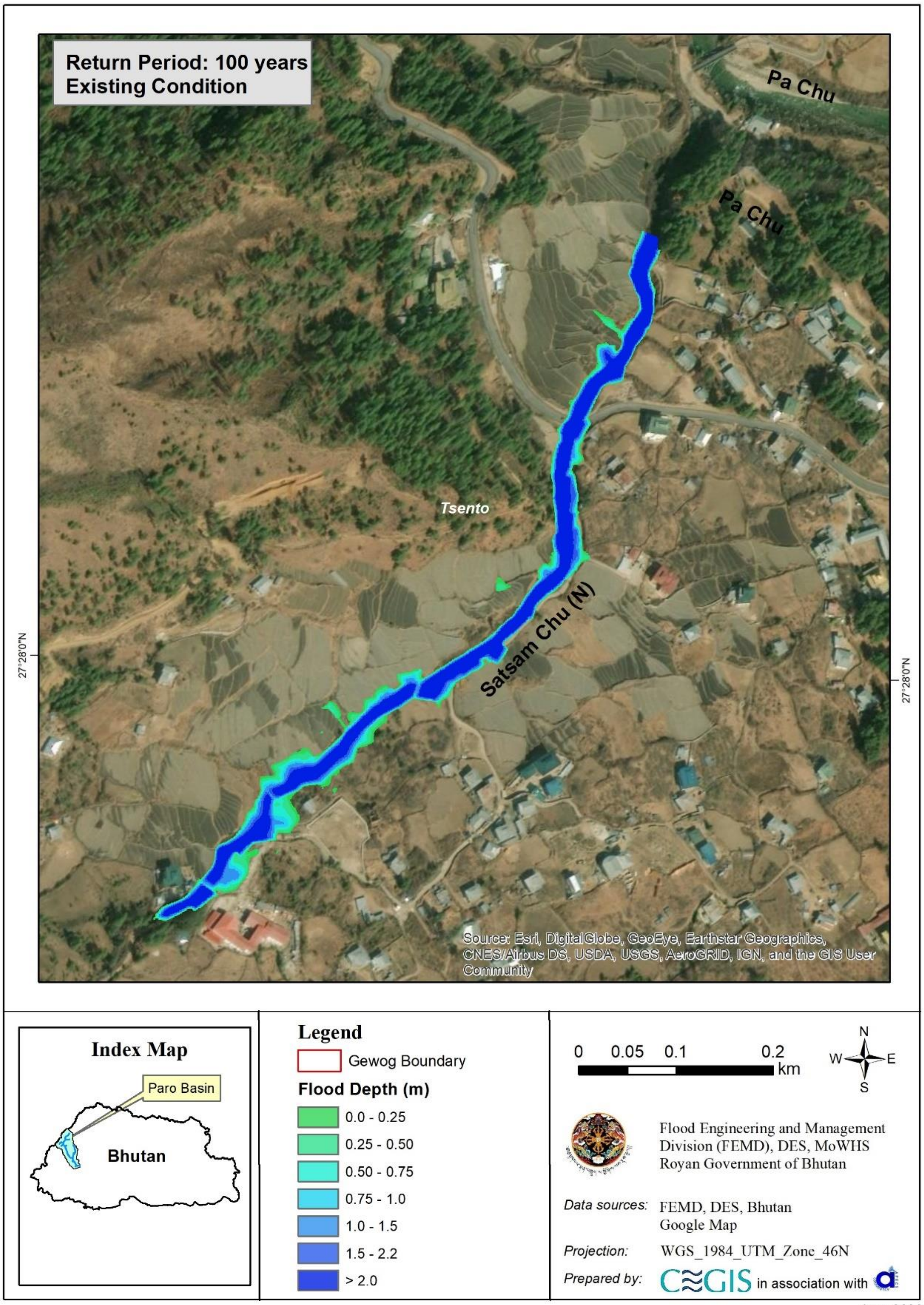
Flood Depth and Extent Map for Satsan Chu (N)



Flood Depth and Extent Map for Satsan Chu (N)



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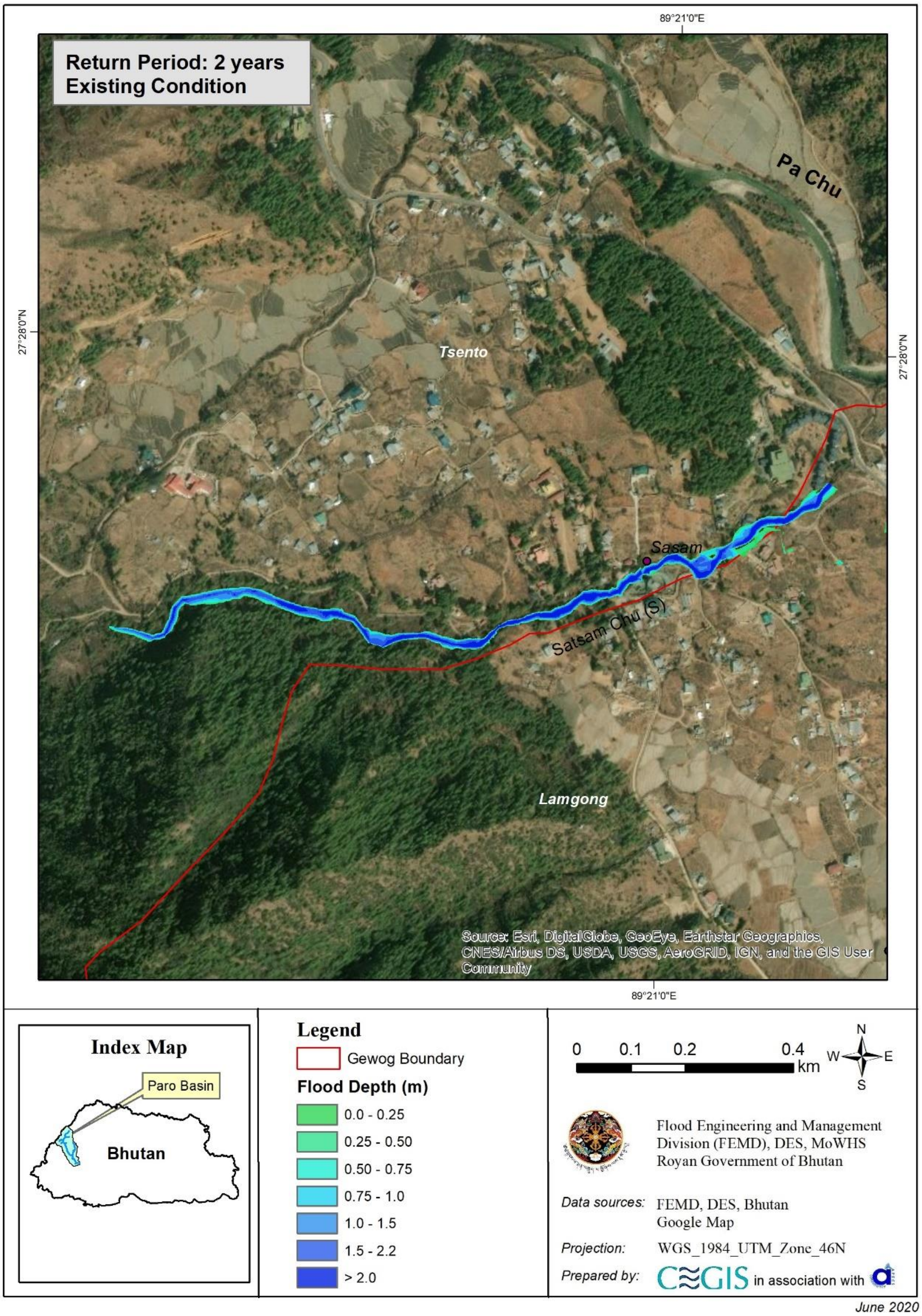
Flood Depth and Extent Map for Satsan Chu (S)



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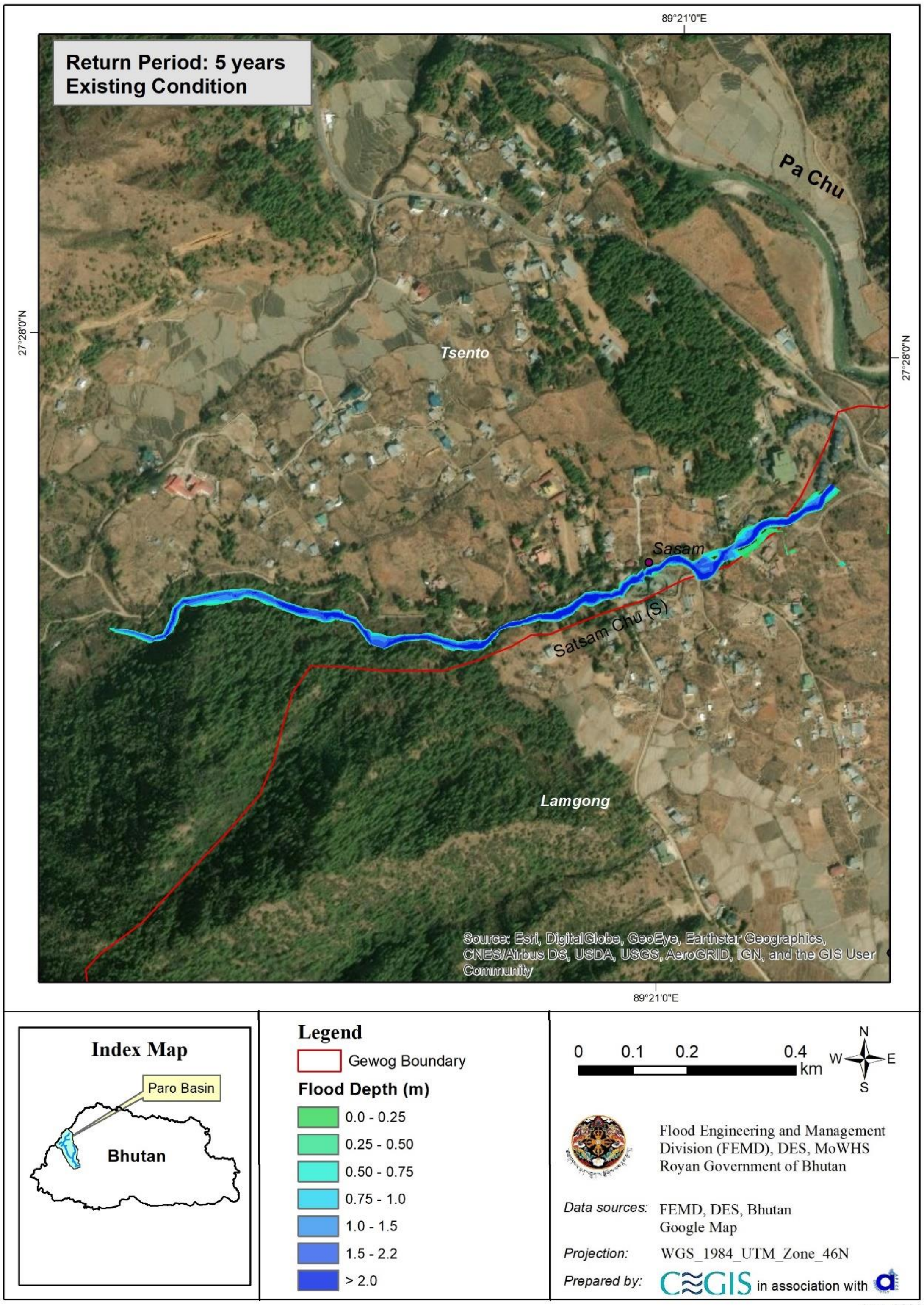

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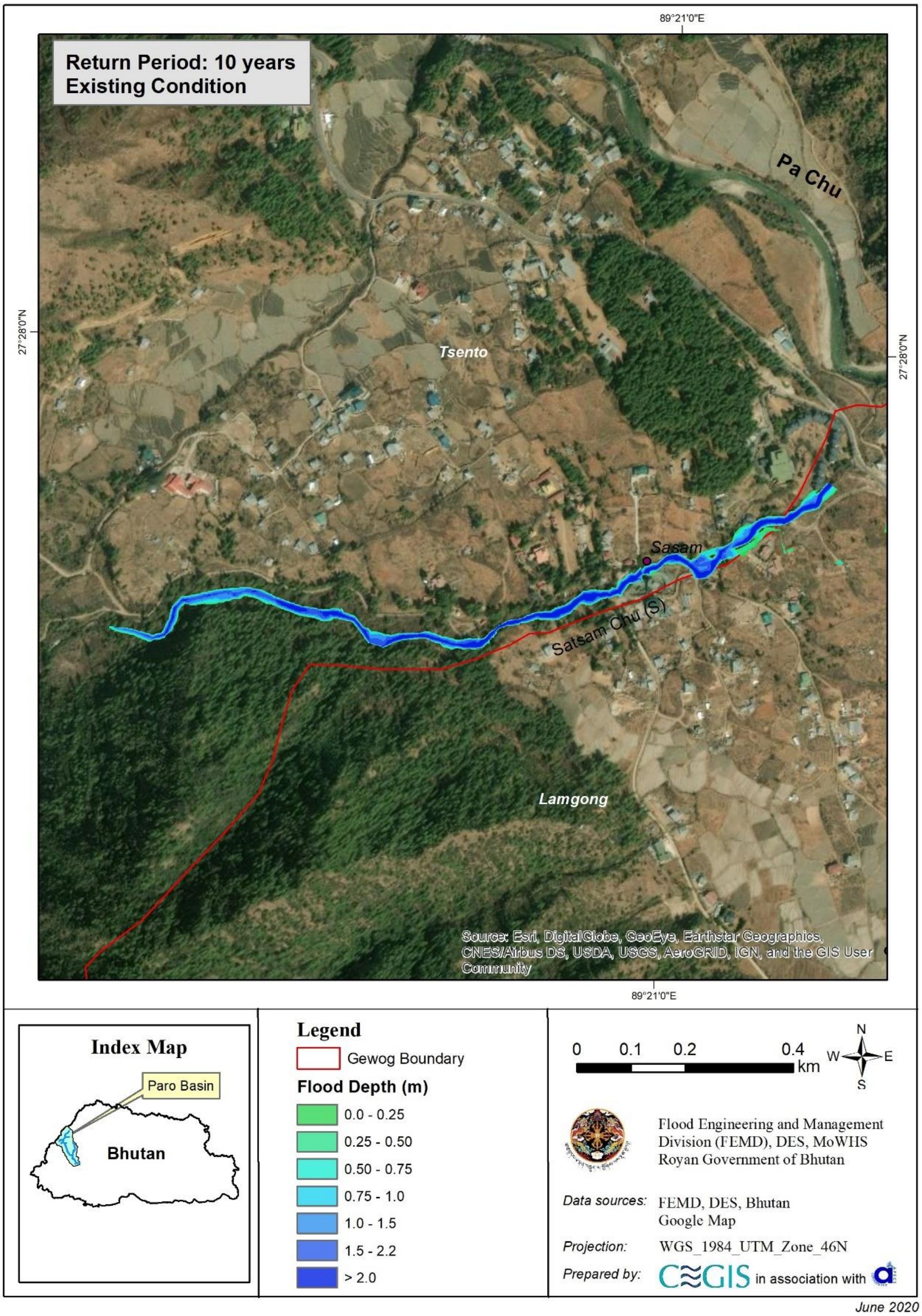

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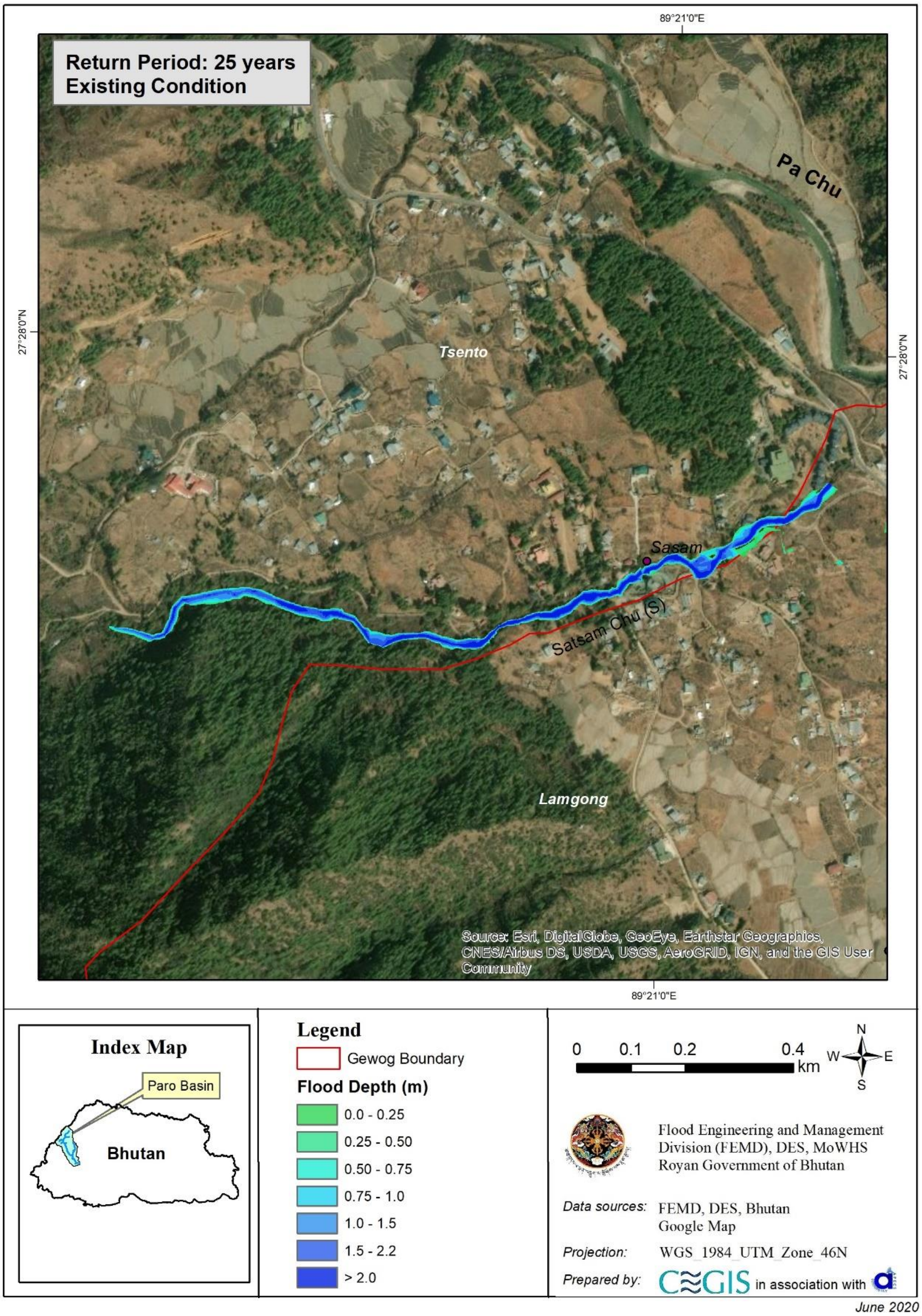

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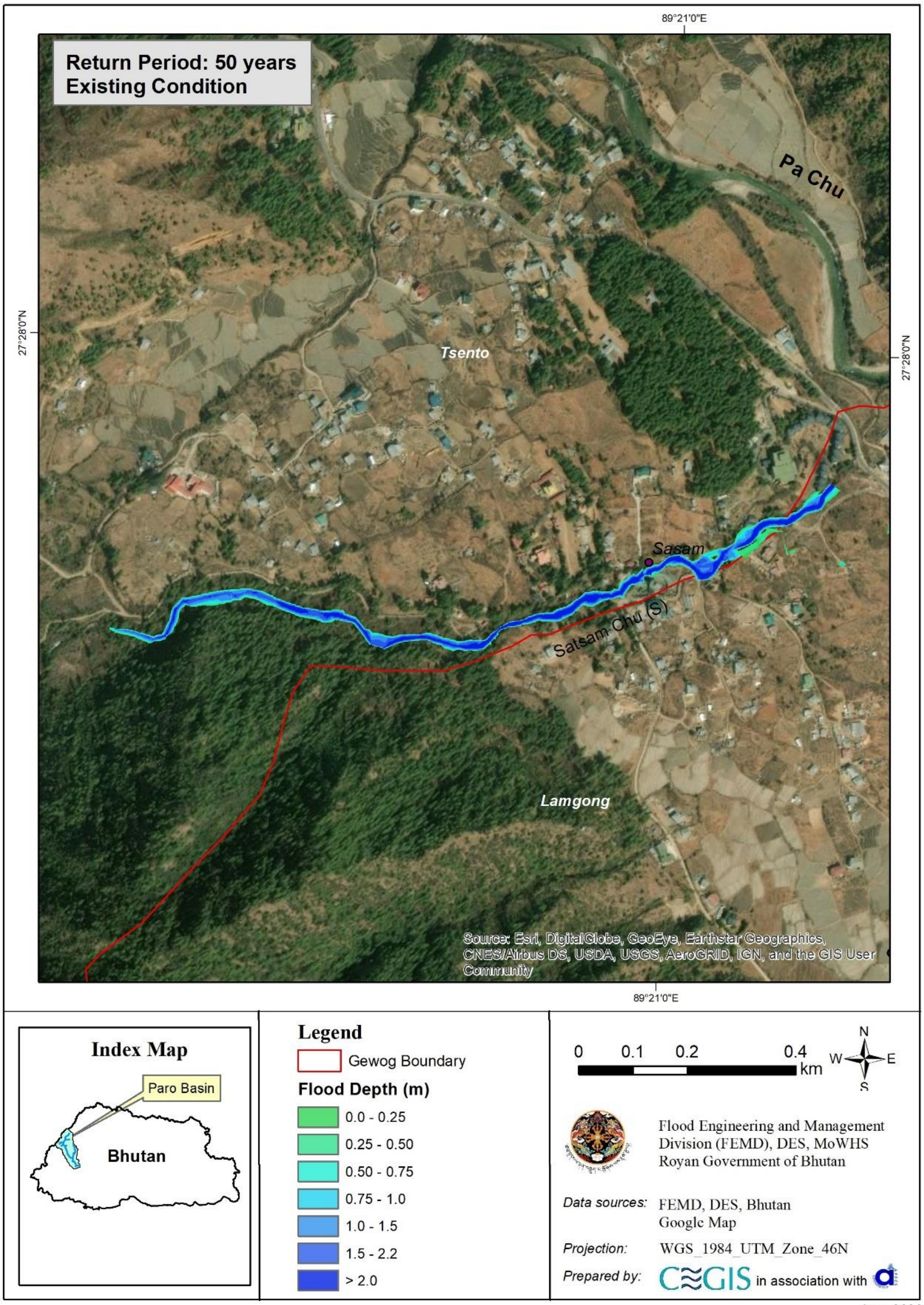

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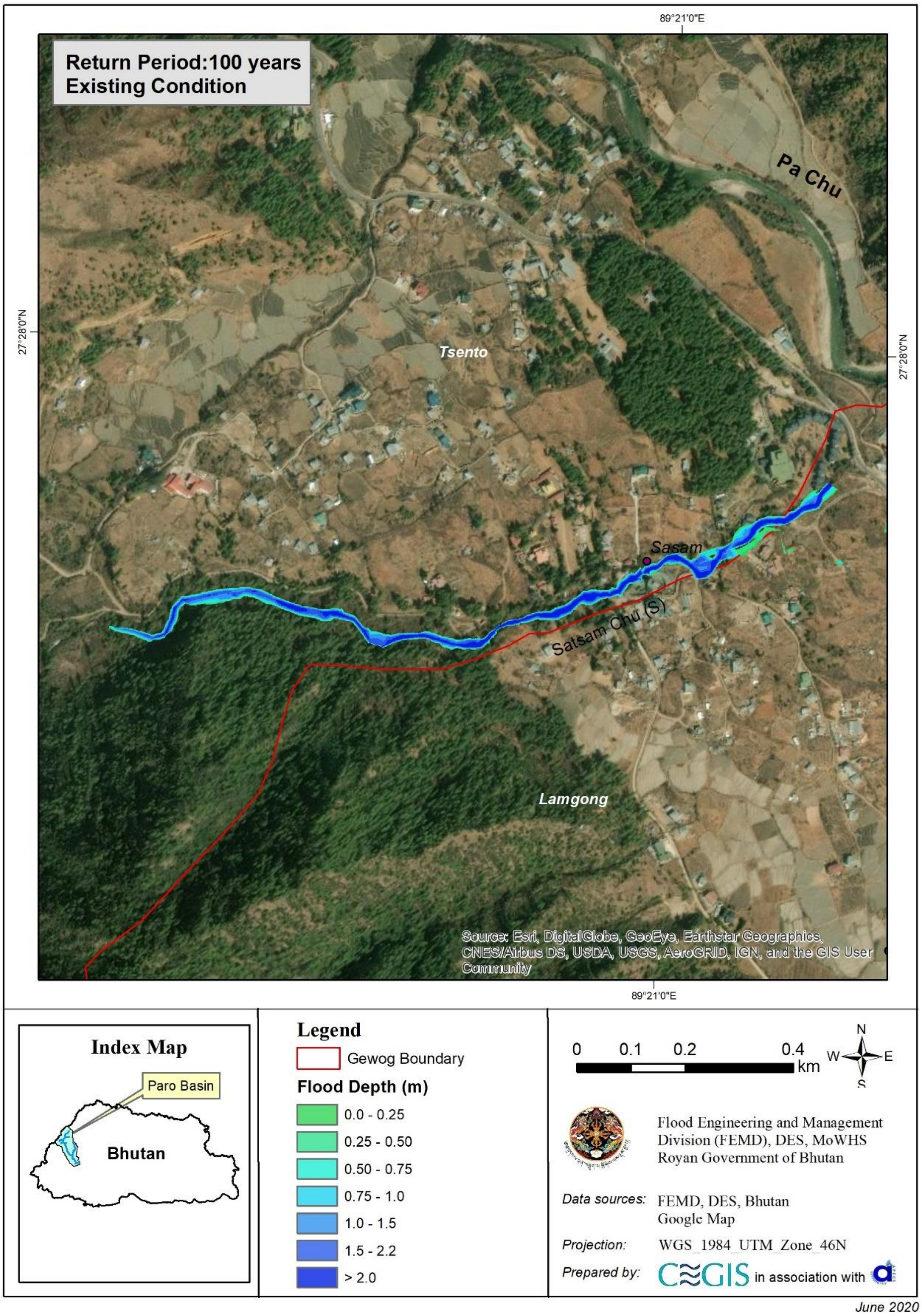
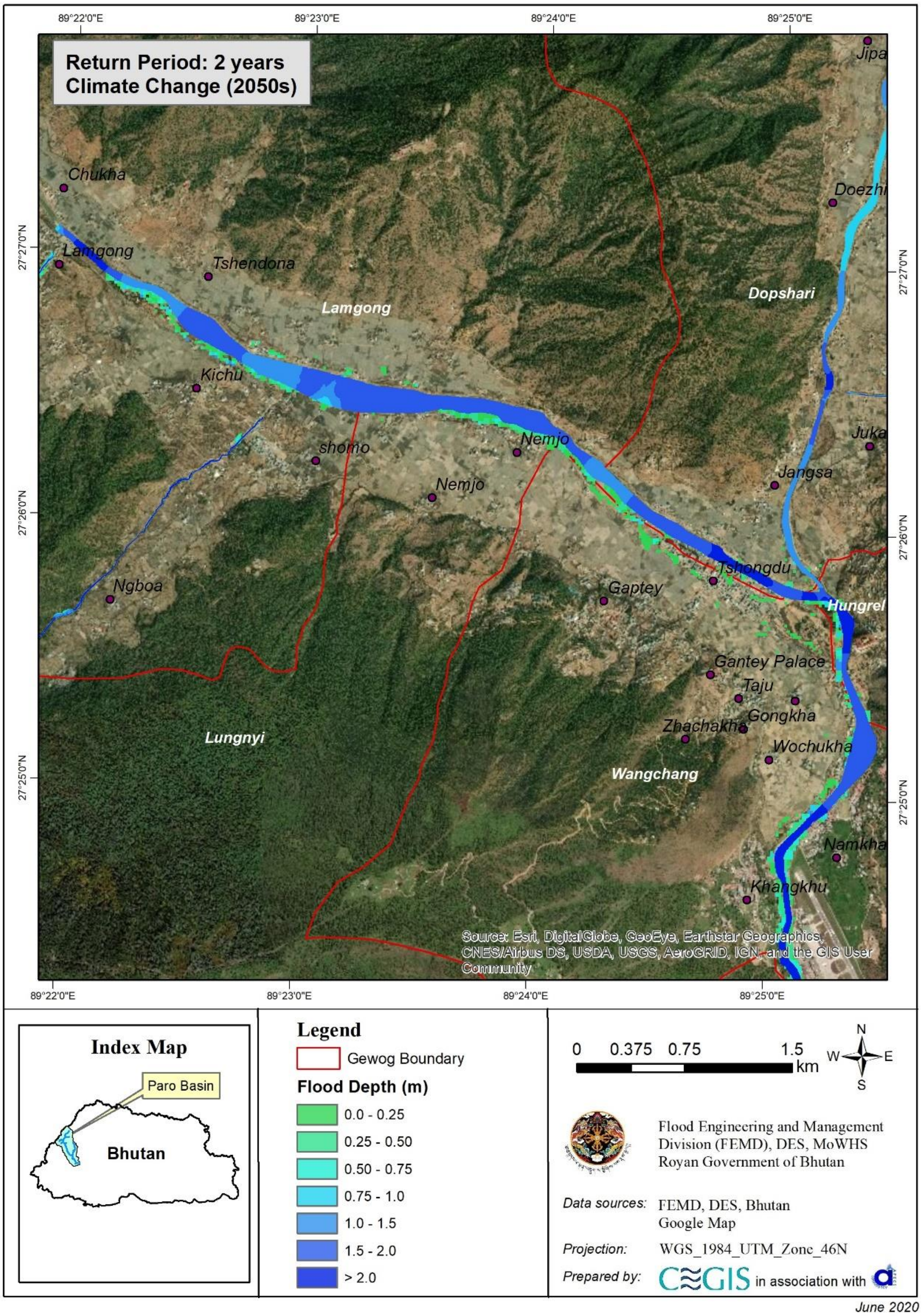
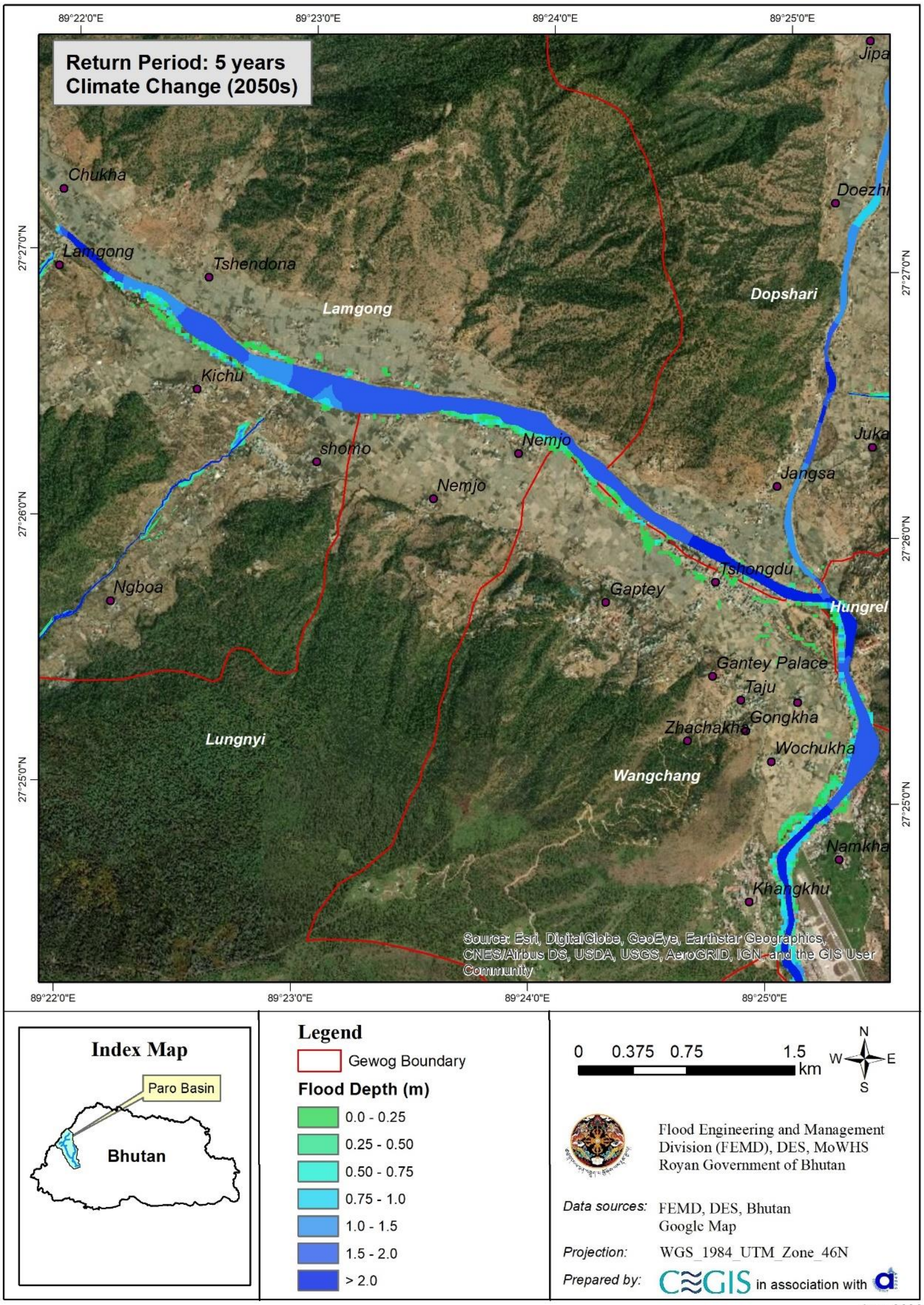
Flood Depth and Extent Map for Satsan Chu (S)



Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



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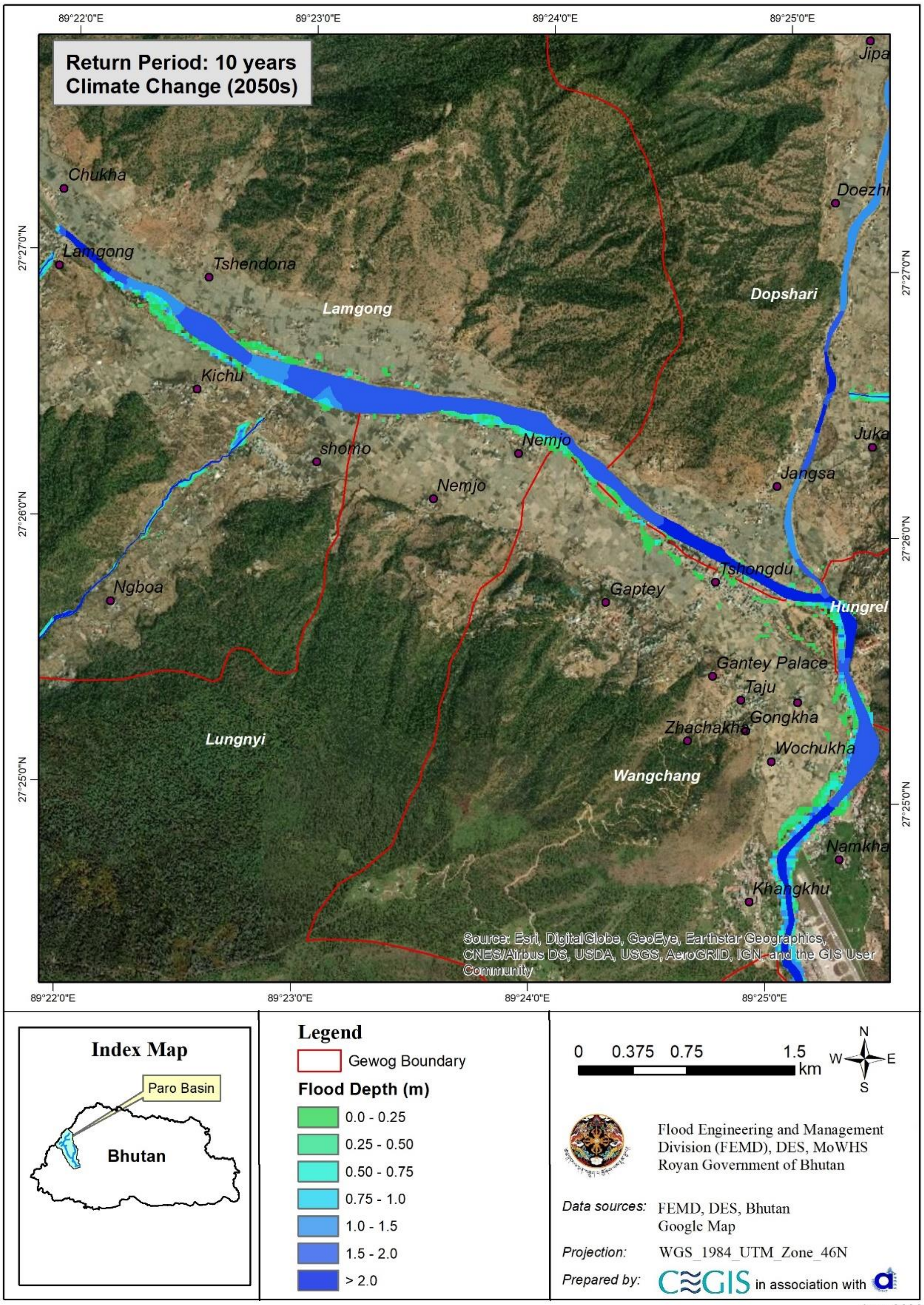
Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



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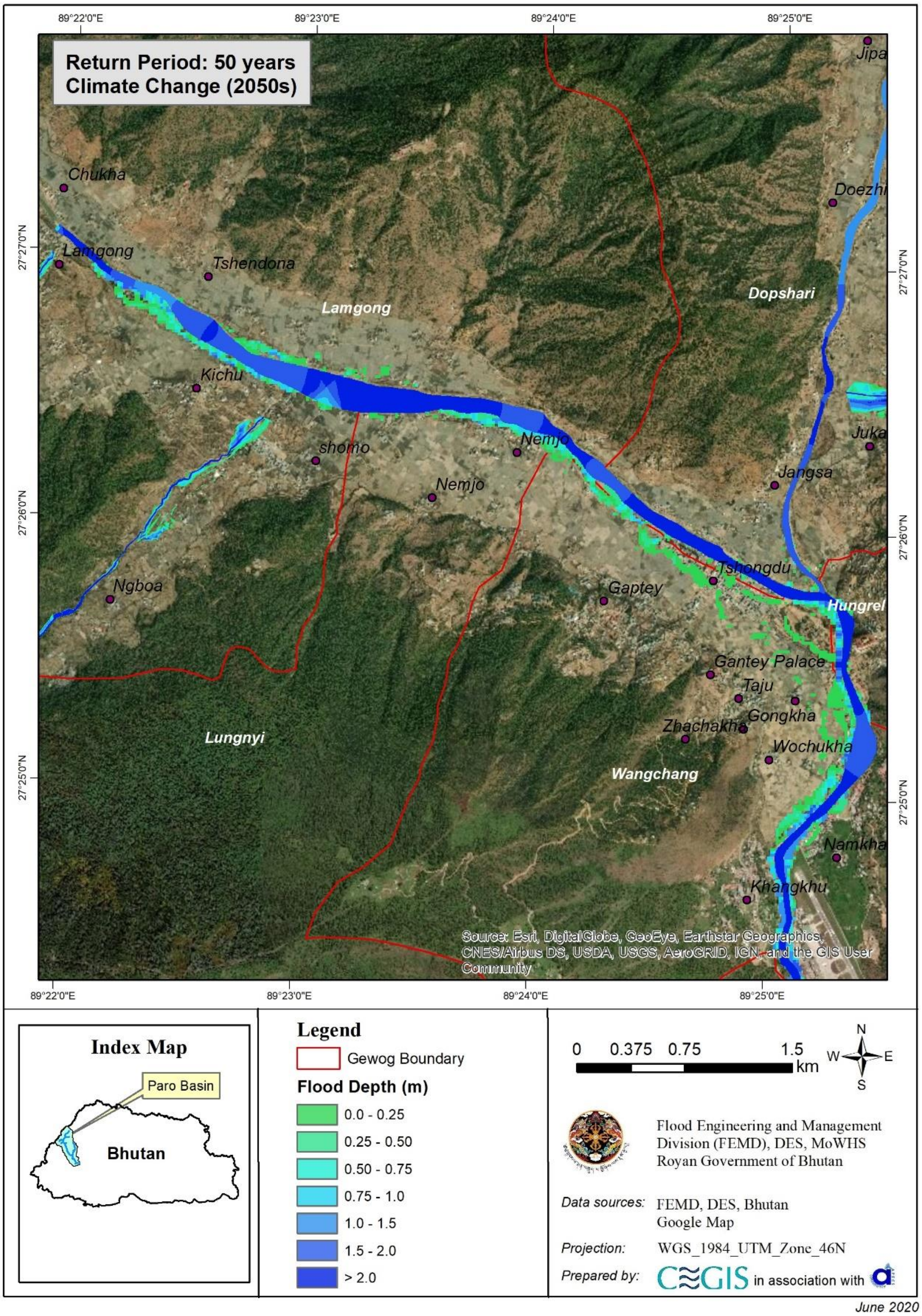
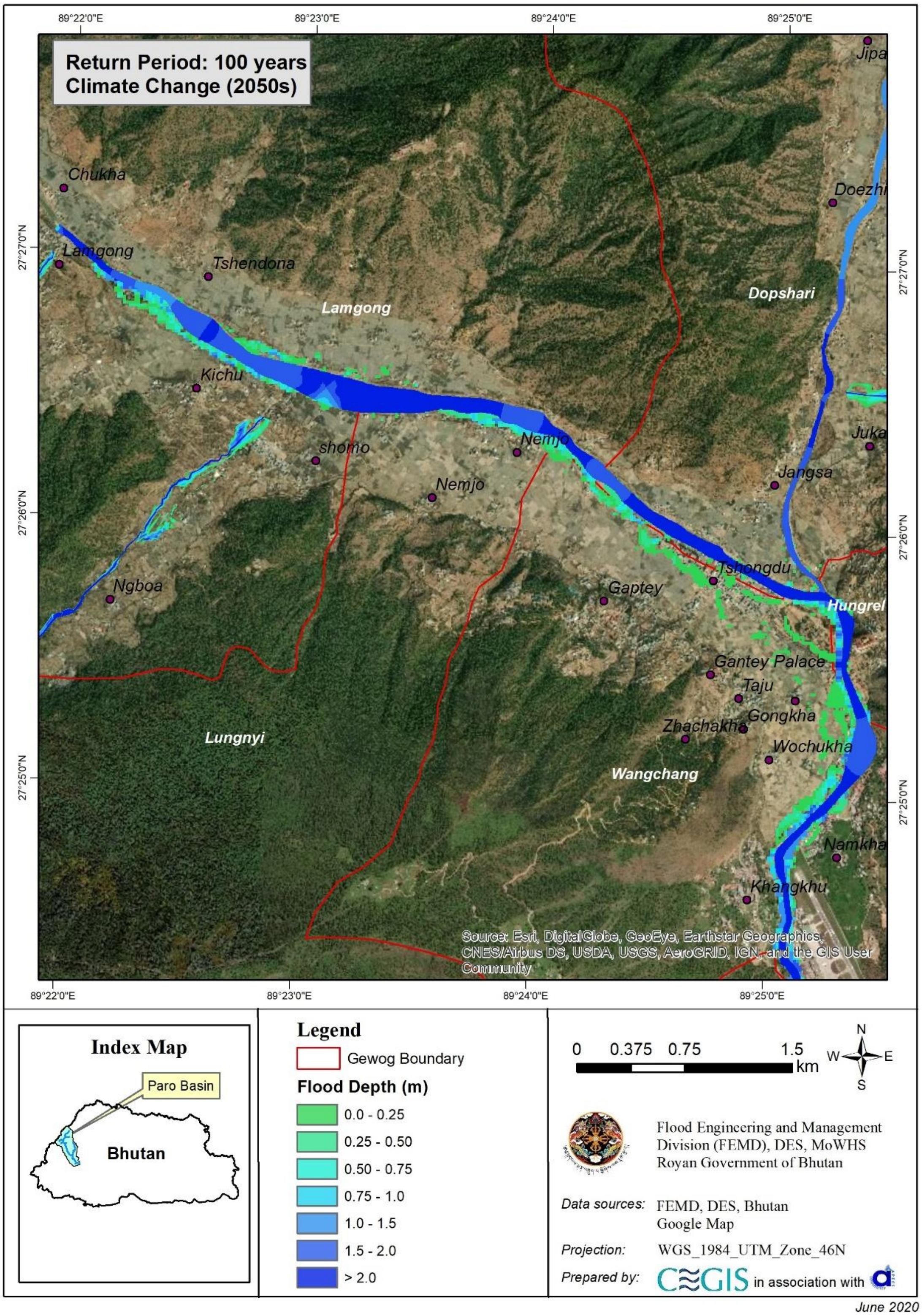
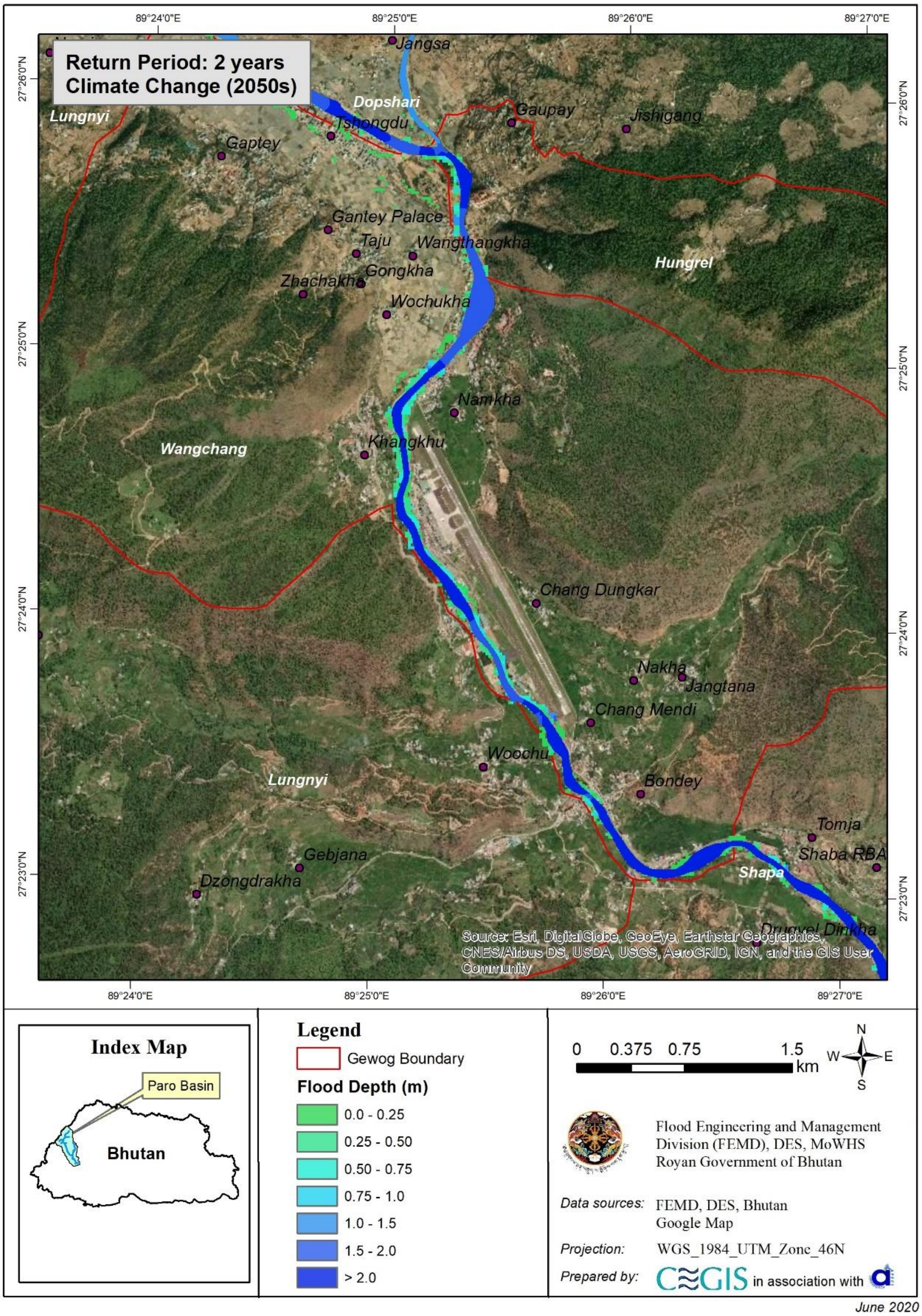


Flood Depth and Extent Map for Pa Chu (Lamgong - Wanchang Gewog)



Flood Depth and Extent Map for the Pa Chu (Hungrel - Shapa Gewog)



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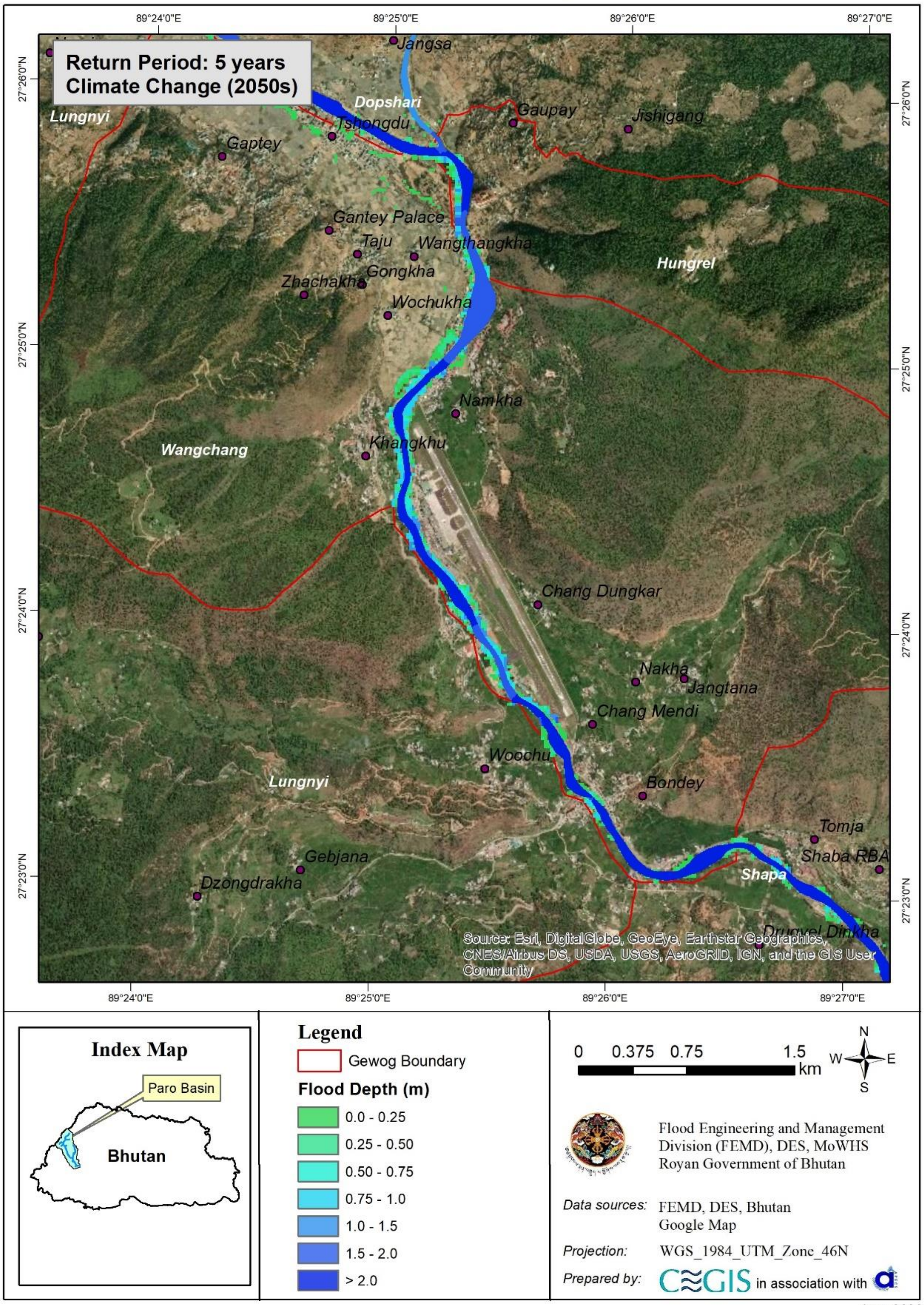

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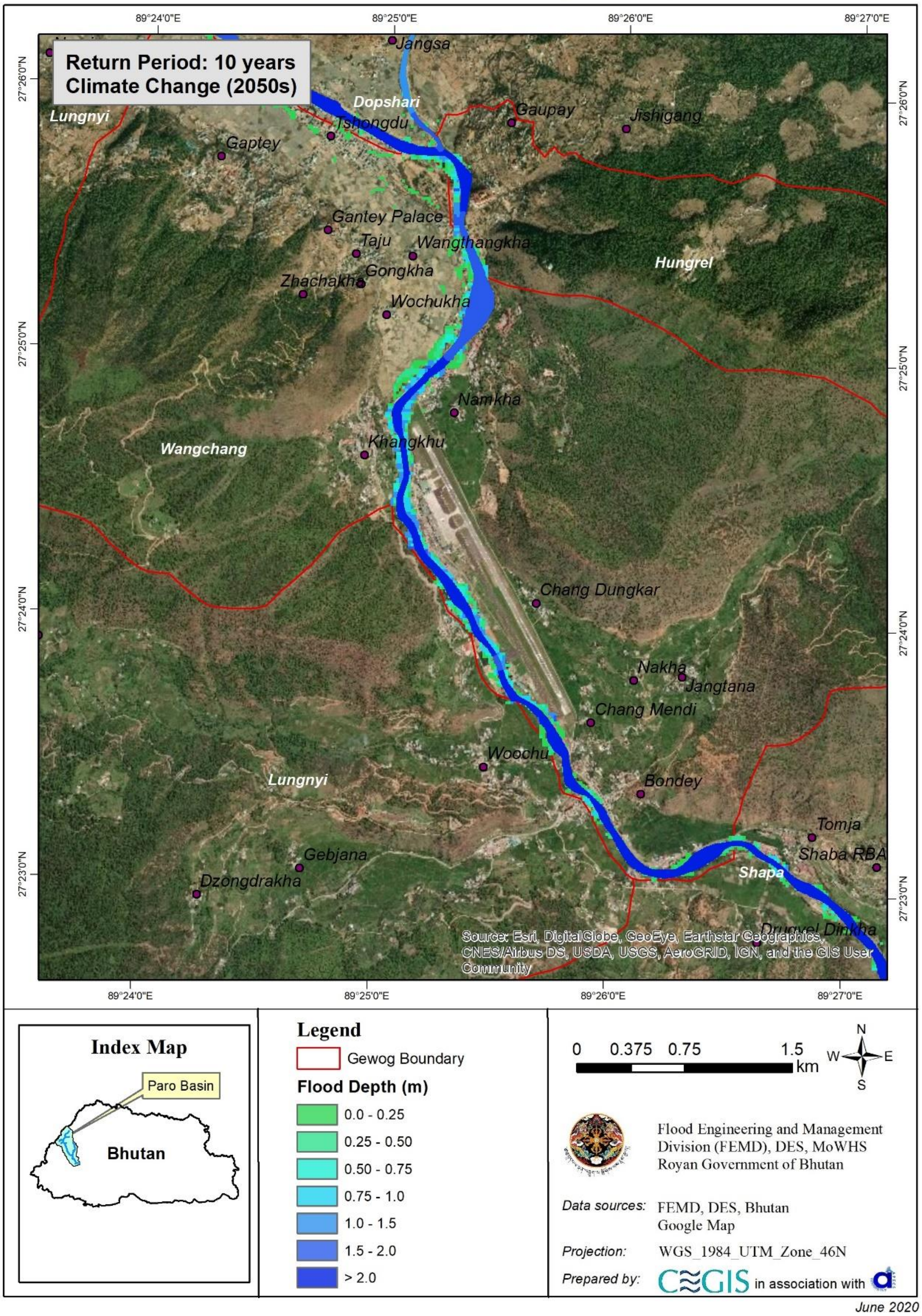

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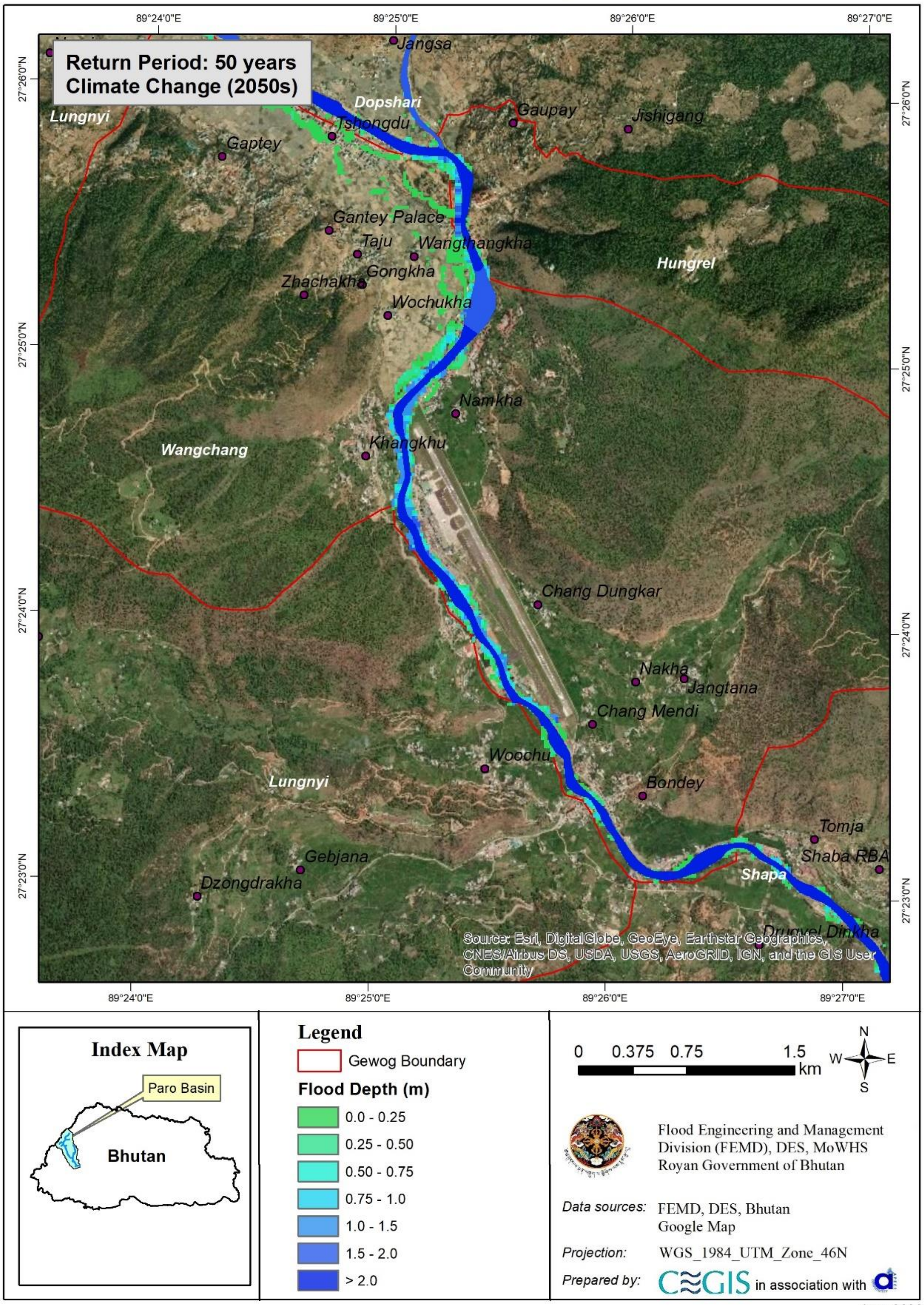

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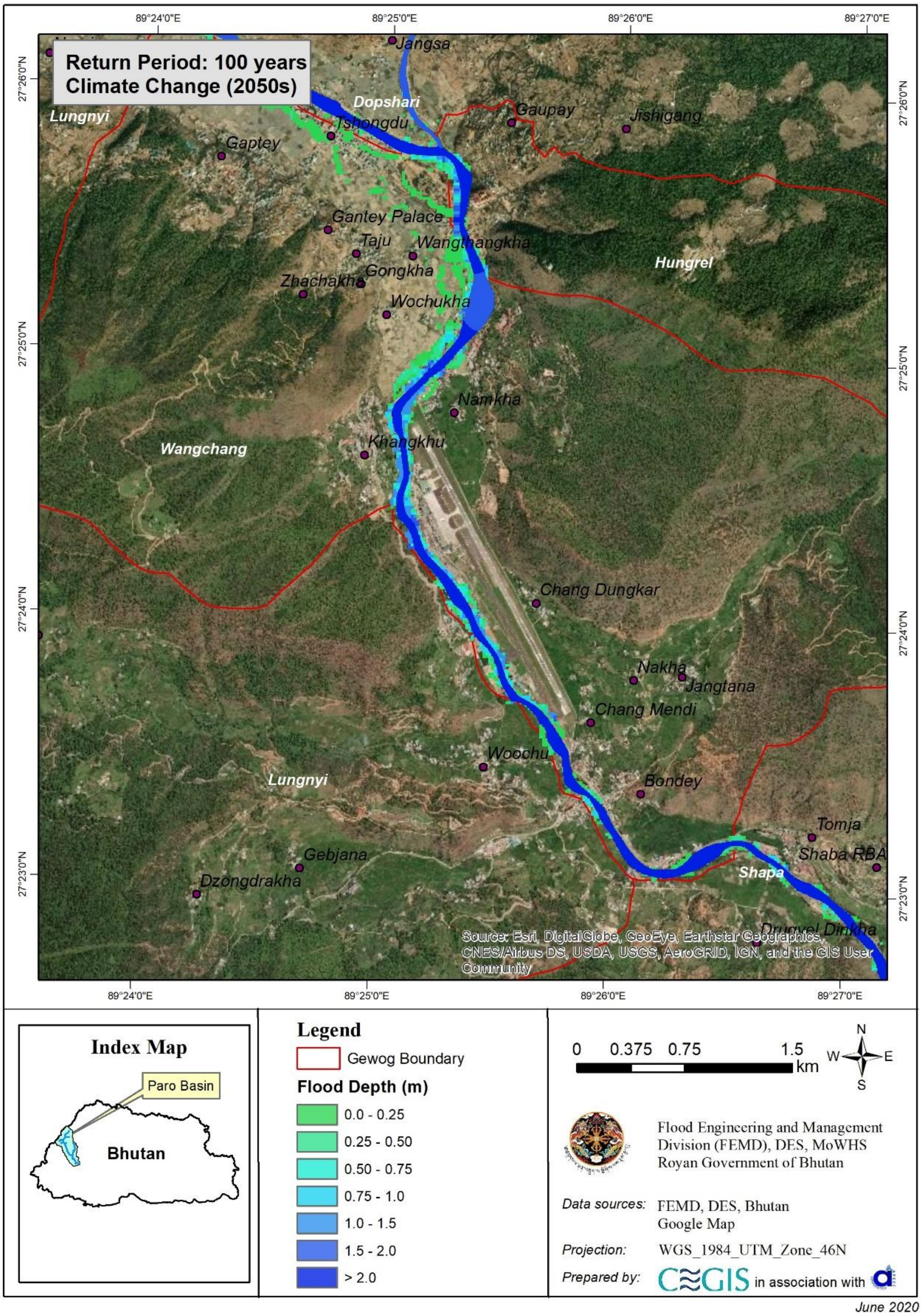

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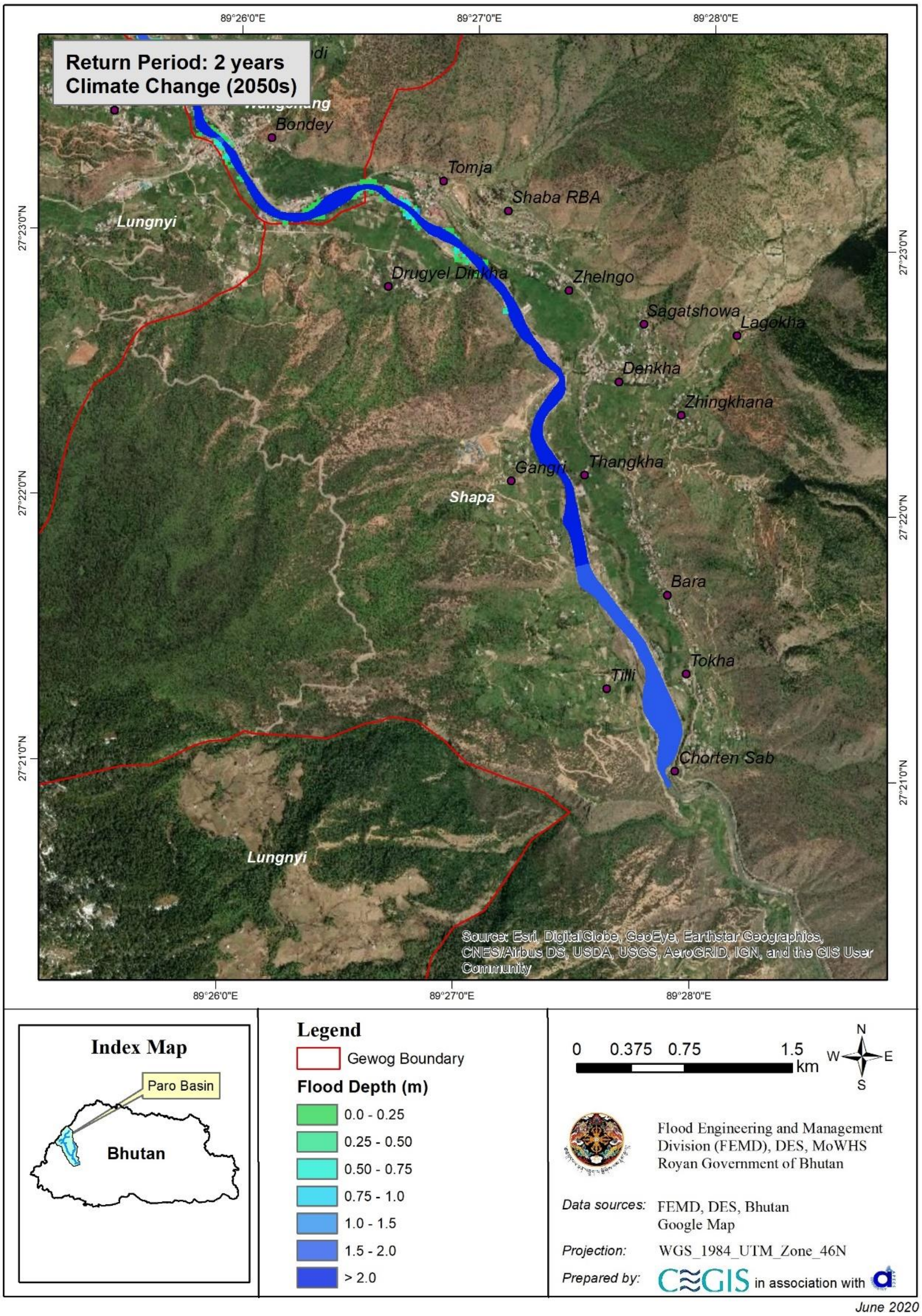

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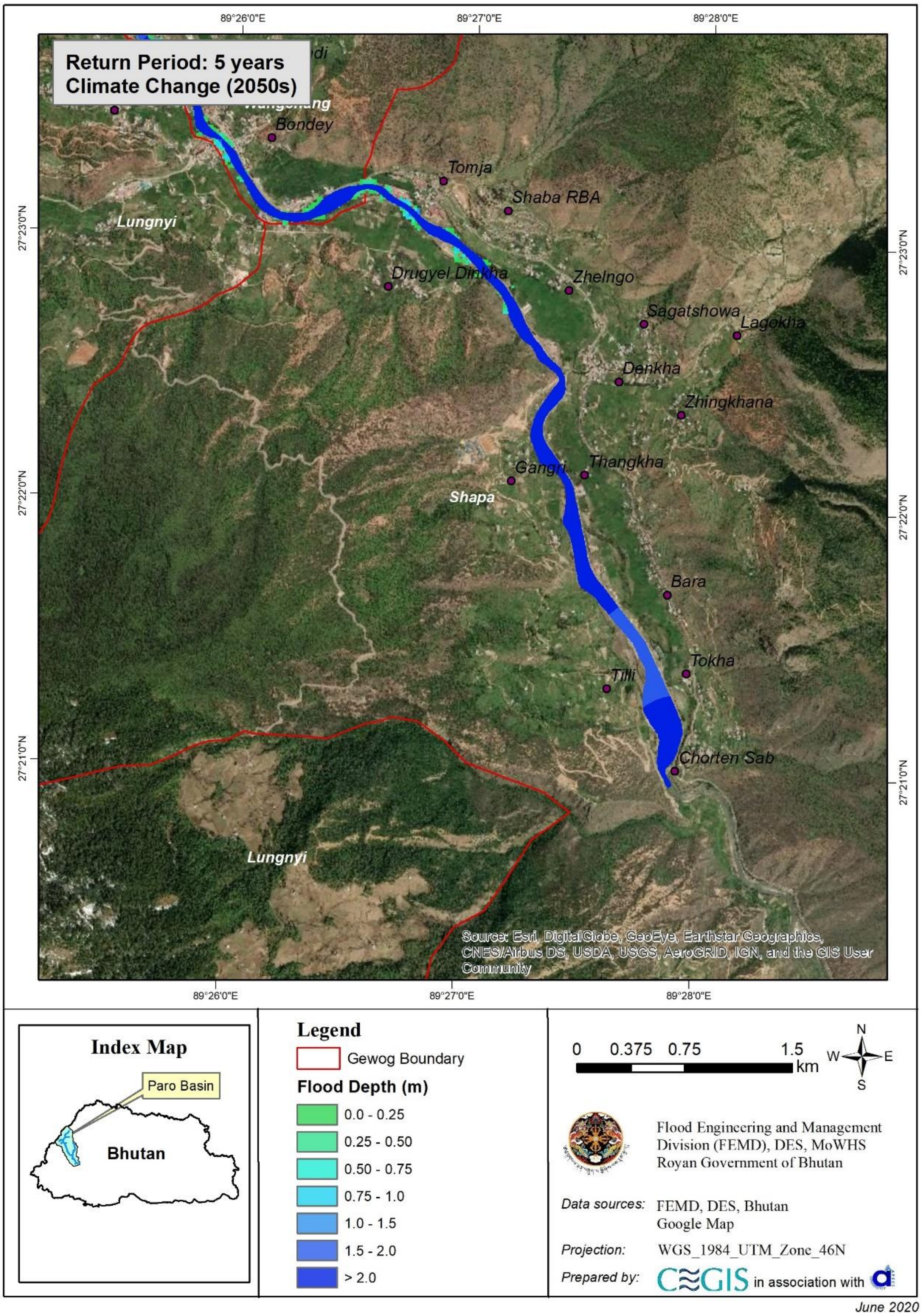

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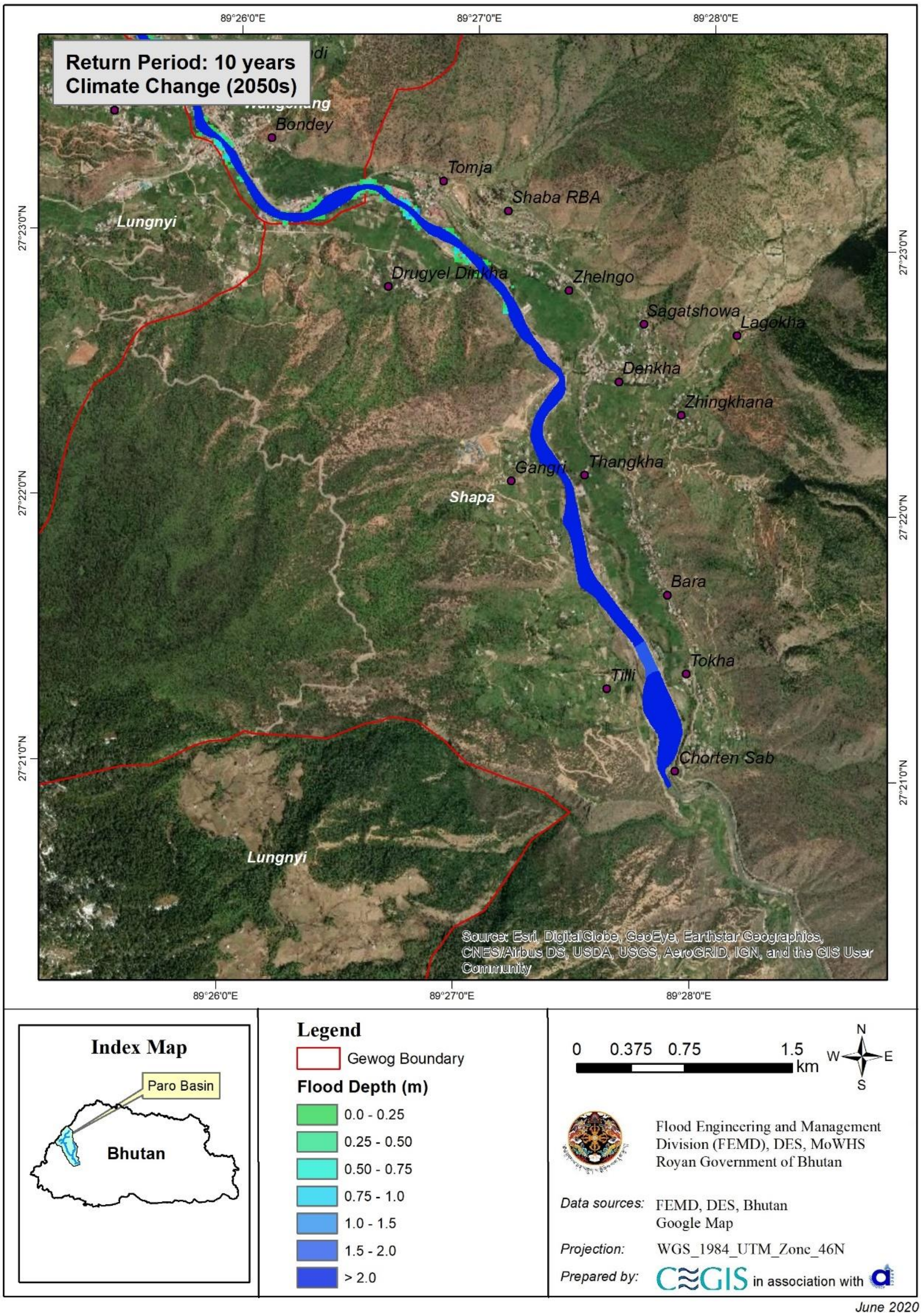

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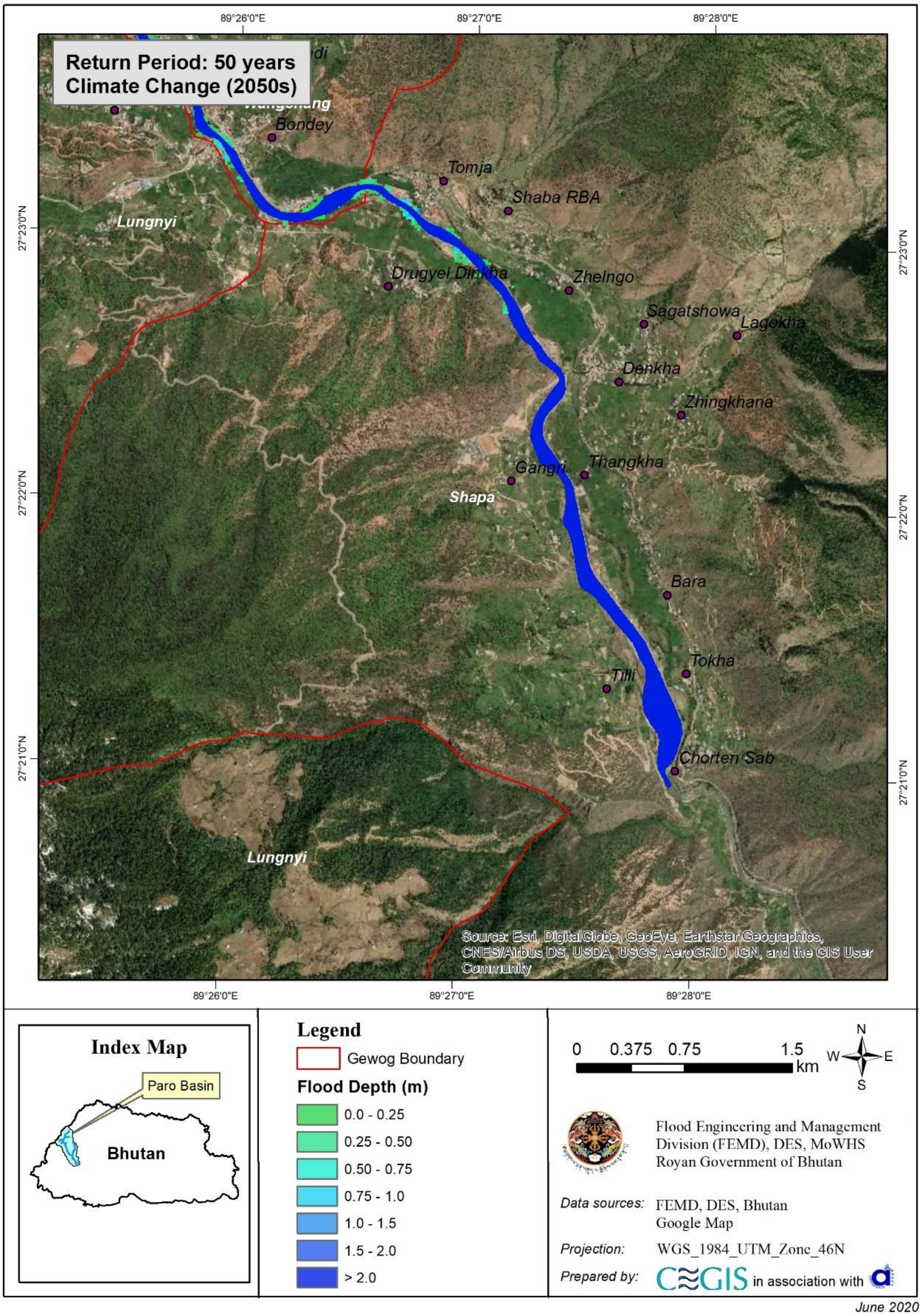

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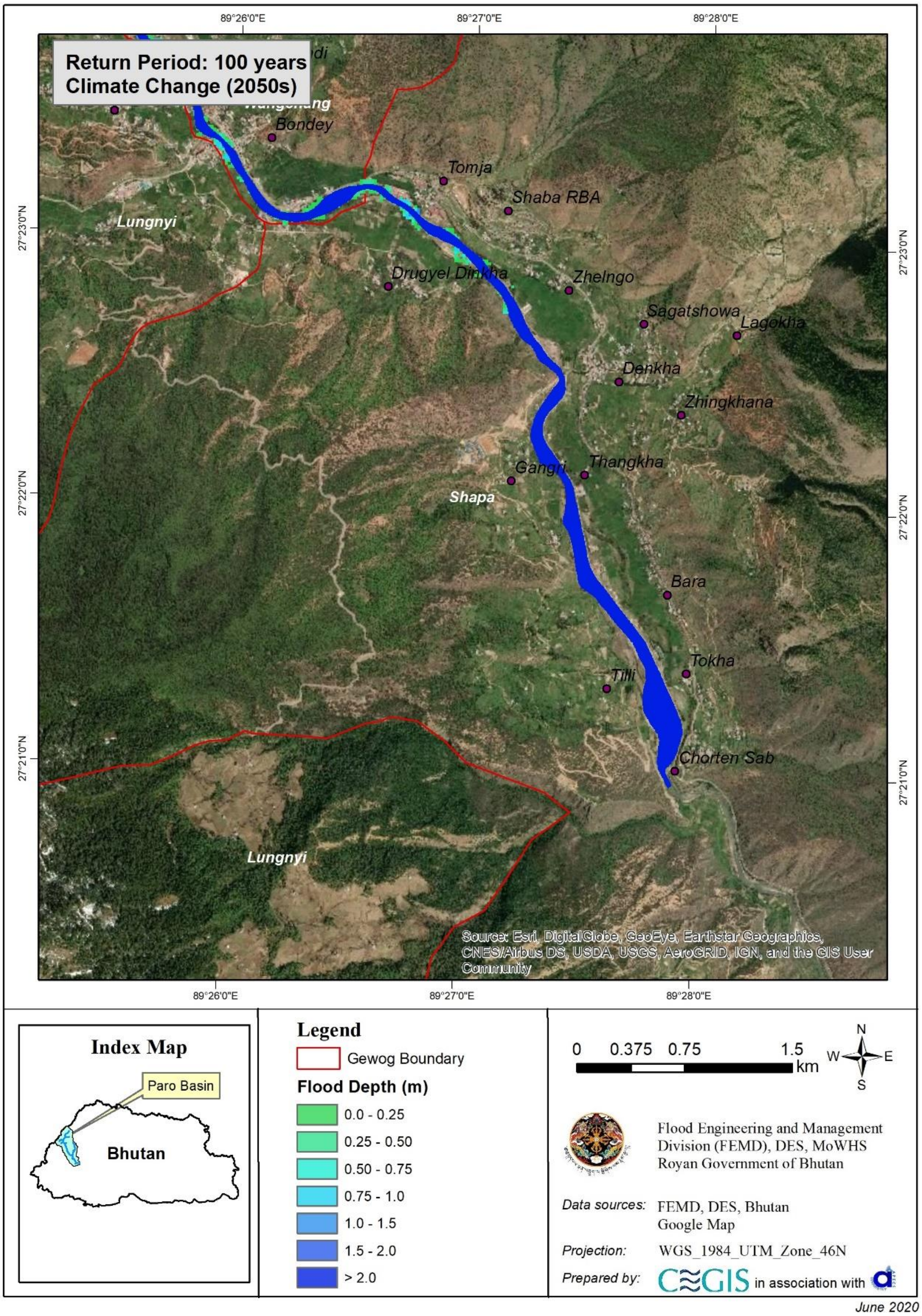
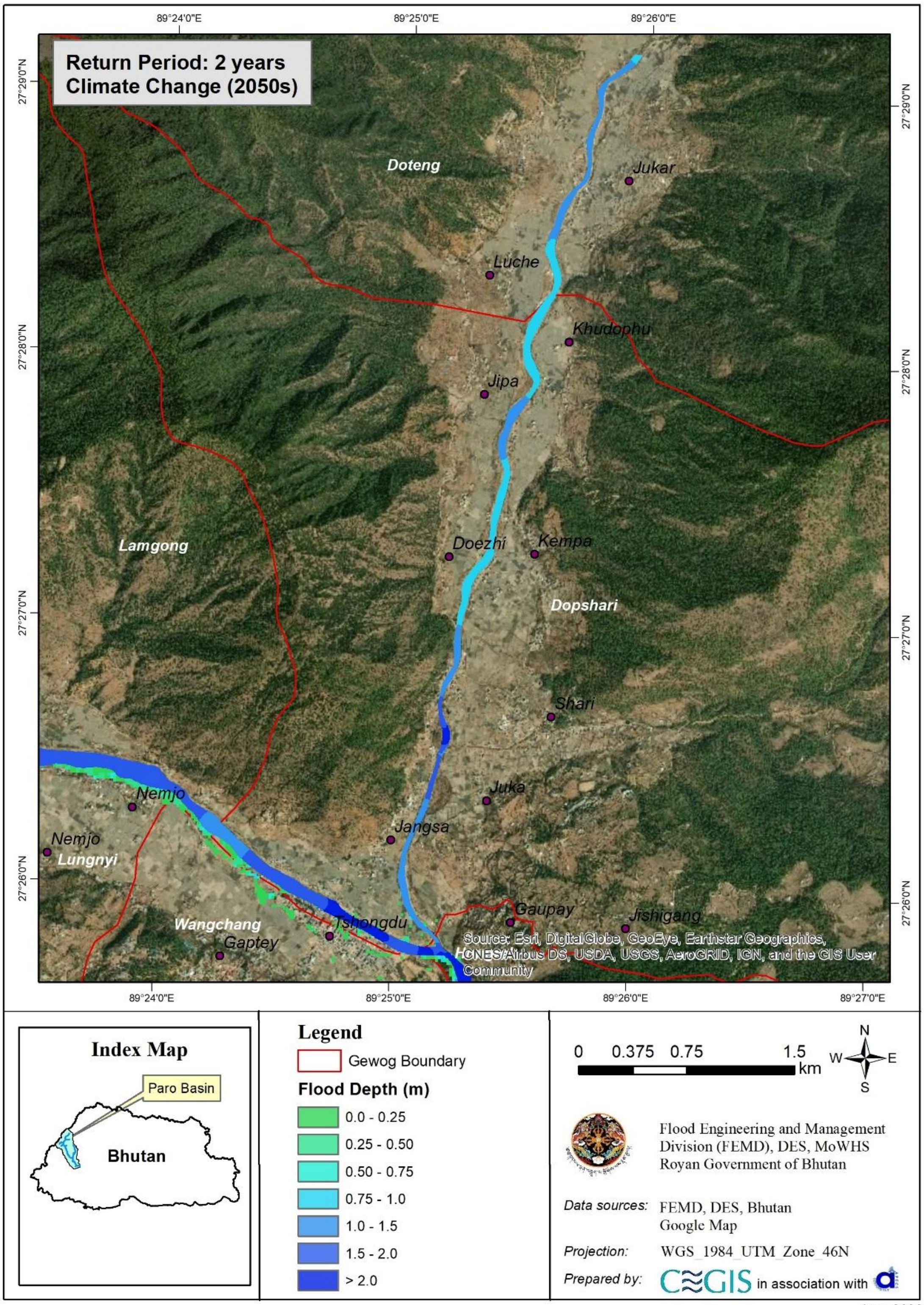


Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



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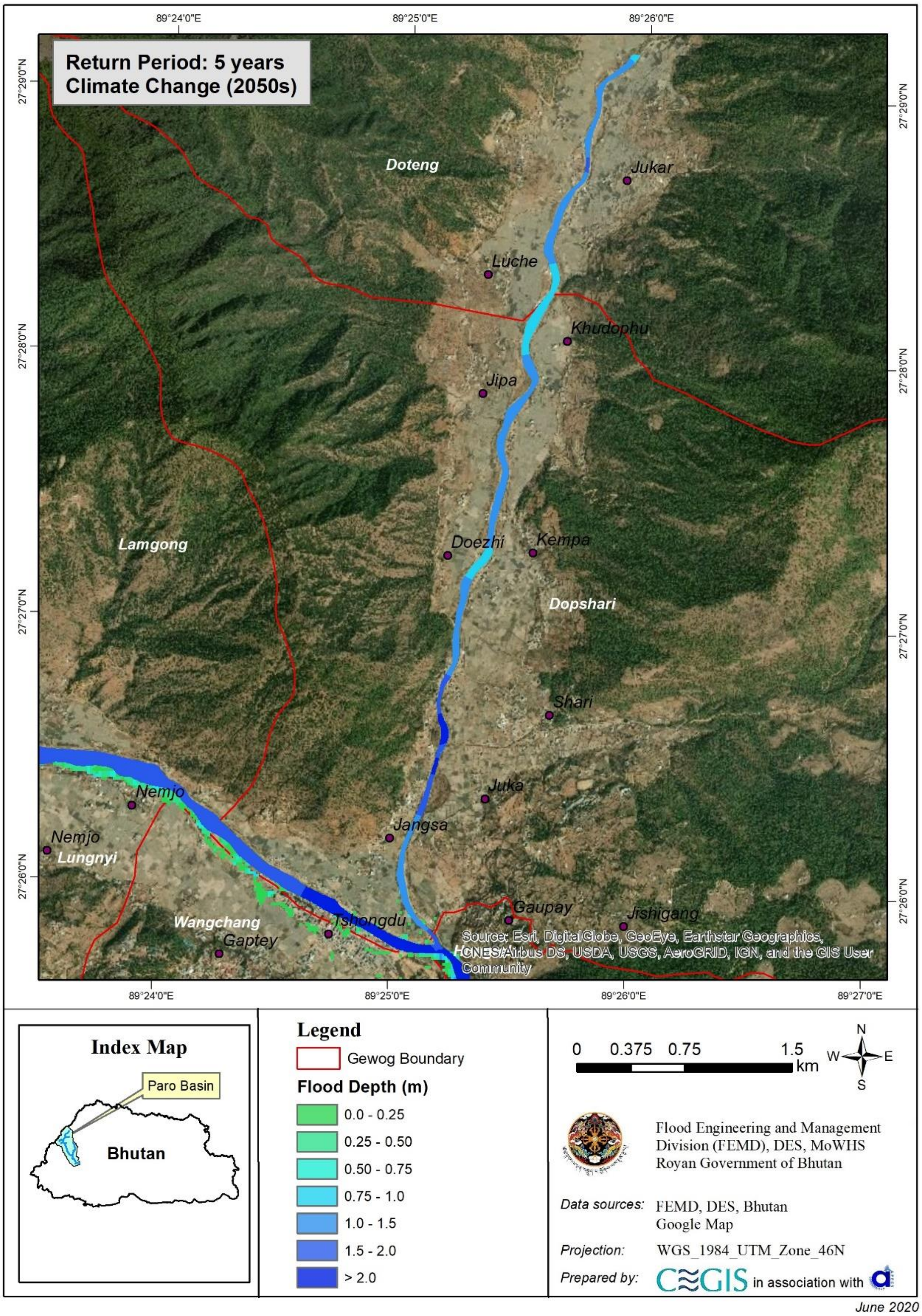
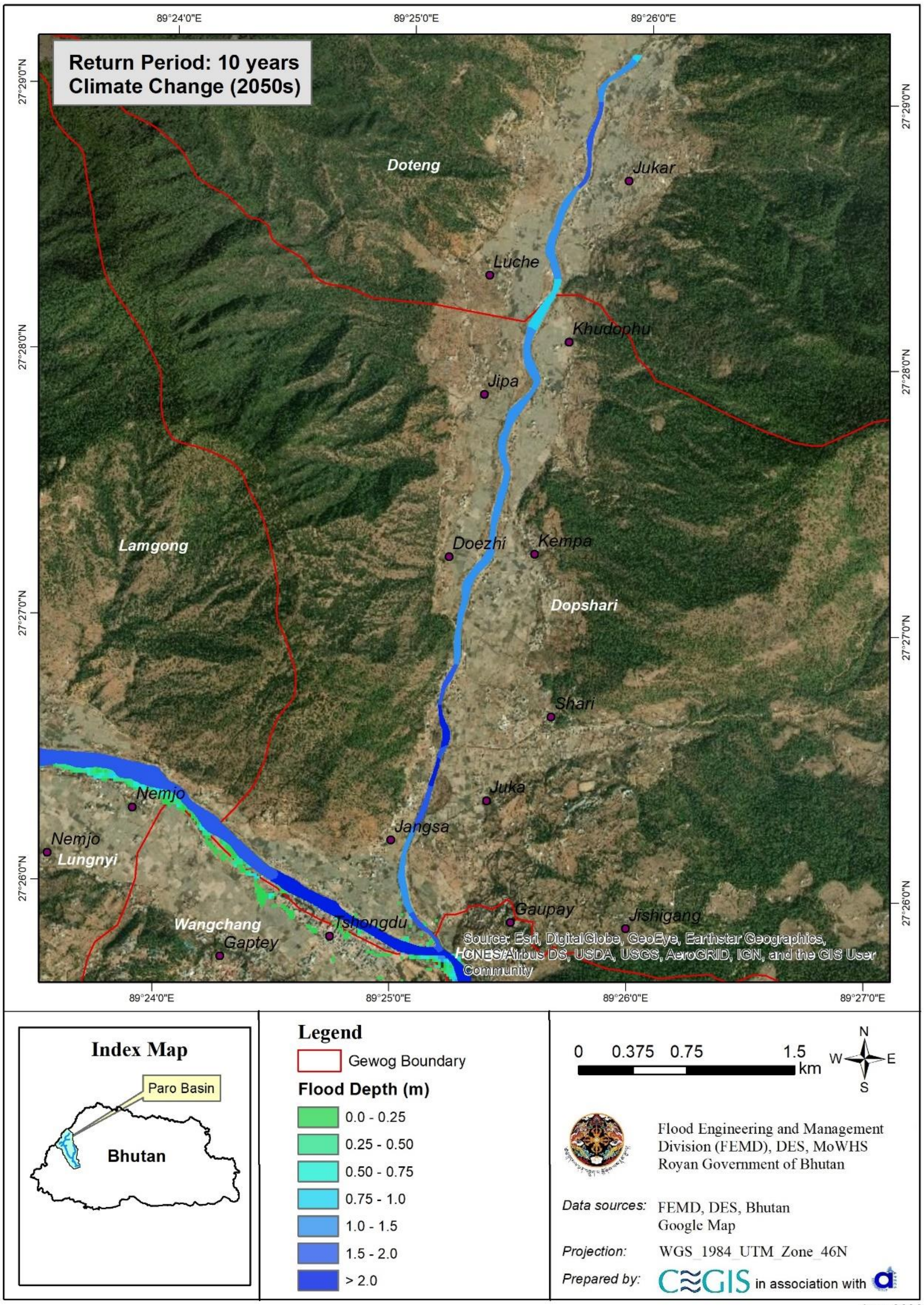
Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



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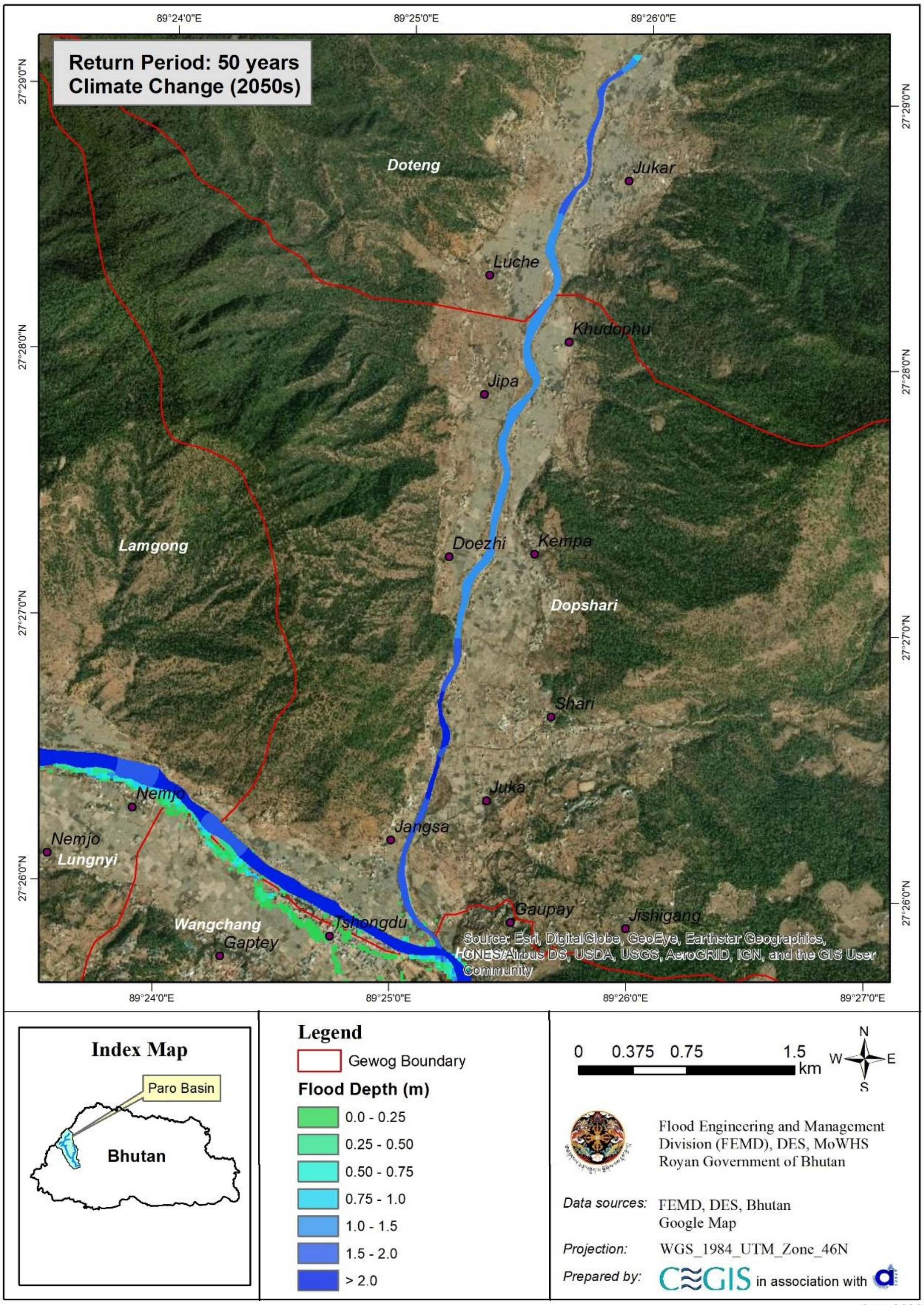
Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



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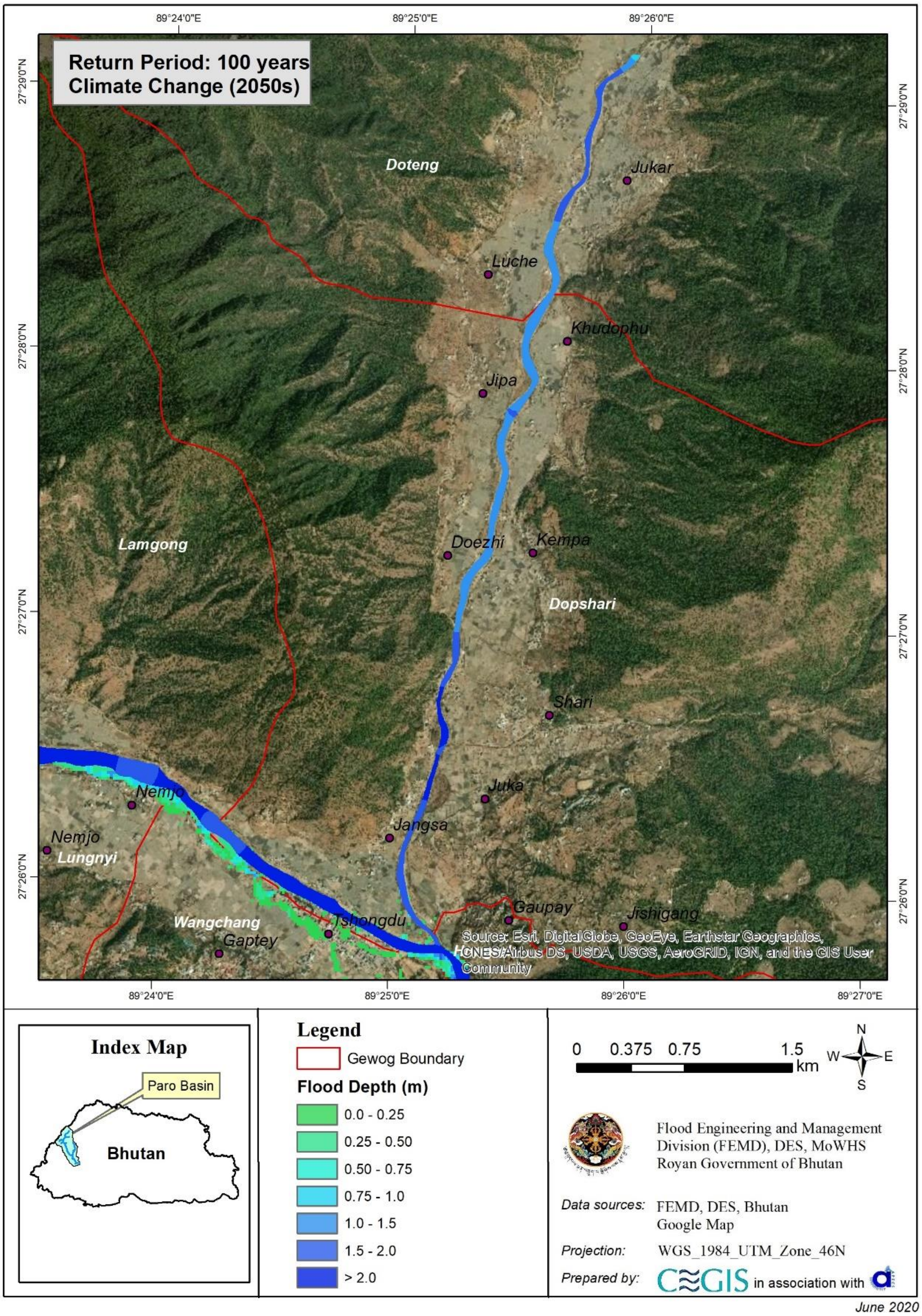
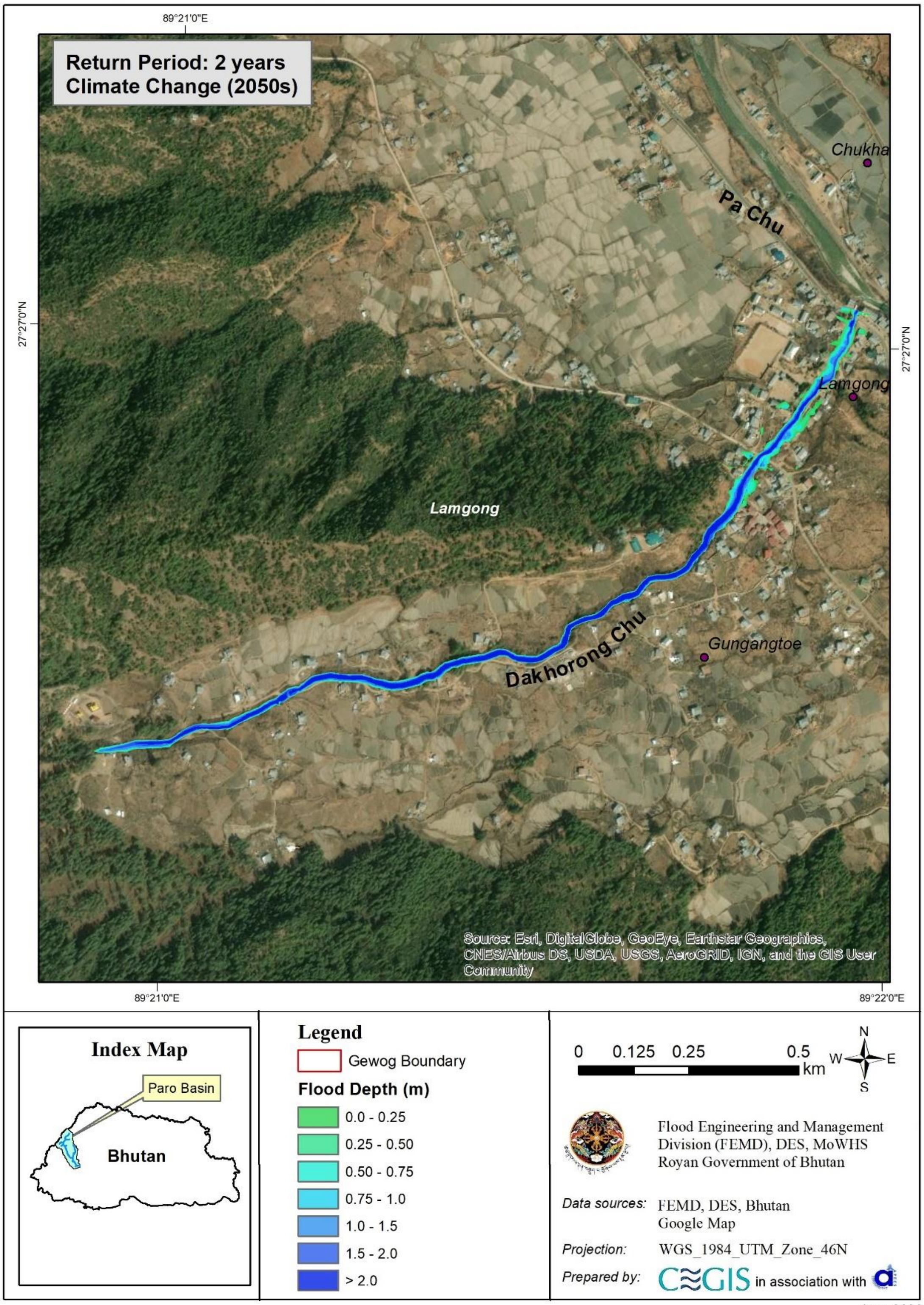
Flood Depth and Extent Map for Do Chu (Doteng and Dopshari Gewog)



Flood Depth and Extent Map for Dakhorong Chu



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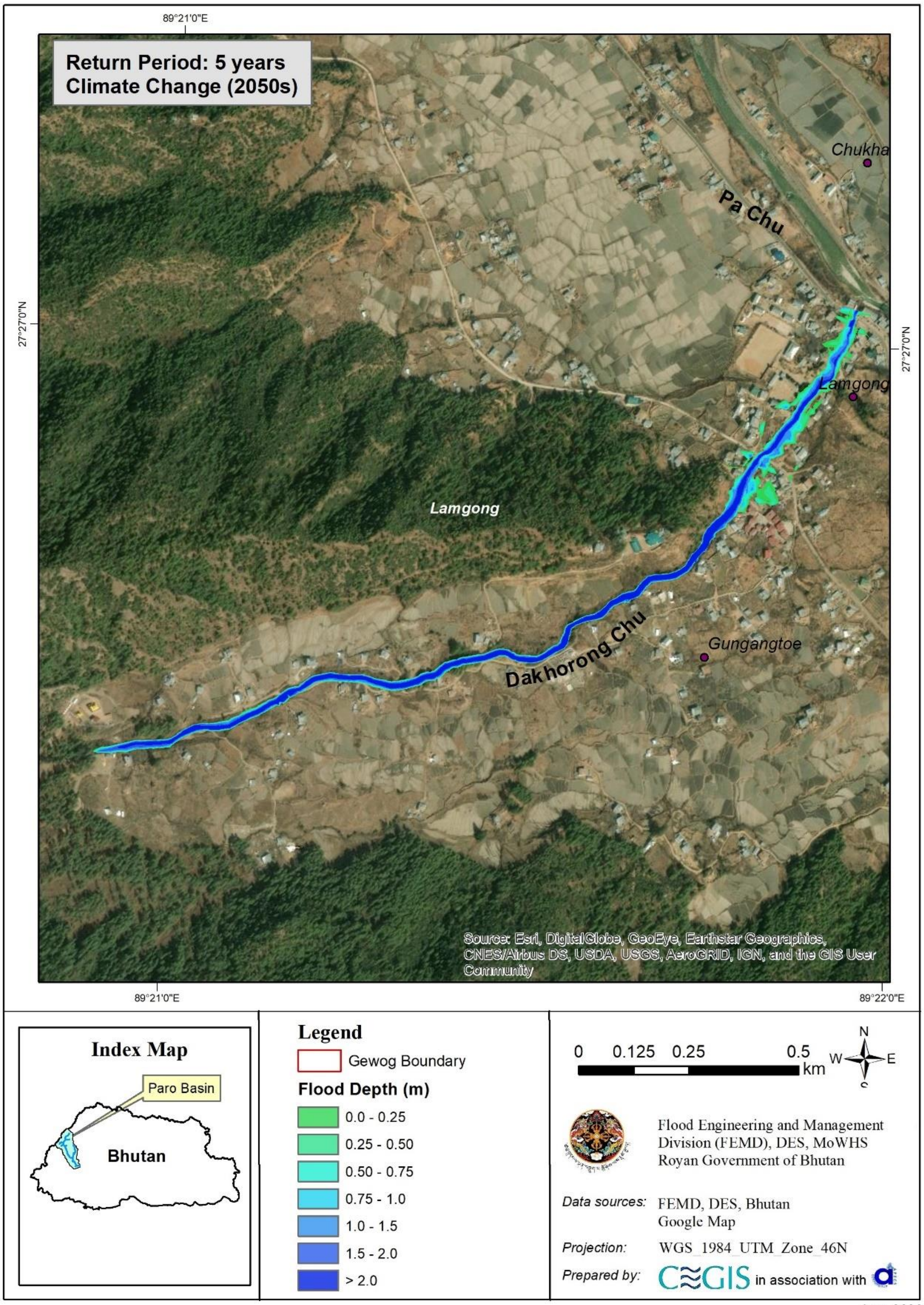
Flood Depth and Extent Map for Dakhorong Chu



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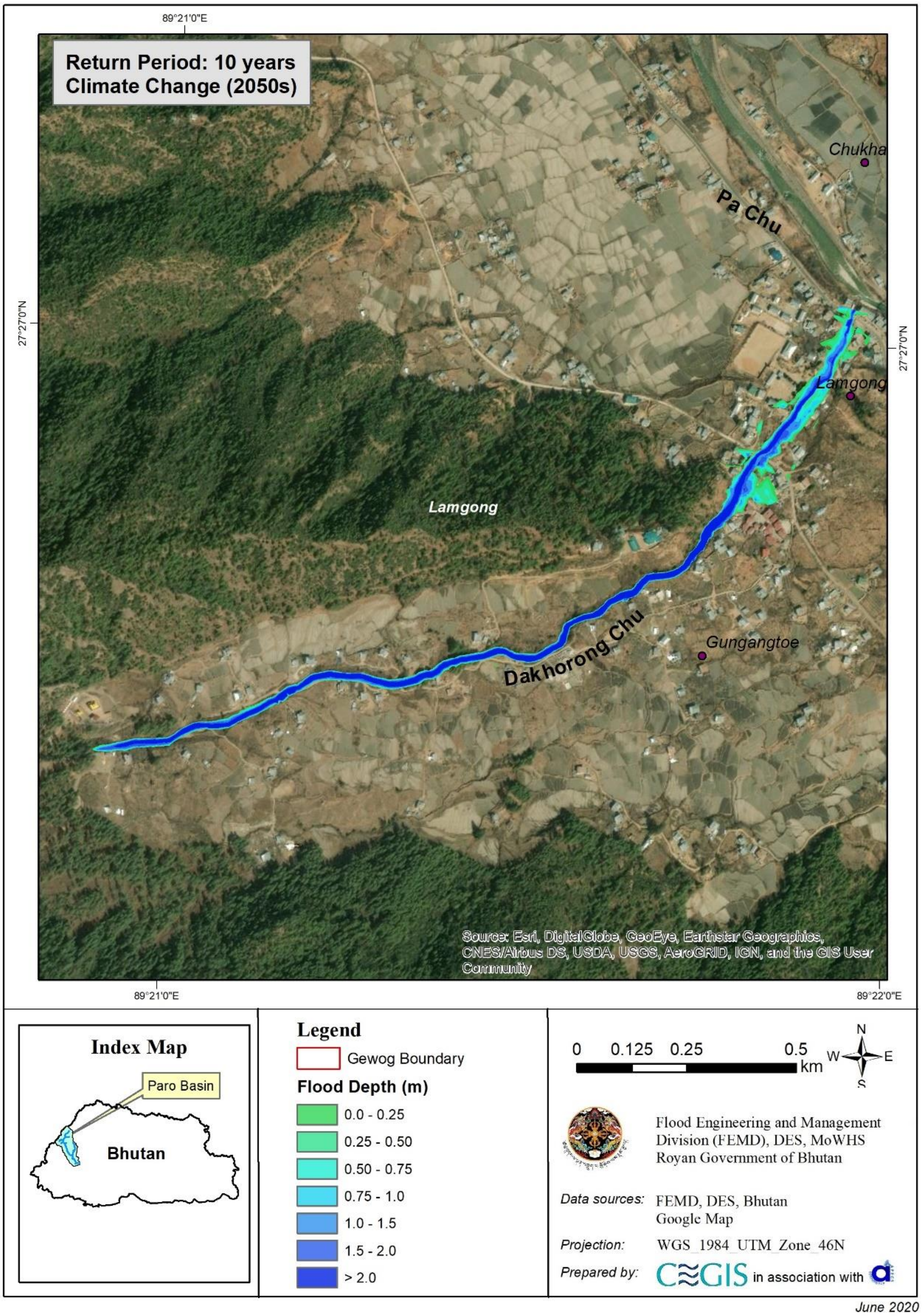
Flood Depth and Extent Map for Dakhorong Chu



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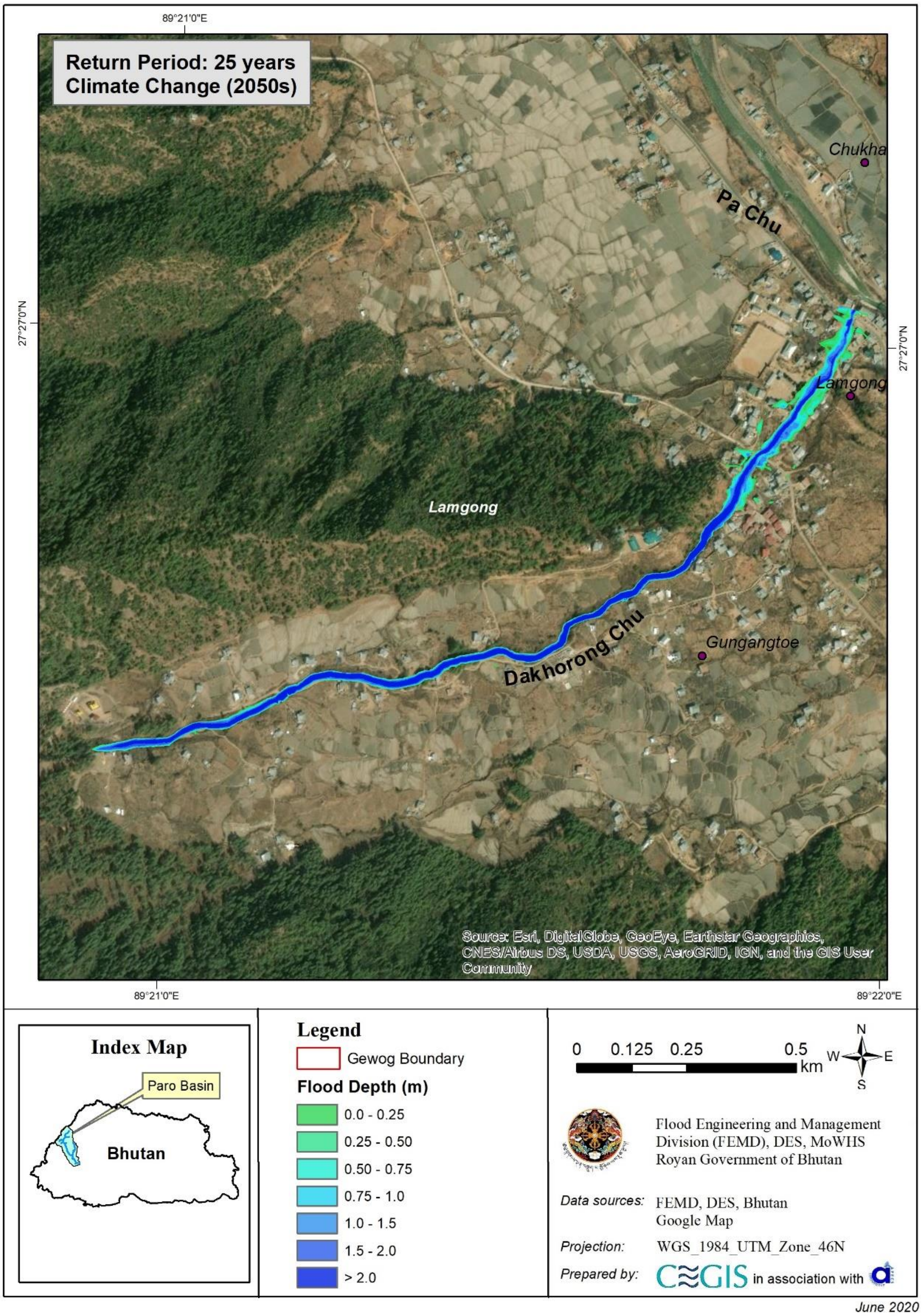

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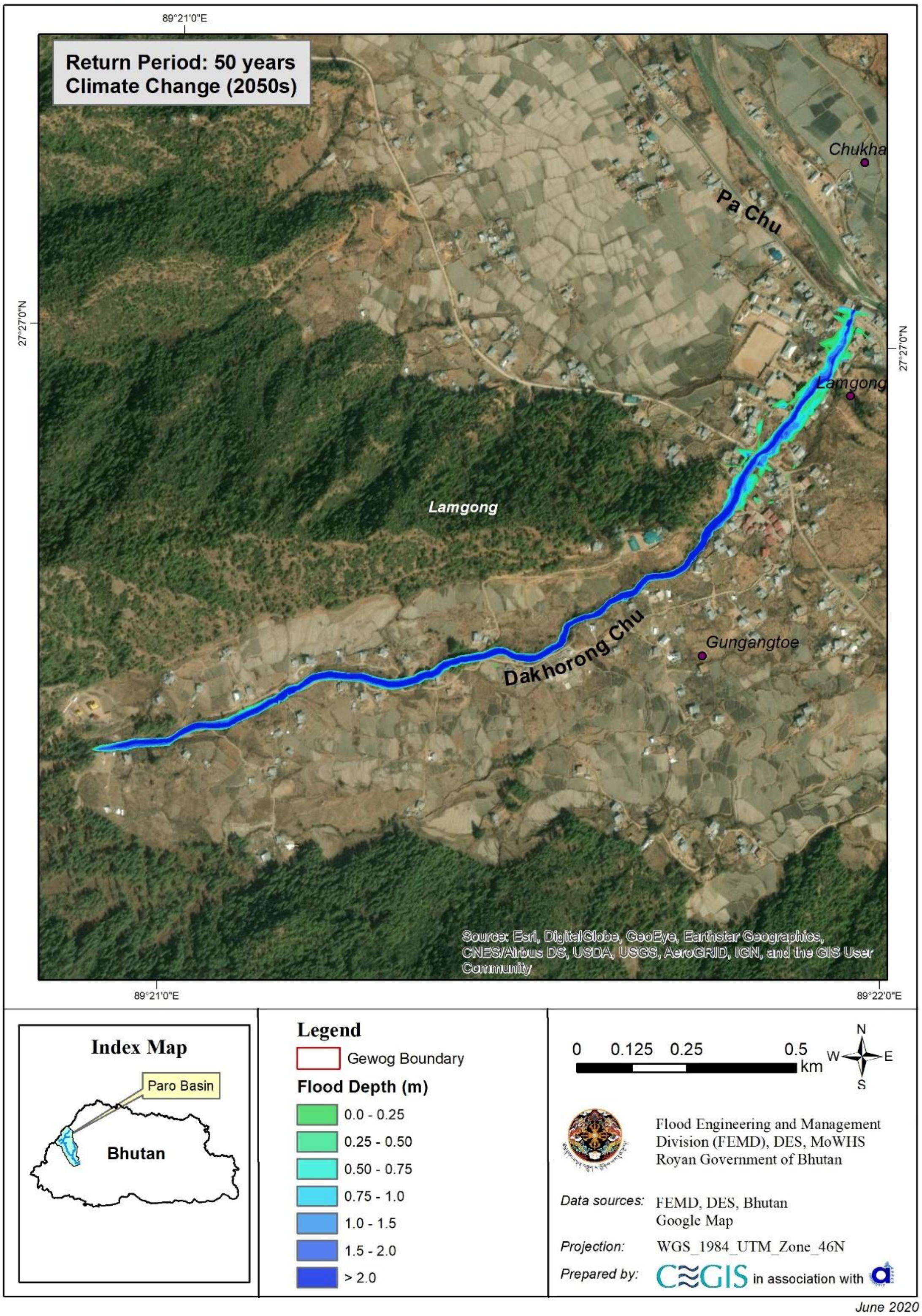

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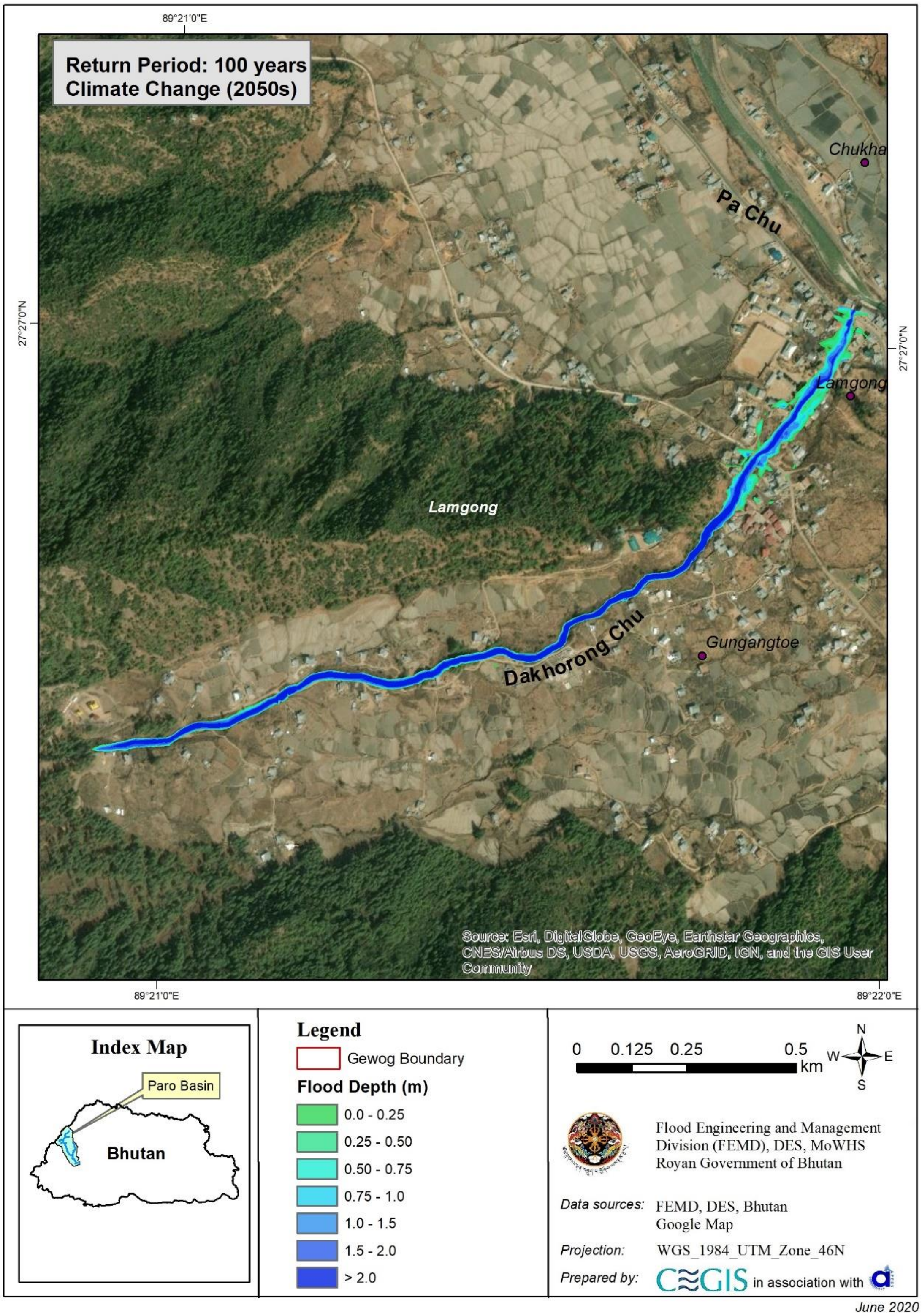
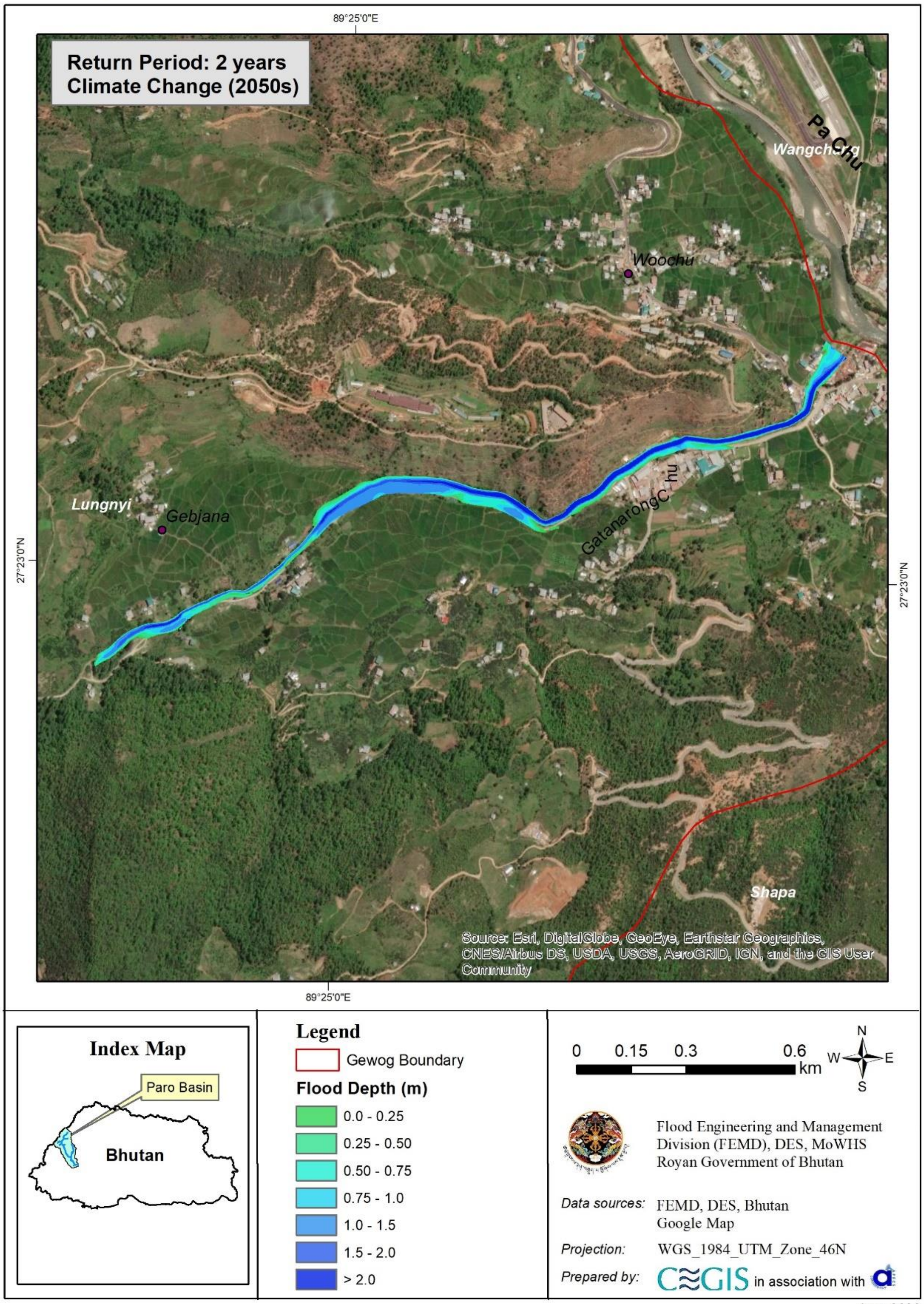


Flood Depth and Extent Map for Gatanarong Chu



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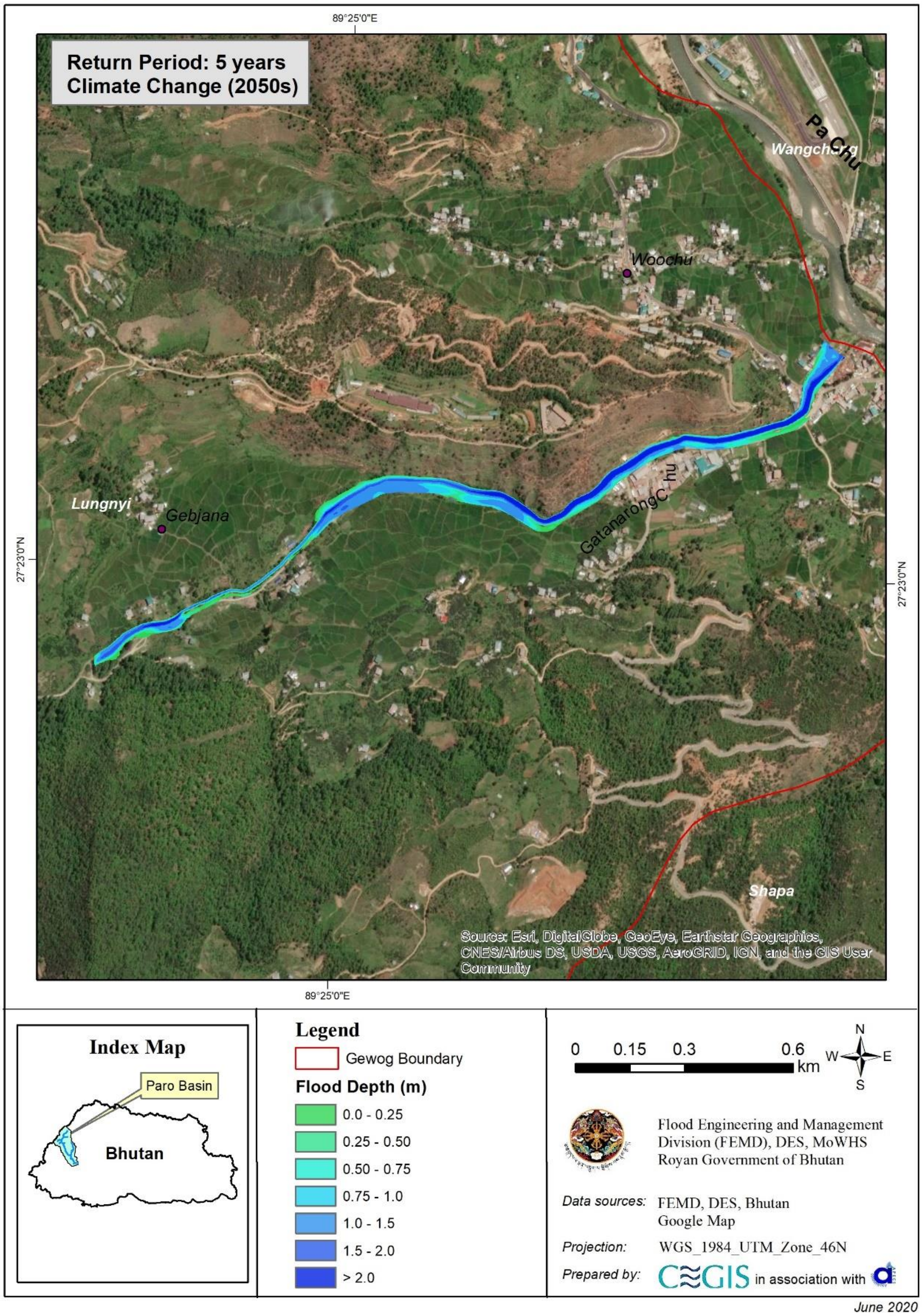
Flood Depth and Extent Map for Gatanarong Chu



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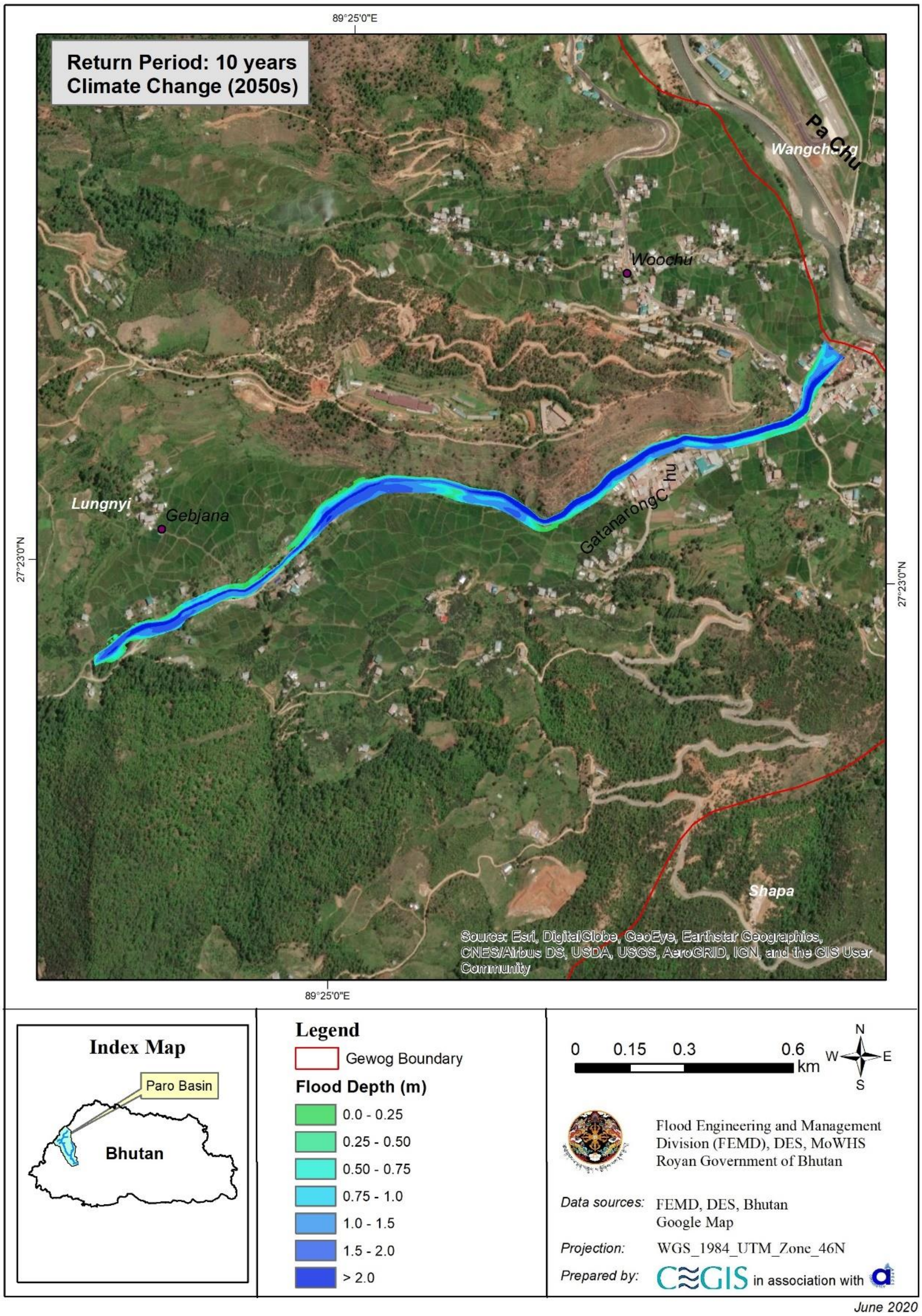

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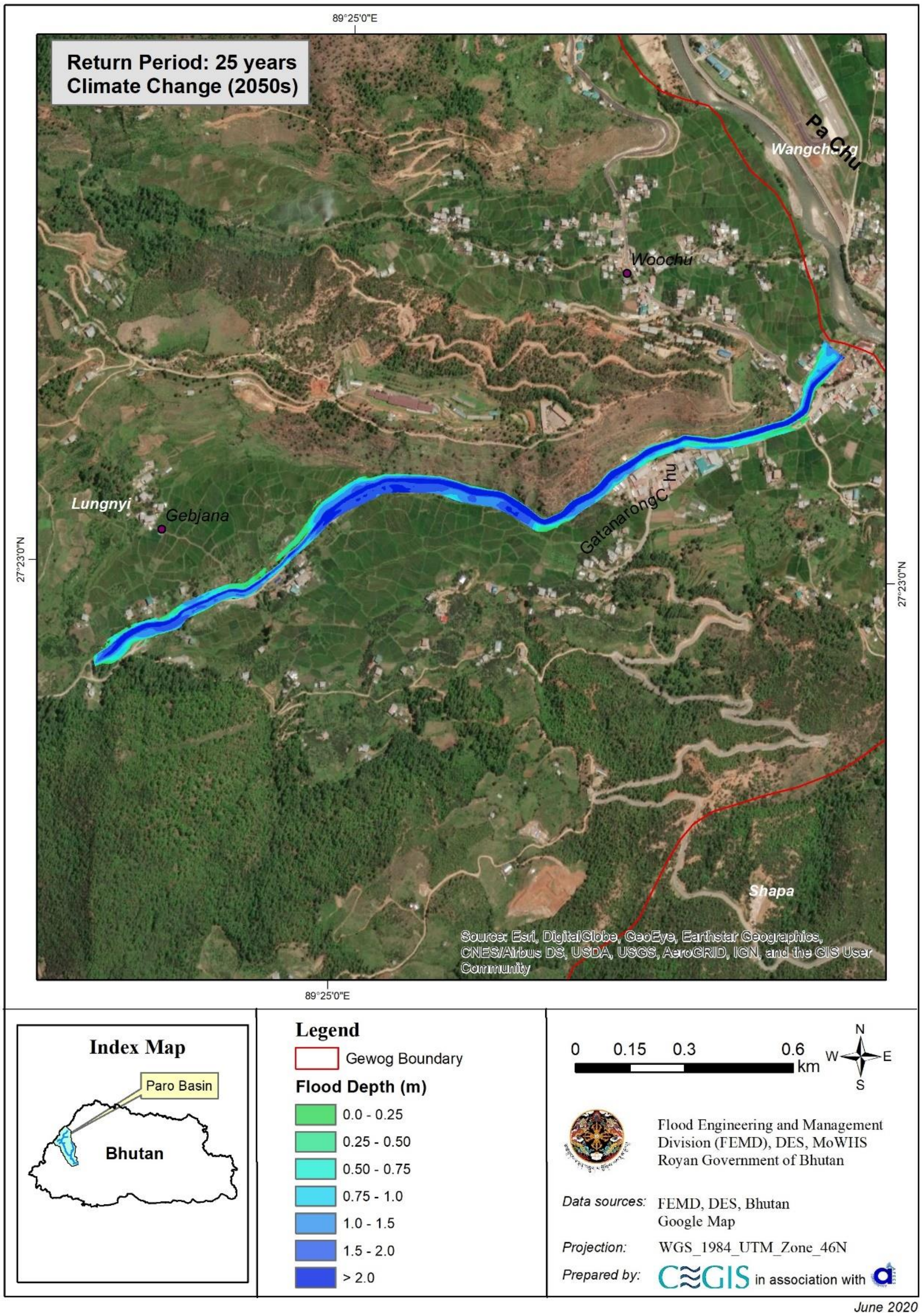

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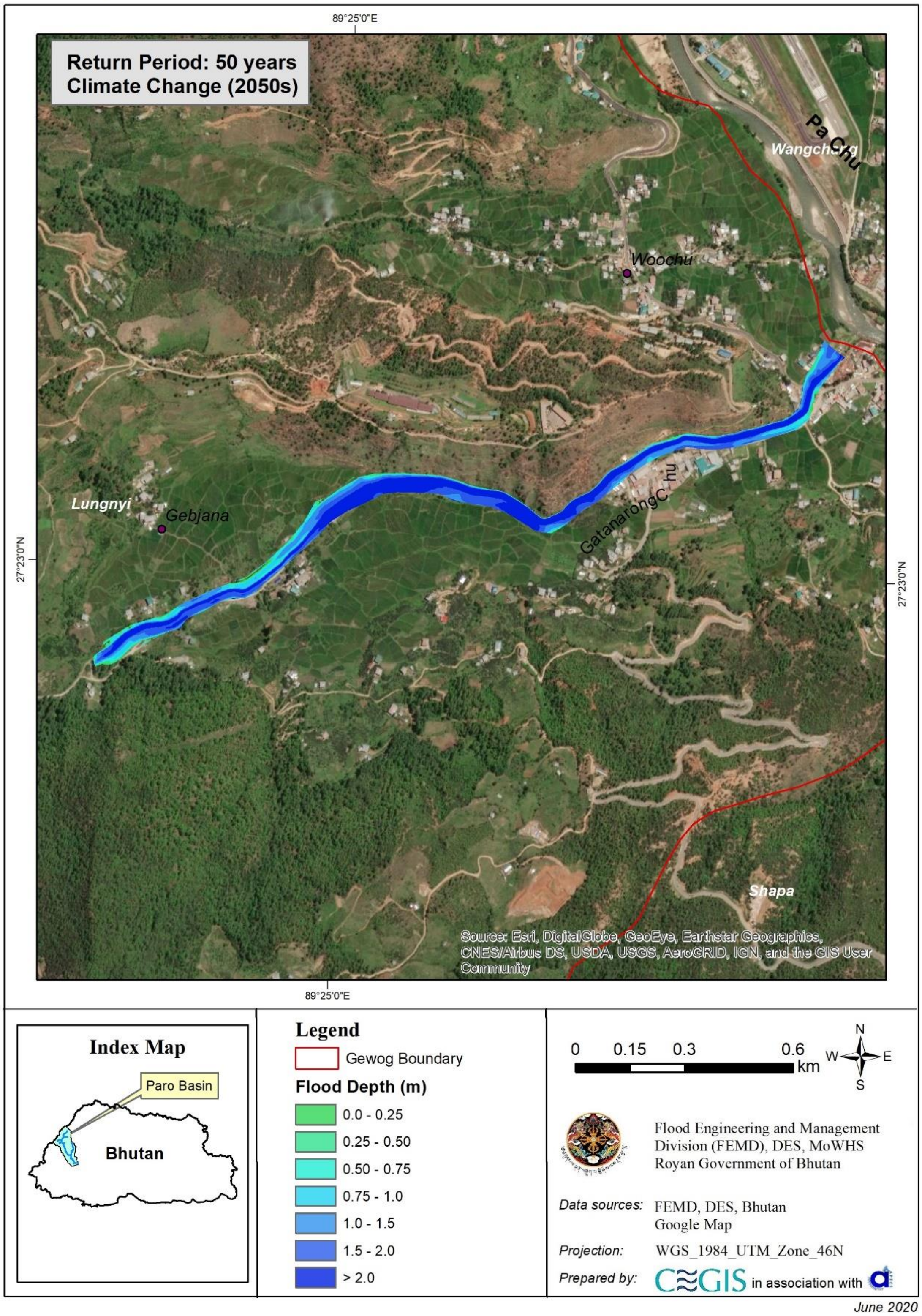

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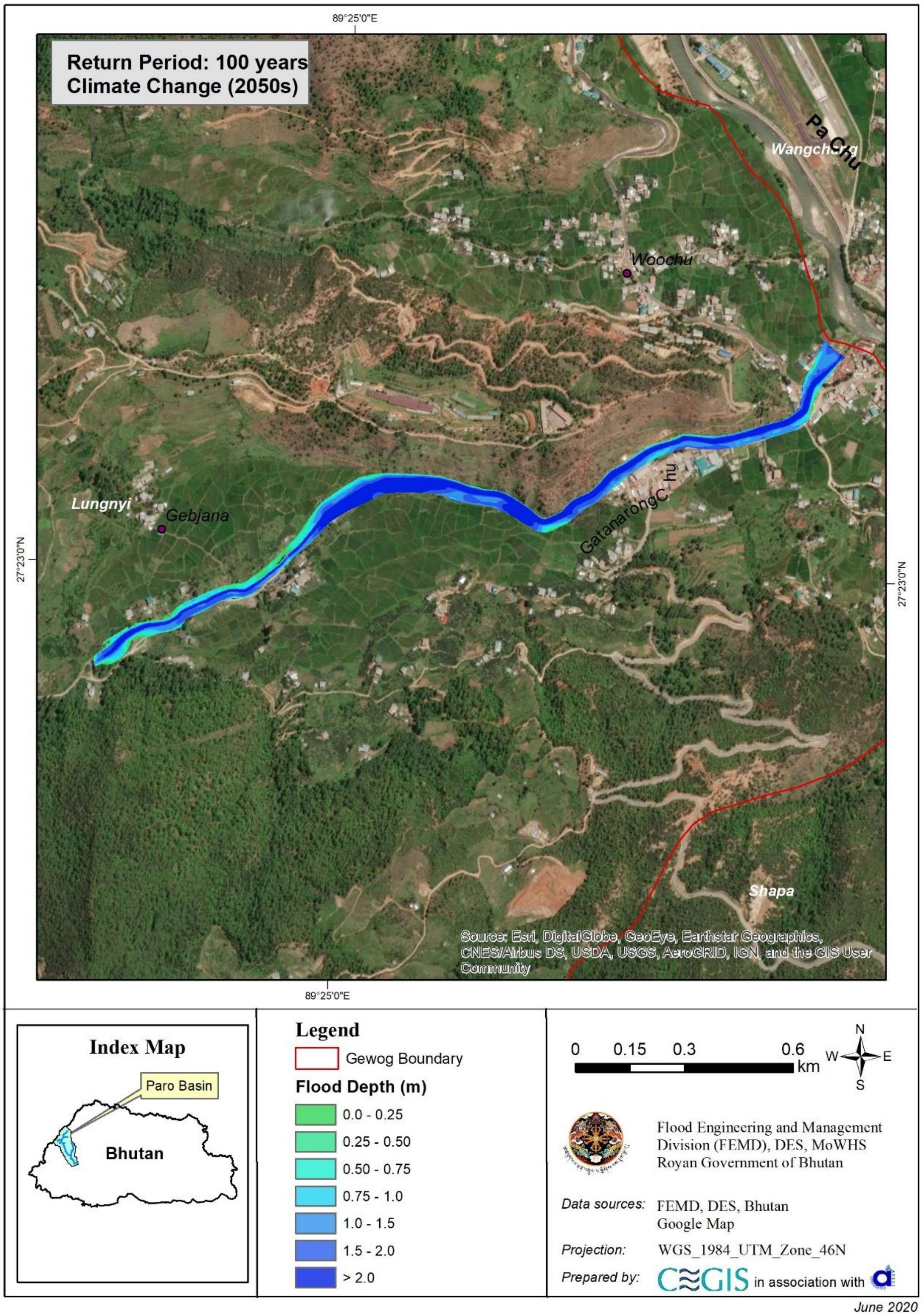
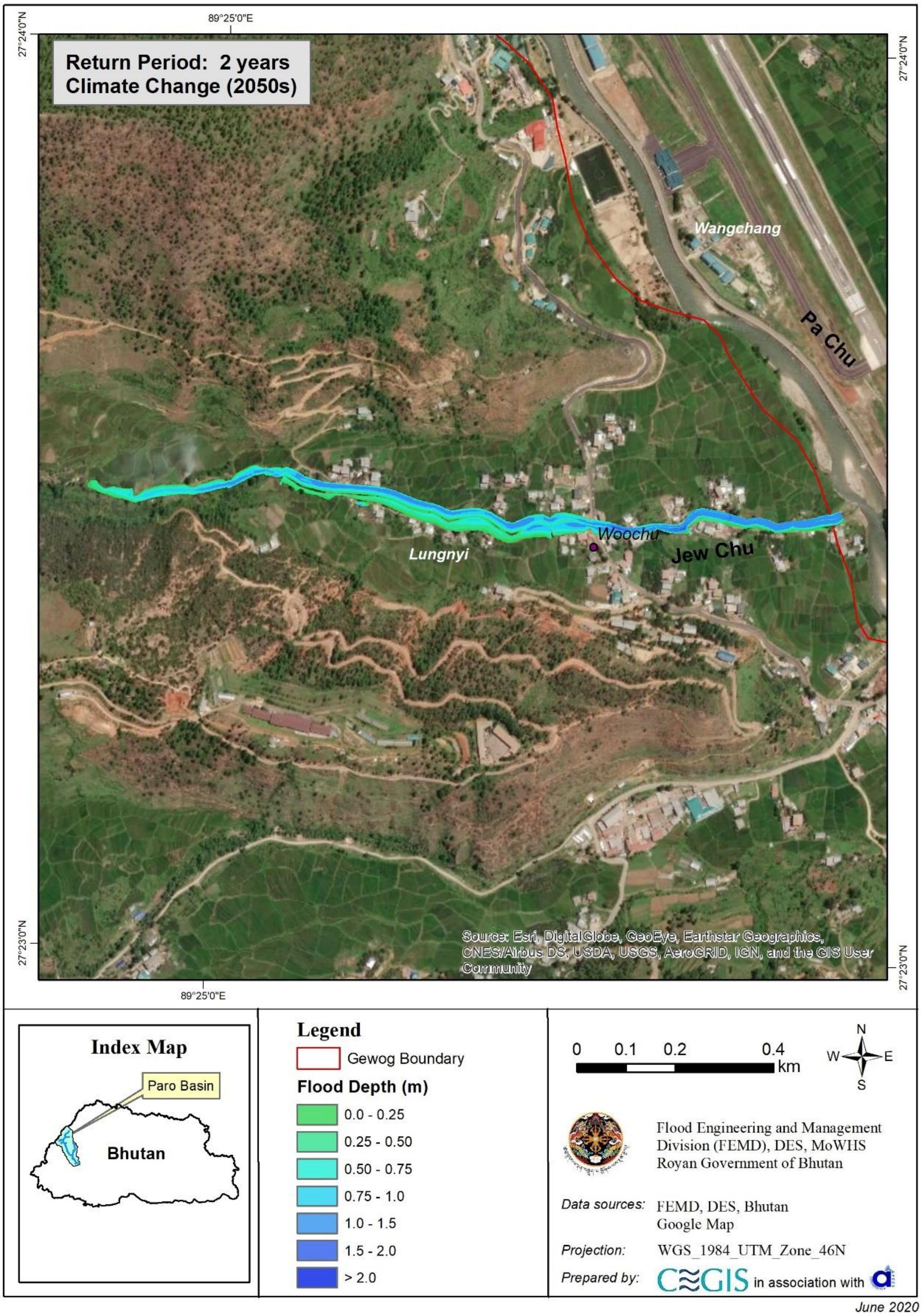


Flood Depth and Extent Map for Jew Chu



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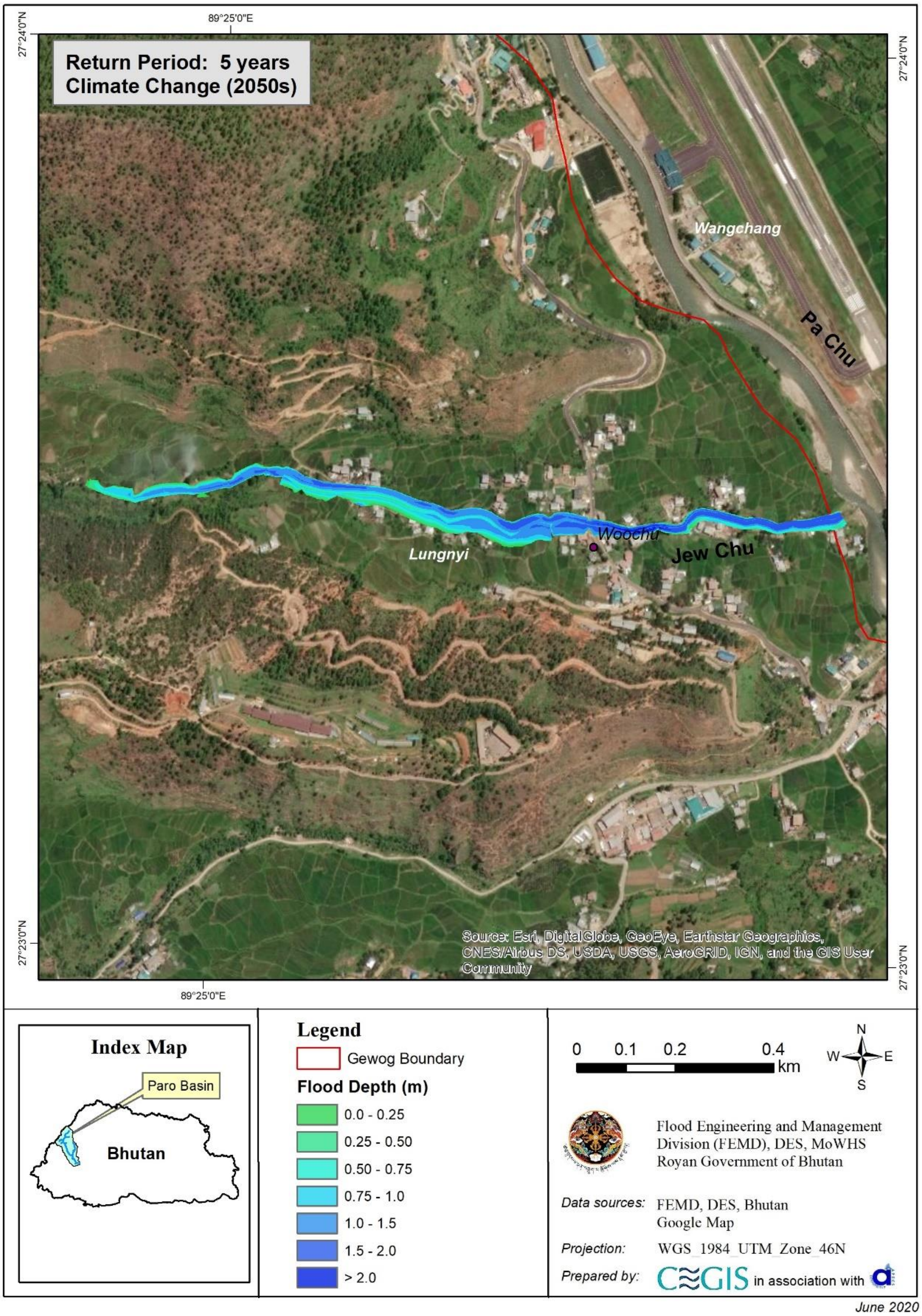

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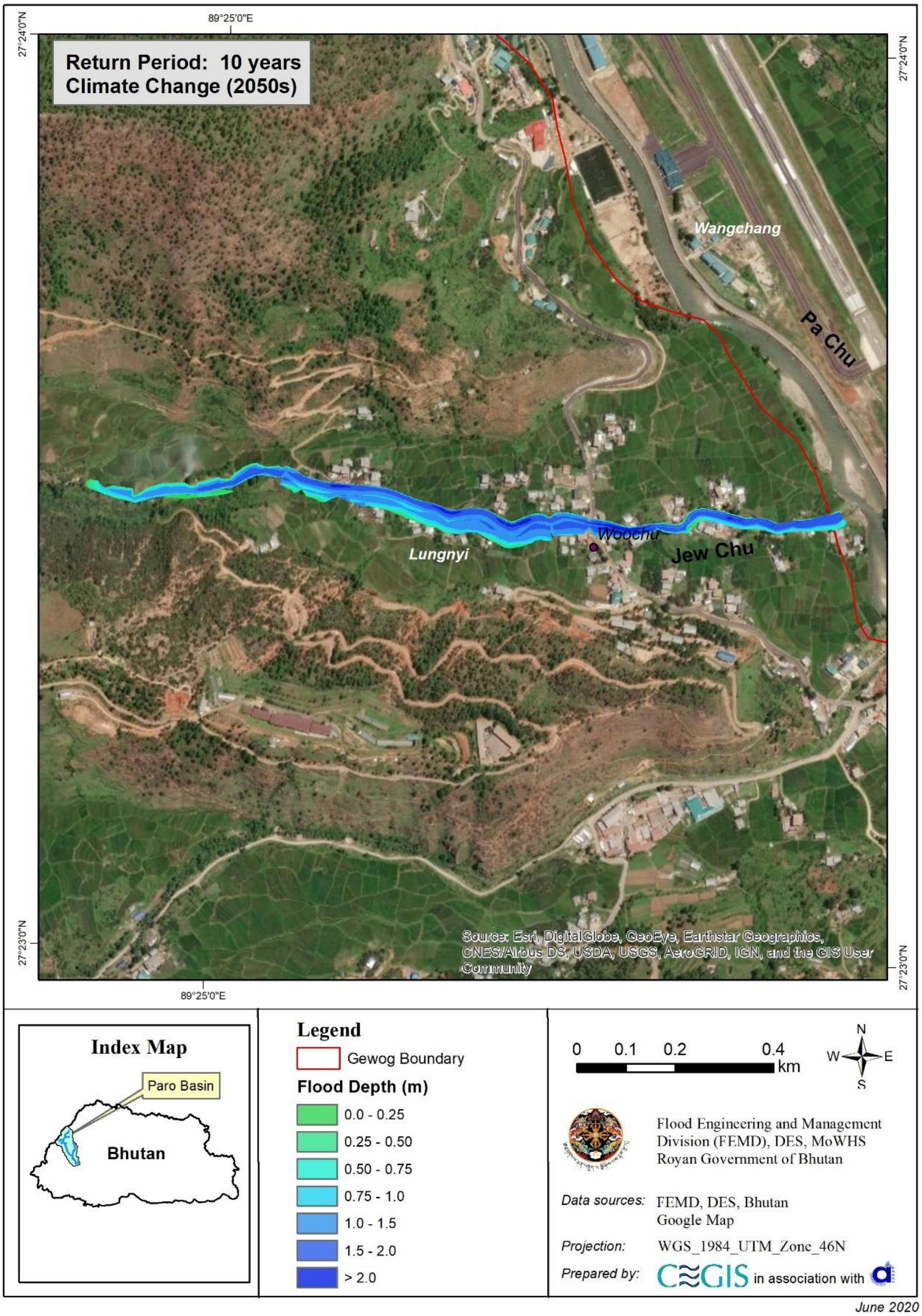

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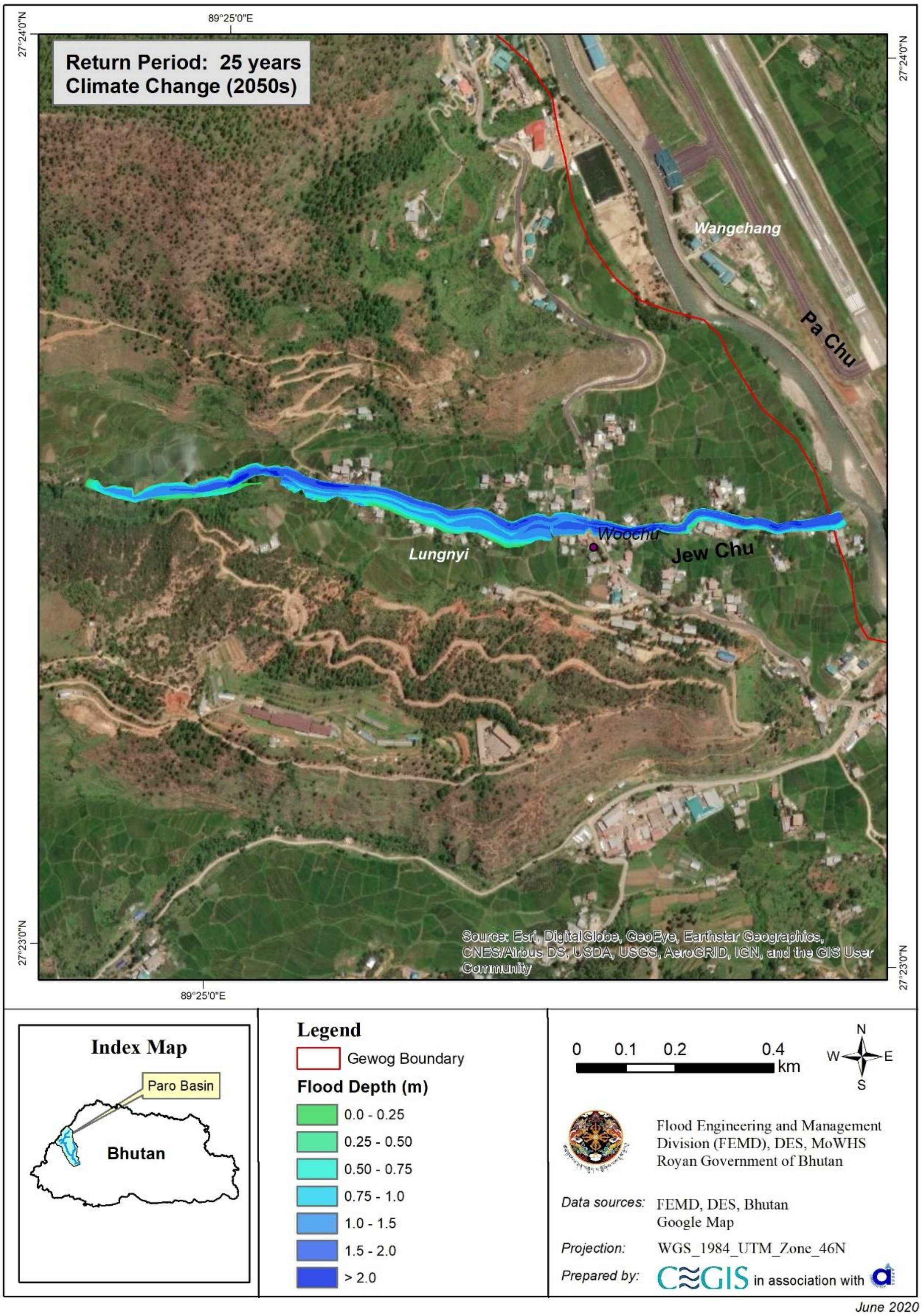

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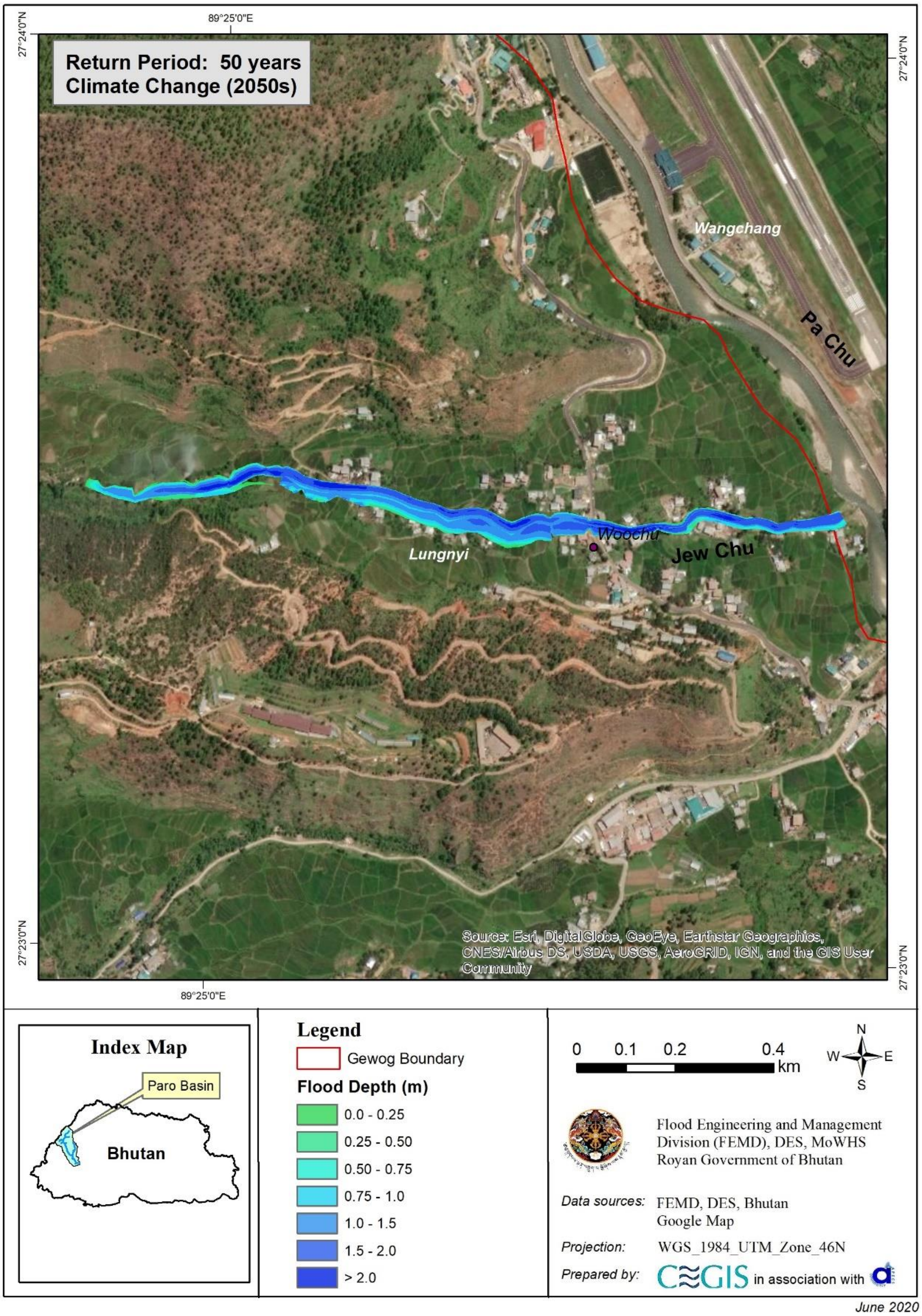

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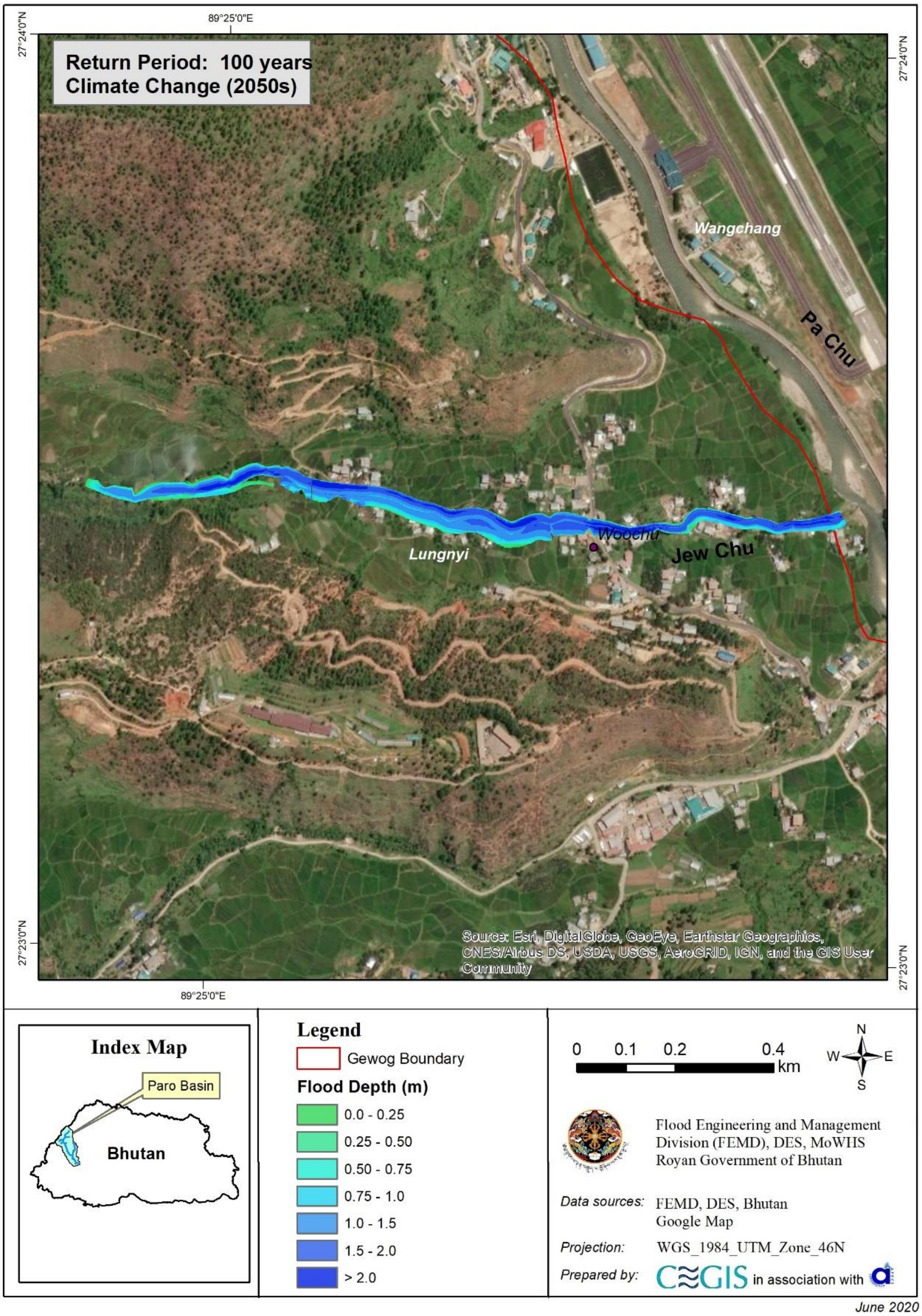
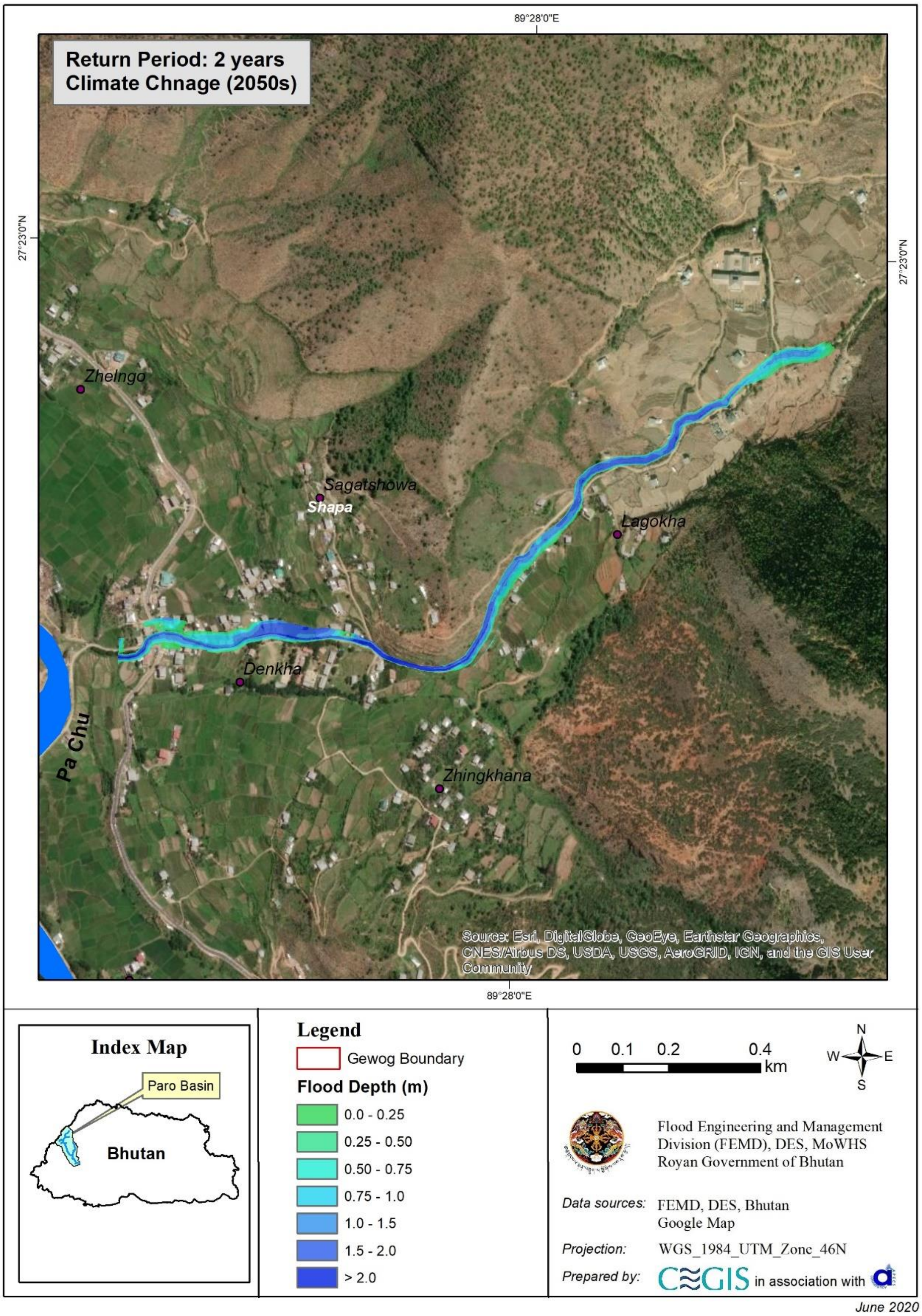
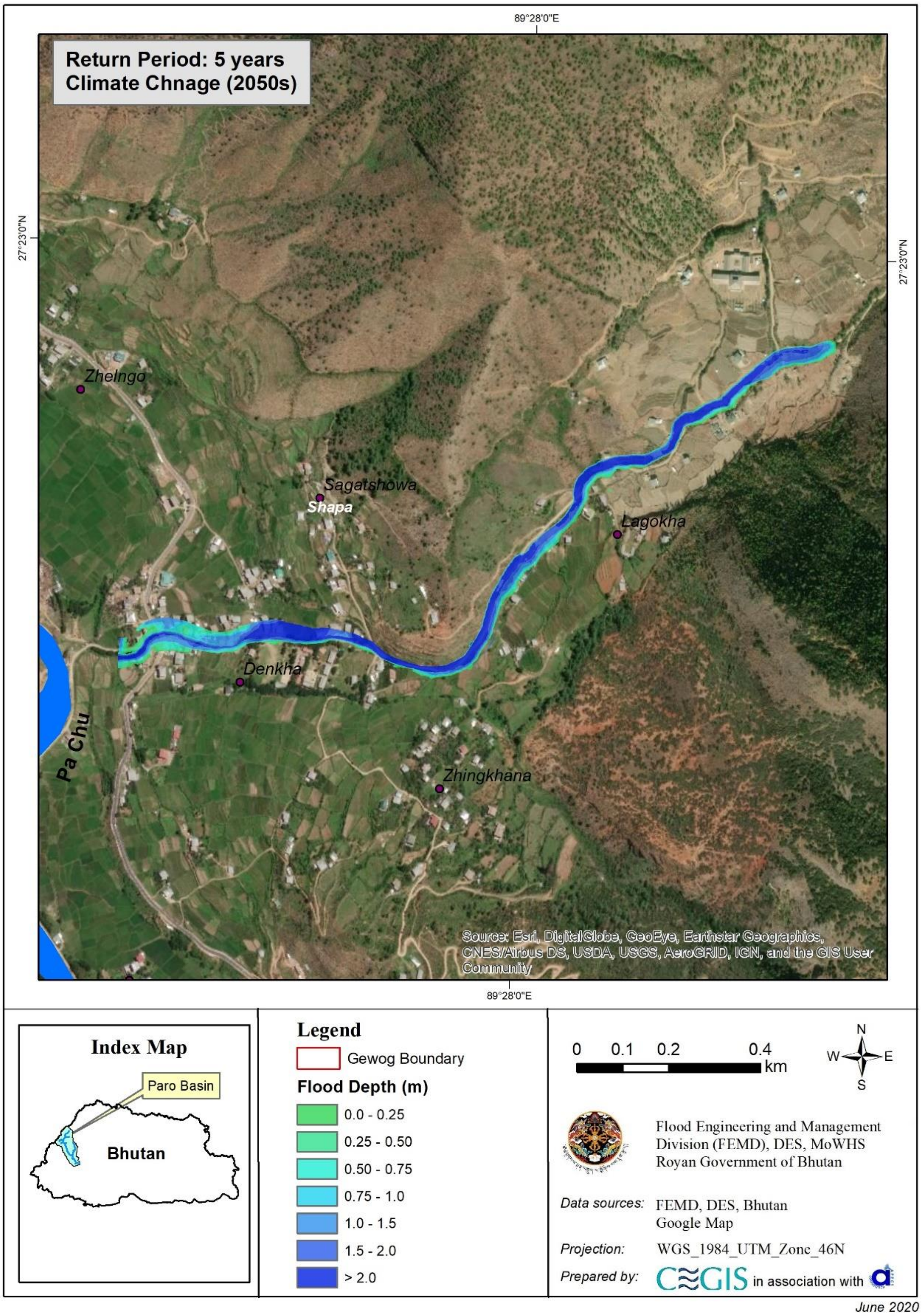


Flood Depth and Extent Map for Nephu Chu



Flood Depth and Extent Map for Nephu Chu



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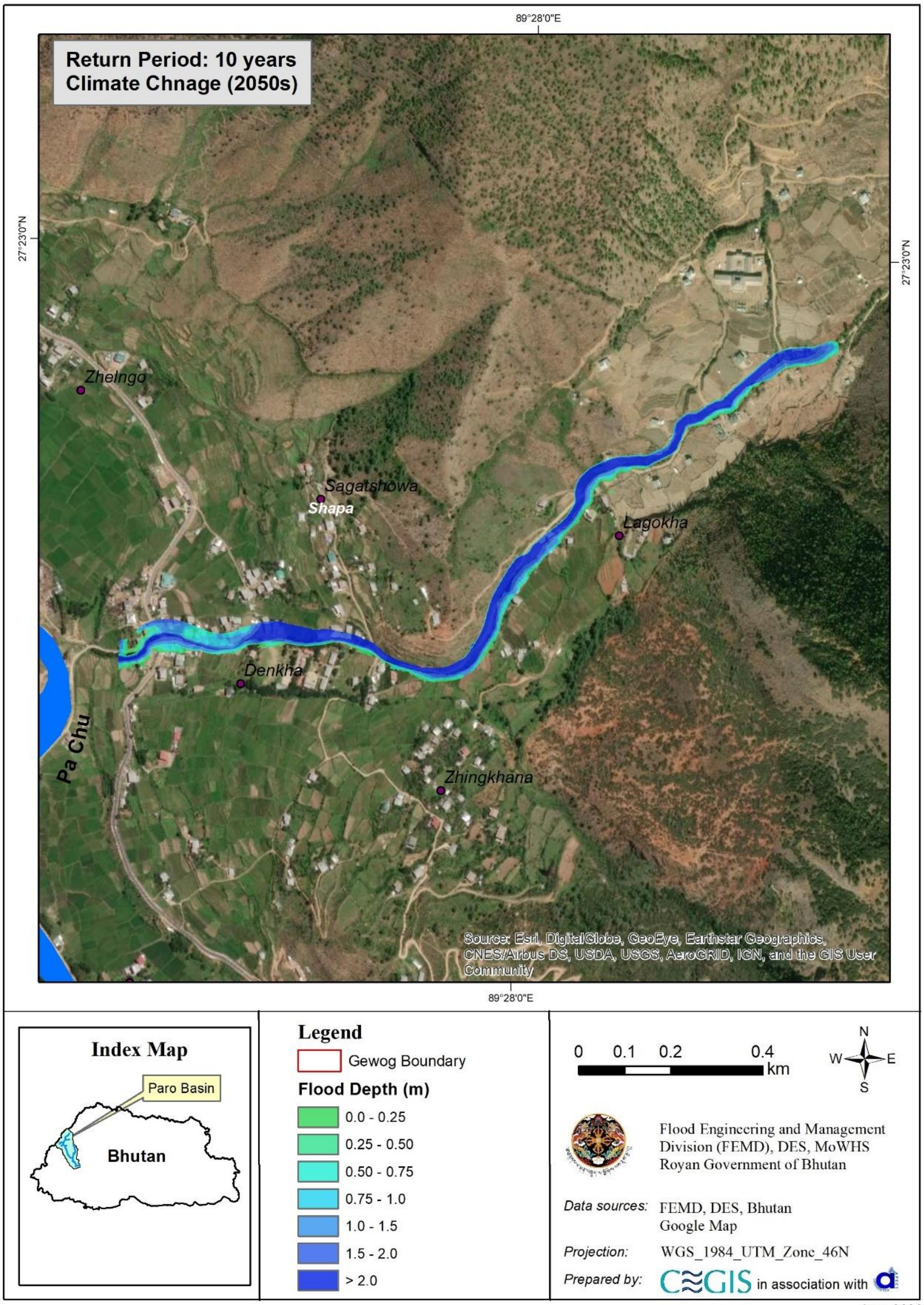

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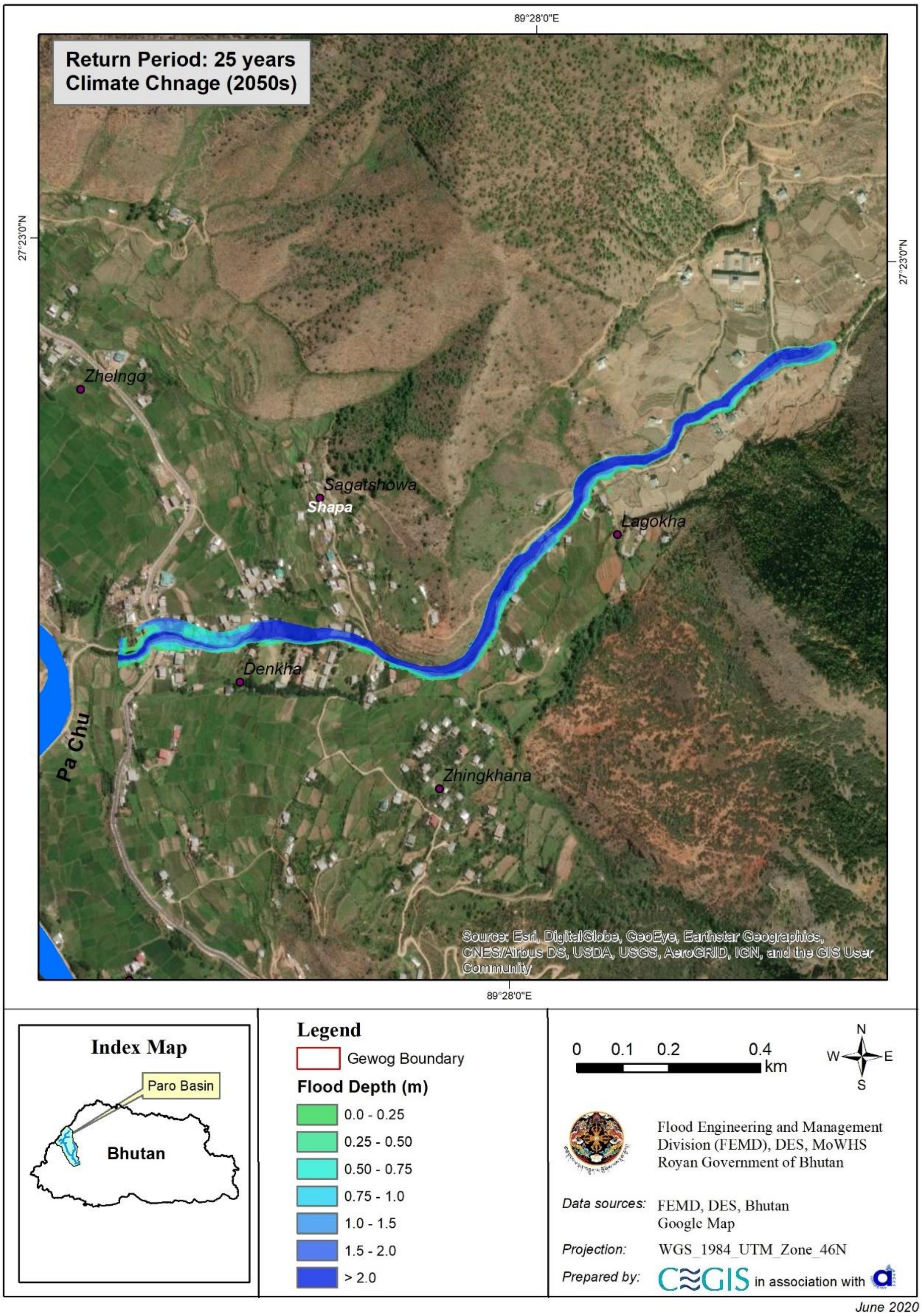
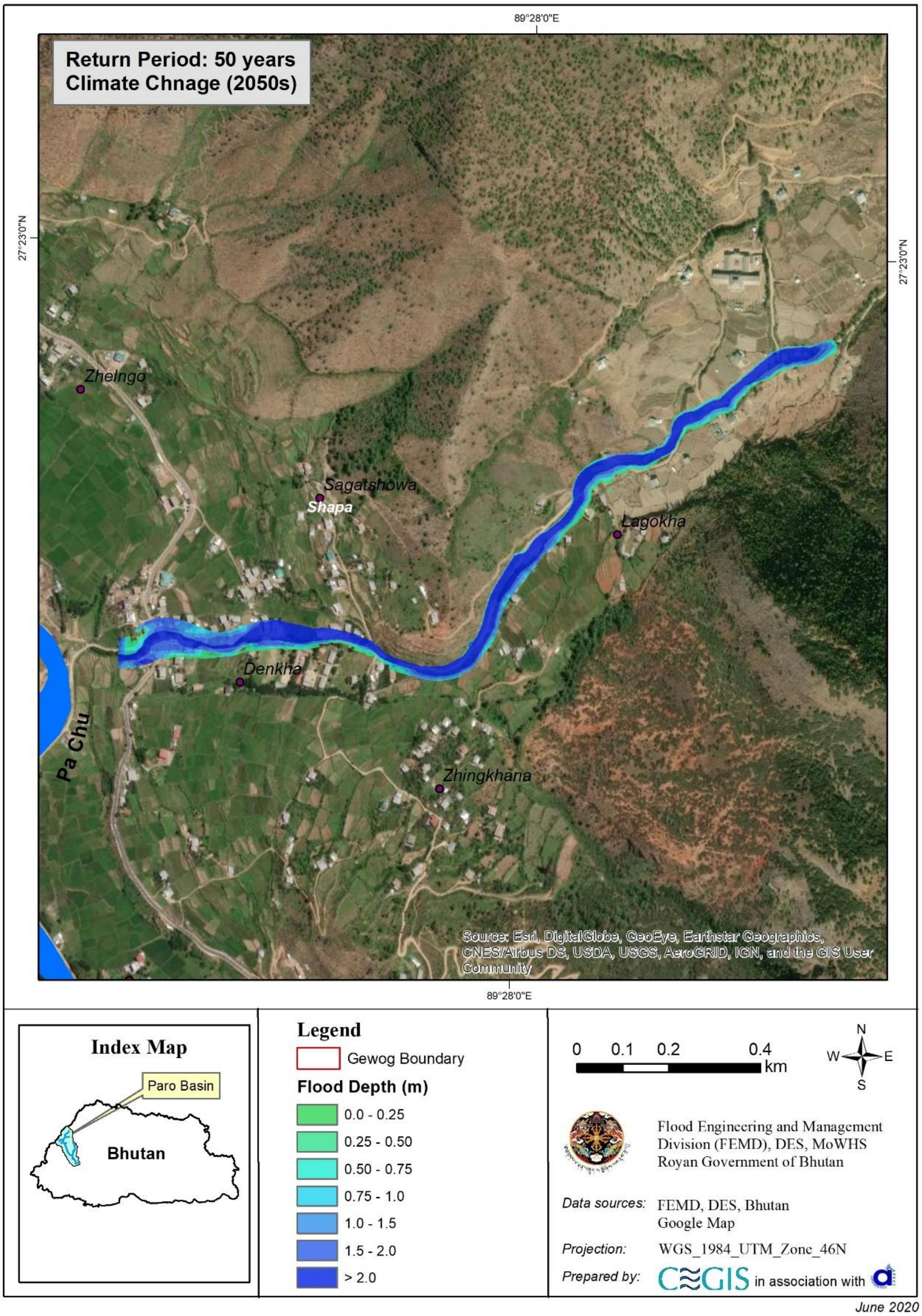
Flood Depth and Extent Map for Nephu Chu



Flood Depth and Extent Map for Nephu Chu



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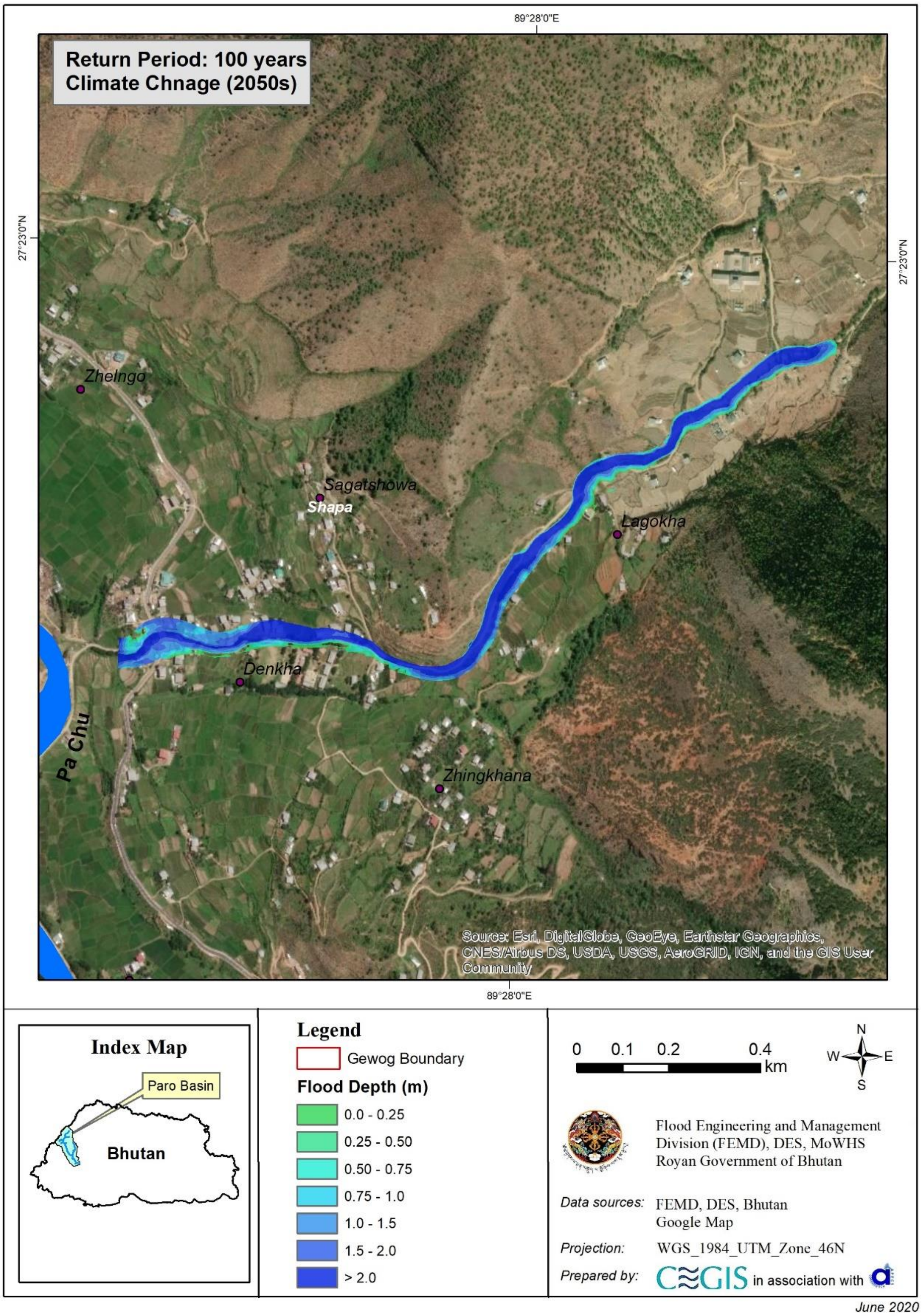
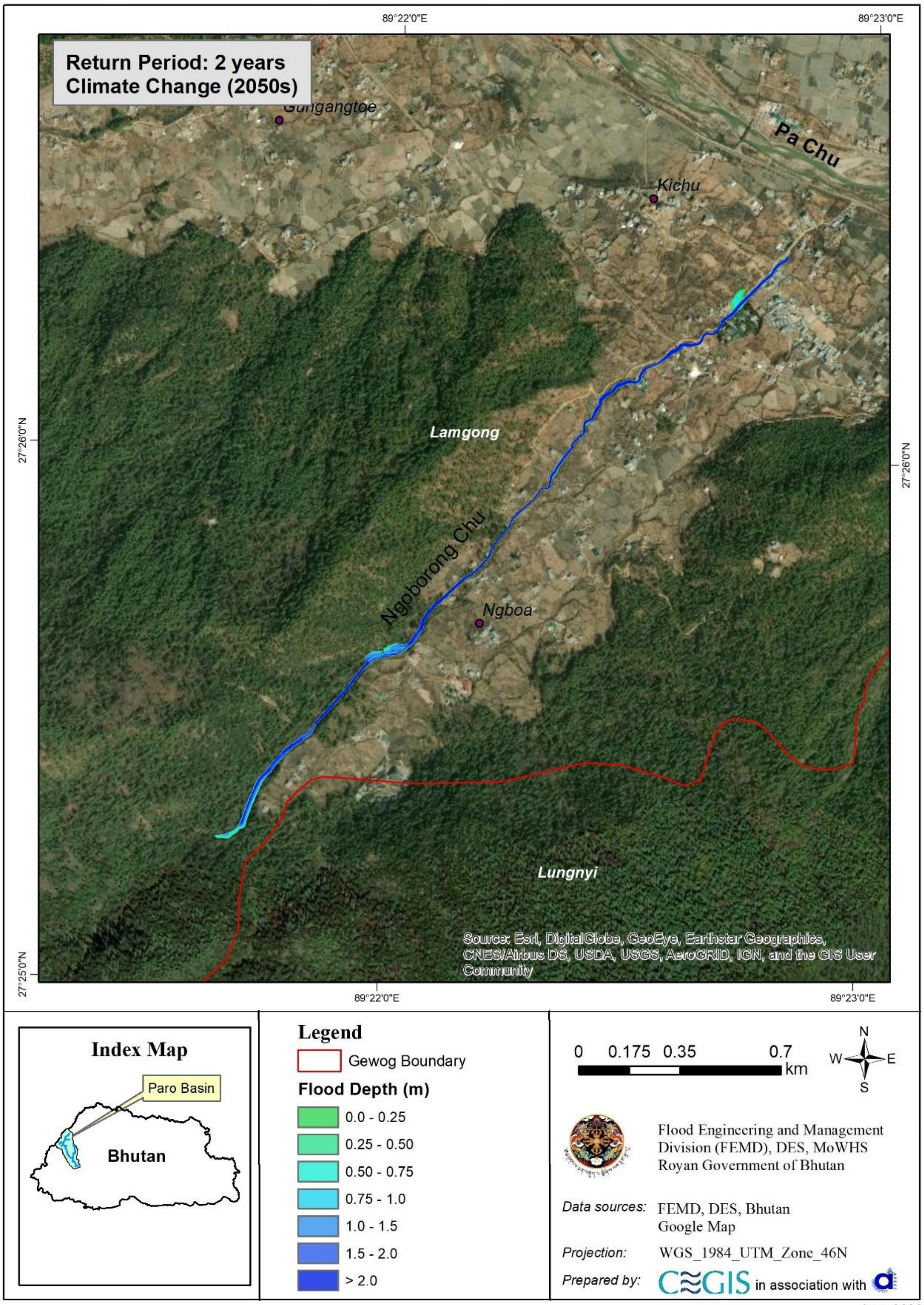
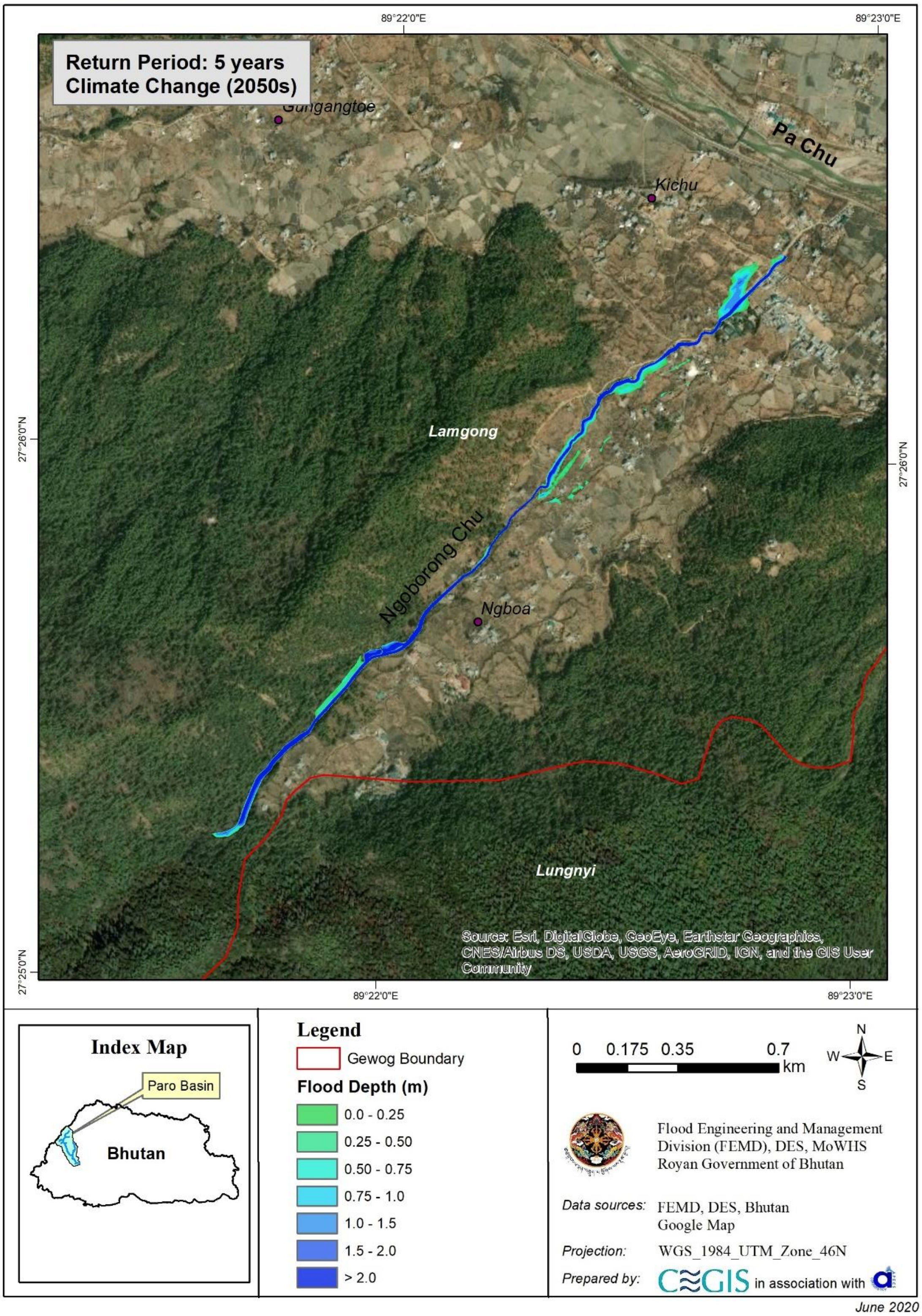


Flood Depth and Extent Map for Ngoborong Chu

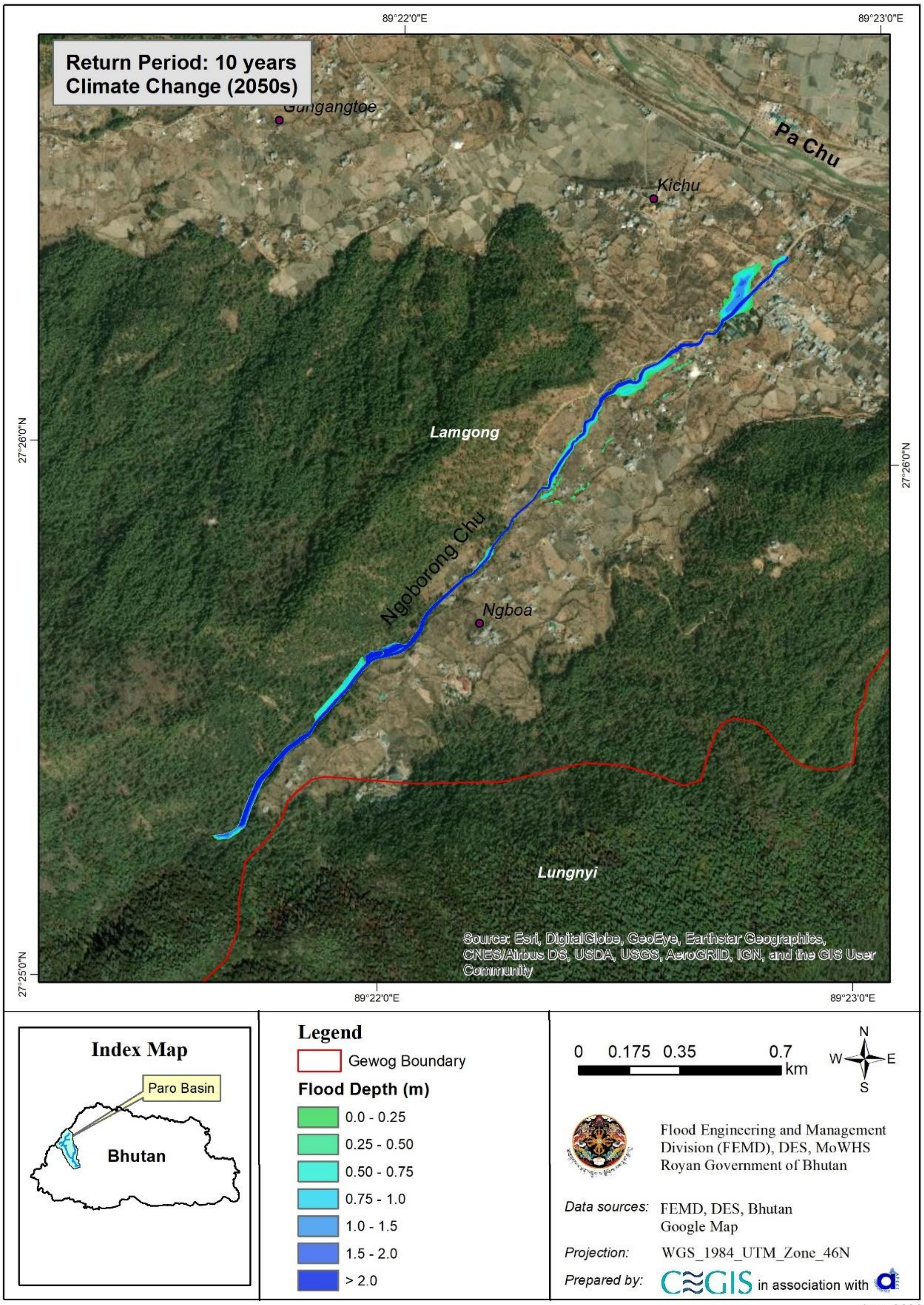


June 2020

Flood Depth and Extent Map for Ngoborong Chu



Flood Depth and Extent Map for Ngoborong Chu



Legend

Gewog Boundary

Flood Depth (m)

- 0.0 - 0.25
- 0.25 - 0.50
- 0.50 - 0.75
- 0.75 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- > 2.0

Flood Engineering and Management Division (FEMD), DES, MoWHS Royan Government of Bhutan

Data sources: FEMD, DES, Bhutan Google Map

Projection: WGS_1984_UTM_Zone_46N

Prepared by: CEGIS in association with

June 2020

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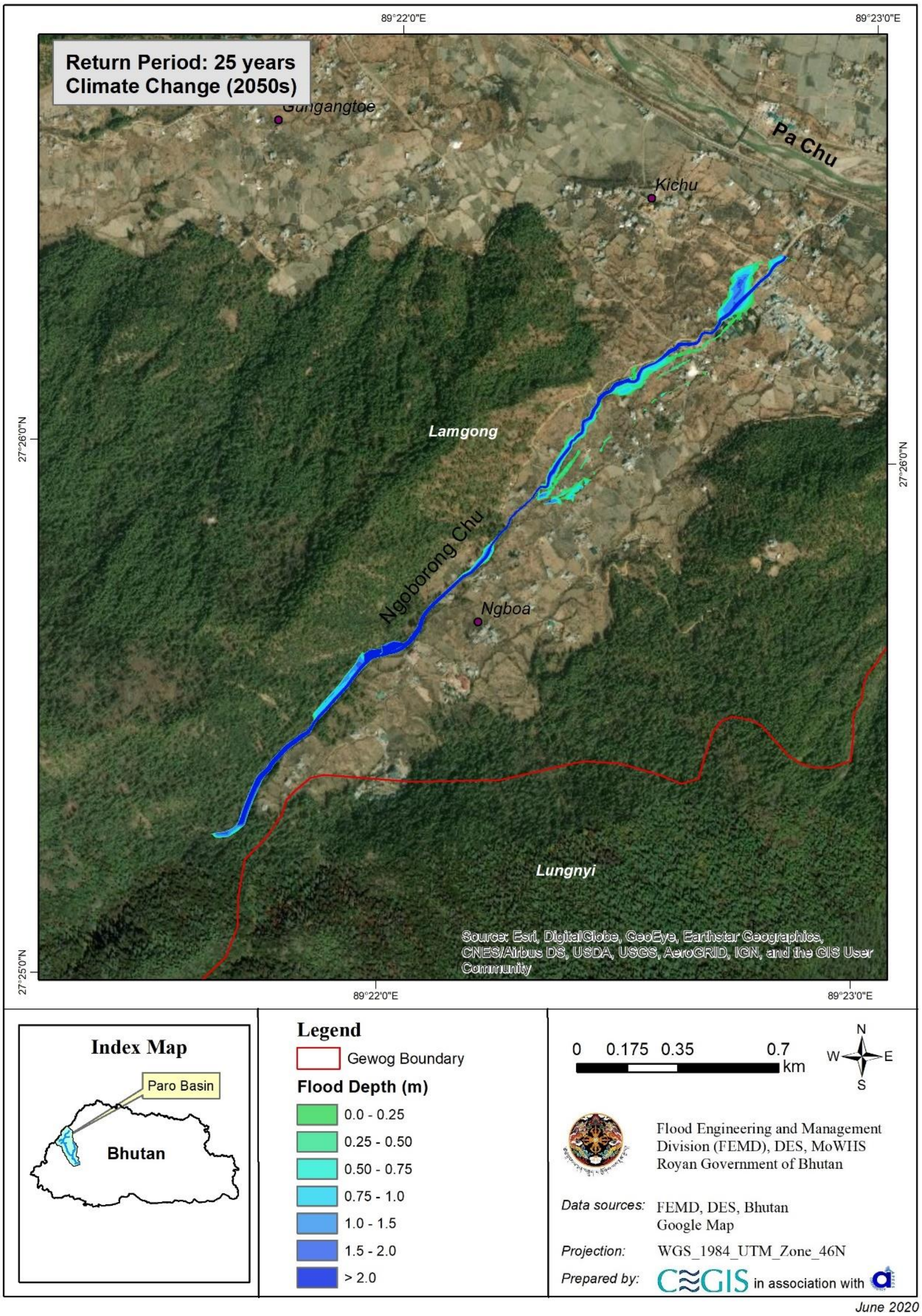
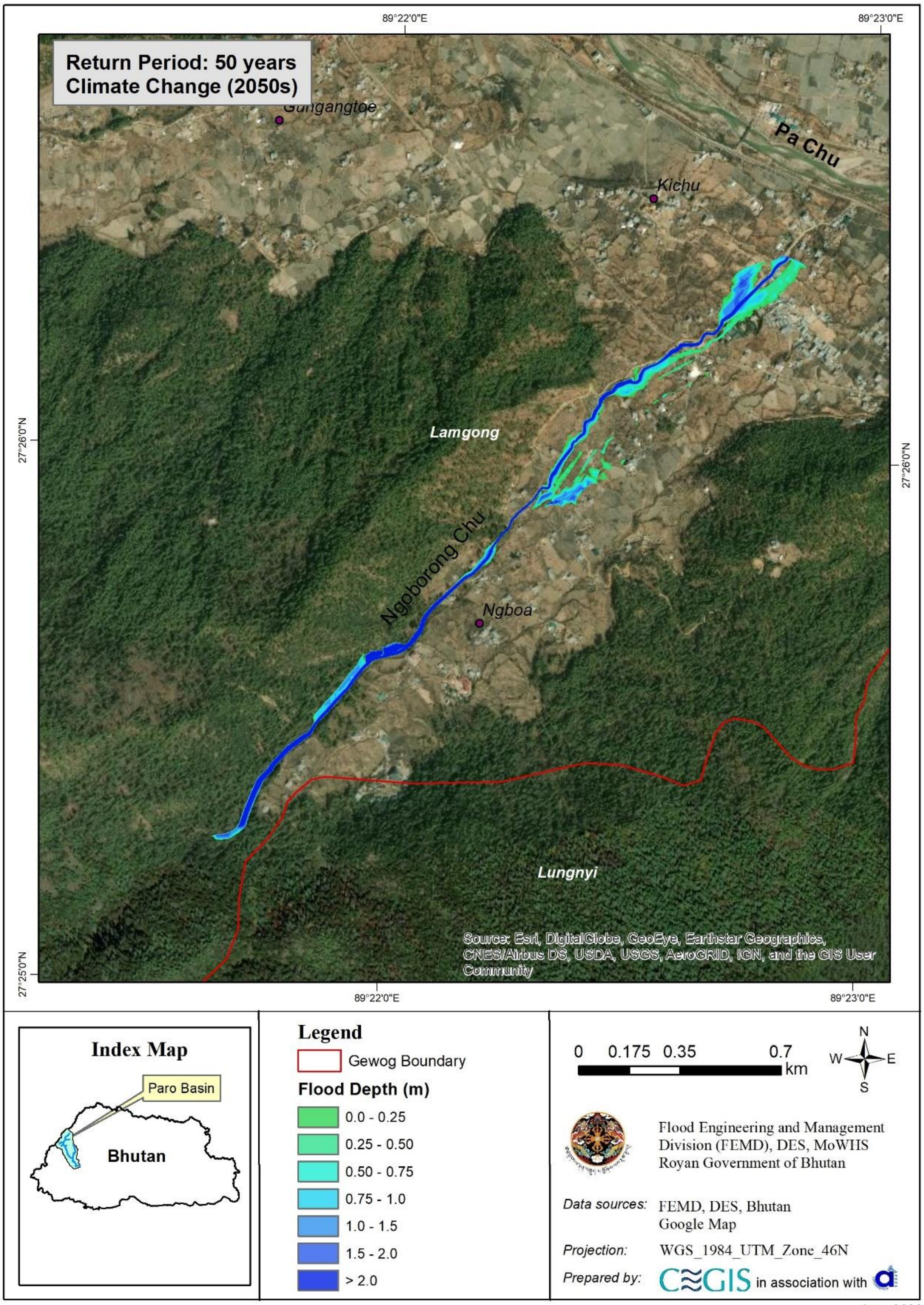


Flood Depth and Extent Map for Ngoborong Chu



June 2020

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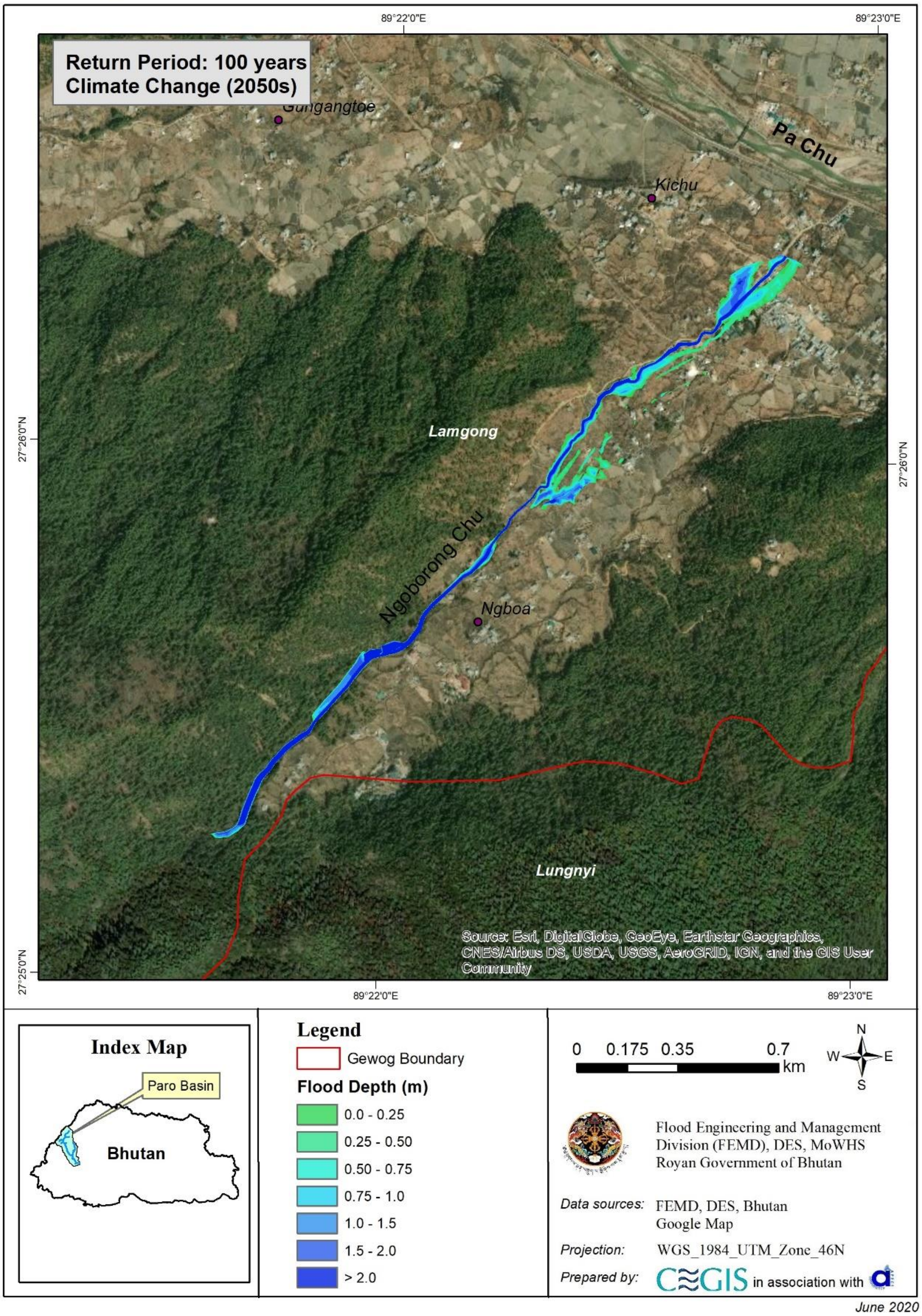
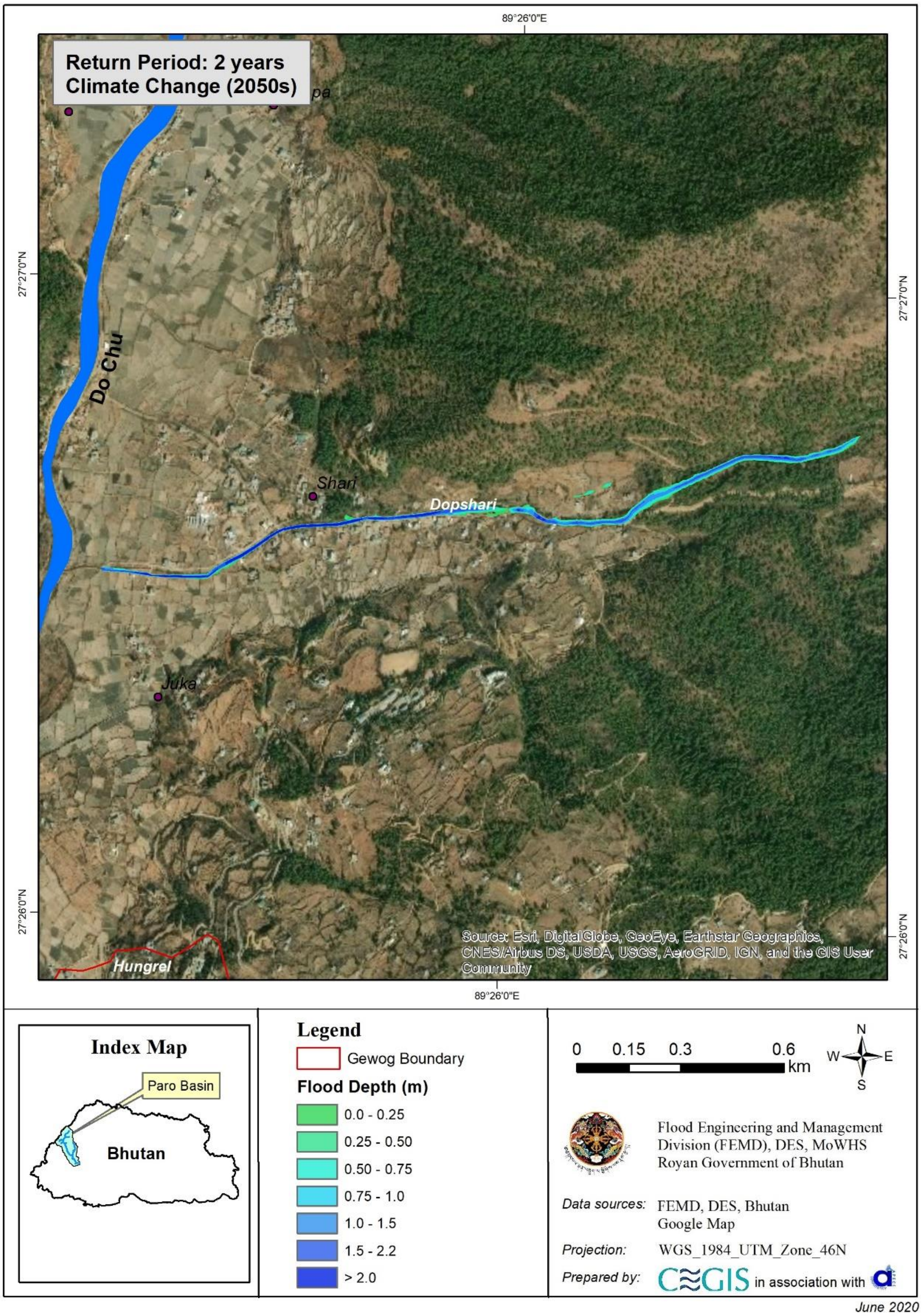
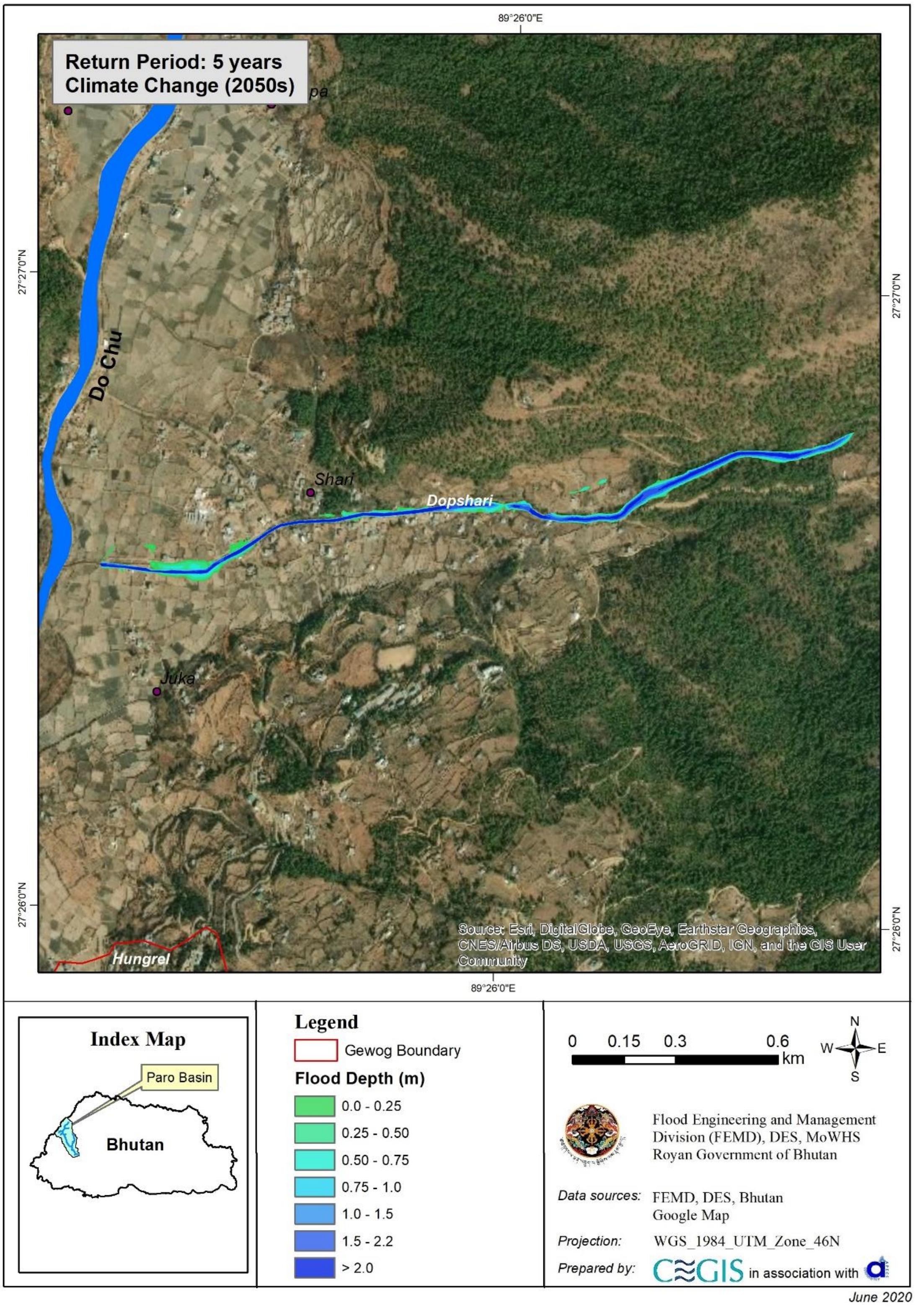


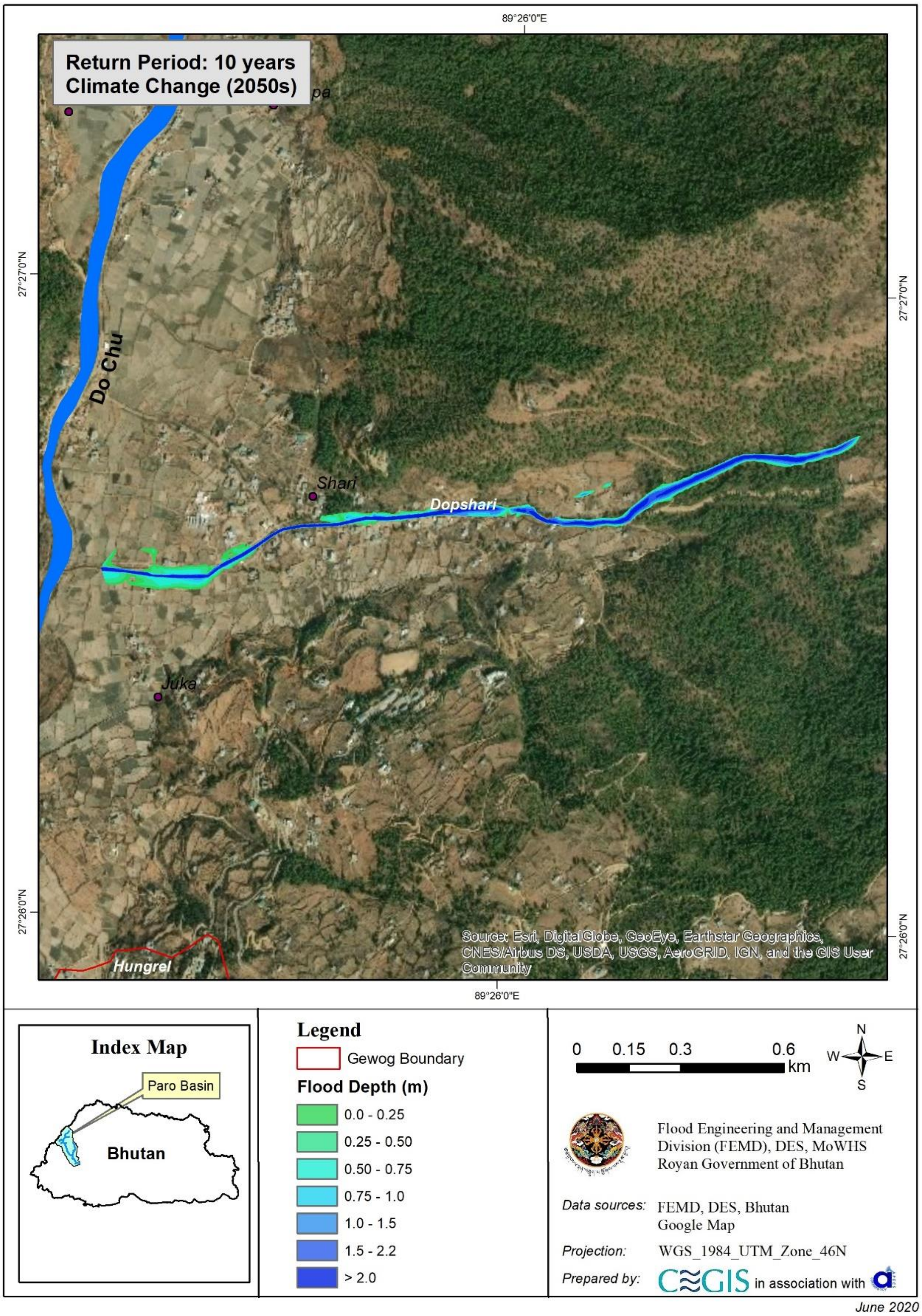
Flood Depth and Extent Map for Ri Chu



Flood Depth and Extent Map for Ri Chu



Flood Depth and Extent Map for Ri Chu



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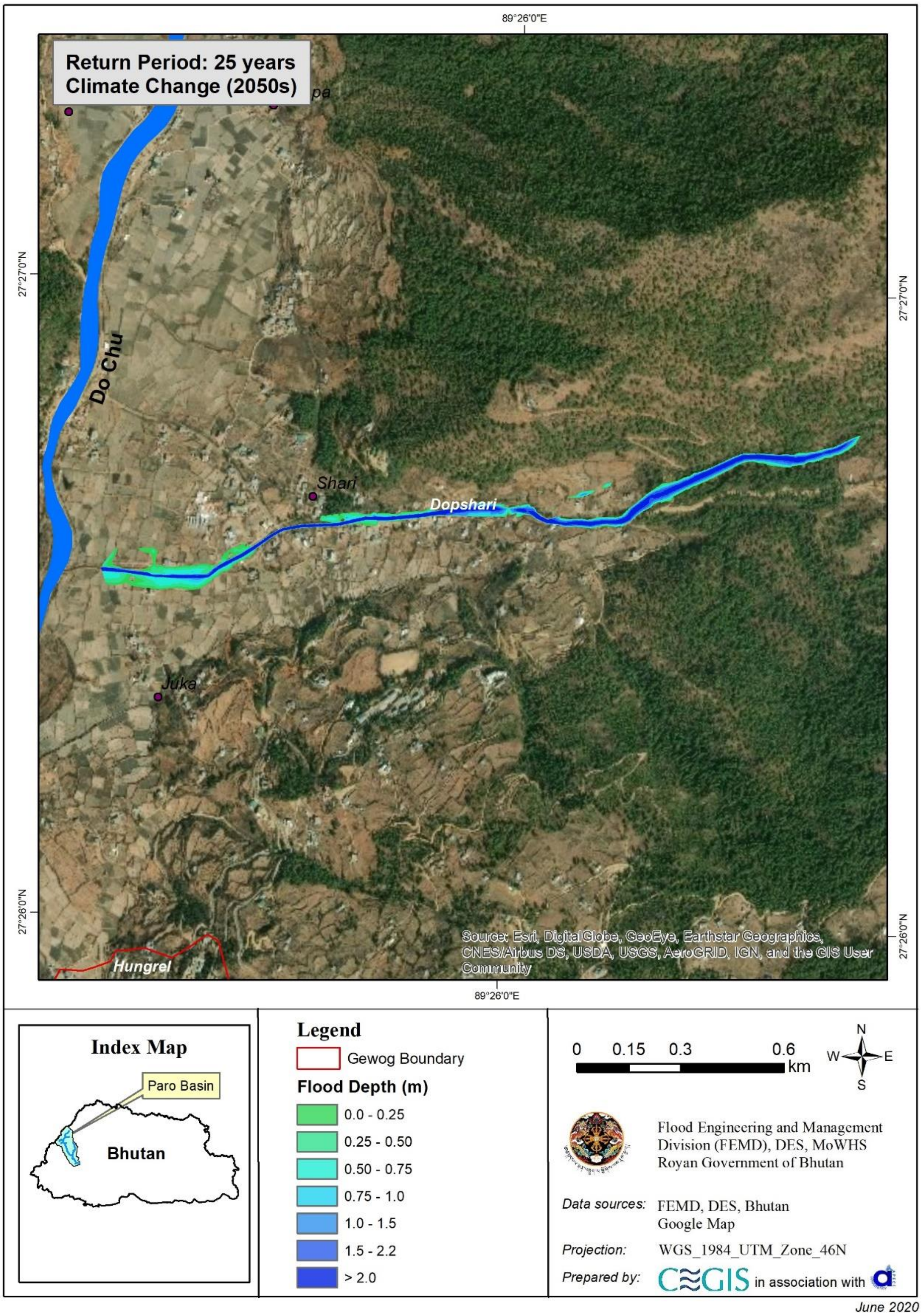

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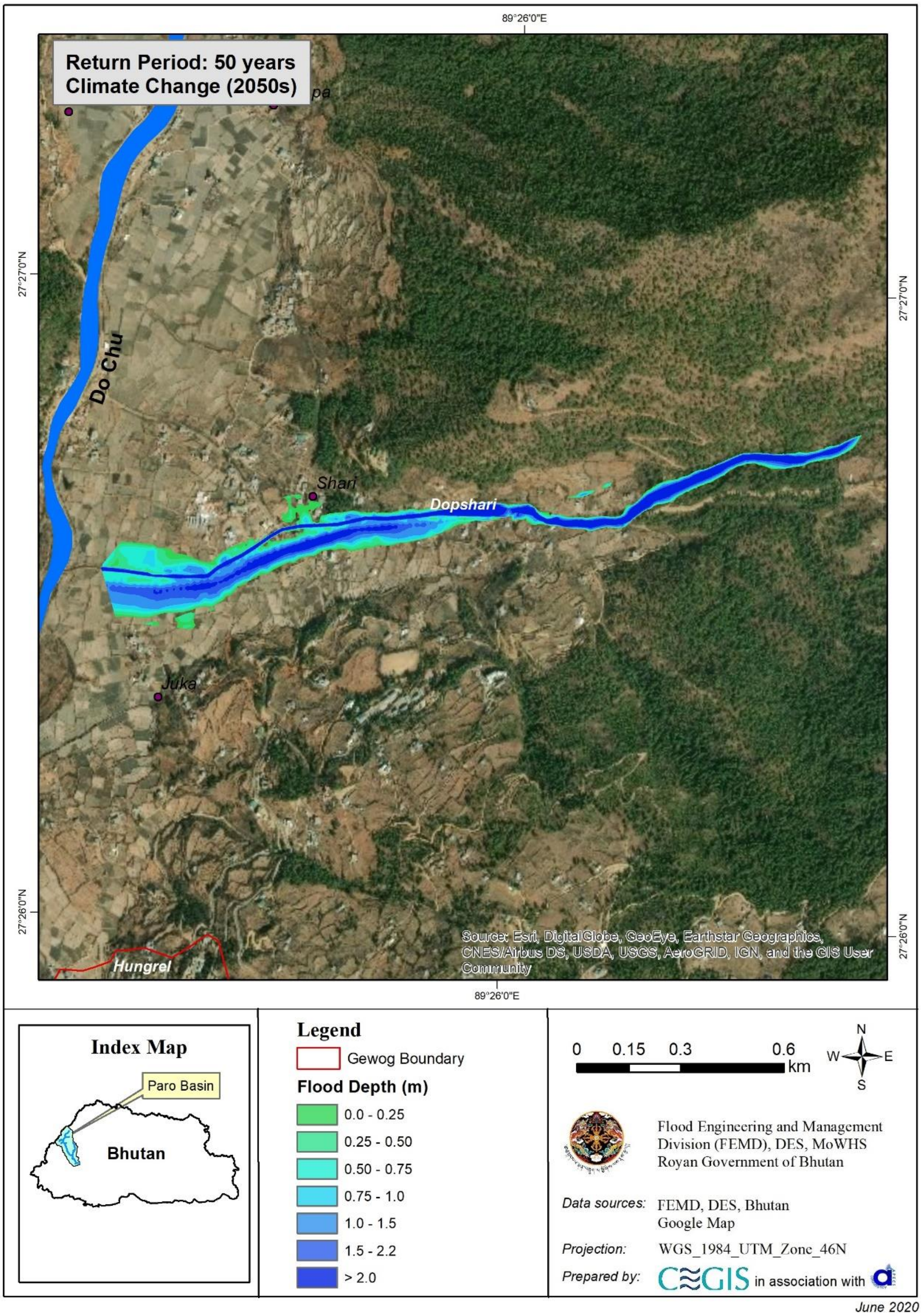

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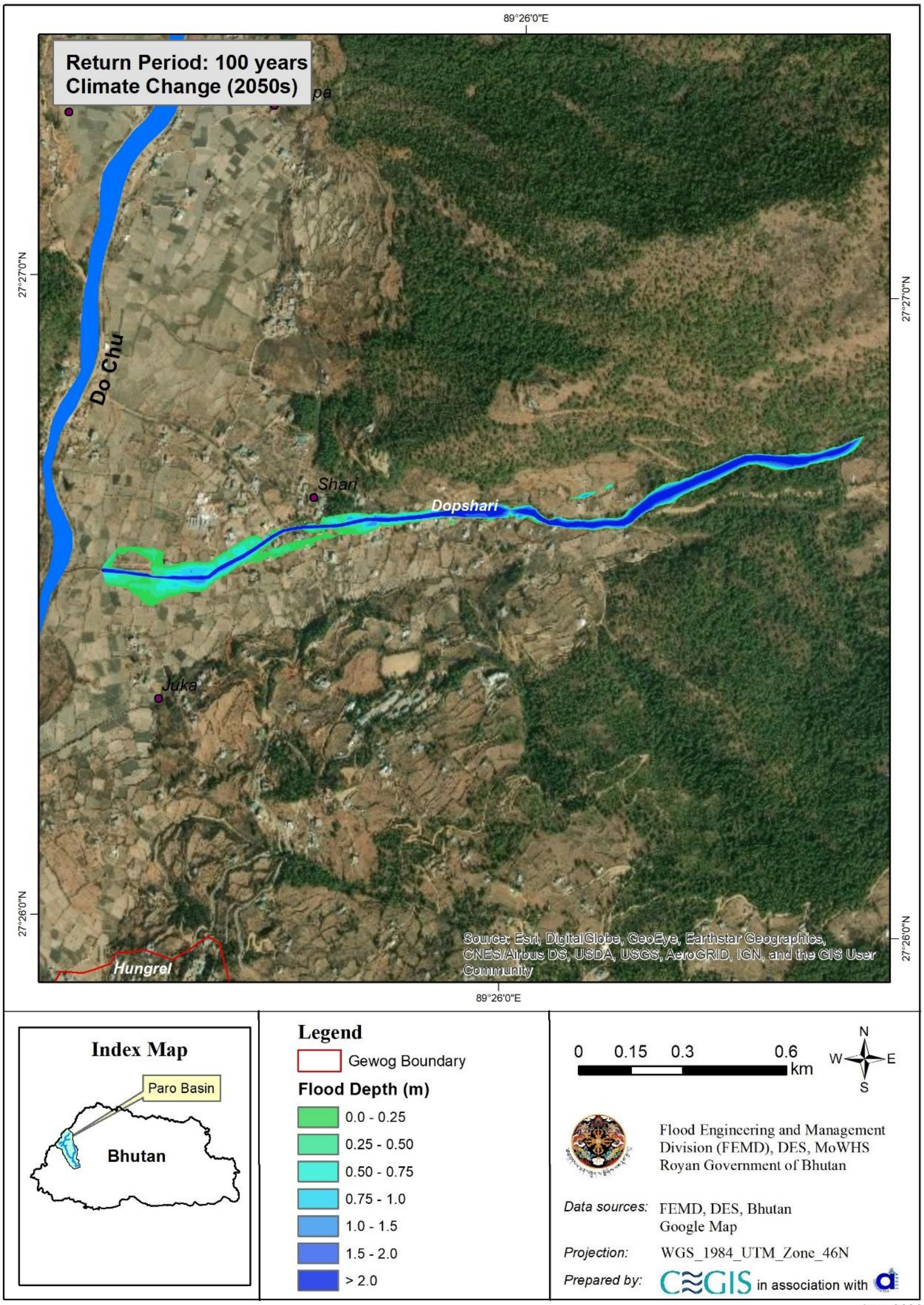
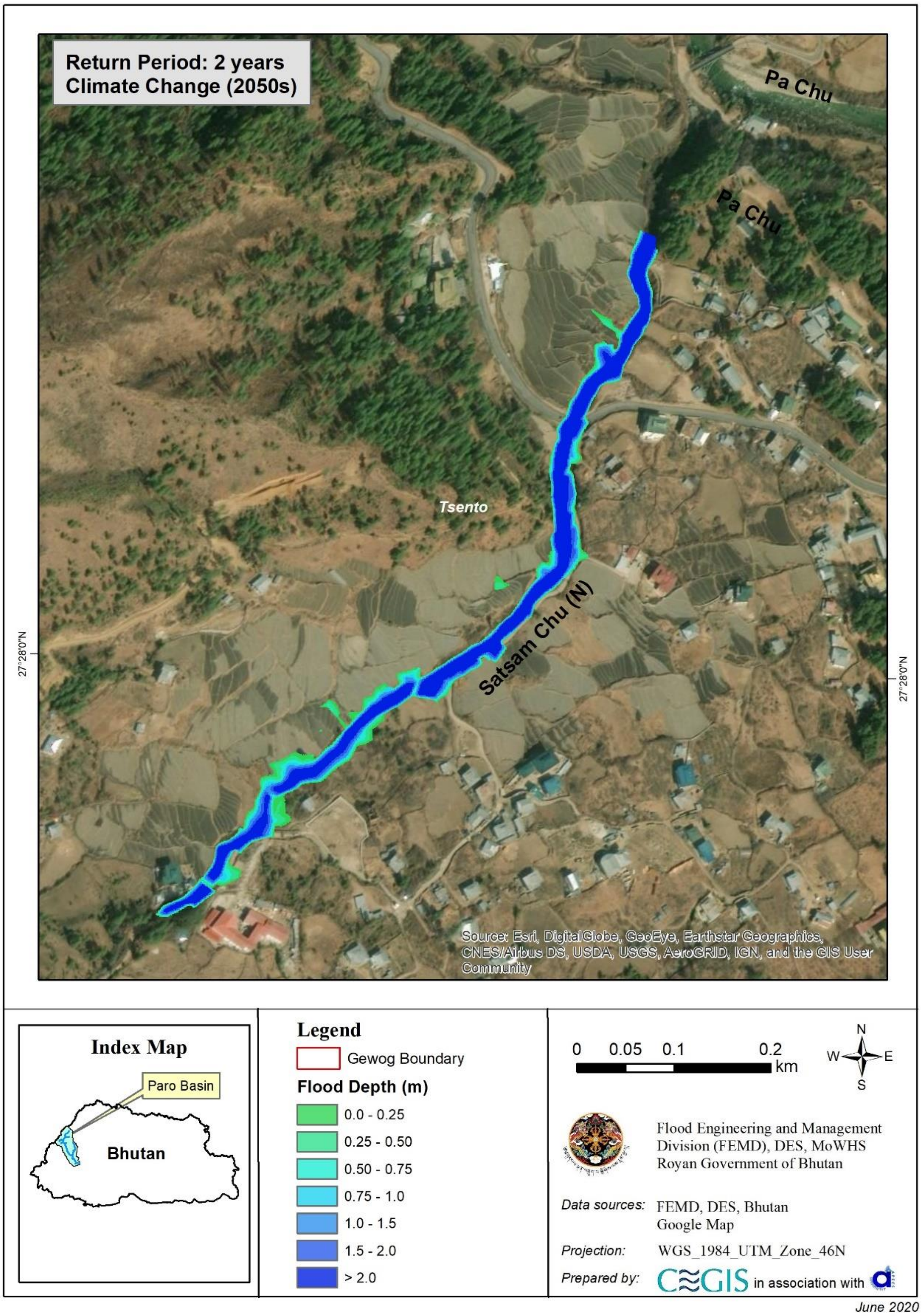
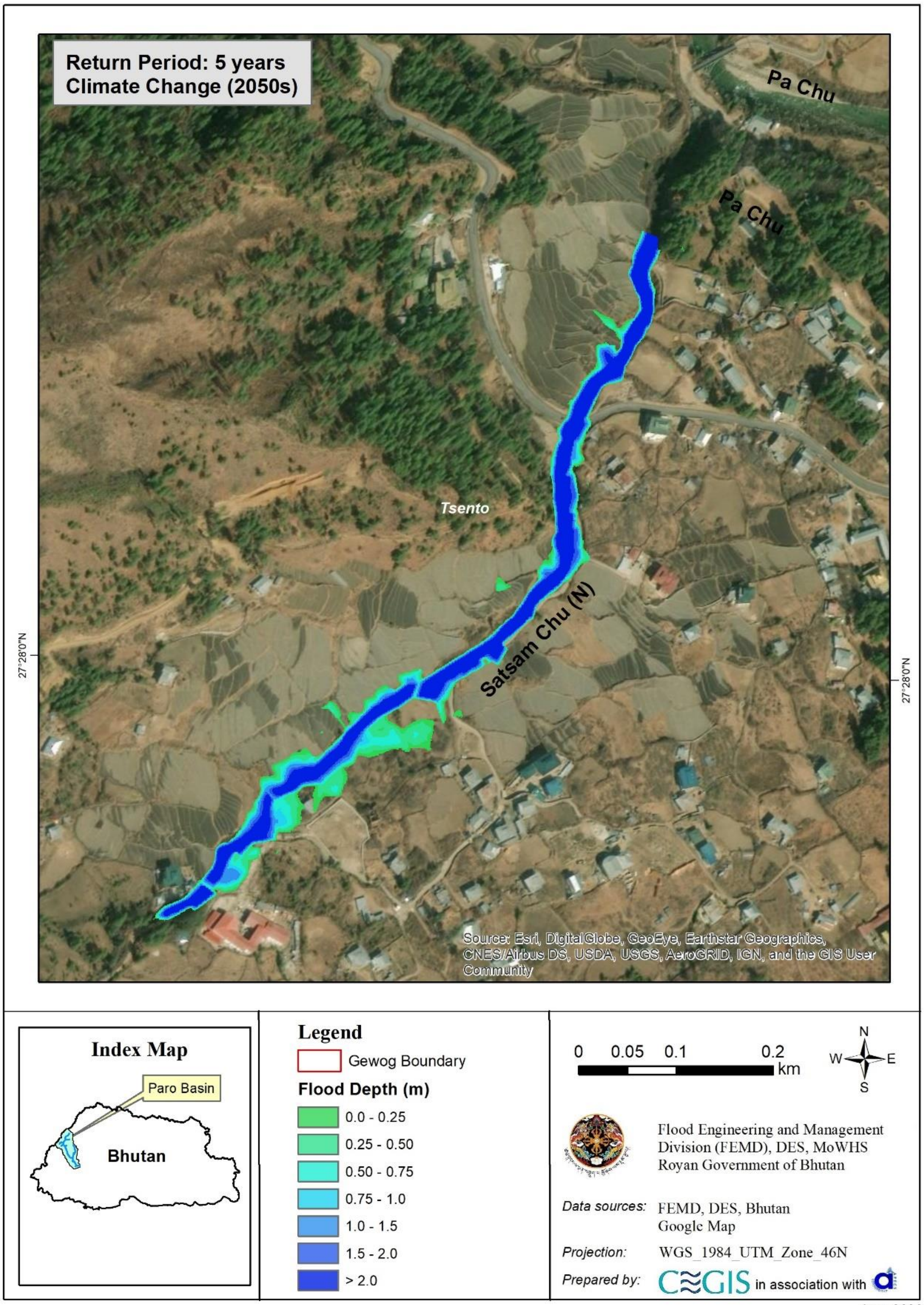


June 2020

Flood Depth and Extent Map for Satsan Chu (N)

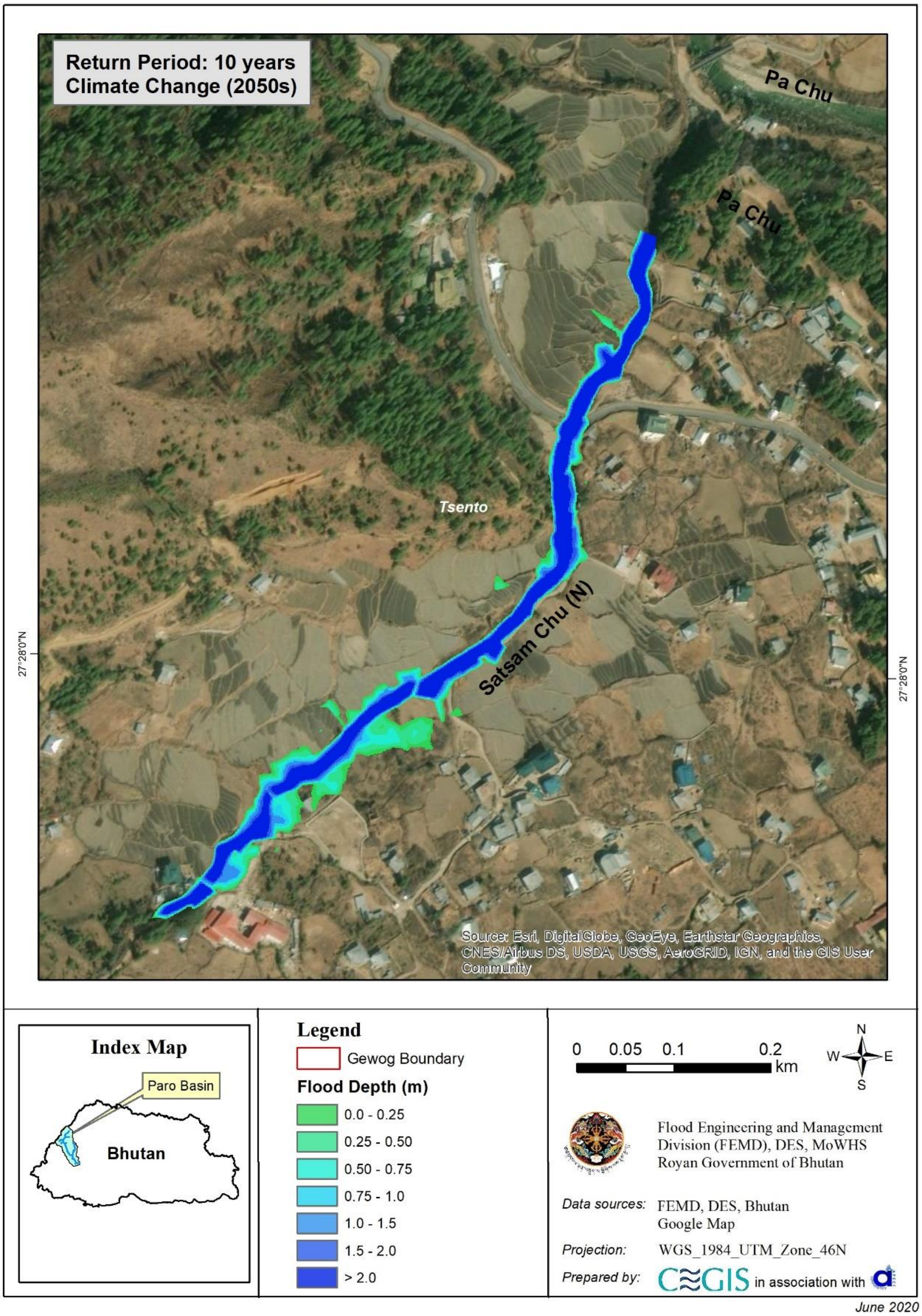


Flood Depth and Extent Map for Satsan Chu (N)

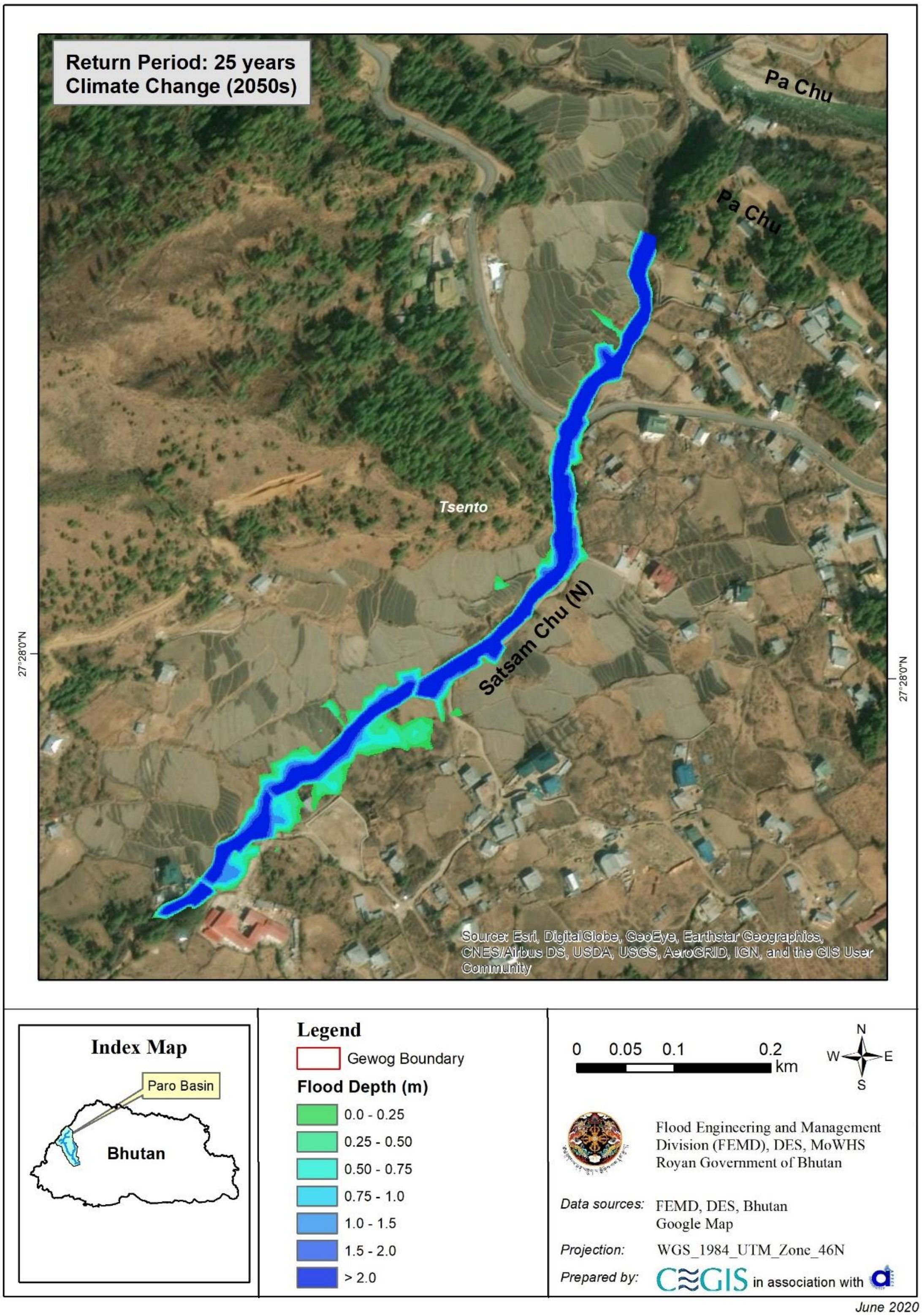


June 2020

Flood Depth and Extent Map for Satsan Chu (N)



Flood Depth and Extent Map for Satsan Chu (N)



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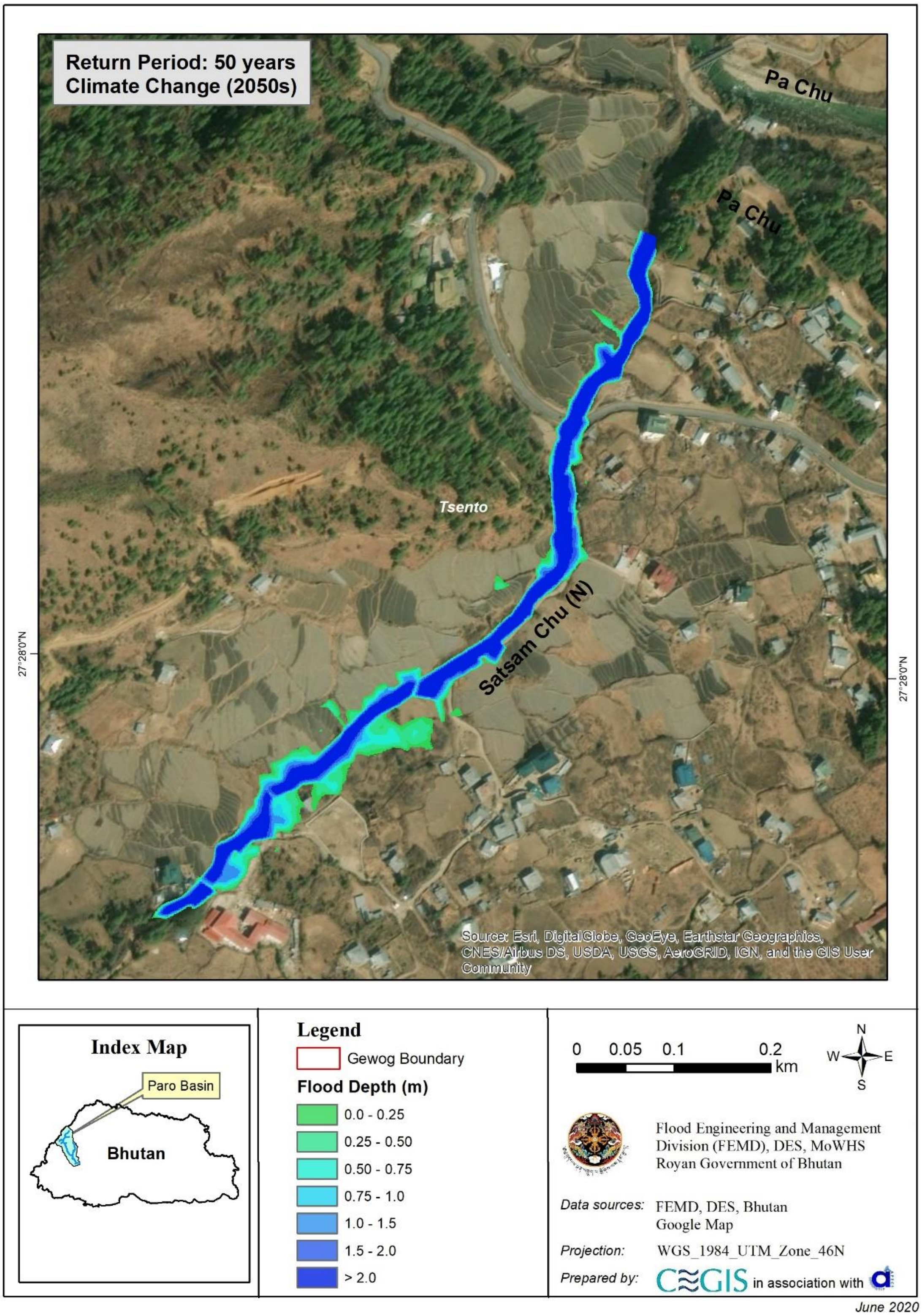
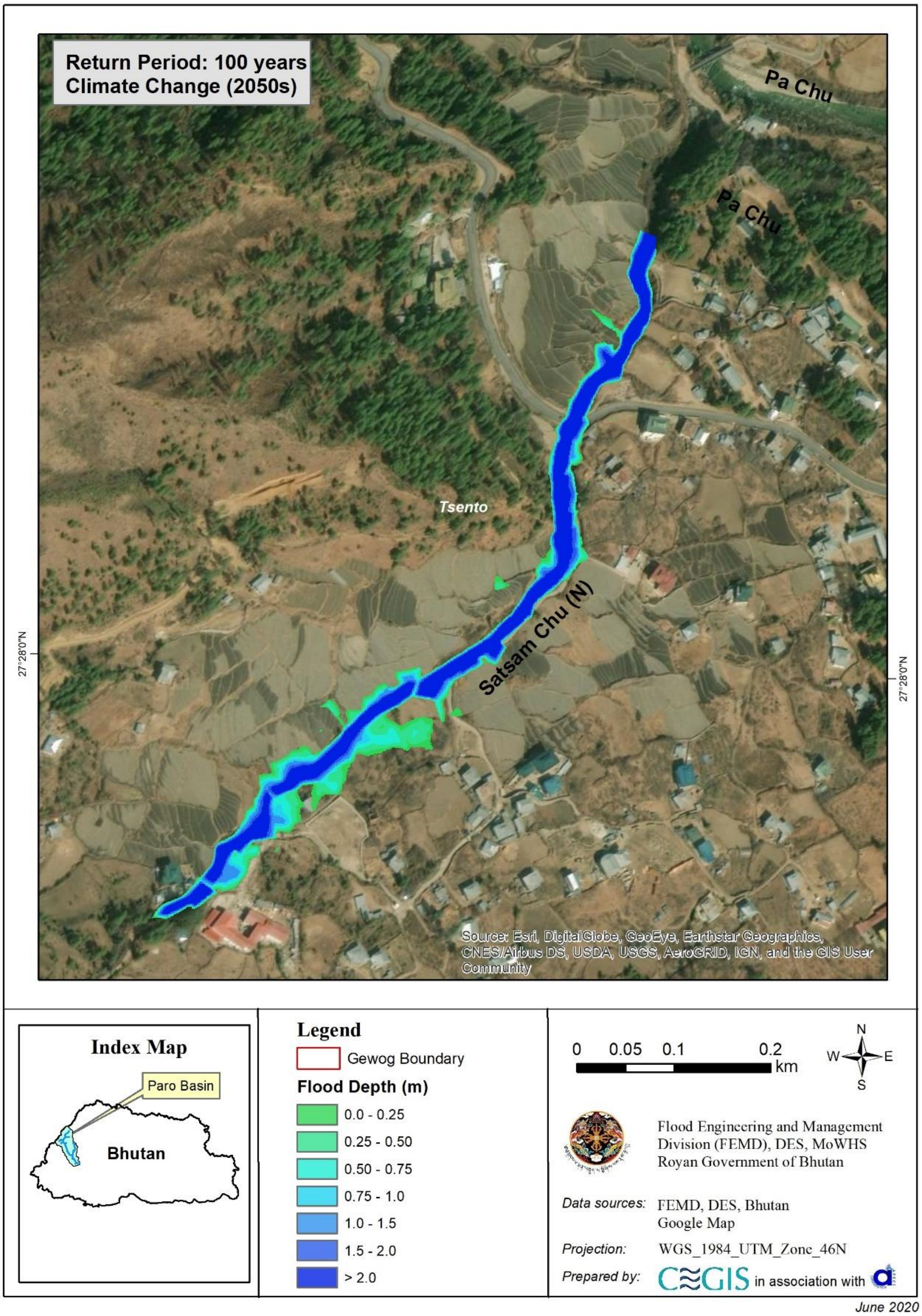
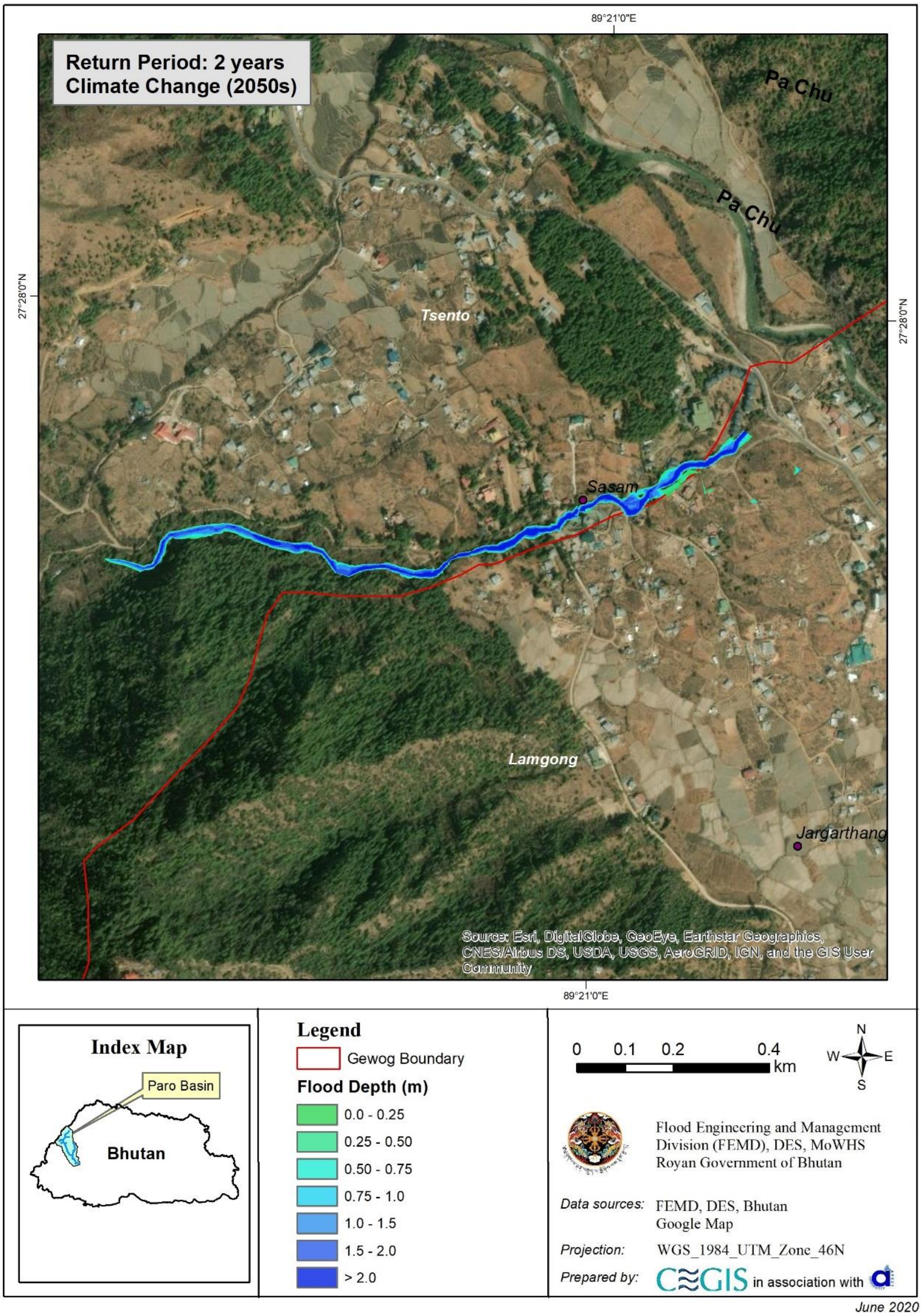


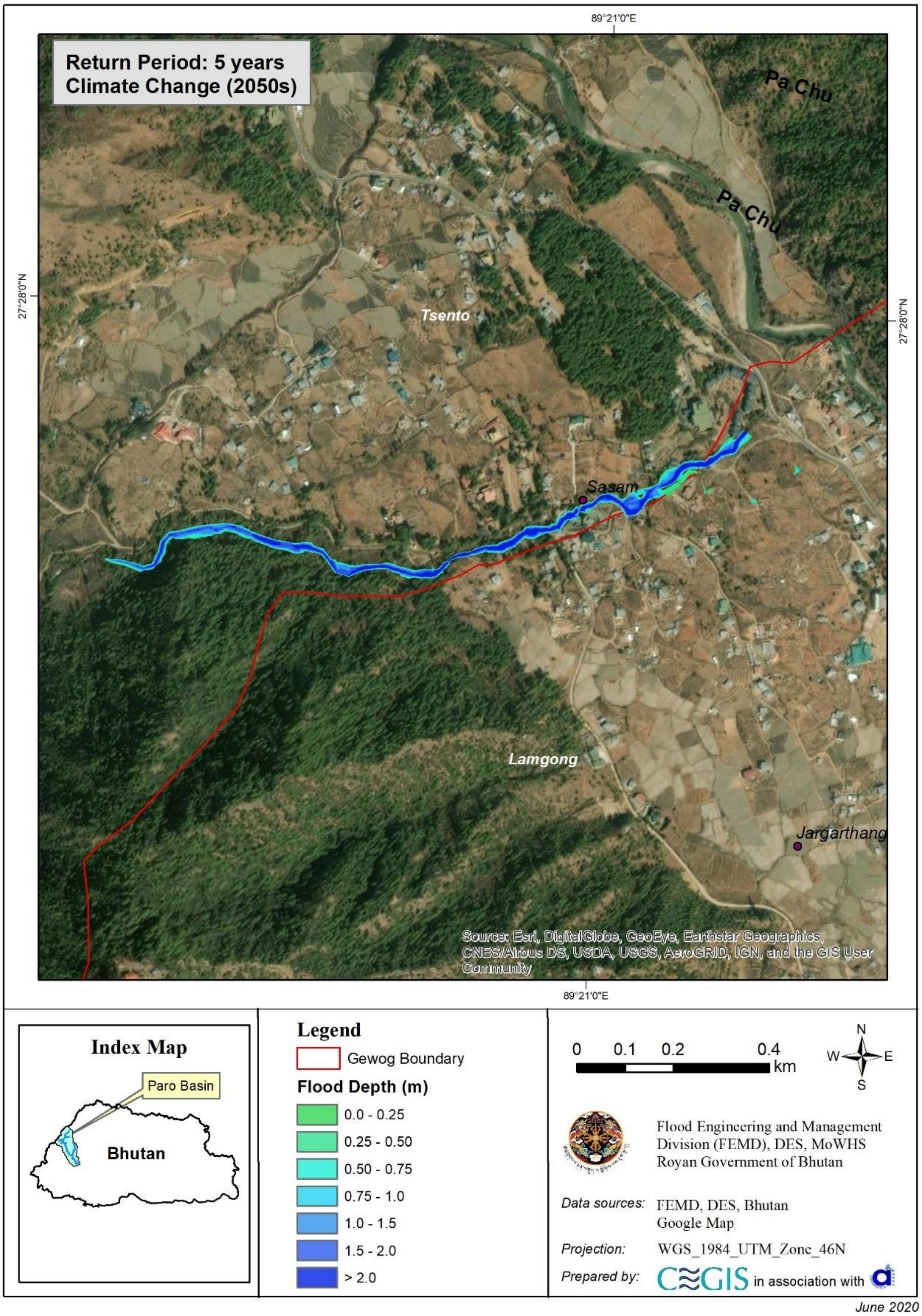
Flood Depth and Extent Map for Satsan Chu (N)



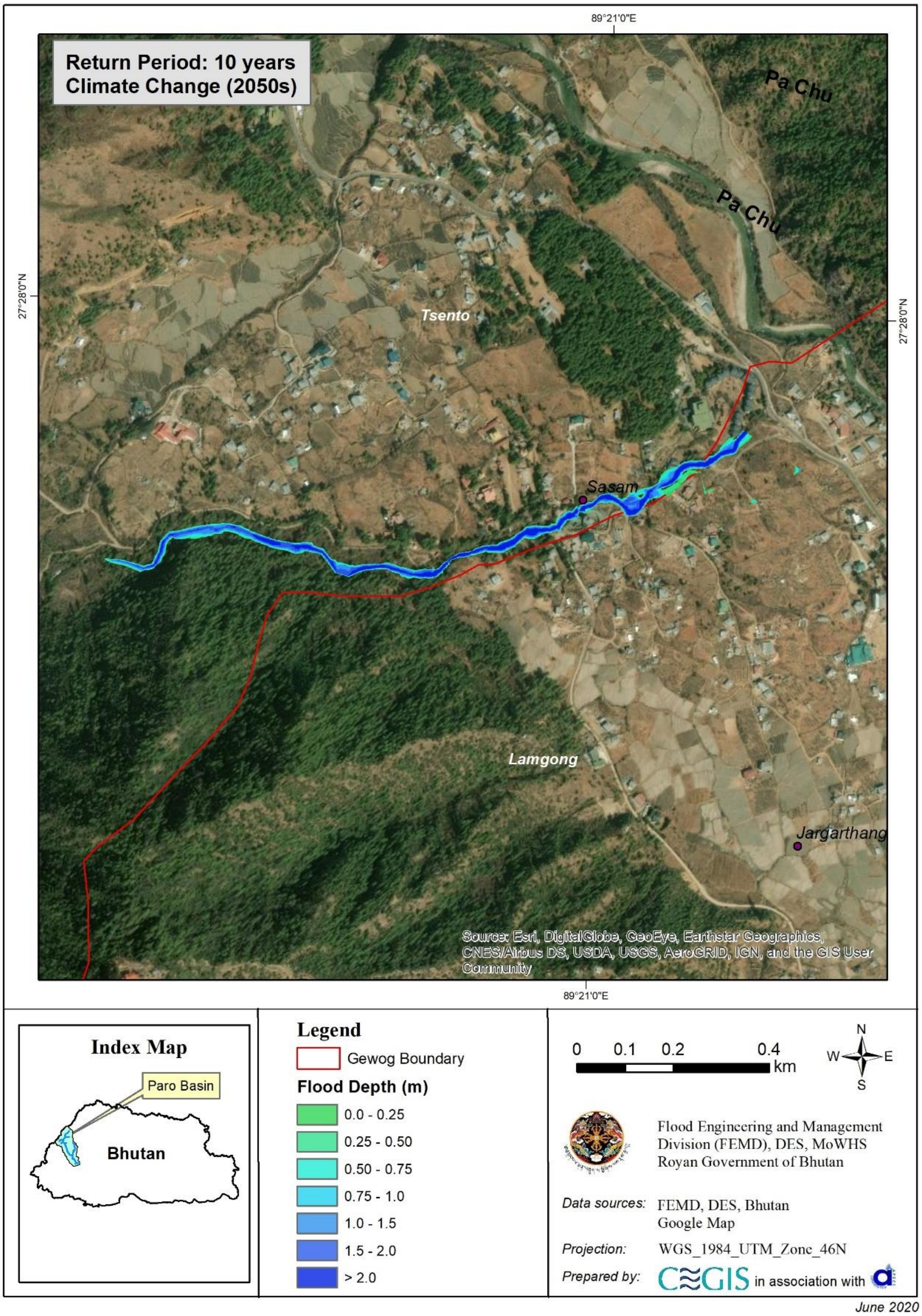
Flood Depth and Extent Map for Satsan Chu (S)



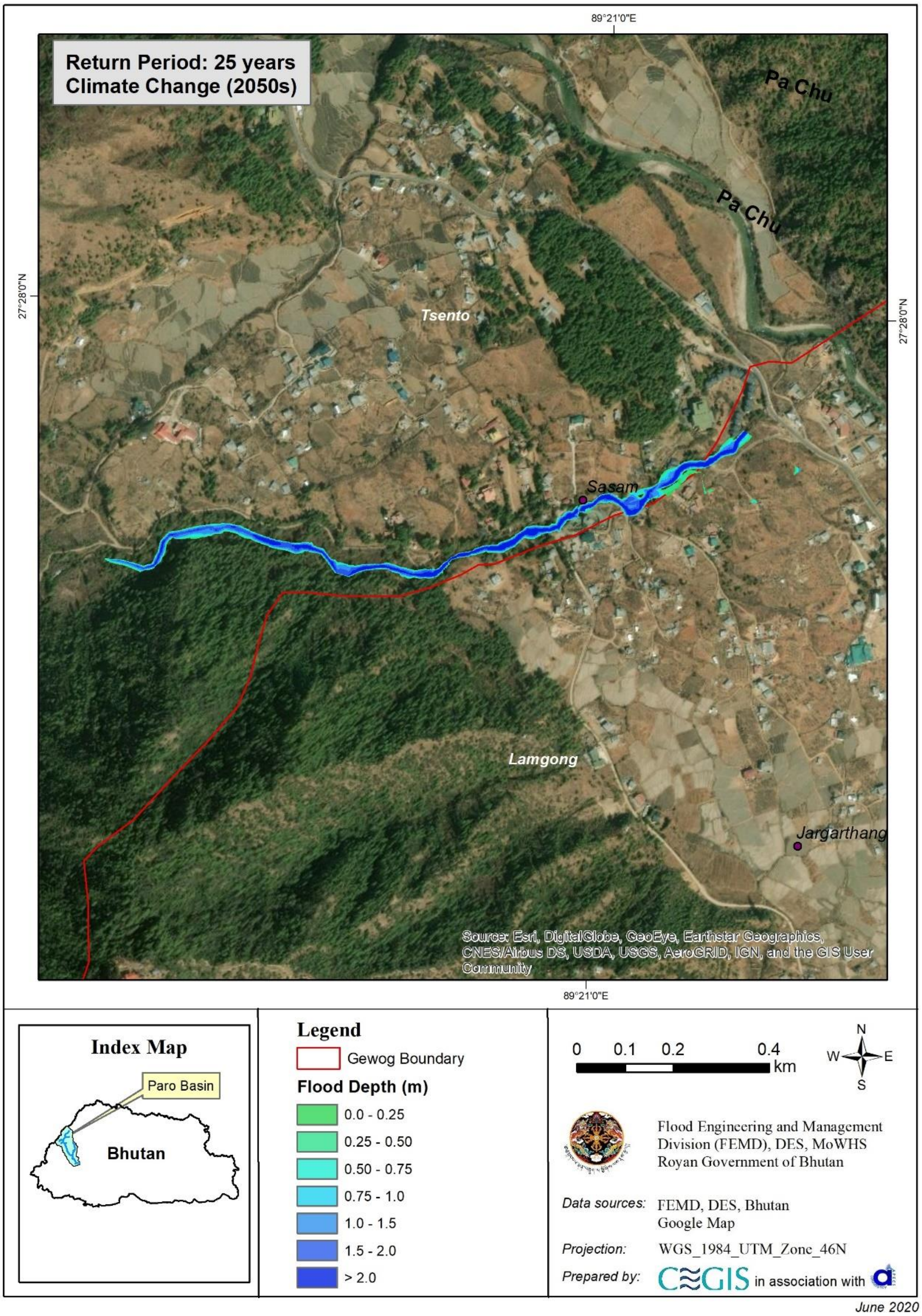
Flood Depth and Extent Map for Satsan Chu (S)



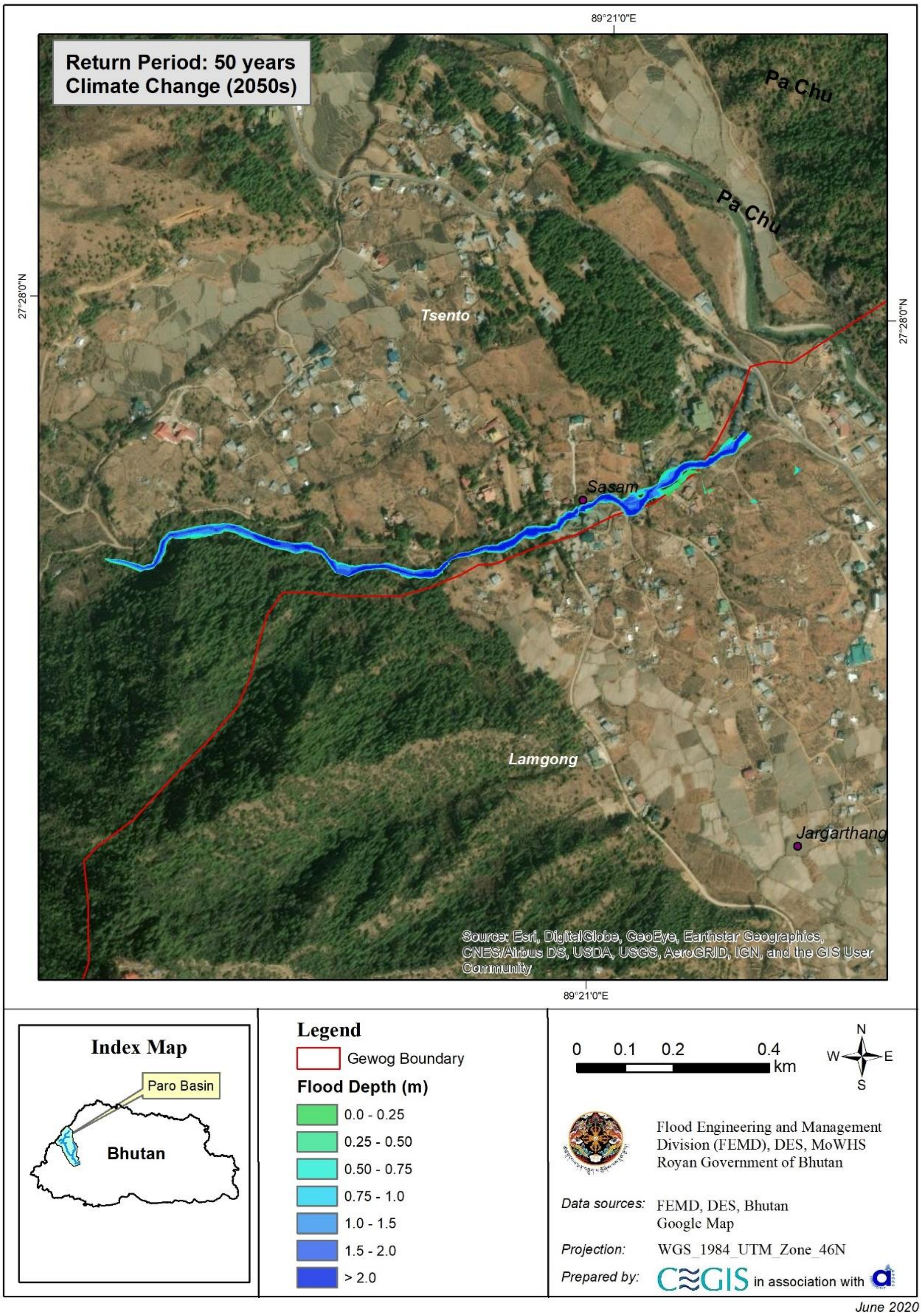
Flood Depth and Extent Map for Satsan Chu (S)



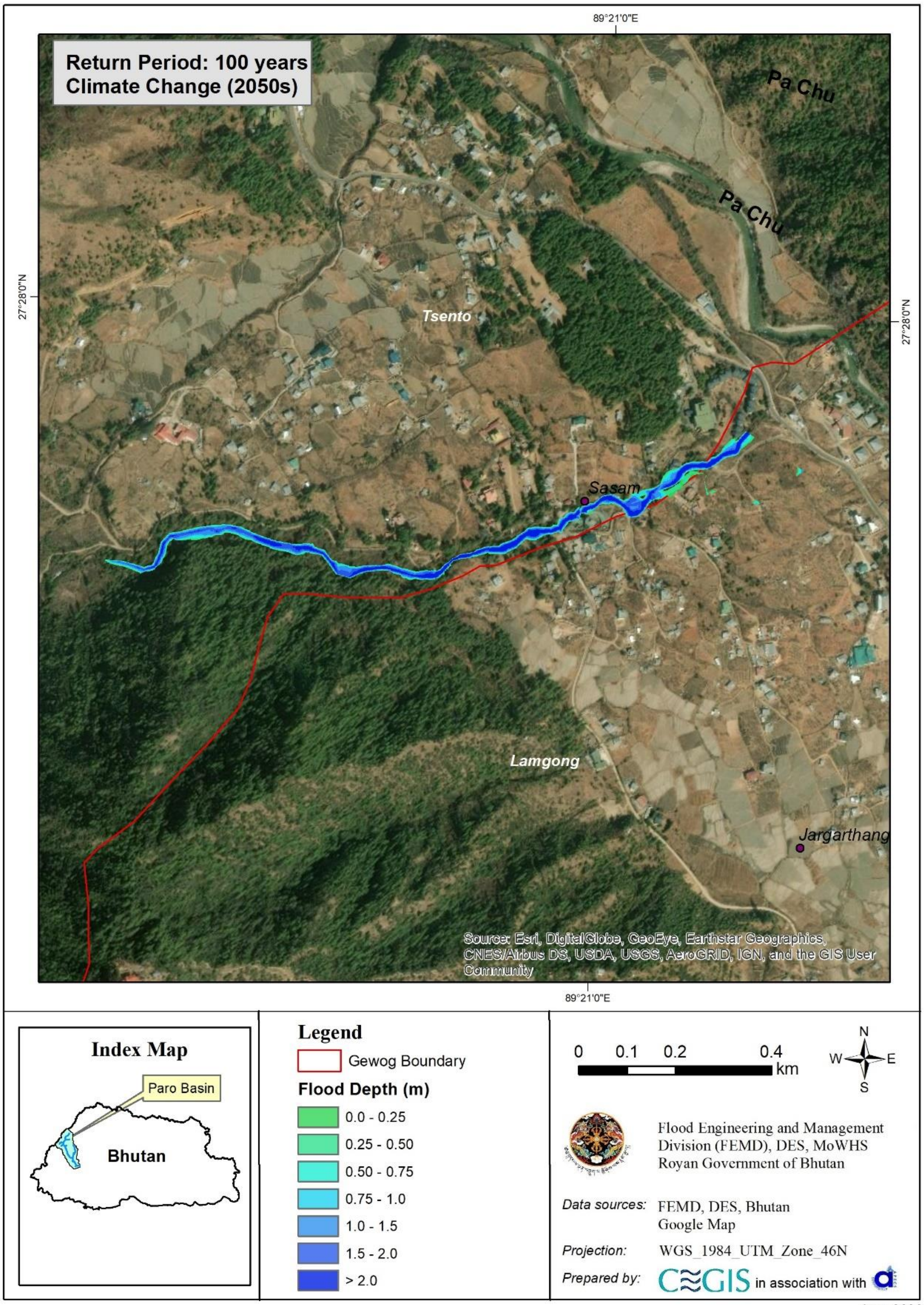
Flood Depth and Extent Map for Satsan Chu (S)



Flood Depth and Extent Map for Satsan Chu (S)

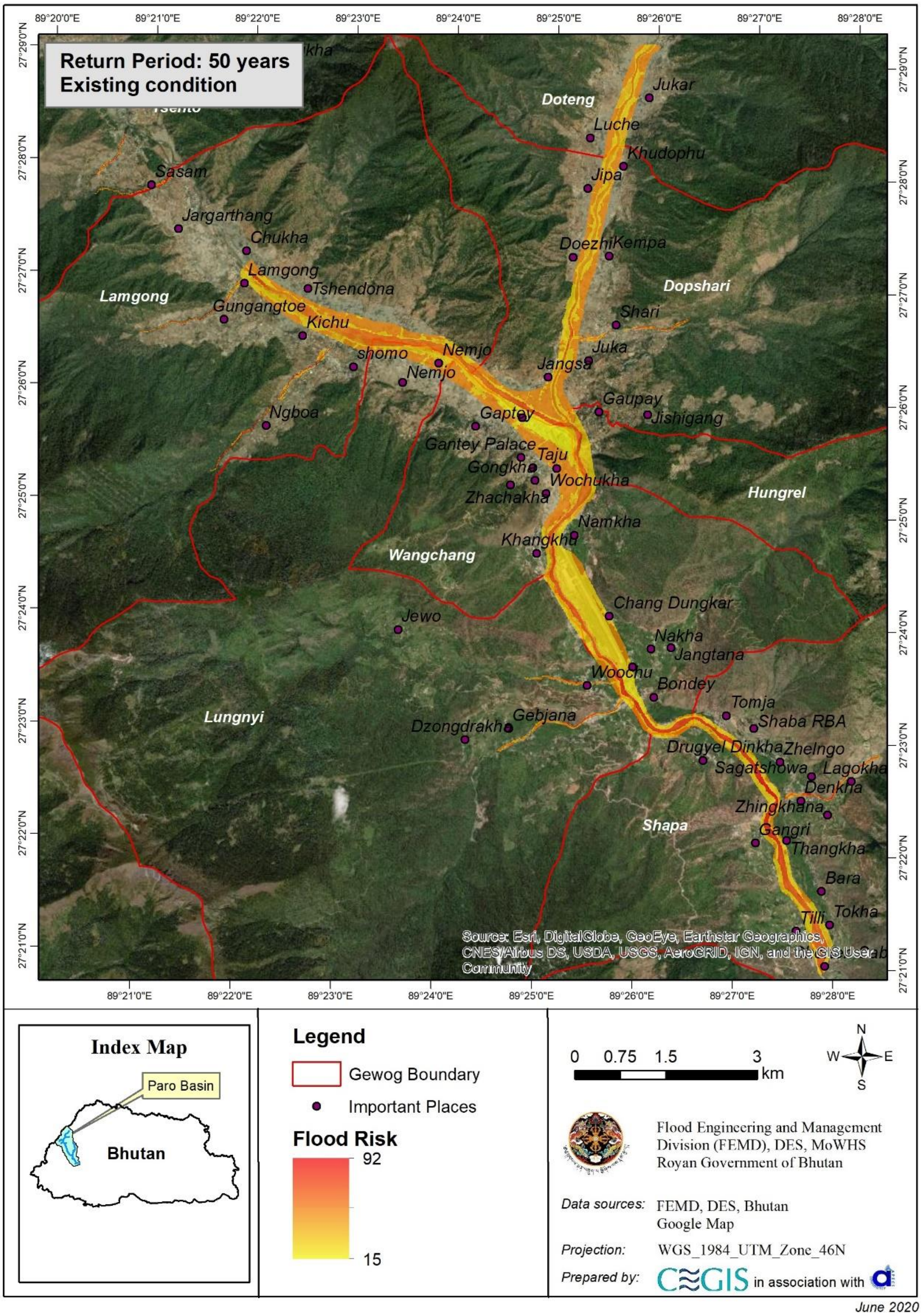


Flood Depth and Extent Map for Satsan Chu (S)

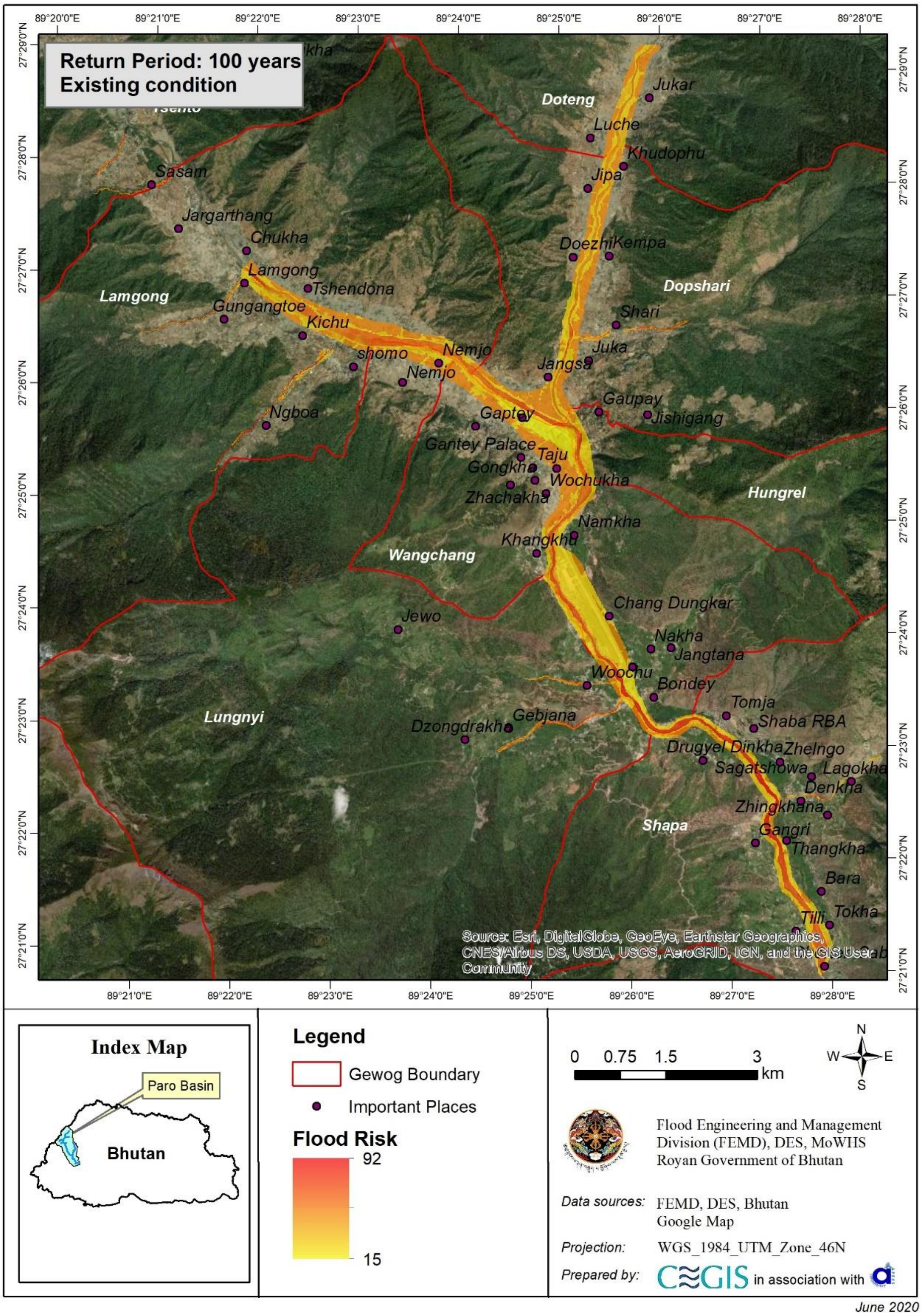


June 2020

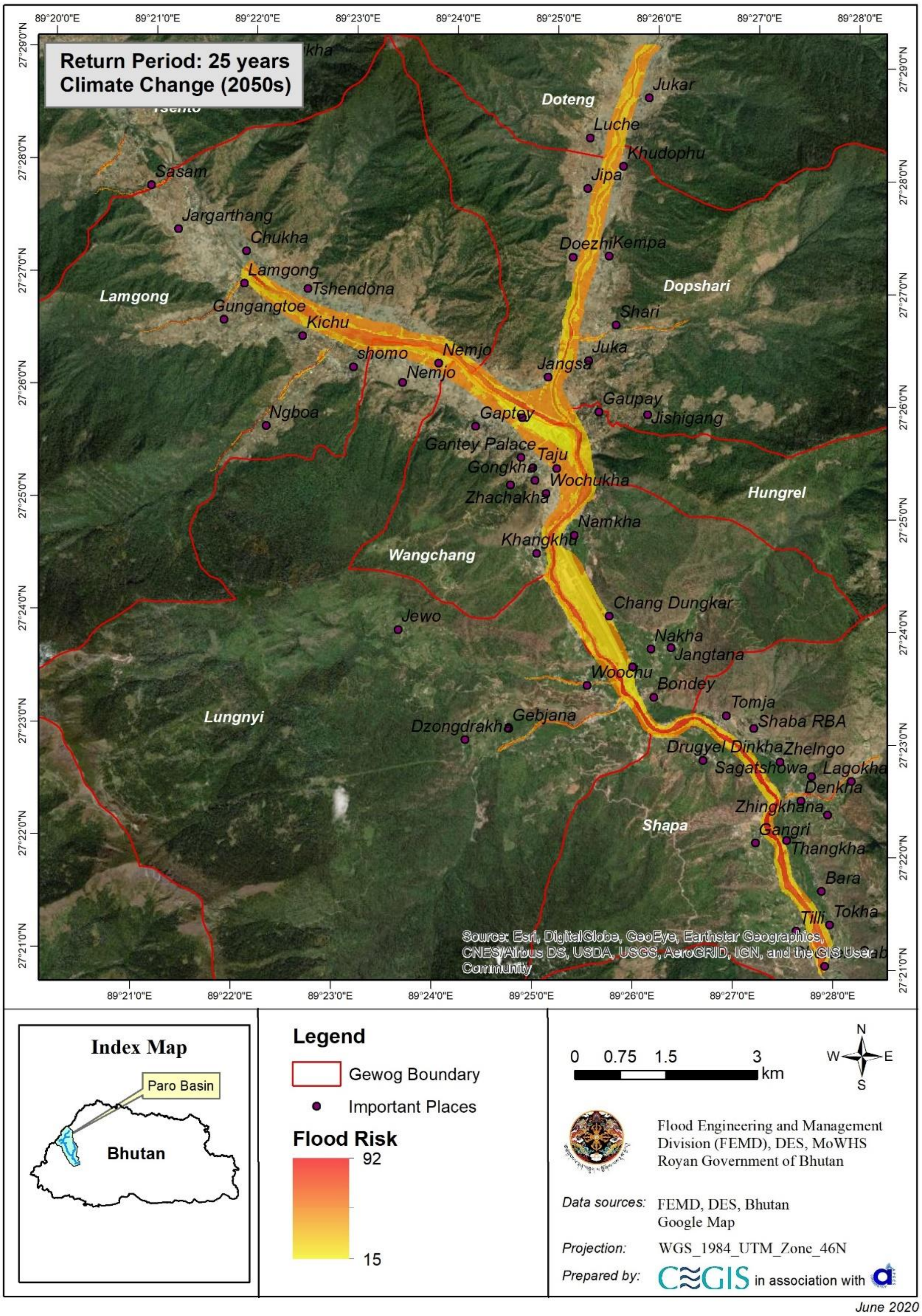
Flood Risk Assessment for Paro Dzongkhag



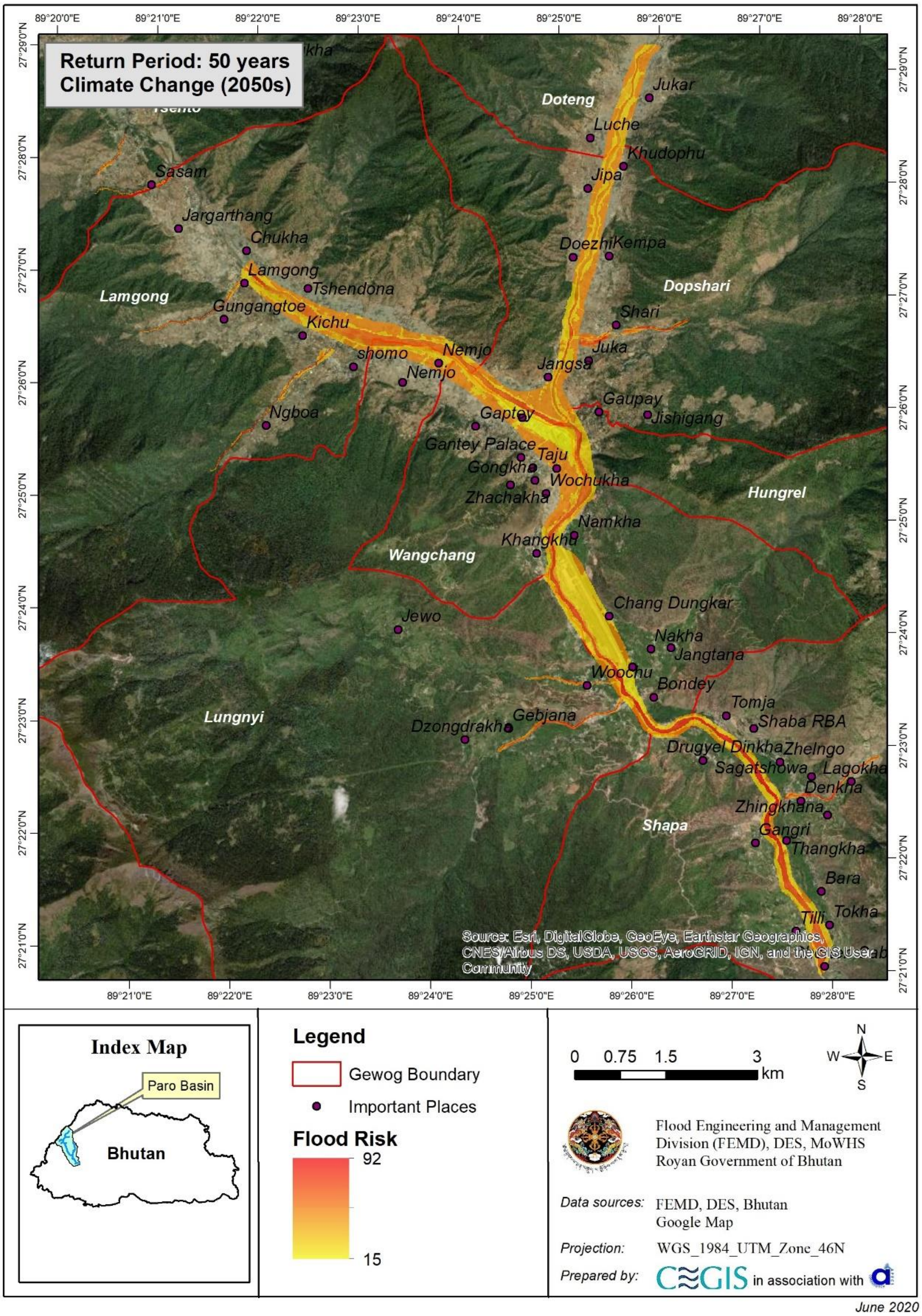
Flood Risk Assessment for Paro Dzongkhag



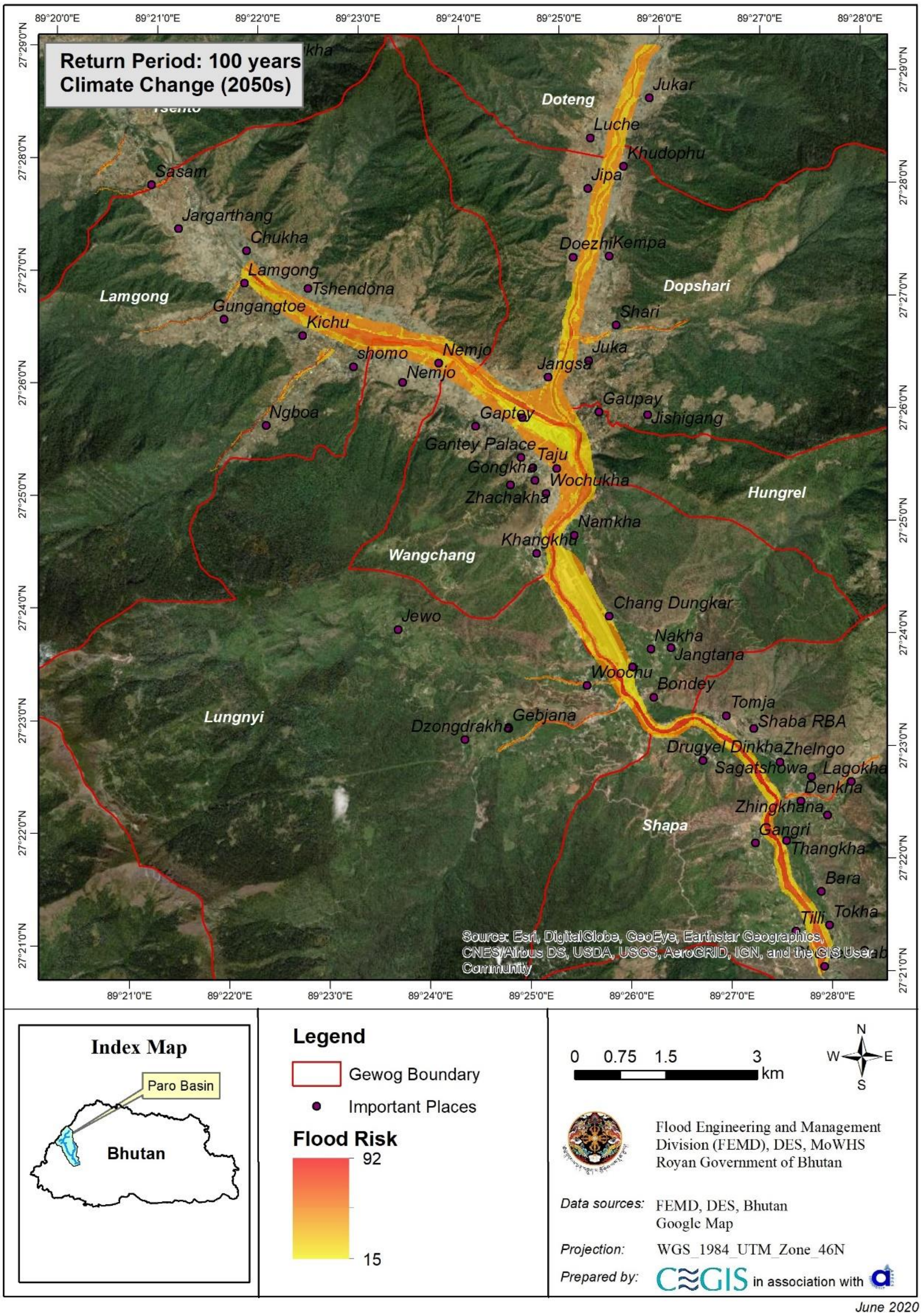
Flood Risk Assessment for Paro Dzongkhag



Flood Risk Assessment for Paro Dzongkhag



Flood Risk Assessment for Paro Dzongkhag



Appendix IV: Socio-economic Survey Questionnaire

Preparation of Flood Management Plan

Household Survey Questionnaire

1. General Information

1. Survey ID (No):		**2. Survey date:**	
3. Name of interviewee:			
4. Dzongkhag:		**5. Geog:**	
6. Village:		**7. Name river/stream:**	
8. Type of property of interviewee	a) Residential b) Commercial c) Infrastructure (include airport, telecommunication, water supply, bridge…) d) Institutional (include: education, govt. office…) e) Hospital f) Historical (including: Dzong, palace, Lhakhang, museum, etc. g) Recreational		
9. Ownership/holding type of the property	a) Owner b) Tenant (rented) c) Leased-in (from private owners) d) Leased-in (from government)		

2. Household Profile of Interviewee

10. Household profile

Sl. No.	Name of household members (start with household head)	Relation with HH head	Age	Sex	Marital status	Education	Occupation		Monthly income from:	
							Main	Secondary	Primary	Secondary
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Code - 15

Relation with HH head

1. Household head
2. Husband/wife
3. Son/daughter
4. Son-in-law/daughter-in-law
5. Grandson/granddaughter
6. Father/mother
7. Brother/sister
8. Nephew/niece
9. Father-in-law/mother-in-law
10. Brother-in-law/sister-in-law
11. Housemaid/butler
12. Servant
13. Others (specify)

Sex

1. Male
2. Female

Marital status

1. Married
2. Unmarried
3. Widow/widower
4. Divorced

Occupation

1. Agriculture
2. Agriculture labor
3. Non-agriculture labor
4. Tourism
5. Forest related work
6. Petty business
7. Service employee
8. Day labor
9. Small cottage (garments, pottery, etc.)
10. Housewife
11. Student
12. Child
13. Livestock, dairy, poultry, piggery
14. Others (specify)

Education

1. Non-formal Education
2. ECCD/Daycare
3. Primary
4. Lower Secondary
5. Middle Secondary
6. Higher Secondary Certificates
7. Diploma
8. Bachelor’s Degree
9. Masters and Above Others

3. Others

11. Landholding

11.1 What is the size of the total land holding? ....acres

11.2 Land acreage by category a) wet b) dry c) Orchard d) others (specify)

11.3 Does your family have land elsewhere other than this village?
a) Yes b) No

11.4 If yes, what is the area of the land that you own? .... acres

12. Household Structure & Amenities

12.1 Type of house	a) Stone wall	b) Stone & wooden wall		c) Bamboo wall		d) Wooden wall e) Others (specify)	
12.2 House roof type:	a) wooden shingles	b) tin roof		c) thatched		d) d) others	
12.3 No. of floors (include attic)	12.4 No. of rooms...........	12.5 Electricity		12.5 Toilet		12.6 Separate kitchen	
		Yes	No	Yes	No	Yes	No

13. Impact of Flooding

13.1 How your property is affected due to flood?	a) b) c)
13.2 How your income is affected due to flood?	a) b) c)
13.3 How education of your children is affected due to flood?	a) b) c)
13.4 If affected, how long children could not go to the school due to flood	.... days

TASHI DELEK

Appendix V: Financial Analysis Tables

Paro: Financial Investment and O&M cost						Paro: Economic Investment and O&M cost				
Channels	Investment Cost in million Nu	Periodic Maintenance Cost in million Nu	Labour Cost 24% of investment	Material Cost 66% of Investment	Import Duty	Labou Cost adjustment by 0.82 factor	Local material Cost	Imported Cement cost	Import Duty	Total Economic cost
Nine Channels at Paro	76		18	50	8	18	27	20	0	66
			0	0	0	0	0	0	0	0
Physical contingency	4		0	0	0	0	0	0	0	3
Price contingency	4		0	0	0	0	0	0	0	0
Total	**84**		**18**	**50**	**8**	**18**	**27**	**20**	**0**	**69**

Periodic maintenance cost	Financial	Economic
After five years of the implementation of the Project.	8.4	6.9

Implementation Year wise Budget requirement in million Nu						
	Year 1		**Year 2**		**ToT Fin**	**ToT Econ**
	Financial	Economic	Financial	Economic		
Paro						
investment	**34**	**28**	**50**	**41**	**84**	**69**

Paro: Without Project Damage Value that is to be Saved (In Million Nu)

Year	Return period	Avoidance of infrastructural damage	Avoidance of crop damage	Annual development in without case	Total Financial value (in million Nu)	Economic Value (adjusted using SCF=0.902)	Net Benefit (W0-W)	
							Fin	Econ
1	25	30.46	0.65	1.03	32.01	28.87	30.73	27.72
2		30.46	0.65	1.06	32.94	29.71	31.62	28.52
3		30.46	0.65	1.09	33.90	30.57	32.54	29.35
4		30.46	0.65	1.12	34.88	31.46	33.48	30.20
5		30.46	0.65	1.15	35.89	32.37	34.45	31.08
6		30.46	0.65	1.19	36.93	33.31	35.45	31.98
7		30.46	0.65	1.22	38.00	34.28	36.48	32.91
8		30.46	0.65	1.26	39.10	35.27	37.54	33.86
9		30.46	0.65	1.29	40.24	36.29	38.63	34.84
10		30.46	0.65	1.33	41.41	37.35	39.75	35.85
11		30.46	0.65	1.37	42.61	38.43	40.90	36.89
12		30.46	0.65	1.41	43.84	39.54	42.09	37.96
13		30.46	0.65	1.45	45.11	40.69	43.31	39.06
14		30.46	0.65	1.49	46.42	41.87	44.56	40.20
15		30.46	0.65	1.54	47.77	43.09	45.86	41.36
16		30.46	0.65	1.58	49.15	44.34	47.19	42.56
17		30.46	0.65	1.63	50.58	45.62	48.55	43.80
18		30.46	0.65	1.67	52.04	46.94	49.96	45.07
19		30.46	0.65	1.72	53.55	48.31	51.41	46.37
20		30.46	0.65	1.77	55.11	49.71	52.90	47.72
21		30.46	0.65	1.82	56.71	51.15	54.44	49.10
22		30.46	0.65	1.88	58.35	52.63	56.02	50.53
23		30.46	0.65	1.93	60.04	54.16	57.64	51.99
24		30.46	0.65	1.99	61.78	55.73	59.31	53.50
25		30.46	0.65	2.04	63.57	57.34	61.03	55.05
26		30.46	0.65	2.10	65.42	59.01	62.80	56.65
27		30.46	0.65	2.16	67.32	60.72	64.62	58.29
28		30.46	0.65	2.23	69.27	62.48	66.50	59.98
29		30.46	0.65	2.29	71.28	64.29	68.43	61.72
30		30.46	0.65	2.36	73.34	66.16	70.41	63.51

Paro: With Project Damage Save Value (In Million Nu)

Year	Return period	Avoidance of infrastructural damage	Avoidance of crop damage	Annual development in without case	Total Financial value (in million Nu)	Economic Value (adjusted using SCF=0.902)
1	25	1.22	0.026	1.029	1.28	1.15
2		1.22	0.026	1.059	1.32	1.19
3		1.22	0.026	1.090	1.36	1.22
4		1.22	0.026	1.121	1.40	1.26
5		1.22	0.026	1.154	1.44	1.29
6		1.22	0.026	1.187	1.48	1.33
7		1.22	0.026	1.222	1.52	1.37
8		1.22	0.026	1.257	1.56	1.41
9		1.22	0.026	1.293	1.61	1.45
10		1.22	0.026	1.331	1.66	1.49
11		1.22	0.026	1.370	1.70	1.54
12		1.22	0.026	1.409	1.75	1.58
13		1.22	0.026	1.450	1.80	1.63
14		1.22	0.026	1.492	1.86	1.67
15		1.22	0.026	1.535	1.91	1.72
16		1.22	0.026	1.580	1.97	1.77
17		1.22	0.026	1.626	2.02	1.82
18		1.22	0.026	1.673	2.08	1.88
19		1.22	0.026	1.721	2.14	1.93
20		1.22	0.026	1.771	2.20	1.99
21		1.22	0.026	1.823	2.27	2.05
22		1.22	0.026	1.876	2.33	2.11
23		1.22	0.026	1.930	2.40	2.17
24		1.22	0.026	1.986	2.47	2.23
25		1.22	0.026	2.044	2.54	2.29
26		1.22	0.026	2.103	2.62	2.36
27		1.22	0.026	2.164	2.69	2.43
28		1.22	0.026	2.227	2.77	2.50
29		1.22	0.026	2.291	2.85	2.57
30		1.22	0.026	2.358	2.93	2.65

Number of Skill and Unskill Labour Utilization During Implementation

Calculation of Skilled and Unskilled Labour Opportunities							Assumptions						
	Item of works	**Total cost (Nu in million)**	**Non-labour cost**		**Labour cost**		**Skilled labour (46 % of 24)**	**Unskilled labour (54% of 24)**	**Cost with wage skilled labour (nu/day**	**Cost with wage unskilled labour nu/day**	**Number of skilled labour-day**	**Number of unskilled labour-day**	**Total**
			cost	%	cost	%	%	%			0.000309	0.000232	
	Direct/Capital cost												
1	RB protection in vulnerable locations via gabion mesh	26.54	20	76%	6	24%	20%	80%	1	5	4,123	21,968	26,091
2	Trapezoidal re-section for ~1400m u/s reach and rectangular section for ~500m d/s reach	23.73	18	76%	6	24%	20%	80%	1	5	3,686	19,636	23,322
3	Brick masonry rectangular channel re-section without top slab	9.77	7	76%	2	24%	20%	80%	0	2	1,518	8,085	9,603
4	Trapezoidal re-section	1.67	1	76%	0	24%	20%	80%	0	0	260	1,384	1,644
5	Trapezoidal re-section	2.23	2	76%	1	24%	20%	80%	0	0	346	1,842	2,188
6	Trapezoidal re-section	4.21	3	76%	1	24%	20%	80%	0	1	655	3,487	4,142
7	Culvert construction	2.87	2	76%	1	24%	20%	80%	0	1	447	2,379	2,826
8	Culvert construction	2.52	2	76%	1	24%	20%	80%	0	0	392	2,087	2,478
9	Culvert construction	2.73	2	76%	1	24%	20%	80%	0	1	424	2,261	2,685
	Total	76.28	57.97		18.31						11,850	63,130	74,979

Paro: Financial Cost Benefit Analysis and Sensitivity

Base Case Financial Cost Benefit Analysis (in million Nu)									Sensitivity Test Sensitivity 1: Benefit decreased by 10%			Sensitivity 2: Total cost increased by 10%			Best Case			Worst Case		
Year	**Investment cost**	**O&M cost**	**Total Cost**	**Value of Damage Save**			**Total benefit**	**Cash flow**	**Reduced benefit**	**Total cost**	**Cash flow**	**Benefits**	**Increased Total cost**	**Cash flow**	**Benefit Increased by 10%**	**Total cost decreased by 10%**	**Cash flow**	**Benefit decreased by 10%**	**Total cost increased by 10%**	**Cash flow**
1	34		34				0	-34	0	34	-34	0	37	-37	0	31	-31	0	37	-37
2	50		50				0	-50	0	50	-50	0	55	-55	0	46	-46	0	55	-55
3			0	31		0	31	31	28	0	28	31	0	31	34	0	34	28	0	28
4			0	32	0	0	32	32	29	0	29	32	0	32	35	0	35	29	0	29
5			0	33		0	33	33	30	0	30	33	0	33	36	0	36	30	0	30
6			0	33		0	33	33	30	0	30	33	0	33	37	0	37	30	0	30
7			0	34		**0**	**34**	**34**	31	0	31	34	0	34	38	0	38	31	0	31
8		8.4	8	35		0	35	27	32	8	24	35	9	26	39	8	31	32	9	23
9			0	36		0	36	36	33	0	33	36	0	36	40	0	40	33	0	33
10			0	38		0	38	38	34	0	34	38	0	38	41	0	41	34	0	34
11			0	39		0	39	39	35	0	35	39	0	39	42	0	42	35	0	35
12			0	40		0	40	40	36	0	36	40	0	40	44	0	44	36	0	36
13			0	41		0	41	41	37	0	37	41	0	41	45	0	45	37	0	37
14		8.4	8	42		0	42	34	38	8	30	42	9	33	46	8	39	38	9	29
15			0	43		0	43	43	39	0	39	43	0	43	48	0	48	39	0	39
16			0	45		0	45	45	41	0	41	45	0	45	49	0	49	41	0	41
17			0	46		0	46	46	42	0	42	46	0	46	50	0	50	42	0	42
18			0	47		0	47	47	43	0	43	47	0	47	52	0	52	43	0	43
19			0	49		0	49	49	44	0	44	49	0	49	53	0	53	44	0	44
20		8.4	8	50		0	50	42	45	8	37	50	9	41	55	8	47	45	9	36
21			0	51		0	51	51	47	0	47	51	0	51	57	0	57	47	0	47
22			0	53		0	53	53	48	0	48	53	0	53	58	0	58	48	0	48
23			0	54		0	54	54	49	0	49	54	0	54	60	0	60	49	0	49
24			0	56		0	56	56	51	0	51	56	0	56	62	0	62	51	0	51
25			0	58		0	58	58	52	0	52	58	0	58	63	0	63	52	0	52
26		8.4	8	59		0	59	51	54	8	46	59	9	50	65	8	58	54	9	45
27			0	61		0	61	61	55	0	55	61	0	61	67	0	67	55	0	55
28			0	63		0	63	63	57	0	57	63	0	63	69	0	69	57	0	57

Year	Investment cost	O&M cost	Total Cost	Value of Damage Save		Total benefit	Cash flow	Reduced benefit	Total cost	Cash flow	Benefits	Increased Total cost	Cash flow	Benefit Increased by 10%	Total cost decreased by 10%	Cash flow	Benefit decreased by 10%	Total cost increased by 10%	Cash flow
Base Case Financial Cost Benefit Analysis (in million Nu)								**Sensitivity Test** **Sensitivity 1: Benefit decreased by 10%**			**Sensitivity 2: Total cost increased by 10%**			**Best Case**			**Worst Case**		
29			0	65	0	65	65	59	0	59	65	0	65	71	0	71	59	0	59
30		8.4	8	66	0	66	58	60	8	52	66	9	57	73	8	66	60	9	51
Net Present Value (NPV) in million Nu at 12% discount rate			**77**			**244**	**167**	**222**	**77**	**145**	**244**	**84**	**160**	**269**	**70**	**199**	**222**	**84**	**137**
Financial Benefit Cost Ratio (BCR)							3.18	FBCR		2.89	FBCR		2.89	FBCR	3.85		FBCR		2.63
Net Present Value (NPV) (Nu in million) at 12% discount rate							167	FNPV		145	FNPV		160	FNPV	199		FNPV		137
Financial Internal Rate of Return (IRR)							35%	FIRR		32%	FIRR		32%	FIRR	41%		FIRR		29%

Paro: Economic Cost Benefit Analysis with Sensitivity

Base Case Economic Cost Benfit Analysis Million Nu								Sensitivity Test Sensitivity 1: Benefit decreased by 10%			Sensitivity 2: Total cost increased by 10%			Best Case			Worst Case		
Year	**Investment cost**	**O&M cost**	**Total Cost**	**Value of Damage Save**		**Total benefit**	**Cash flow**	**Reduced benefit**	**Total cost**	**Cash flow**	**Benefits**	**Increased Total cost**	**Cash flow**	**Benefit Increased by 10%**	**Total cost decreased by 10%**	**Cash flow**	**Benefit decreased by 10%**	**Total cost increased by 10%**	**Cash flow**
1	28	0	28			0	-28	0	28	-28	0	30	-30	0	25	-25	0	30	-30
2	41	0	41			0	-41	0	41	-41	0	46	-46	0	38	-38	0	46	-46
3		0	0	28	0	28	28	25	0	25	28	0	28	30	0	30	25	0	25
4		0	0	29	0	29	29	26	0	26	29	0	29	31	0	31	26	0	26
5		0	0	29	0	29	29	27	0	27	29	0	29	32	0	32	27	0	27
6		0	0	30	0	30	30	27	0	27	30	0	30	33	0	33	27	0	27
7		0	0	31	0	31	31	28	0	28	31	0	31	34	0	34	28	0	28
8		**7**	**7**	**32**	**0**	**32**	**25**	**29**	**7**	**22**	**32**	**8**	**24**	**35**	**6**	**29**	**29**	**8**	**21**
9		0	0	33	0	33	33	30	0	30	33	0	33	36	0	36	30	0	30
10		0	0	34	0	34	34	31	0	31	34	0	34	37	0	37	31	0	31
11		0	0	35	0	35	35	32	0	32	35	0	35	38	0	38	32	0	32
12		0	0	36	0	36	36	33	0	33	36	0	36	39	0	39	33	0	33
13		0	0	37	0	37	37	34	0	34	37	0	37	41	0	41	34	0	34
14		**7**	**7**	**38**	**0**	**38**	**31**	**35**	**7**	**28**	**38**	**8**	**30**	**42**	**6**	**35**	**35**	**8**	**27**
15		0	0	39	0	39	39	36	0	36	39	0	39	43	0	43	36	0	36
16		0	0	40	0	40	40	37	0	37	40	0	40	44	0	44	37	0	37
17		0	0	41	0	41	41	38	0	38	41	0	41	45	0	45	38	0	38
18		0	0	43	0	43	43	39	0	39	43	0	43	47	0	47	39	0	39
19		0	0	44	0	44	44	40	0	40	44	0	44	48	0	48	40	0	40
20		**7**	**7**	**45**	**0**	**45**	**38**	**41**	**7**	**34**	**45**	**8**	**37**	**50**	**6**	**43**	**41**	**8**	**33**
21		0	0	46	0	46	46	42	0	42	46	0	46	51	0	51	42	0	42
22		0	0	48	0	48	48	43	0	43	48	0	48	52	0	52	43	0	43
23		0	0	49	0	49	49	45	0	45	49	0	49	54	0	54	45	0	45
24		0	0	51	0	51	51	46	0	46	51	0	51	56	0	56	46	0	46
25		0	0	52	0	52	52	47	0	47	52	0	52	57	0	57	47	0	47
26		**7**	**7**	**53**	**0**	**53**	**47**	**49**	**7**	**42**	**53**	**8**	**46**	**59**	**6**	**53**	**49**	**8**	**41**
27		0	0	55	0	55	55	50	0	50	55	0	55	61	0	61	50	0	50

Base Case Economic Cost Benfit Analysis Million Nu							Sensitivity Test Sensitivity 1: Benefit decreased by 10%			Sensitivity 2: Total cost increased by 10%			Best Case			Worst Case		
Year	**Investment cost**	**O&M cost**	**Total Cost**	**Value of Damage Save**	**Total benefit**	**Cash flow**	**Reduced benefit**	**Total cost**	**Cash flow**	**Benefits**	**Increased Total cost**	**Cash flow**	**Benefit increased by 10%**	**Total cost decreased by 10%**	**Cash flow**	**Benefit decreased by 10%**	**Total cost increased by 10%**	**Cash flow**
28	0	0	57	0	57	57	51	0	51	57	0	57	62	0	62	51	0	51
29	0	0	58	0	58	58	53	0	53	58	0	58	64	0	64	53	0	53
30	0	0	60	0	60	60	55	0	55	60	0	60	66	0	66	55	0	55
Total		**63**			**220**	**157**	**200**	**63**	**137**	**220**	**69**	**151**	**242**	**57**	**185**	**200**	**69**	**131**
Economic Benefit Cost Ratio (EBCR)						3.49	EBCR		3.18	EBCR		3.18	EBCR		4.23	EBCR		2.89
Economic Net Present Value (ENPV) (Nu in million) at 12% discount rate						157	ENPV		137	ENPV		151	ENPV		185	ENPV		131
Economic Internal Rate of Return (EIRR)						37%	EIRR		34%	EIRR		34%	EIRR		44%	EIRR		32%

Appendix VI: Comment Matrix

Comments from 10 July, 2020

Sl.No	Comments	Report Volume No	Page no	Remarks	Action
1	The flood extend map should be properly demarcated with coordinates and id where the specific structures is proposed.	Vol 5		Identified the risk areas	**Has been incorporated.**
2	**Longterm:** **Option: 1**-Resectioning of flow path with slope protection using of gabion revetment or any other appropriate materials without bed soling/aurmaring. **Option 2:** Resectioning only	Vol 2		Inclcude most sustanable structures in long term measeres	**Has been incorporated.**
3	**Short term/immediate measures:** **Option 1:** Locating critical areas along River banks from the flood risk map and than propose embankment with gabion revetment or any other structures which blands with the existing structures. (For Eg: The structures like gabion revetment should be designed with lunching apron as per the site condition). **Option 2:** Embankment with CC block or any other alternatives which fits with the existing structures.	Vol 2 & 4		Proposed immediate measure are not implementable at site.	**Has been incorporated. A separate "immediate-term" added incorporating location specific measures at right bank of Pa Chu upstream.**
4	**Dakhorongchu stream near the Lamgong school**. The 2 existing hume pipe is adequate or not?.				**The existing 2-piped culvert has been found to be adequate.**
5	**Ngoborongchu.** Cross section details and levelling is missing.Explain?				**Has been incorporated.**
6	**Box culvert in the stream,** designer has given 2 smaller opening which may cause blockage during the high discharge.Explain?			The span is only 3 m	**Design has been changed.**
7	**Main Report:** still reflecting remarks column, the adequcy need to check/ need to design.	Vol 2		Field observation has to be corected (stream like Richu.)	**Has been modified.**
8	**Main Report** : under Remarks column, it was refected that **Need box culvert with wing way**,	Vol 2	230	Explain? However, Field visit remarks column should be checked and revise after checking discharge adequacy.	**Has been corrected.**
9	**Summary of investment project**: In the responsibility agency, it was refected FEMD and gewog are responsible for implementation.	Vol 2	203	Write MoWHS, Dzongkhag and Gewog	**Has been corrected.**

Sl.No	Comments	Report Volume No	Page no	Remarks	Action
10	Capacity development	Vol 2	203	Write Nu: 5-10 Million	**Has been adjusted.**
11	All units for amounts is in lakhs			Write in Million	**Has been corrected.**
12	Flood zoning responsible agency			Mention MoWHS, MoHCA,NCHM,Dzongkhag and other relevant agency.	**Has been incorporated.**
13	There is no resection proposed between the bridge point (way to tiger nest), chainage 0 and 1				**No resectioning required. Mentioned in Chapter 6**
14	Short term period should start from			2023 to 2027	**Has been incorporated.**
15	Long term period should prosed from			2027	**Has been incorporated.**
16	Funding source			Include GoI and DRIVE	**Has been incorporated.**
17	Reflected kings property in report		216 and 243	Need to change	**Has been incorporated.**
18	ECoP, WMO and WMGs			Reflect in Acronyms	**Has been incorporated.**
19	Detailed Rate Analysis			Please write correct project title and location	**Has been incorporated.**
20	Detailed Rate Analysis			Items should be checked.	**Has been incorporated.**
21	Excavation			Should be checked and correct for long term and short term	**Has been incorporated.**
22	Rates			BSR 2020 rates should be applied.	**Has been incorporated.**

Name of works: Preparation of Flood Management Plan for Paro Dzongkhag.

Reviewed and Commented: By FEMD officials on 23rd July 2020

The following comments were made during the review of FMP, Paro:

1. **Location:** *Between Utpal Higher Secondary School and Jagathang village (as marked in Google image):* During our recent site visit it was observed that height between water level and ground level was almost equal and island was formed. Please explore and propose some structural measures around this area.
   Answer: This has been incorporated.

2. **Maps**: In the report, you have modelled after placing of immediate measures only. Provide maps after placing long term and short term structures in the model as well. (Provide 3 different maps, after placing of immediate measures, short term and long term measures)
   Answer: This has been incorporated.

3. **Page No. 170/171**: Check cross reference for maps.
   Answer: Has been incorporated.

4. **Source of funding**: Elaborate on **DRIVE** funding.
   Answer: After thorough search in international portals, we can find no information on the DRIVE Project or funding mechanism.

5. **Drawing labeling:** Refer the IS code: 16014:2012, Bhutan Schedule of Rates (BSR) and specifications for Building and Roads Works 2020 for gabion specification, thickness and size should label correctly. Replace wire net by gabion mesh/revetment in the drawing.
   Answer: This has been incorporated.

6. **Volume II, Main report:** Write Flood Engineering and Management Division (FEMD) in the maps legend.
   Answer: This has been incorporated.