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FLOOD HAZARD MAPPING OF SELECTED WATERSHEDS ACROSS THE KARNALI, MAHAKALI AND RAPTI RIVER BASINS

Cover photo: DHM river monitoring gauge in the Karnali river at Chisapani (left) and a man showing how high floods have reached in a settlement in Asaraghat (right).

Photo credit: Nature's Conservation Pvt. Ltd. for USAID Paani Program

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The Study Team
Nature's Conservation Pvt. Ltd.
Kathmandu, Nepal

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LIST OF ACRONYMS

DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DPR	Detail Project Report
DPRP	Disaster Preparedness and Response Plan
D/S	Downstream
EOC	Emergency Operation Centers
EVI	Extreme Value I
EWS	Early Warning System
FFA	Flood Frequency Analysis
GCM	Global Circulation Model
GeoTIFF	Georeferenced Tagged Image File Format
GEV	Generalized Extreme Value
GIS	Geographical Information System
GLOFs	Glacier Lake Outburst Floods
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HFL	Highest Flood Level
LEOC	Local Emergency Operation Centre
LN	Log Normal
LP	Log Pearson
MoHA	Ministry of Home Affairs
NCVST	Nepal Climate Vulnerability Study Team
NLUP	National Land Use Project
NRCS	Nepal Red Cross Society

OSM	Open Street Map
SRTM	Shutter Radar Topography Mission
U/S	Upstream
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WECS	Water and Energy Commission Secretariat
WERDP	Water and Energy Resource Development Project
WISP	WECS/NEA Institutional Support Programme
WMO	World Meteorological Organization

1. BACKGROUND

1.1 INTRODUCTION

As a country, Nepal is highly prone to natural disasters due to steep, high-relief slopes, complex geology with active tectonic processes, frequent seismic activity, and excessive seasonality in climate. These risk factors are exacerbated by Nepal's climate change vulnerability, which ranks 4th in the world, according to the Global Climate Risk Index, which assesses the impacts of meteorological events in relation to economic losses and human fatalities (Eckstein et al., 2019). Nepal also ranks 30th in the world and 2nd in South Asia in terms of flood risk (UNDP, 2009 & MoHA, 2015). Overall, more than 80% of the population is exposed to the risk of natural hazards (MoHA, 2017), which include droughts, floods, earthquakes, landslides, extreme temperatures, and glacier lake outburst floods (GLOFs).

An estimated ~6,000 rivers and rivulets flow through Nepal from north to south. These rivers can be divided into three distinct categories.

1) **Four large rivers with perennial sources**. These include the Koshi, Narayani, Karnali and Mahakali, which originate in the high Himalayas. The Mahakali River in the far west is a border river between Nepal and India has many major stretches. These rivers are fed by glaciers, snowmelt, and rainfall in the Himalaya and flow down to India through the lower hills and Tarai plains.
2) **Perennial middle mountain rivers** that flow down to the lower flood plain areas of Nepal and India. These rivers flow with very high variation of discharge between the dry and rainy seasons.
3) **Ephemerals or torrents** that originate in the foothills of the Churia range in Siwalik region. These small rivers flow only during the monsoon and dry up after the rainy season is over. Many are activated within a single rainstorm.

Water-induced disasters of different intensity and magnitude have affected various parts of the country. The principal triggering factor is monsoon rainfall, which occurs June and September (Chalise et al., 1995). About 80% of the country's total annual rainfall occurs during monsoon season. Hence, extreme flood events are observed at this time due to concentrated spells of heavy rainfall (Shakya, 1998). In recent years, changing precipitation patterns have increased the magnitude and frequency of floods in Nepal (MoHA, 2009b).

Flood is a common issue in the rainy season in Nepal and has been the most frequent, highly devastating and widespread natural hazard in the country. During monsoon, rivers swell and cause damage to villages, crops lands, and livestock within the river flood plains in the south. Due to global warming, the probability of occurrence of potentially damaging floods is likely to increase because of the high intensity of extreme precipitation (>100 mm/day) events (Baidya et al. 2008) and the formation of glacial lakes in high mountain areas. Global Circulation Model (GCM) projects a wide range of precipitation changes, especially during monsoon seasons: 14 to +40% by the 2030s increasing 52 to 135% by the 2090s (NCVST 2009). The monsoon precipitation patterns are changing, too, with fewer days of rain and more high-intensity and incessant rainfall events. In recent decades, the withdrawal dates of monsoon have been delayed, and the duration of the monsoon has increased (Gautam and Regmi, 2013).

Downpour generated by cloudbursts in the far-western region in 2008 eroded agricultural lands, deposited sands and silt on nearby houses, and inundated settlements for days, damaging irrigation projects, transmission lines, and other public and private infrastructure. The 2013 and 2014 floods in the mid- and far-western regions caused not only immense loss of human life and property but also had a devastating impact on development (MoHA, 2015).

Identification of flood risk areas will help to plan more effective disaster risk reduction and emergency response when the risk information is disseminated to user groups in a more efficient manner. A lack of public understanding about the benefits of flood hazard mapping might be one of the barriers for implementation. When locals are unaware about the benefits of the hazard maps, they prioritize costly structural flood protection measures for risk reduction. Hence, the creation of flood hazard maps should promote greater awareness of the risk of flooding.

Flood forecasting and warning is one of the most important non-structural measures in comprehensive flood loss prevention and management (Lin, 1995). Thus, flood forecasting is very important for efficient means for minimizing flood damage and loss of life. Flood early warning systems are useful to inform people and institutions ahead of impending disaster so that they can take effective preparedness measures to reduce loss of life and properties. Considering this fact, DHM has already established the flood early warning system in several river basins, mostly in Tarai region. Flood hazard mapping provides information on the magnitude, extent and duration of flood for flood warning and danger level thresholds for the purpose of flood warning and preparedness. It creates easy-to-read, rapidly-accessible charts and maps that help administrators and planners to identify areas of risk and prioritize their mitigation/response efforts as a non-structural measure. In other words, flood hazard maps makes the process of resource allocation simpler, resulting in smooth and effective implementation of flood management strategies.

1.2 OBJECTIVE

The main objective of the assignment was to provide flood hazard maps with data and information for the Department of Hydrology and Meteorology (DHM) of Nepal to be used to determine flood warning and danger levels across ten of Paani's priority watersheds in the Mahakali, Karnali, and Rapti river basins, specifically worded as follows:

- To generate different scenarios of flooding/inundation and provide flood hazard maps for ten Paani priority watersheds with 2, 5, 10, 25, 50, 100, and 200 year return periods, including warning levels, danger levels, and historical flood mark levels for the different scenarios.

2. STUDY AREA

Of the major rivers in Nepal, the Karnali and Mahakali rivers are snow-fed and originate in the Himalayan range, while the West Rapti River is a rain-fed river that originates in the middle mountain range. The study areas are the 10 watersheds: Lower Mahakali, Rangun, Lower Karnali, Middle Karnali, Tila Karnali, West Seti, Thuligaad, Bogatan Lagam Karnali, Middle Rapti and Jhimruk – each of which is located in one of three river basins: the Mahakali (2), Karnali (6) and West Rapti (2) river basins. See figure 1 for the locations of each watershed. Below we provide greater detail on each watershed.

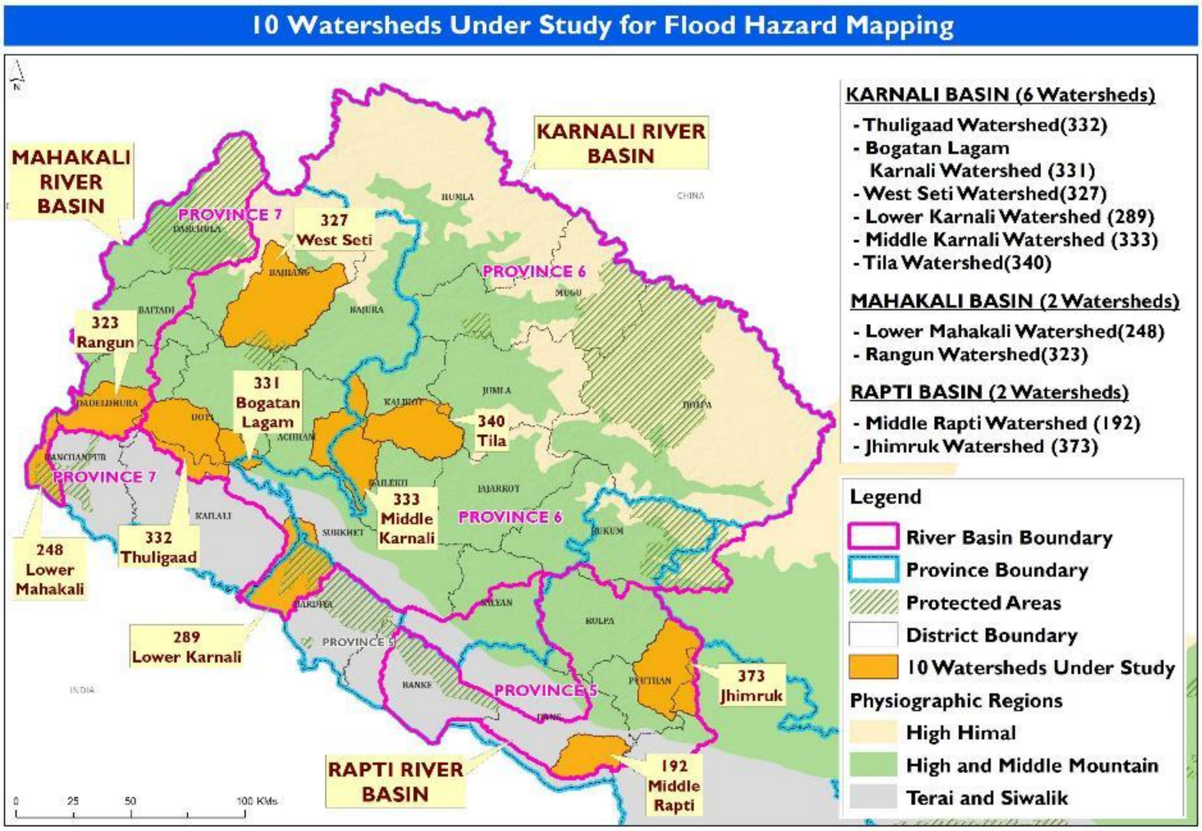

Figure 1: The 10 watershed study areas for flood hazard mapping

2.1 STUDY WATERSHEDS IN MAHAKALI BASIN

a) Lower Mahakali Watershed

The Lower Mahakali watershed is located in Kanchanpur District of far-western Nepal and borders India to the west and south. Administratively, the watershed is divided into three zones: 1) Bhimdatta Municipality occupies the northern portion; 2) Mahakali Municipality lies to the west; and 3) Shuklaphanta National Park in the southern portion.

The vast majority of the watershed area is characterized as Tarai plain, which is predominately flat, alluvial plain topography with a small portion in the Churia/Siwalik hills to the north. The elevation ranges from 180 to 250 meters (m) in the Tarai to the highest point in the watershed at 1,000 m in the Churia/Siwalik hills. The Mahakali River, Tilkeni Khola, Jogbuda Nadi, Bhujela Khola, and Malaria Khola are the major water bodies of this particular watershed (USAID, Paani Program, 2018).

b) Rangun Watershed

The Rangun watershed has a total are of 687 sq. km and stretches across parts of Doti and Dadeldhura districts in the far-western province of Nepal. The watershed elevation ranges from 2,500 m in the north, near the Mahabharat range, to 300 m along its southern reaches, where the river joins the Mahakali River at Parshuramdham. The watershed includes all of Parshuram Municipality and Alital Rural Municipality in Dadeldhura District, and Jorayal Rural Municipality in Doti district. The Rangun Khola joins the Puntura Khola before draining into the Mahakali River downstream, which ultimately joins the Karnali River in India (USAID, Paani Program, 2018).

2.2 STUDY WATERSHEDS IN KARNALI BASIN

A) West Seti Watershed

The West Seti watershed covers almost the entire Bajhang District, with small parts extending into Doti and Bajura. The area is hilly and remote, ranging in altitude from 3,400 m to just 750 m in the southern reaches. The watershed covers an area of 1,488 km^2. The total drainage length of the watershed is 963 km, as the many rivers of the watershed run southward to the confluence with the Karnali River and eventually the Ganges Basin in India (USAID, Paani Program, 2018).

B) Thuligaad Watershed

The Thuligaad watershed lies in the Karnali River Basin and belongs to parts of Doti and Kailali Districts in southwestern Nepal. The watershed stretches across the Jorayal and Baddikedar Rural Municipalities (in Doti), and the Chure and Mohanyal Rural Municipalities (in Kailali) District. The total area of the watershed is 850 km^2. Water drains from the north between the Karnaso Gaad of Doti through to the Khimadi near Mohanyal in the south from where it eventually flows into Karnali River (USAID, Paani Program, 2018).

C) Bogatan Lagam Karnali Watershed

The Bogatan Lagam Karnali watershed stretches over an area of 205 km^2 and extends partly over two districts in the far- and mid-western regions of Nepal. The majority of the watershed lies in Doti District and a small portion in Surkhet District. The topography of the Bogatan Lagam Karnali watershed is characterized by steep, hilly terrain with large variations in elevation. The highest ridge point of the watershed is 2,357 m and the lowest point is 313 m. The geology of the watershed is characterized by carbonaceous rock, limestone, and dolomite. (USAID, Paani Program, 2018).

D) Middle Karnali Watershed

The Middle Karnali watershed includes a 67.7-kilometer-long section of the Karnali River, from the confluence of the Humla Karnali and Tila Rivers at Jitegada downstream to the Karnali's confluence with the Lohore Khola at Tallo Dungeshwor. The river bed is primarily boulders in the north and sandy in the south, contributing to a high sediment load. Three-fourths of the Middle Karnali watershed sits in the mid-hills of Nepal, its topography comprised of steep and fragile slopes vulnerable to erosion and landslides. The remaining area is categorized as middle mountain (USAID, Paani Program, 2018).

E) Lower Karnali Watershed

The Lower Karnali watershed covers parts of three districts: Surkhet, Kailali and Bardiya with the majority of its area in the latter. Of the 875 km^2 in the Lower Karnali Watershed, 65% is considered

Tarai (plains), and 35% is Siwalik Hills. The elevation ranges from 1,457 m in the north to 118 m in the south near the Indian border. The Lower Karnali watershed forms the southern outlet for the Karnali River. The Karnali River takes a braided form with diverging and converging channels separated by bars. At Chisapani, the watershed exits the mountains and enters the Tarai. The Karnali bifurcates into the Geruwa River (eastern branch), which forms the western boundary of Bardiya National Park, and the Kauriala Karnali (western), which flows between the Kailali and Bardiya districts (USAID, Paani Program, 2018).

F) Tila Karnali Watershed

Tila Karnali River is one of the six major tributaries of the Karnali River. The Tila Karnali River originates from the middle mountains of mid- western Nepal and covers an area of 545 km^2 (USAID, Paani Program, 2018).

2.3 STUDY WATERSHEDS IN WEST RAPTI BASIN

A) Middle Rapti Watershed

The Middle Rapti watershed stretches from Dang district in Nepal southward to India, across the border. The watershed covers an area of 1303 km2 with the Rapti, Arjun Khola, Khabhari, Gurung Khola, Supaila, Dolai, Kakrahawa, Sikrahawa, Narti, Kaudiya, Arnahawa as its major rivers. The landform is fragile, comprised of Churia hills. The Rapti River is an intertwined stream that runs east to west, cutting through the middle of the watershed parallel to the national East-West Highway. As frequently occurs in the Tarai, the river configuration changes its patterns frequently, as does the extent to which it reaches through the floodplains, delivering sediment for agricultural development but also increasing the risk of flooding. The Rapti River descends more than 2,000 meters from the mid-hills to the plains. The river frequently changes its course, which has increased the risk of flooding (USAID, Paani Program, 2018).

B) Jhimruk Watershed

The Jhimruk watershed is located in Province 5 in southwestern Nepal. It falls primarily within the mid-hills along the Jhimruk River. The Jhimruk watershed forms a drainage system for the Rapti River basin with elevation ranging from 3,000 meters in the north to 410 meters in the south. The watershed contains five rural municipalities (Naubahini, Jhimruk, Gaumukhi, Mallarani, and Airawati) and one municipality (Pyuthan). The Jhimruk watershed covers the area from the confluence of Jhimruk and Lung Kholas upstream at Batule and features a complex network of 169 rivers and streams (USAID, Paani Program, 2018).

3. METHODOLOGY

3.1 DIGITAL ELEVATION MODEL PREPARATION

To prepare a digital elevation model, we used Shutter Radar Topography Mission (SRTM) 1 Arc-second global elevation data, which offers worldwide coverage of void-filled data at a resolution of 1 arc-second (30 meters) and provides open access to this high resolution global data set.[1] The Digital Elevation Model (DEM) data is available in a Georeferenced Tagged Image File Format (GeoTIFF), which is a standard image format for GIS applications. Each cell contains a matrix of vertical elevation values spaced at regular horizontal intervals (1 arc second) measured in geographic latitude and longitude units. SRTM DEMs are expected to have linear vertical absolute height error of less than ±16 m, linear vertical relative height error of less than ±10 m, circular absolute geo-location error of less than ±20 m, and circular relative geo-location error of less than ±15 m (Farr et al., 2007).

SRTM-30m accuracy assessments showed the absolute vertical error to be much smaller, with the most reliable estimates being approximately 5m (Kellndorfer et al., 2004). As well, in discussions with DHM technical members, we arrived at a consensus that, considering the free availability and watershed level output scale of nearly 1:50,000, the SRTM 30m DEM is fit for purpose for watershed-level flood hazard mapping.

For this study, tiles of SRTM 30m covering the Karnali, Mahakali and West Rapti basins were downloaded from the United States Geological Survey (USGS). After generating the DEM, sinks were filled using tools available in the Spatial Analyst Toolbox of ArcGIS.

3.2 FLOOD FREQUENCY ANALYSIS

Flood frequency analysis is an important method for estimating flood peaks for specified probabilities of exceedance at gauged sites where sufficiently long (~30 years) historical records are available. The maximum instantaneous discharge data was fitted with log-normal 2- parameter (LN2), log-normal 3-parameter (LN3), Log-Pearson Type III (LP3), Gumbel, Extreme value – I (EVI) and Generalized extreme value (GEV) distributions to find out the best probability distribution representing the peak flows. Freely available Hydrognomon software (Source: https://hydrognomon.software.informer.com/4.1/) was adopted to identify the best-fit method and for estimating peak discharge at several return periods.

[1] Source: USGS EROS Archive: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1-arc?qt-science_center_objects=0#qt-science_center_objects

3.3 ESTIMATION OF PEAK FLOW FOR UNGAUGED BASIN

For ungauged basins, WECS/DHM[2] devised a method for estimating peak flow (DHM, 2004). The DHM 2004 method employs a regional flood frequency analysis method and is a modification of the WECS/DHM 1990 method. The following equations were used to estimate peak flow:

Instantaneous Peak flood for a return period of 2 years, $Q_2 = 2.29A^{0.86}$
Instantaneous Peak flood for a return period of 100 years, $Q_{100} = 20.7A^{0.72}$
The peak flow for any other return period, T years, is calculated as:

$Q_T = \exp(\ln Q_2 + S_T\,\sigma)$

Where,

A = area below 3000m elevation
Q_T = T-year flood in m^3s^{-1}
Q_2 = 2-year flood in m^3s^{-1}
S_T = Standard normal variate for T-year flood
σ = standard deviation of natural logarithms of annual floods = $\ln(Q_{100} / Q_2) / S_{100}$
S_{100} = Standard normal variate for 100-year flood (2.326)
S_T = Standard normal variate for a particular return period, T
= 0.0, 0.842, 1.282, 1.645, 2.054, 2.326, and 2.576 for T = 2, 5, 10, 20, 50, 100, and 200 years, respectively.

3.4 UPSTREAM AND DOWNSTREAM BOUNDARY CONDITIONS

The peak flows at the nearest DHM gauging stations in the watersheds were taken as the upstream boundary conditions, while the normal slopes as the outlet of the watersheds were taken as the downstream boundary conditions.

3.5 DETERMINATION OF MANNING'S ROUGHNESS

The variation in the Manning's n values were determined using land use/land cover information and aerial imagery from ESRI, Open Street Map (OSM), and Google Earth. On the basis of the land use/land cover types around the watershed area, the Manning's n value was determined. The estimates for Manning's n value for natural channels and flood plains (Table 1) were calculated based on method provided by Chow (1959).

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[2] WECS is the Water and Energy Commission Secretariat. They serves as a public advisor to the Government of Nepal on water and energy issues and frequently provide technical guidance to relevant government agencies, such as the DHM.

Table 1: Manning's roughness

LAND USE TYPE	MANNING'S N VALUE
Barren land	0.030 – 0.050
Brush	0.050 – 0.11
Cultivation area	0.035 – 0.050
Forest	0.100 – 0.200
Grassland	0.035 – 0.050
River	0.030 – 0.10
Sand	0.030 – 0.10

3.6 HYDRAULIC MODELLING USING HEC-RAS

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) was developed by the US Army Corps of Engineers to perform steady flow water surface profile computations, one- and two-dimensional unsteady flow simulations, movable boundary sediment transport computations, and water quality analysis.

In this study, HEC-RAS 5.0.7 was used for one-dimensional steady flow multiple profile analysis. One-dimensional models treat flow through the channel and floodplain only in the longitudinal direction. The equations for modeling one-dimensional flow are derived from the conservation of mass and conservation of momentum equations between adjacent cross-sections (Bates et al., 2005).

The following major steps were used in flood hazard mapping procedure (Figure 2).

- Preparation of Digital Elevation Model (DEM);
- Analysis of flow data, Flood Frequency Analysis, peak flow computation;
- Determination of upstream, downstream and lateral boundary conditions;
- Preparation of cross-section data;
- Estimation of spatial variation of stream flows for different return periods using hydrodynamic model (HEC-RAS); and
- Preparation of flood hazard maps for various return period floods using GIS.

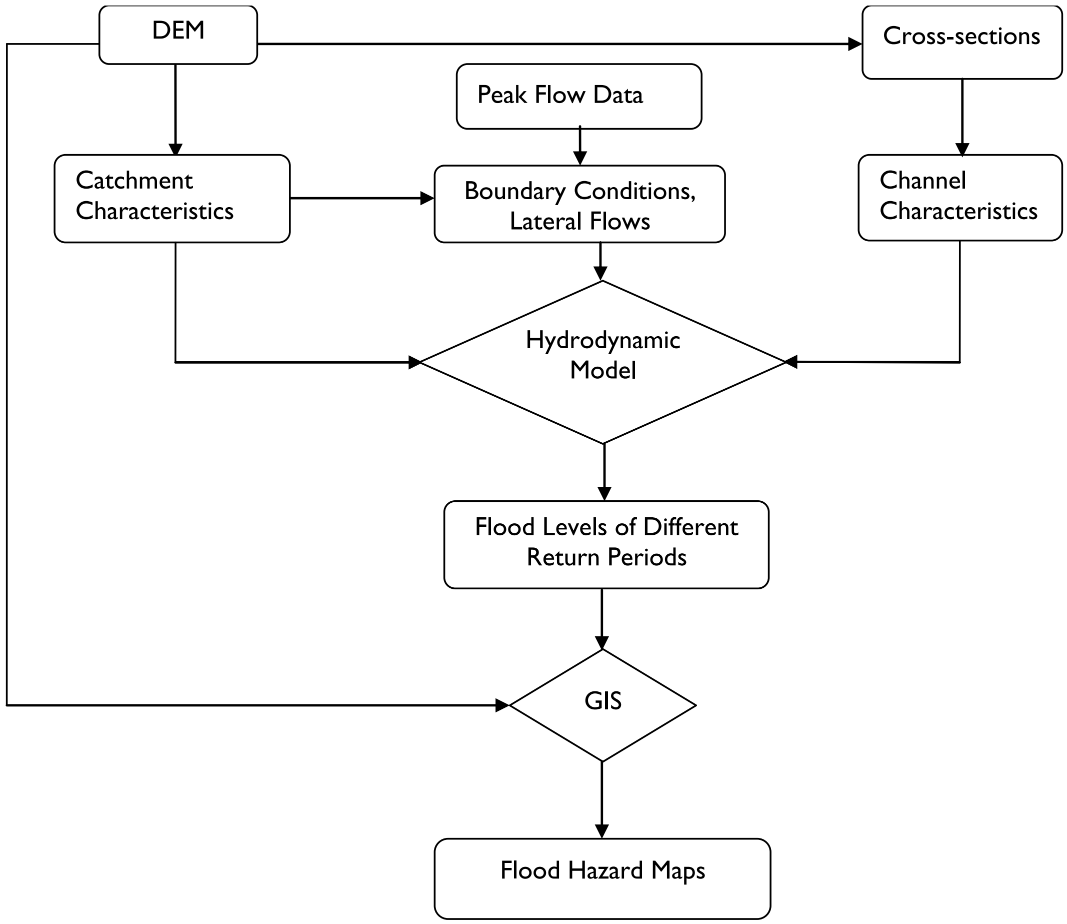

Figure 2: Flow chart of flood hazard mapping method using HEC-RAS

3.6.1 Running the Hec-Ras Model

Cross-sectional geometry data in the river and overbank (floodplain) area were derived from DEM. The RAS mapper was used to create and digitize the geometry components, such as river centerline, banks, flow paths, and cross sections. Aerial imagery in RAS Mapper was adopted as the base map to guide the digitization process.

Steady flow option was selected and necessary flow data and boundary condition data were inserted. Manning's n values for each cross-section were specified on the basis of land use land cover. With different magnitudes of discharge upstream, the flood inundation scenarios were generated using the HEC-RAS model.

3.6.2 FLOOD INUNDATION MAPPING USING ARC GIS

The results obtained from the HEC-RAS model run were imported to the Arc GIS environment. The flood inundation maps were prepared on the basis of water depth. The results of the flood hazard mapping were sorted into five depth categories to indicate risk of inundation at various levels:

- 0 – 15 cm : Very Low Risk
- 15 - 30cm : Low Risk
- 30 – 60 cm : Medium Risk
- 60 – 100 cm : High Risk
- > 100 cm : Very High Risk

Different flooding scenarios and flood hazard maps were generated for the 10 Paani priority watersheds for 2, 5, 10, 25, 50, 100, and 200 year return periods, including indicators for warning levels, danger levels and historical flood mark levels. The information was presented on a 1:50,000 scale map.

3.6.3 DETERMINATION OF WARNING AND DANGER LEVEL

The Flood Forecasting Section of the DHM defines warning level as the flood flow that exceeds a river bank, but does not affect nearby settlements. In other words, it is the flow level at the bankfull stage of a river[3]. The danger level is the level of flow at which flood water rises above the main stream channel and enters nearby settlements, affecting lives and properties, but remaining less than one meter of inundation.

The water surface profile plot in HEC-RAS indicates whether the water level has crossed the river bank at any location. The bankfull water level is taken as the warning level. When the water level exceeds the warning level, that is referred to as the danger level. In other words: bankfull level → warning level → danger level.

3.7 FIELD VERIFICATION AND CONSULTATIONS

After preparing the flood hazard maps with different return periods, the maps were verified and refined through field consultations. Local stakeholders were asked to comment on prepared maps of the flood prone areas and historical flood information to validate the results and identify hazardous areas as depicted through our hydraulic modeling exercises. We used a standard questionnaire (Annex 1) with the stakeholders to inquire about formation on historical flood events, channel shifting, old flood marks, bank heights, and other details of interest.

The following stakeholders were consulted:

- Local government representatives

[3] Bankfull stage is an established gage height at a given location along a river or stream, above which a rise in water surface will cause the river or stream to overflow the lowest natural stream bank somewhere in the corresponding reach. The term "lowest bank" is however, not intended to apply to an unusually low place or a break in the natural bank through which the water inundates a small area. Bankfull stages on streams with natural or manmade high banks can be defined by the predominant vegetation line on the banks. The bankfull stage on many streams is associated with the 2-year recurrence interval flood. Bankfull stage is not necessarily the same as flood stage. (Source: High water level terminology, US National Weather Service: https://www.weather.gov/aprfc/terminology).

- Local Disaster Management Committee
- Local Emergency Operation Centre (LEOC)
- Nepal Red Cross Society (NRCS) sub-chapters
- Watershed Management Specialist, Paani Program
- Field and basin/regional offices of the Department of Hydrology and Meteorology
- NGOs working in the disaster risk and development areas within various municipalities
- Residents in vulnerable communities

4. DATA PREPARATION AND PROCESSING

4.1 TERRAIN DATA

SRTM 30m resolution DEM of mid-western and far-western Nepal was downloaded and DEM of all 10 assigned watersheds were extracted in Arc GIS. The DEM, which is in the WGS84 co-ordinate system, was re-projected into the modified UTM with central meridian 84 degree projection.

Parameters for re-projection

False Easting = 500000
False Northing = 0
Central meridian = 84^0
Scale factor = 0.9996
Latitude of origin: 0
Linear unit: Meter

4.2 RIVER LINE

The RAS mapper toolbox in HEC-RAS was used to create and digitize the river line. Aerial imagery in RAS mapper served as a base map to guide the digitization process. The river center line was digitized following the center of the river and aligned in the direction of flow, from upstream to downstream.

4.3 BANK LINE

The bank lines were created to distinguish the main channel from the overbank region. Bank lines were digitized by considering the bank full terrain elevation. Digitization was carried out starting at the upstream limit and looking downstream. The left bank was digitized and then the right bank.

4.4 FLOW LINE

Flow lines were digitized considering the total flood area that would be affected during high flood conditions. Flow path lines were used to determine the reach lengths between cross sections, in both the main channel and overbank areas. The left and right flow lines were digitized within the flood plains.

4.5 CROSS-SECTION

The cross sections were drawn and digitized from left to right, moving from upstream (U/S) to downstream (D/S). Aerial imagery in RAS Mapper was used as guidance so that no two cross sections intersected each other. The cross sections were drawn out 20 - 30 times the width of the stream so that all the variability of the area was captured in the modeling. Figure 3 shows the cross section of the Rangun watershed.

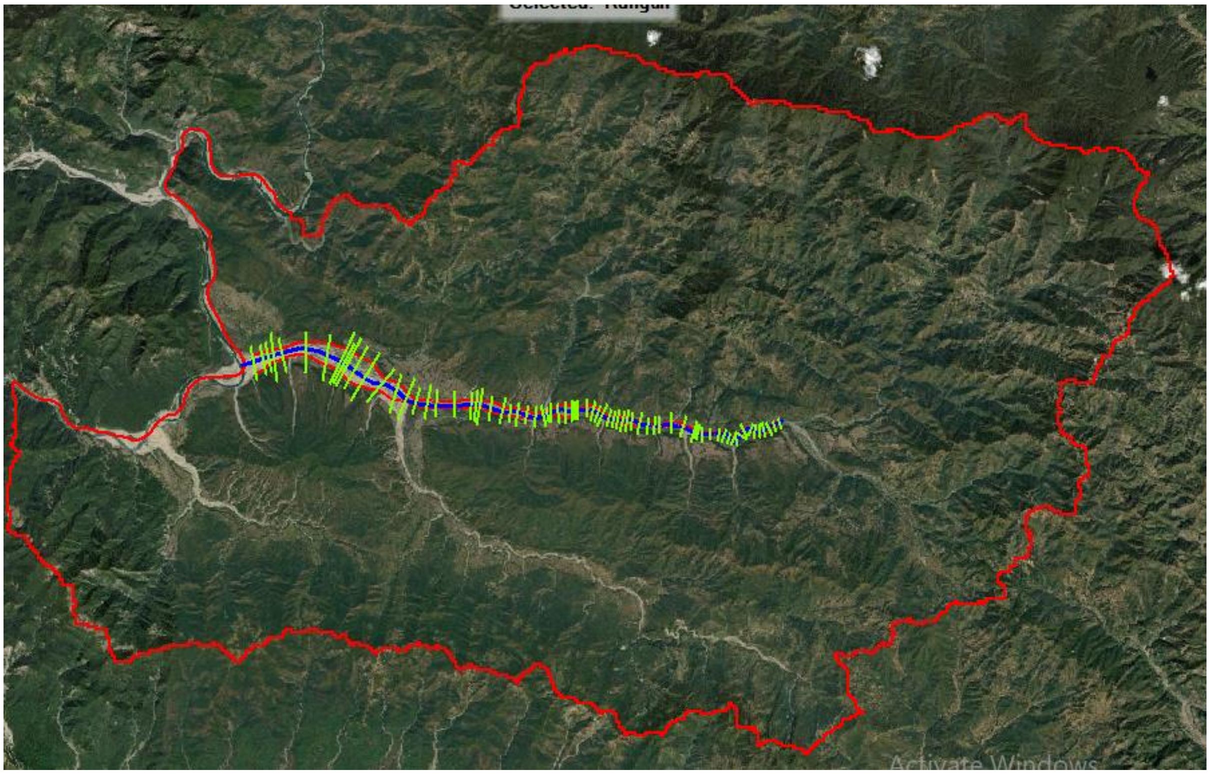

Figure 3: Cross section of the Rangun watershed

4.6 LAND USE LANDCOVER

Land use data was obtained from the National Land Use Project (NLUP) of the Government of Nepal. Different scenarios were analyzed, and the resulting inundation DEMs were overlaid on the land use layer for estimating Manning's roughness.

4.7 MANNING'S ROUGHNESS

A channel's Manning's n values were selected based on the stream characteristics, ranging between 0.025 and 0.050. A Manning's n value of 0.035 was generally assigned for the agricultural areas. On the basis of the land use/land cover types in the flood plain, the Manning's n values were determined for all 10 watersheds (Table 2).

Table 2: Estimation of manning's roughness for 10 watersheds

Watershed	Manning's roughness			Watershed	Manning's roughness		
	LEFT BANK	CHANNEL	RIGHT BANK		LEFT BANK	CHANNEL	RIGHT BANK
Middle Rapti	0.035	0.03	0.1	Thuligaad and Bogatan Lagam Karnali	0.03	0.035	0.03
	0.035	0.03	0.035		0.035	0.035	0.1
	0.1	0.03	0.035		0.045	0.035	0.1
					0.035	0.035	0.1
	0.03	0.03	0.035		0.035	0.035	0.1
					0.035	0.035	0.1
					0.1	0.035	0.1
	0.03	0.03	0.035		0.1	0.035	0.035
Jhimruk	0.035	0.035	0.1	Middle & Tila Karnali	0.1	0.035	0.035
	0.045	0.035	0.045		0.03	0.035	0.035
	0.035	0.035	0.035		0.035	0.035	0.1
	0.1	0.035	0.035		0.1	0.035	0.1
	0.1	0.035	0.1		0.1	0.035	0.035
	0.03	0.035	0.03		0.03	0.035	0.1
	0.03	0.035	0.1		0.045	0.035	0.1
					0.03	0.035	0.1
					0.1	0.035	0.03
Mahakali	0.035	0.025	0.035	Lower Karnali	0.07	0.04	0.07
Rangun	0.035	0.035	0.035		0.1	0.04	0.1
	0.035	0.035	0.1				
	0.1	0.035	0.1				
	0.1	0.035	0.045				

	0.03	0.035	0.035				
West Seti	0.045	0.04	0.045				

4.8 UPSTREAM AND DOWNSTREAM BOUNDARY

As noted in Section 3.4, upstream and downstream boundaries for each watershed were fixed in order to run model. Other details of each upstream and downstream boundary in the separate watersheds are provided in Table 3.

Table 3:Upstream and downstream boundary conditions

ASSIGNED WATERSHED	UPSTREAM BOUNDARY	DOWNSTREAM BOUNDARY
Lower Mahakali	Parigaun Kainpani	Nepal-India border
Rangun		
Lower Karnali	After the confluence of Bheri and Karnali rivers	Nepal-India border
Middle Karnali	Sinja Khola at Diware, Tila Nadi at Nagma and Humla Karnali at Lalighat	Tallo Dungeshwor: Confluence of Karnali and Lohare Khola
Tila Karnali		
West Seti	Langur Khola (Bajhang district)	Deura
Thuligaad	Seti at Banga and Karnali at Beni Ghat Lateral boundary: Thuligaad at Khanayatal	Thuligaad: Seti confluence Bogatan Lagam: Confluence of Thuligaad and Karnali
Bogatan Lagam Karnali		
Middle Rapti	Bagasoti	Confluence of West Rapti and Arjun Khola
Jhimruk	Bijuwatar	Confluence of West Rapti and Jhimruk near Naumure

4.9 HYDROLOGY OF CHISAPANI AND BAGASOTI STATIONS

The data at the Chisapani gauging station (station number 280) sits at an outlet from the mountainous part of the Karnali River Basin, located at 81^{0}17'30"E and 28^{0}38'40"N and an elevation of 191m. This station began keeping records in 1962.

The plot of maximum instantaneous discharge at Chisapani showed a maximum flood of 25,600 m^3/s on the Karnali River, which occurred on 15 August 2014 (Figure 4).

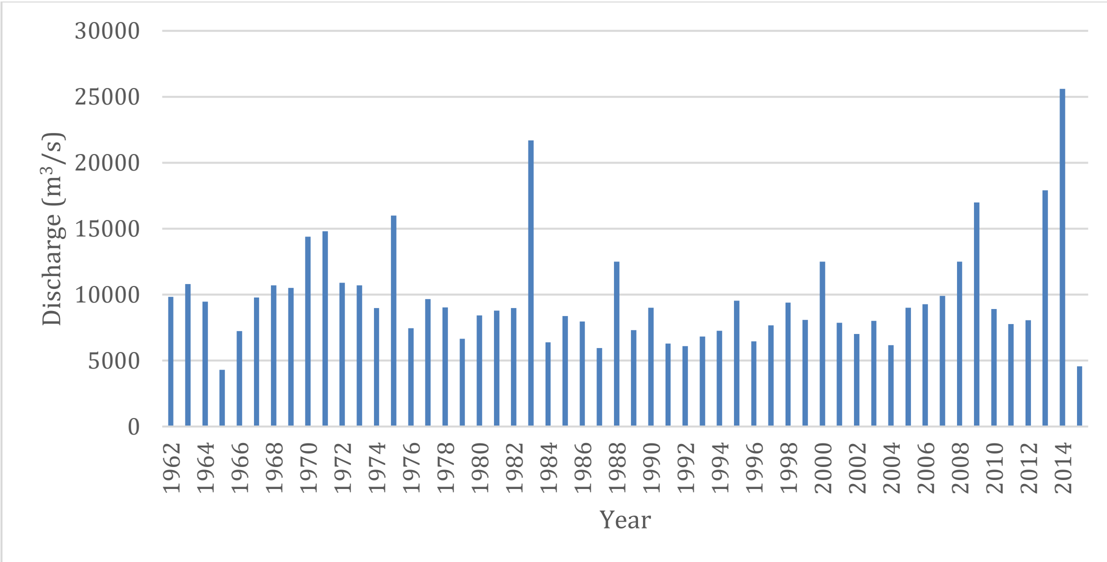

Figure 4: Maximum instantaneous discharge at Chisapani, 1962-2014

The data at the Bagasoti gauging station (#350) sits at an outlet in the mountainous part of the Rapti River Basin, located at 82°47'48" E and 27°51'59" N. The gauging site has records from the year 1976.

The plot of maximum instantaneous discharge at Bagasoti shows a maximum flood of 6,030 m^3/s on the Middle Rapti at Bagasoti on 11 September 1981 (Figure 5).

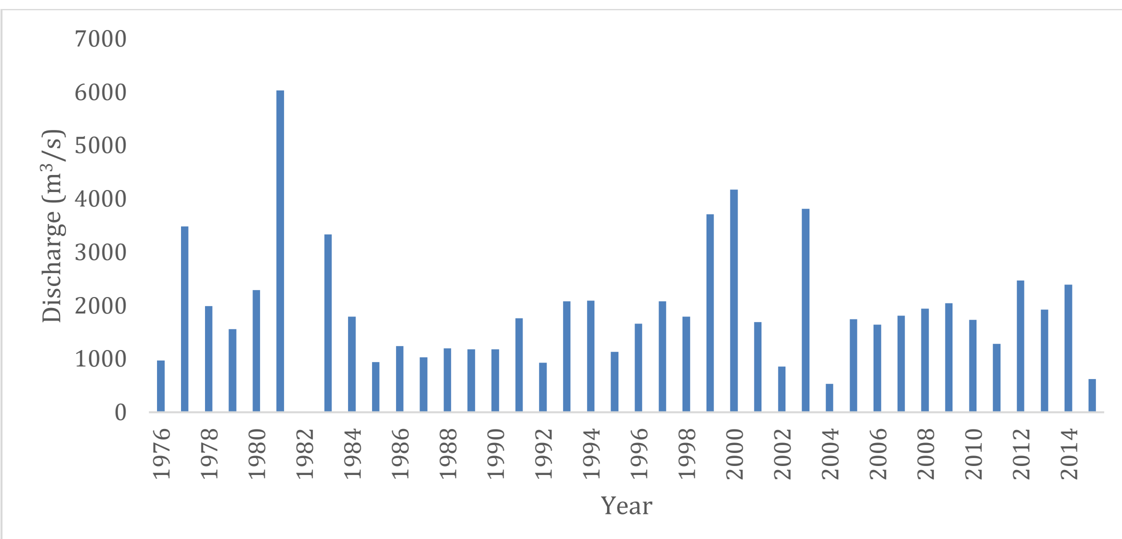

Figure 5: Maximum instantaneous discharge at Bagasoti, 1976-2014

4.10 MODEL SET UP AND RUN

The geometric data (the river center line, flow path, main channel banks, and cross-sectional cut lines, hydraulic data, flow data and associated boundary conditions) were supplied as input to HEC-RAS. The water surface profile calculation for various magnitudes of discharge upstream was performed with a subcritical flow regime. Once the water surface profiles were calculated, the results were exported to GIS for further analysis.

The flood frequency analysis at the upstream boundaries was calculated based on the available data series of maximum instantaneous flow recorded at the DHM stations for different return periods: 2, 5, 10, 25, 50, 100 and 200 years (Table 4)

Table 4: Peak Discharge for various return period.

STATION	DATA	BEST FIT DISTRIBUTION	RETURN PERIOD						
			2	5	10	25	50	100	200
Karnali Asaraghat	1962-2015	LogPearson III	2,176	2719	3,099	3,605	4,000	4,412	4,843
West Rapti Bagasoti	1976-2015	LogPearson III	1,720	2,638	3,298	4,186	4,883	5,608	6,366
Bheri Jamu	1963-2015	LogPearson III	2,379	3,358	4,078	5,071	5,873	6,730	7,649
Karnali Chisapani	1962-2015	LogPearson III	8,819	11,955	14,285	17,532	20,180	23,034	26,123
Karnali Beni	1963-2015	LogPearson III	2,819	3,901	4,785	6,115	7,277	8,601	10,113
Humla Karnali Lalighat	1977-2015	LogPearson III	1,625	2,040	2,298	2,609	2,832	3,049	3,262
Seti Banga	1963-2015	LogPearson III	3,100	4,658	5,852	7,556	8,972	10,518	12,212
Sinja Khola Diware	1967-2015	LogPearson III	115	143	166	200	229	262	300
Thuligad Khanayatal	1970-2008	LogPearson III	683	1,185	1,605	2,245	2,808	3,449	4,180
Tila Nagma	1973-2015	LogPearson III	212	288	343	418	477	541	608

The Karnali River bifurcates into two channels about one kilometer downstream of the Karnali Bridge. Historically, the Geruwa channel (left channel) is the main channel, but in recent years, since a flood in 2014, more water now flows in the right branch. A study of hydrological surveys in October 2016 at low flow (2200 m^3/s at Chisapani station) showed that 70% of the flow goes through the right branch.[4] However, the ratio of that flow changes during monsoon season. For the initial simulation, it was assumed that 60% of water flows through the right channel and 40% through the Geruwa channel. The river bed slope of the right branch is slightly higher than that of the left branch. This may be due to erosion in the right branch and deposition in the left branch after recent flood events. Stakeholders have endorsed this explanation.

The distribution of flow in these two channels was refined by a trial and error approach: the flow in the two channels was adjusted until the elevation of the energy gradient line was almost the same for the sections in the left and right channels immediately downstream of the junction.

4.11 CONSULTATION AND FIELD VERIFICATION

Per the decisions made at the inception meeting 3 January 2020 at DHM, stakeholder consultations and field verifications were made in six of the ten watersheds (Jhimruk, Middle Rapti, Lower Karnali, Middle Karnali, Lower Mahakali and Rangun). The remaining four watersheds (West Seti, Thuligaad, Bogatan Lagam and Tila Karnali) were excluded because the flood hazard maps for these areas were low compared to the others. Therefore, field consultations and verification were not performed in these areas. It was also decided at the inception meeting that field verification sites would be selected on the basis of two aspects: 1) severe inundation areas in plain regions and 2) strategically important areas in the flood plain in the middle hill areas with active development projects. Table 5 lists the dates and locations of the field consultations for the six watersheds.

Several meetings were held in flood prone areas with the concerned municipalities (Annex 4). The findings of the draft flood hazard maps were presented and ensuing conversation focused on the process of the flood hazard map preparation, challenges of flood risk reduction, verification of the flood hazard area shown in the maps, utilization of the flood hazard maps both in disaster preparedness and response, and urban planning and development. Similar meetings were then held at the ward and community levels, featuring all the topics covered at the municipal level, but also including discussions about flood depth, flood extent, and historical verification of events. All suggestions from all meetings have been summarized in the Recommendations section of this report.

Similarly, key informant interviews were also carried out in respective watersheds to collect information related to historical flood events, impacts caused by flood events, and details about vulnerable communities (Annex 2). During the site visits, community residents confirmed the locations of

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[4] Dingle, E. H., Sinclair, H. D., Attal, M., Milodowski, D. T., & Singh, V. (2016). Subsidence control on river morphology and grain size in the Ganga Plain. *American Journal of Science*, *316*(8), 778-812.

embankment constructed along the various rivers (Middle Rapti, Lower Karnali, Mahakali). This information was desired because embankment construction alters the bank line, flow line and cross-section of the channel. Most of the embankments built in the watersheds have been constructed along the bank line, which may not provide enough area to pass-out the maximum flow in monsoon season. Thus, the embankments need to be built above and beyond the active channel area.

Table 5: Consultation meetings at different watershed

WATERSHED	LOCATION	DATE
Middle Rapti	Lamahi	31 Jan
Lower Karnali	Rajapur	2 Feb
Mahakali	Mahendranagar	3 Feb
Rangun	Jogbuda	4 Feb
Middle Karnali	Rakam	6 Feb
Jhimruk	Cherneta	8 Feb

5. ACCOMPLISHMENTS, OUTPUTS AND DELIVERABLES

5.1 FLOOD HAZARD MAPS

As stated in the Methodology Section (Section 3), the flood hazard maps of the study watersheds were prepared for different return periods (2-year, 5-year, 10-year, 25-year, 50-year, 100-year and 200-year). Likewise, other important maps, including warning level maps, danger level maps, and maximum flood level maps, were also prepared.[5] The draft flood hazard maps of some of the watersheds were discussed, verified and finalized at the stakeholder consultation meetings (see Section 4.11). The refined flood hazard maps were drafted in size A3 for several return periods (2, 5, 10, 25, 50, 100 and 200-year). Warning and danger levels are presented in Annex 3.

5.1.1 MIDDLE RAPTI WATERSHED

Figure 6 shows the 100-year return period flood hazard map for the Middle Rapti watershed. The map indicates a maximum inundation depth of 8.4 m, which could affect approximately 40% of the cultivated areas downstream. In addition, both the right and left floodplains are also equally affected by the different return period flood events. Over a 30 year period (1984-2015), the highest flood level (HFL) at the DHM's Bagaswoti hydrological station on the upstream boundary was 9m. Combining the HFL with a Rating Curve resulted in a highest possible flow of 5030 m3/s). Figure 7 presents a flood hazard map for maximum flood levels. This map was verified in the field.

[5] The maximum flood level maps were only prepared for three watersheds – Middle Rapti, Lower Karnali and Middle Karnali – because historical maximum flood levels were not available for the other seven.

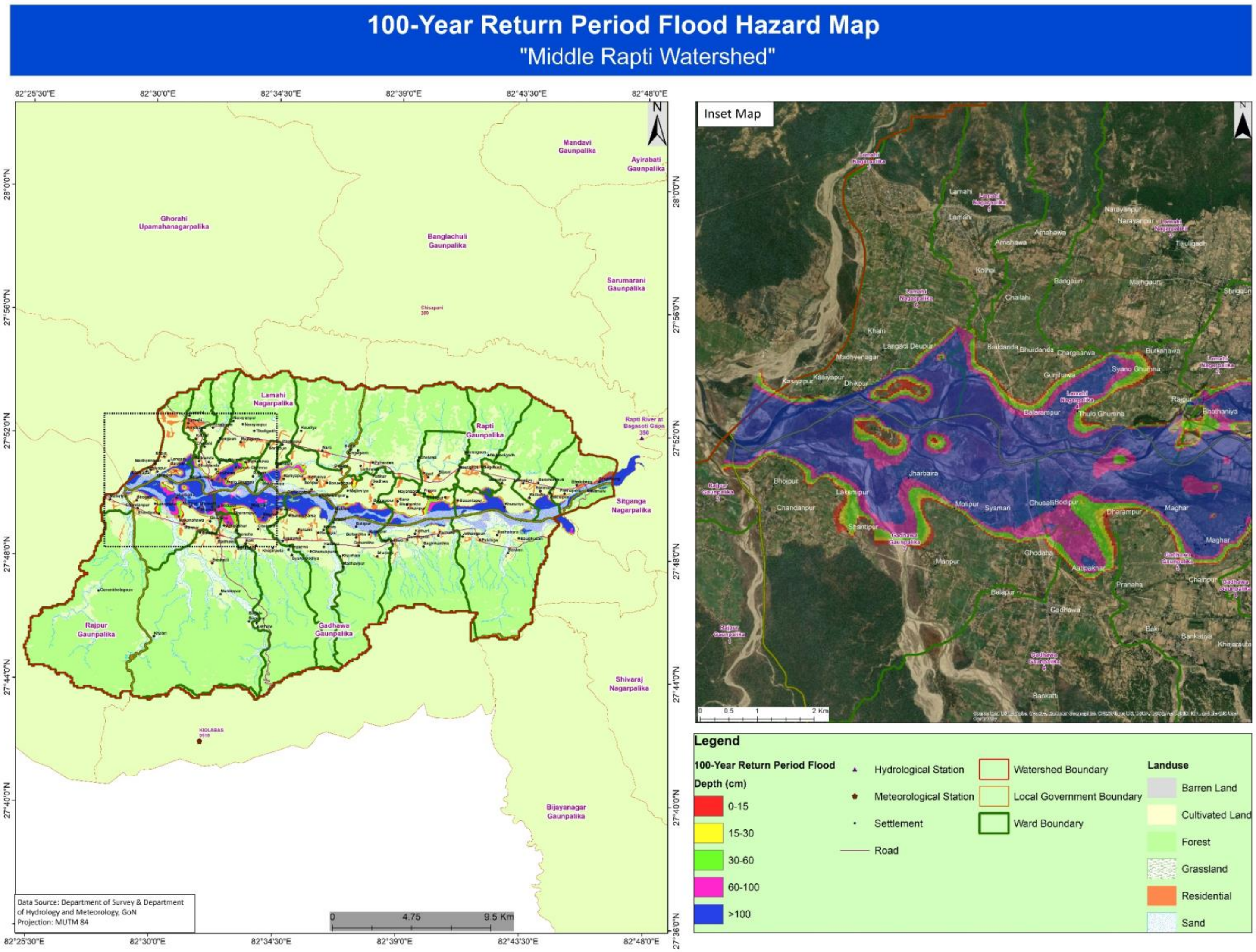

Figure 6: 100-year return period flood hazard map of the Middle Rapti watershed

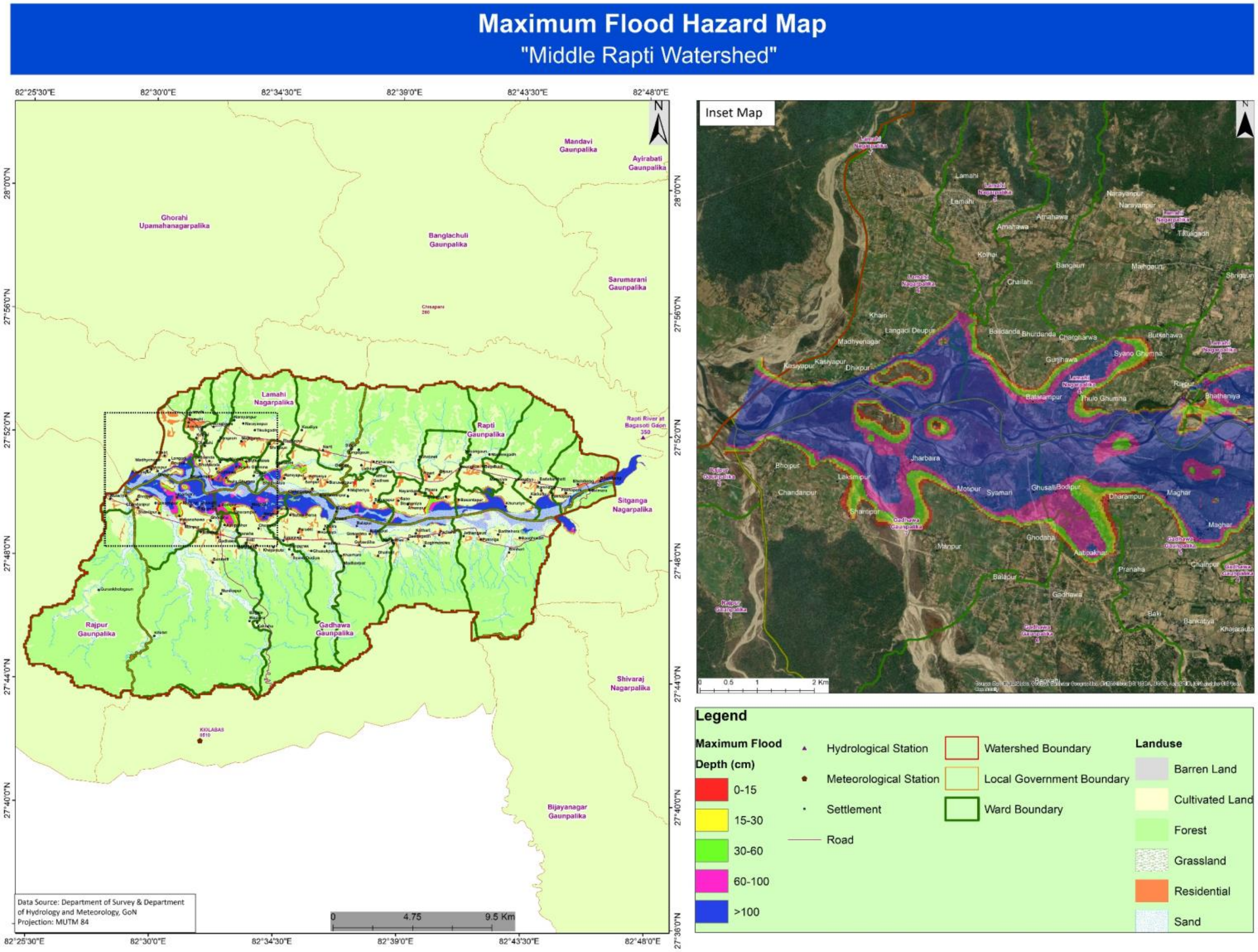

Figure 7: Maximum flood hazard map for the Middle Rapti watershed

5.1.2 JHIMRUK WATERSHED

The 100-year return period flood hazard map for Jhimruk watershed is shown in Figure 8. The map shows the maximum flood depth of 8.60 m, which could affect approximately 35% of the cultivated areas downstream. In addition, the wide meandering of the river contributes to the inundation, bank erosion and sand deposition. Jhimruk hydropower is located at 28°4'25"N and 82°48'52."E diverts from the main channel approximately 7.05 m3/s of flow during the wet season and 0.2 m3/s of flow during the dry season. These amounts are insignificant flow amount compared to the 100-year return period peak flow (991 m3/s) and several other return period flows in the watershed.

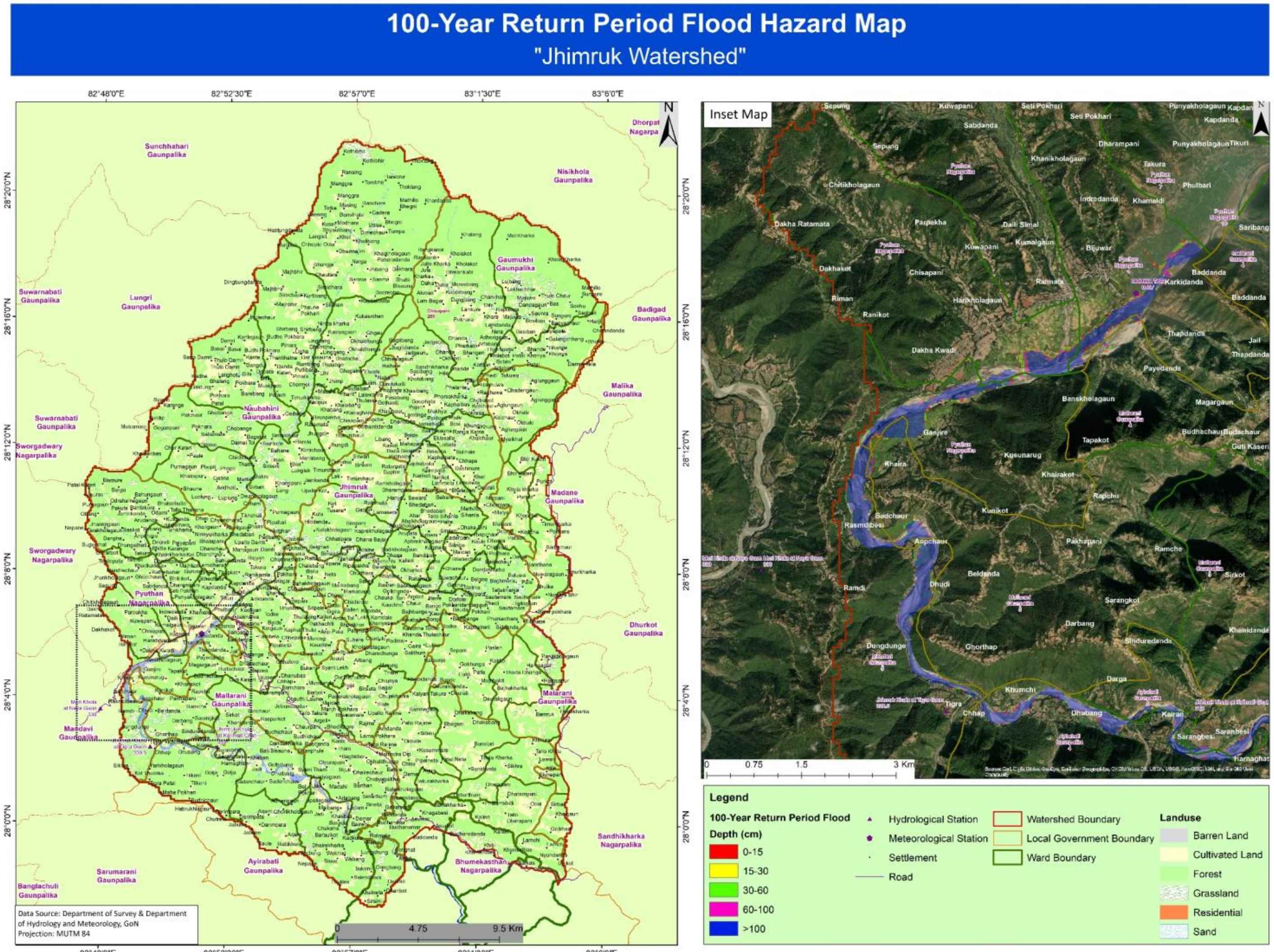

Figure 8: 100-year return period flood hazard map of the Jhimruk watershed

5.1.3 LOWER KARNALI WATERSHED

Figure 9 shows the flood depths for the 100-year return period flood in Lower Karnali. The map shows the maximum flood depth of 13.40 m, which could affect approximately 45% of the cultivated areas. The highest observed flood levels (HFL) were 16.50m at the Chisapani hydrological station at the upstream boundary. The corresponding value of the highest flow (21900m^3/s) was obtained by using the rating curve. The flood depths corresponding to the HFL were also verified during the field visit (Figure 10).

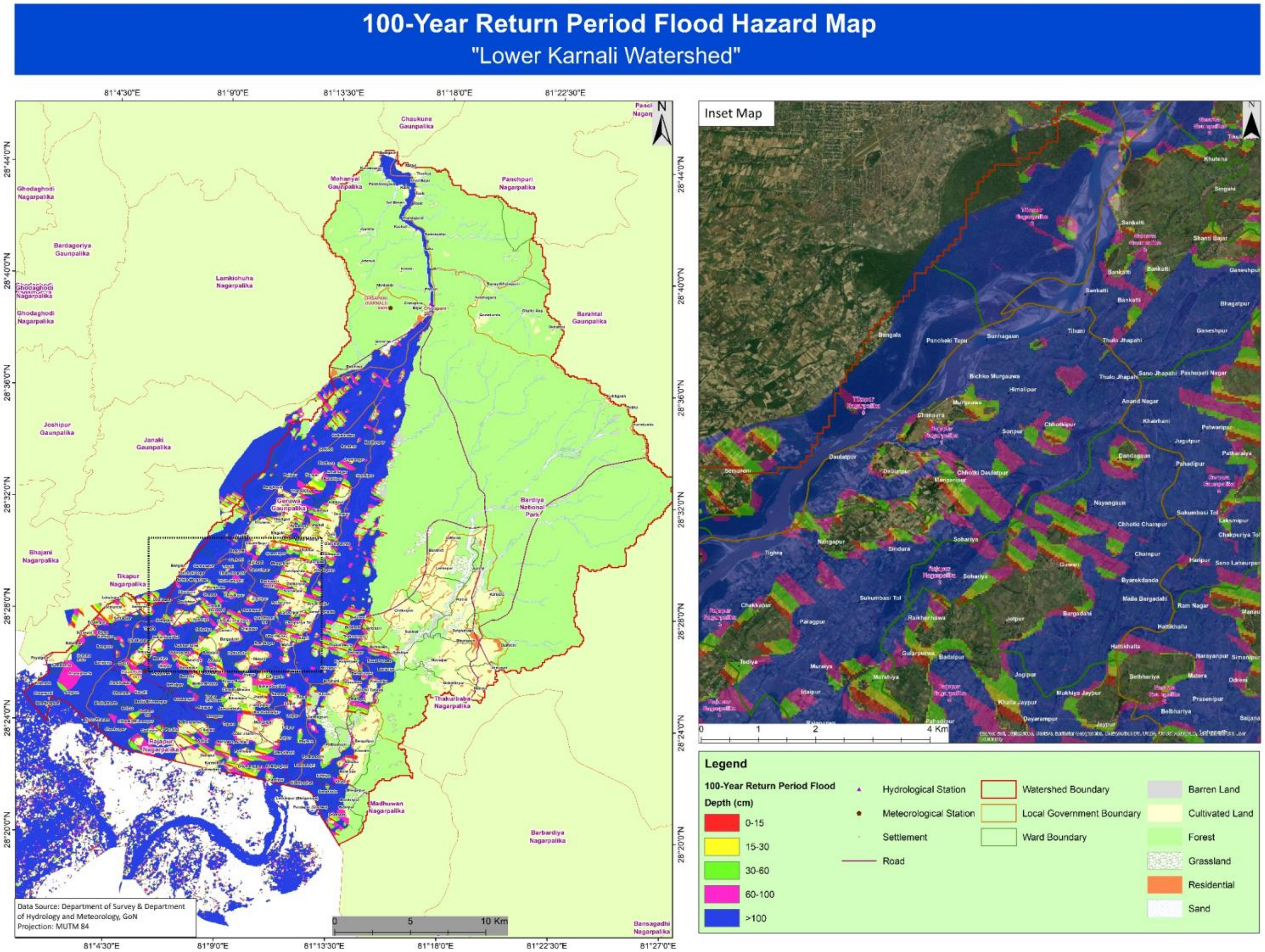

Figure 9: 100-year return period flood hazard map of the Lower Karnali Watershed

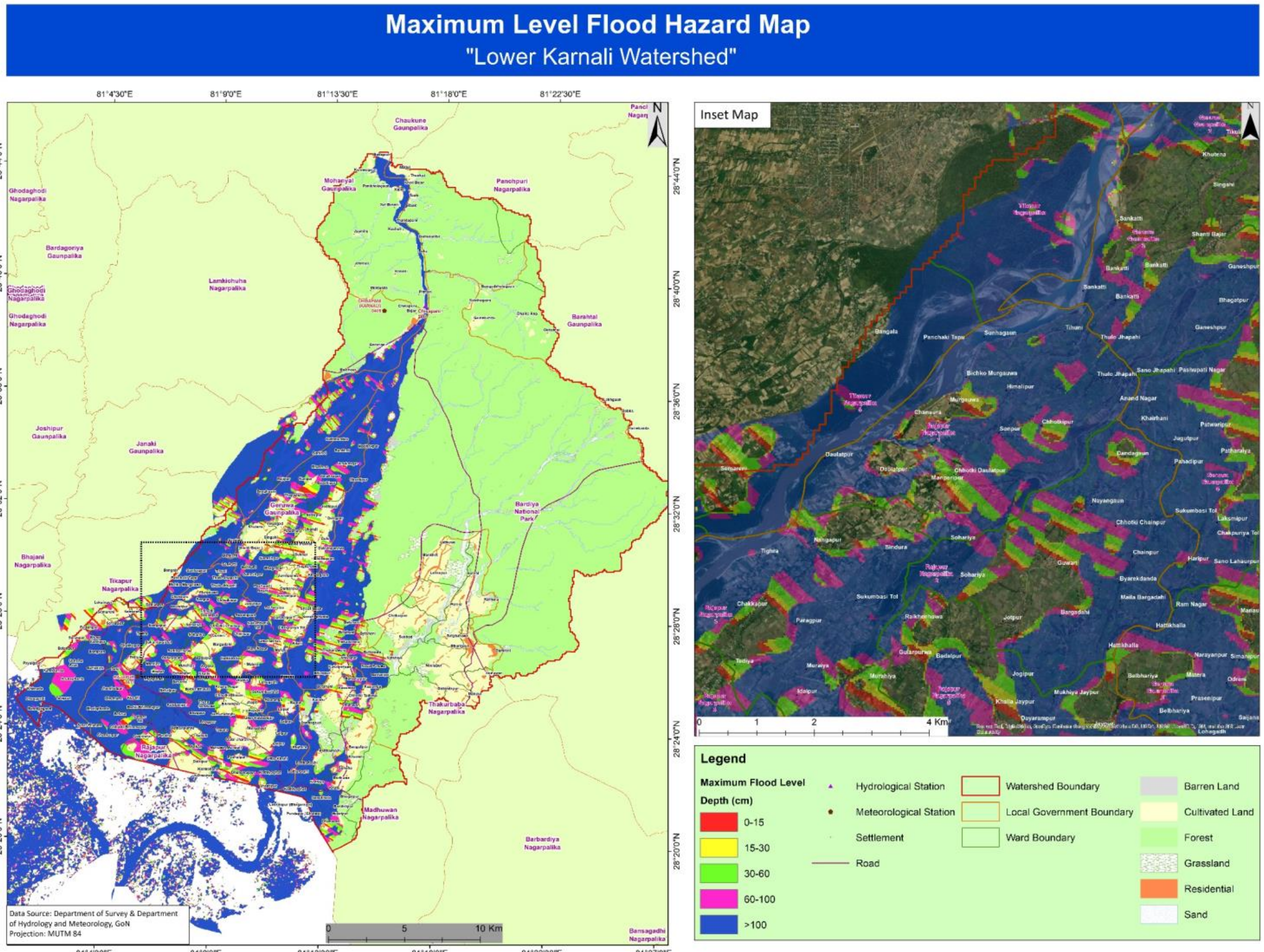

Figure 10: Maximum flood hazard map for the Lower Karnali watershed

5.1.4 MIDDLE KARNALI WATERSHED

The flood depths for the 100-year return period for Middle Karnali watershed are shown in Figure 11. The map shows maximum depth of 13.10m, which could affect approximately 25% of the cultivated area around the river. The meandering of the river has further contributed to inundation, deposition of sand and bank erosion. DHM reported a highest flood level (HFL) of 8.80m at the Asaraghat hydrological station at the upstream boundary. The corresponding value of the highest flow at the station (4266 m^3/s) was obtained using the rating curve. The flood hazard map for the maximum flood levels is presented in Figure 12.

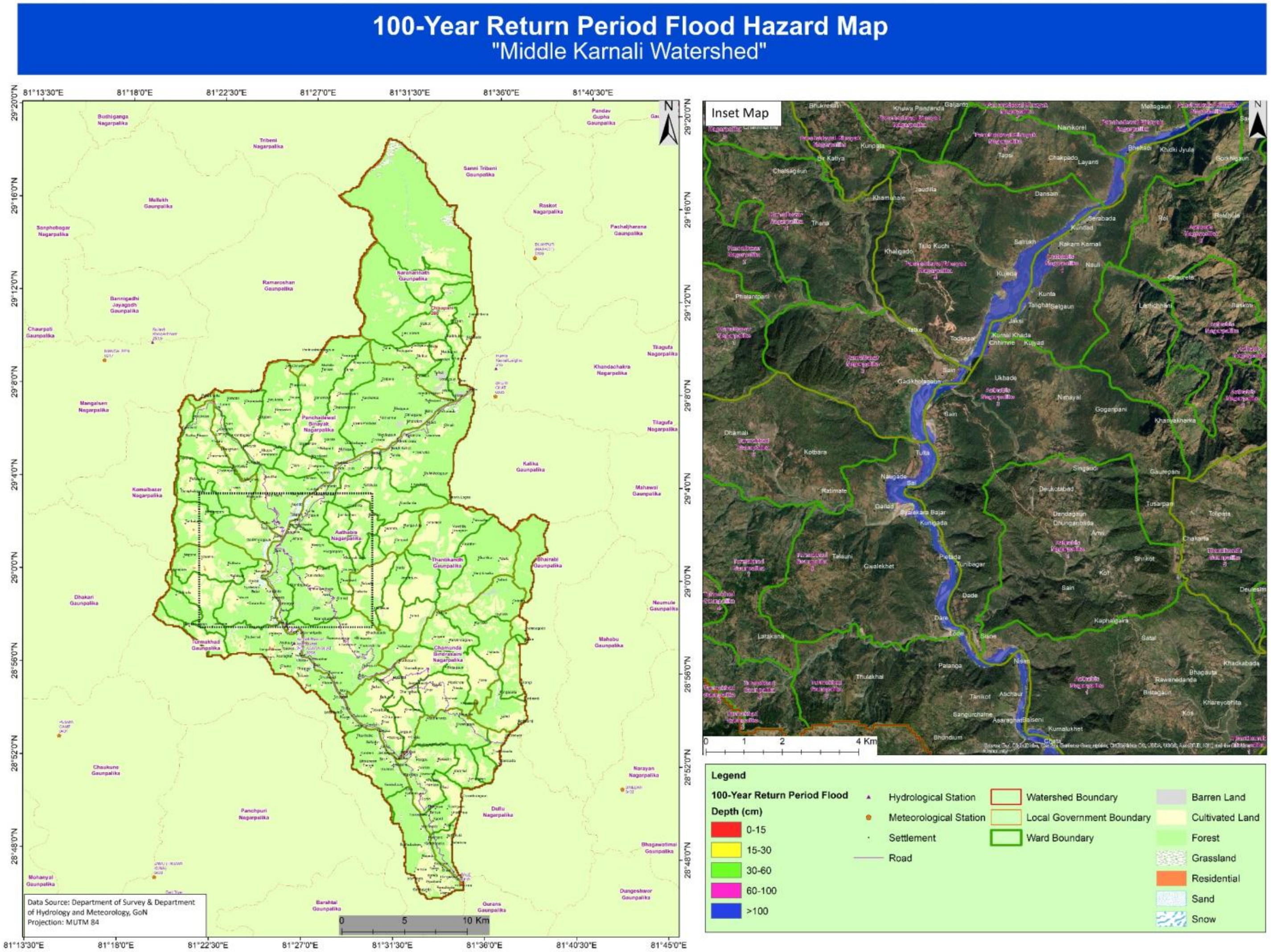

Figure 11: 100-year return period flood hazard map of the Middle Karnali watershed

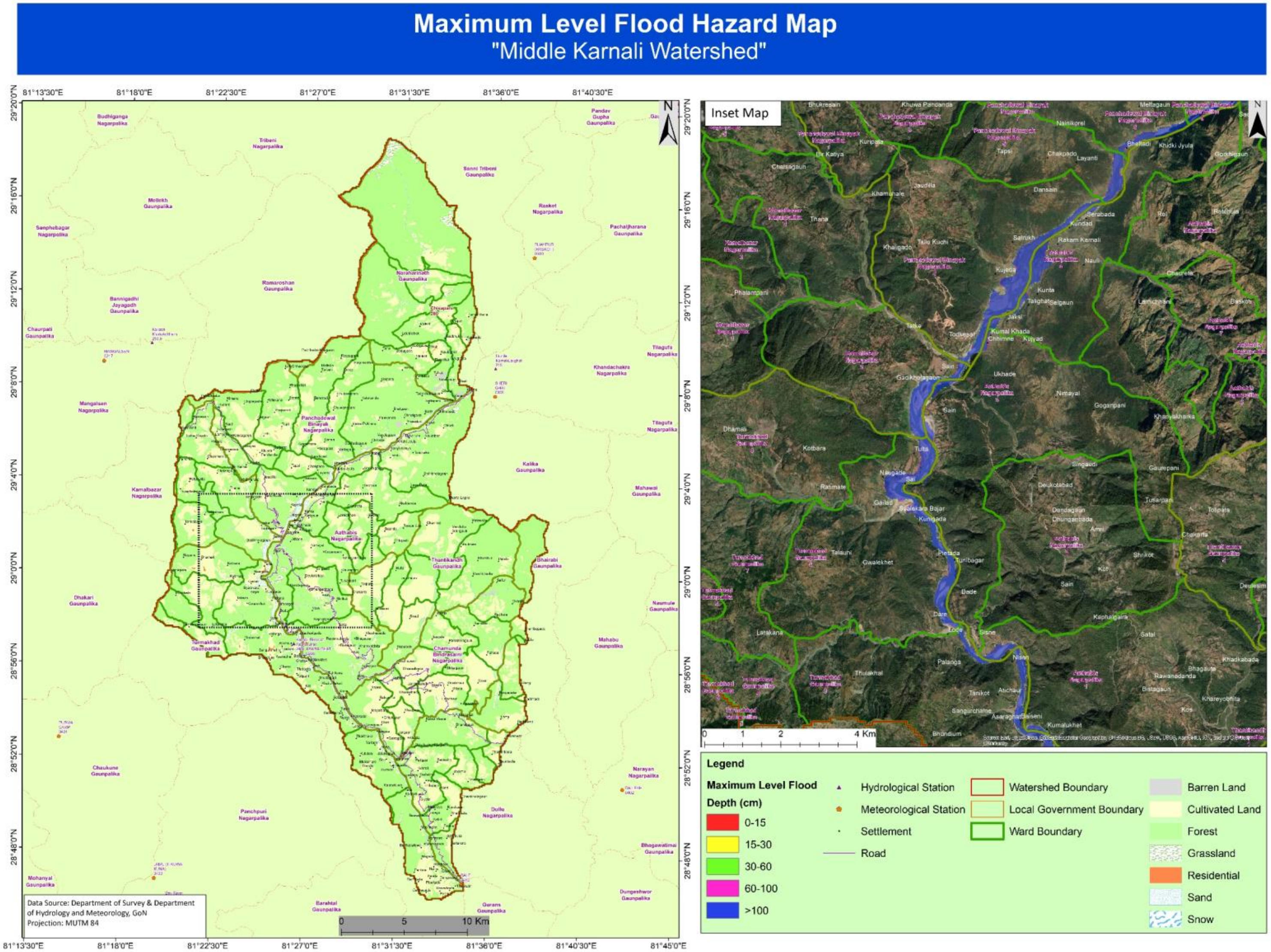

Figure 12: Maximum flood hazard map for the Middle Karnali watershed

5.1.5 TILA KARNALI WATERSHED

The flood depths for the 100-year return period for the Tila Karnali watershed are shown in Figure 13. The map shows maximum depth of 15m, which could affect around 5% of the cultivated area. The river flows through a deep gorge, and there are no significant floodplains.

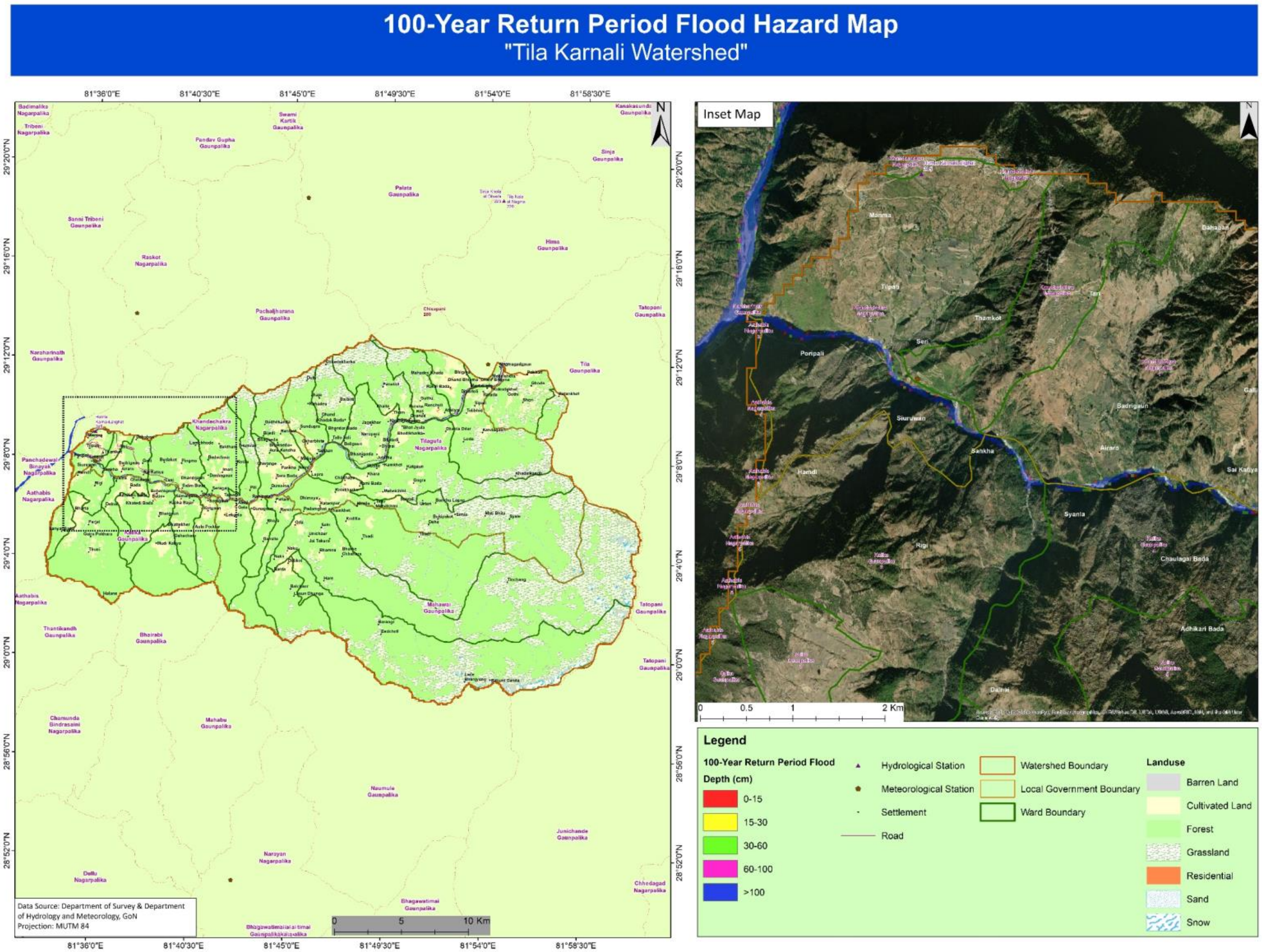

Figure 13: 100-year return period flood hazard map for the Tila Karnali watershed

5.1.6 WEST SETI WATERSHED

The flood depths for the 100-year return period for West Seti watershed are shown in Figure 14. The maximum depth of 8.90m and could affect approximately 15% of the cultivated area. The inundation downstream is not significant due to the narrow valley of West Seti watershed.

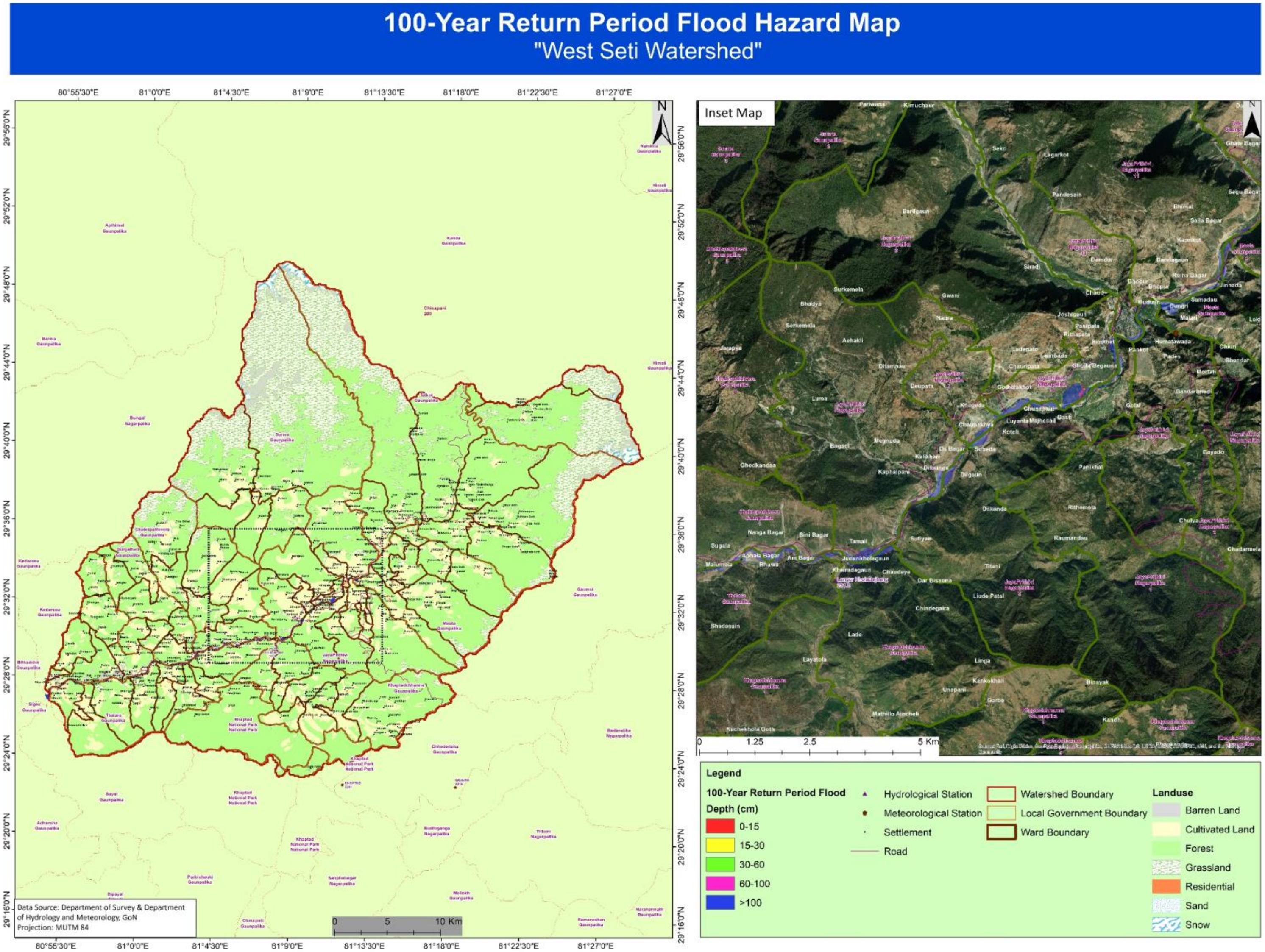

Figure 14: 100-year return period flood hazard map for the West Seti watershed

5.1.7 THULIGAAD WATERSHED

The flood depths for the 100-year return period for Thuligaad watershed are shown in Figure 15. The map shows the maximum depth of 14.60 m, which could affect around 15% of the cultivated area. However, inundation does not appear a significant threat due to the narrow valley of the watershed.

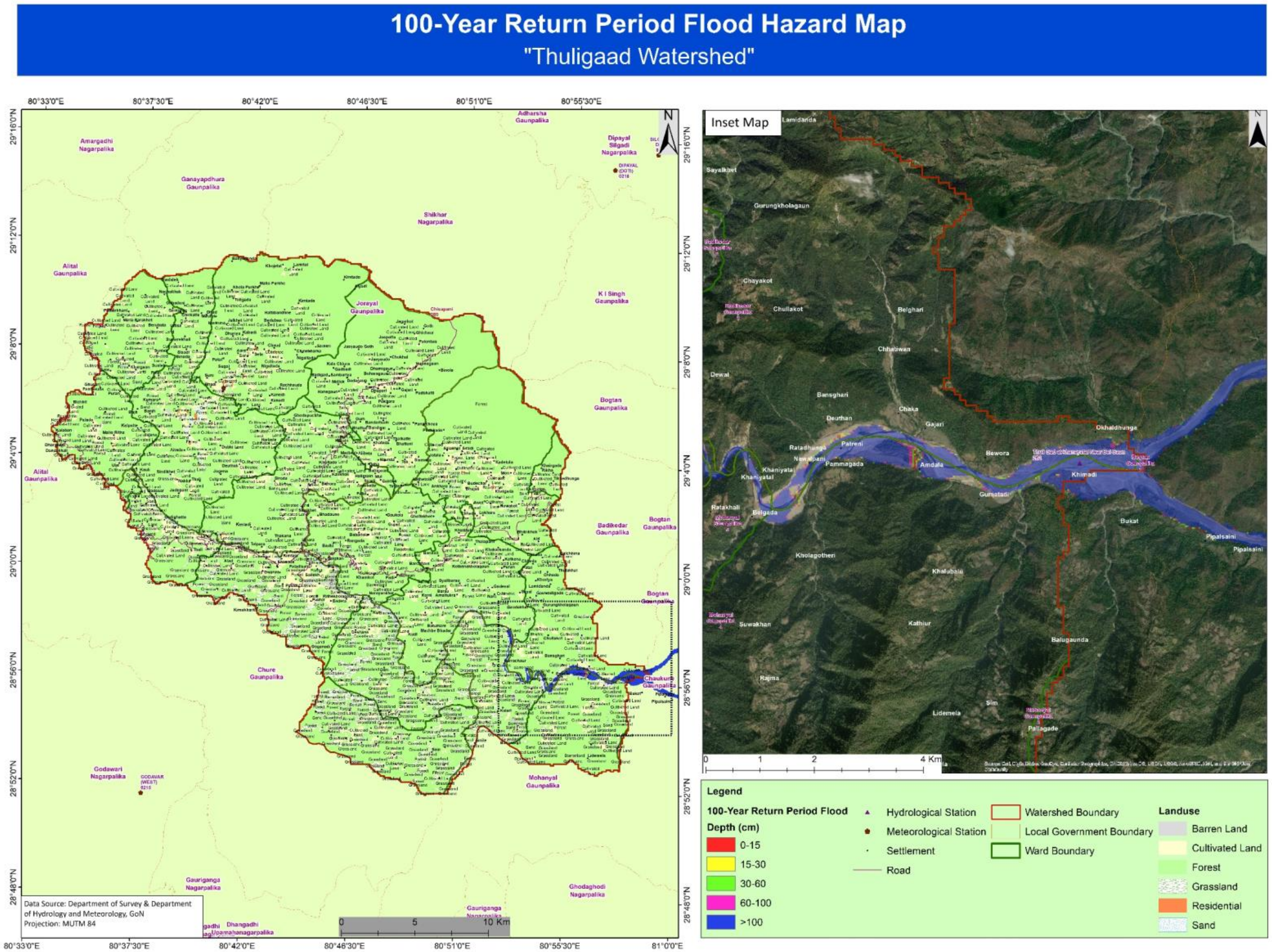

Figure 15: 100-year return period flood hazard map for the Thuligaad watershed

5.1.8 BOGATAN LAGAM KARNALI WATERSHED

The 100-year return period flood hazard map for Bogatan Lagam Karnali watershed shows maximum depth of 13m, which could impact approximately 8% of the cultivated areas (Figure 16). The meandering of the river has contributed to bank erosion and affected parts of the cultivated areas. The inundation does not appear to be a significant threat due to the narrow valley that runs east-west through the Bogatan Lagam Karnali watershed (Annex 3).

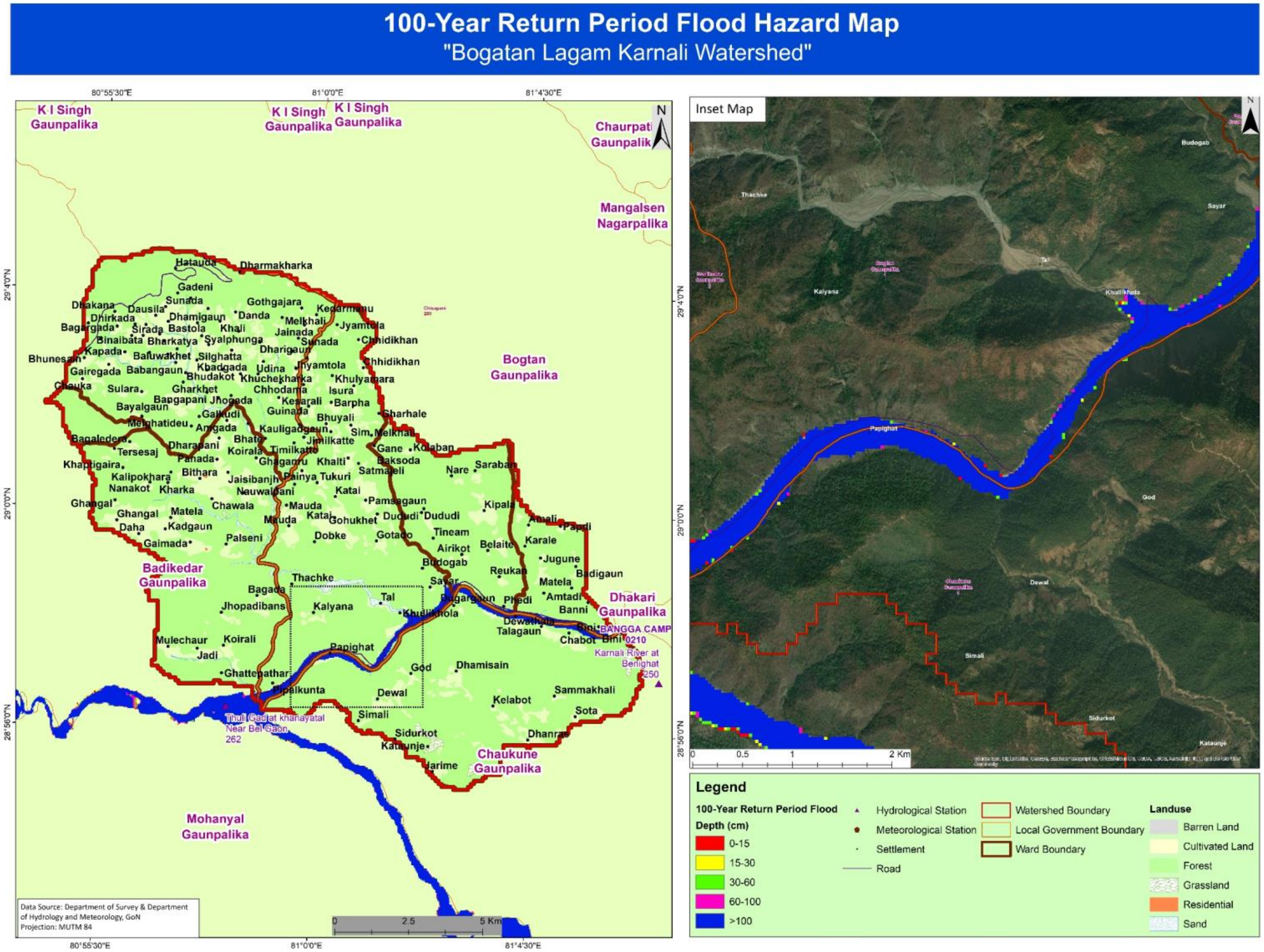

Figure 16: 100-year flood hazard map for the Bogatan Lagam Karnali watershed

5.1.9 RANGUN WATERSHED

The flood depths for the 100-year return period in Rangun watershed are shown in Figure 17. The map shows a maximum depth of 9m, which could affect around 25% of the cultivated area. The meandering of the river has affected the cultivated areas with bank erosion and heavy sand deposits.

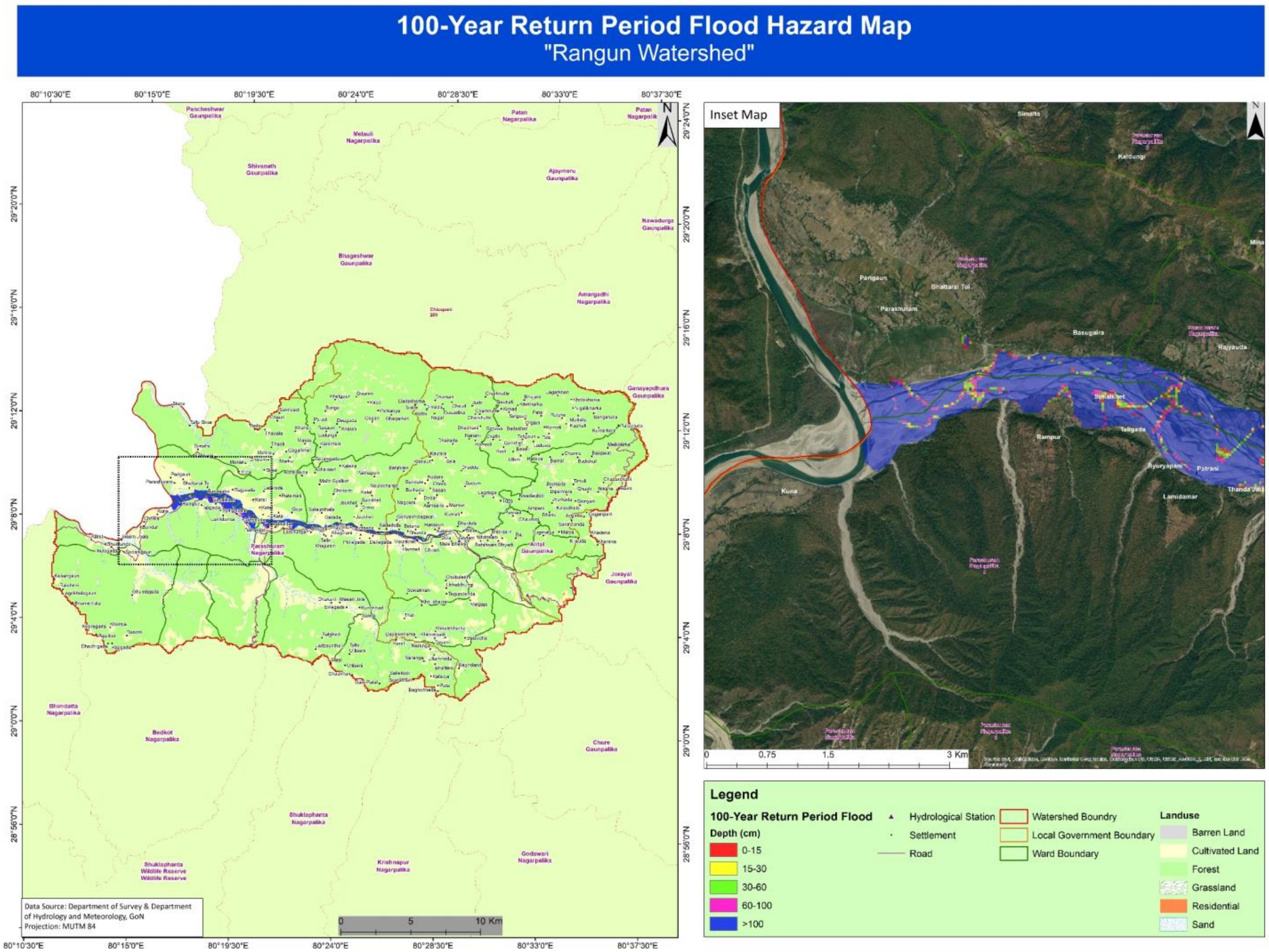

Figure 17: 100-year flood hazard map for the Rangun watershed

1.10 LOWER MAHAKALI WATERSHED

The flood depths for the 100-year return period in Lower Mahakali watershed are shown in Figure 18. The map shows the maximum depth of 17m, which could affect approximately 45% of the cultivated area. The meandering of the river has affected the cultivated areas with inundation of the lowlands, sand deposition, and bank erosion. Both right and left floodplains are equally affected during return period flood events (Annex 3).

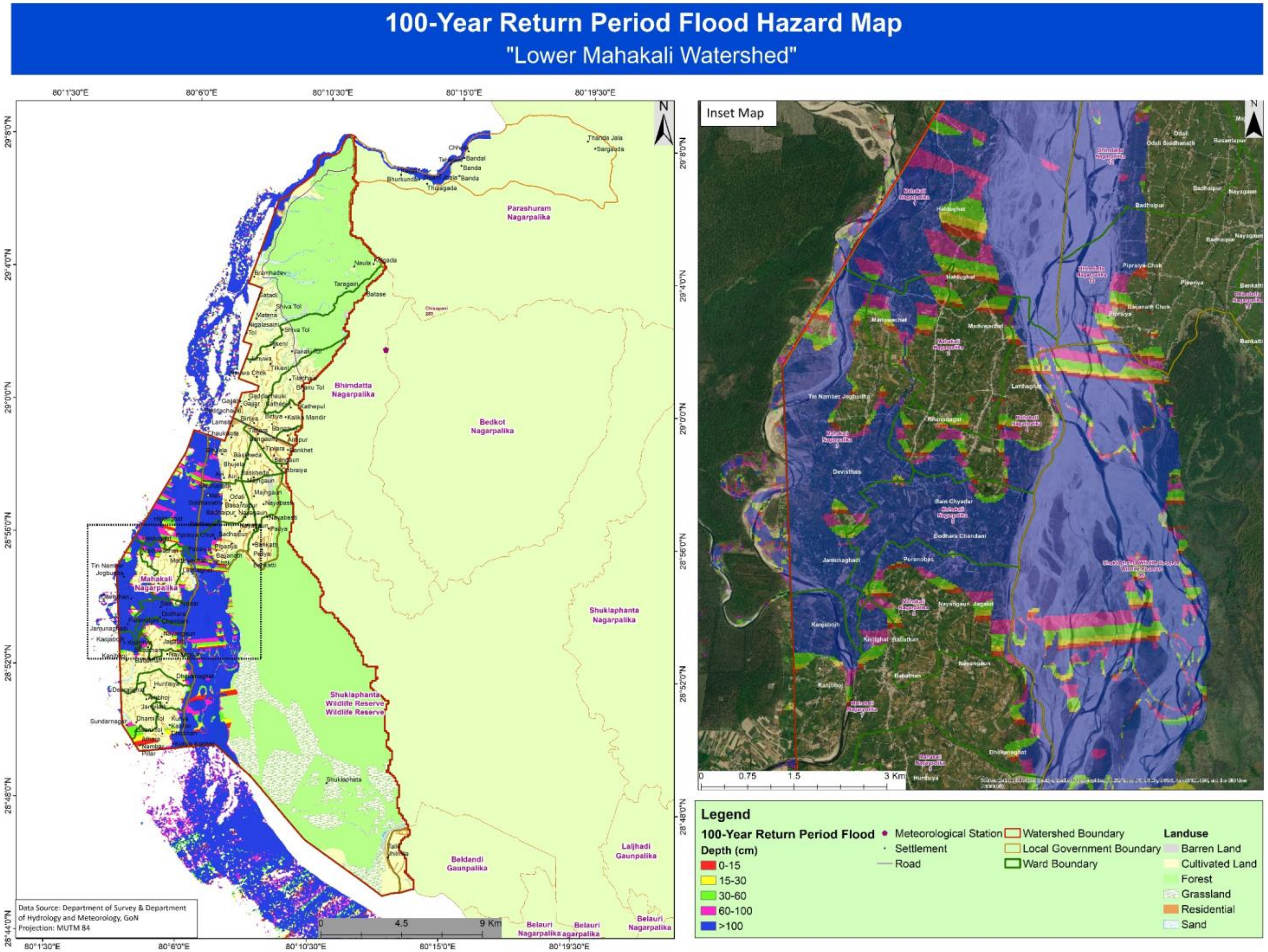

Figure 18: 100-year flood hazard map for Lower Mahakali watershed

5.2 ASSESSMENT OF WARNING AND DANGER LEVELS

The warning and danger levels of the study watersheds were assessed with corresponding gauge height. Here, the warning and danger level gauge heights have been determined for only six watersheds (Table 6). The warning and danger level maps of all watersheds have been prepared and presented (Annex 3).

Table 6: Warning and Danger Levels

WATERSHED	STATION	WARNING LEVEL (M^3/S)	GAUGE HEIGHT (M)	DANGER LEVEL (M^3/S)	GAUGE HEIGHT (M)
West Seti		669		878	
Jhimruk	Chernata	448	2.33	583	2.7
Lower Karnali	Chisapani	8,190	10	9,955	10.82
Mahakali	Parigaun	5,500	2.94	6,000	3.36
Middle Rapti	Bagasoti	1,761	5.44	2,358	6.27
Middle + Tila Karnali	Sinja	262	4.66	300	5.01
	Tila Nagma	541	5.81	608	7.2
	Lalighat	3,049	8.8	3,262	10.3
	Asaraghat	4,412	8.94	4,843	9.33
Rangun		202		288	
		395		570	
Thuligaad	Thuligaad	797	4.05	1,194	4.36
Bogatan Lagam Karnali	Seti Banga + Karnali Beni	6,033		8,567	

5.3 ASSESSMENT OF AFFECTED SETTLEMENTS

The settlements of all 10 watersheds were overlaid on the warning and danger level flood hazard maps to identify the most vulnerable and affected settlements in the respective watersheds. Most affected settlements areas were identified with GIS and verified during field visits (Table 7).

Table 7: List of affected settlements

WATERSHED	INUNDATION LEVEL	AFFECTED SETTLEMENTS
Jhimruk	Warning level	Bel Pokhari, Dhudi
	Danger level	Bel Pokhari, Dhudi, Hariyagaun
Bogatam Lagam Karnali	Warning level	Dewathala, Papighat
	Danger level	Same settlements as warning level
Lower Mahakali	Warning level	Badhaipur, Odali Siddhanath, Haldughat, Pipraiya Chok, Sain Chyadar, Dodhara Chandani, Tatapani, Sisam Jhala, Gatadi, Kutiya Kabhar, Jamunaghadi, Devisthan, Tin Number Jogbuda, Kanjabojh, Kistighat
	Danger level	Same settlements as warning level
Lower Karnali	Warning level	Patharbojhi, Dhundirajpur (Gidarpur), Kothiyaghat, Kothiya, Kothiyaghat, Sanokhata, Bhangaha, Laksmipur (Bhagaraiya), Bandalipur, Pandepur (Gholwa), Ram Nagar, Kathmandau, Madhavpur, Bankhet, Sarkhol, Bhathera, Janaknagar, Shantipur, Sunahagaun, Badkapurwa, Tikuligad, Ganeshpur, Thulo Jhapahi, Sankatti, Bankatti, Bhagatpur, Tihuni, Sunhagaun, Panchaki Tapu, Pashupati Nagar, Sano Jhapahi, Thulo Jhapahi, Bichko Murgauwa, Himalipur, Anand Nagar, Khairhani, Patwaripur, Chhotkipur, Jugutpur, Patharaiya, Pahadipur, Nayangaun, Sukumbasi Tol, Laksmipur, Chhotki Chainpur, Chakpuriya Tol, Sohariya, Chainpur, Sindura, Haripur, Sano Lahaurpur, Byarekdanda, Sohariya, Maila Bargadahi, Ram Nagar, Sukumbasi Tol, Bargadahi, Raikhenhawa, Hattikhalla, Simanipur, Badalpur, Matera, Odreni, Mukhiya Jaypur, Prasenipur, Belbhariya, Saijana, Lohagadh, Kusumba, Basanta, Kailasi, Patharpurwa, Chhotki Bhaura, Nauranga, Tharu Sanduwa, Banjaridanda, Lalpur, Dhobinipur, Bhogpur, Phattepur, Jamunabojhi, Lalpur, Bhogpur, Bathanpurwa, Koili, Tapara, Dalai Jharan, Mahuwa (Manpur), Pahadiyapur, Pattharbojhi, Butkauwa, Kusal Patuwa, Bantariya, Chakkapur,Daulatpur, Tighra, Bisnu Kantipur, Bangaun, Banjariya, Rajapurwa, Basanta, Shantipur, Jhanjhatpur, Khimada, Lalitapur, Kusahi, Badki Bhimmapur, Baithakpur, Bandiyagaun, Belasa, Rampur, Phattepur, Satar Pharam, Puraina Purba Khairiphant,, Shankarpur, Chainpur, Damakantar, Murtiya, Badka Bhakraiya, Jagatpur, Daulatpurghat
	Danger level	Same as WL including Karmohani, Bipatpur, Khunpurgaun, Thakurdwara, Narayanpur, Badka Bhaura, Uttar Kalabanjar, Khaireni, Kajenipur, Betahani, Nangapur, Chakkapur, Paragpur, Batanpur, Muraiya, Dalai, Uchcha Arun, Rajapur, Chaugurdi, Toligaun, Bhaluphanta, Chhotki Bhimmapur, Taule
Middle Karnali	Warning level	Chhimne, Hulma, Panmare, Sai, Dub, Paletada, Jangsa
	Danger level	Same settlements as warning level
Middle Rapti	Warning level	Bhalubang, Satmara, Balapur, Syano Ghumna, Thulo Ghumna, Balarampur, Bodipur, Ghusalli, Syamari, Maghar, Baklahi, Maghar
	Danger level	Same settlements as warning level including Jharbaira

Rangun	Warning level	Maurikhet, Tulabhadi, Kainpani, Lamijala, Selaning Syalchaudi, Simalkhet, Patrani, Jogbuda, Batranigau
	Danger level	Same settlements as warning level
Thuligaad	Warning level	Barrachaur, Patreni
	Danger level	Same settlements as warning level including Khimadi
Tila Karnali	Warning level	Not affected
	Danger level	Not affected
West Seti	Warning level	Morail, Utgadi, Moyal, Listada, Khani, Malumela, Aphala Bagar, Dungri
	Danger level	Same as WL

6. LIMITATIONS AND LESSONS LEARNED

The key limitations and lessons learned in this study include the following:

1. SRTM 30m DEM has a vertical accuracy of ±16m, which is too coarse to obtain reliable inundation maps, especially for the low-lying watersheds of Lower Mahakali, Lower Karnali and Middle Rapti. DEM with the vertical accuracy of ±1m would be required to obtain reliable inundation maps.
2. Flow data series of four watersheds (Jhimruk, Lower Mahakali, Rangun, and West Seti) were insufficient for flood frequency analysis. Hence, the WECS/DHM regional flood frequency formula was used to estimate peak flows.
3. Detailed data and information about the hydraulic structures (weirs and embankments) present in some watersheds were not available (Middle Karnali, Lower Mahakali, Rangun, Middle Rapti, and Lower Karnali). Hence, the model does not include these hydraulic structures and their potential impacts.
4. Some of the hydrological gauge stations are far from the upstream boundary of the watersheds thus the data collected, though proximate, is less reliable than data collected at the upstream boundary.
5. The cross-sections extracted from coarse resolution DEM may not be realistic. Detailed topographic and bathymetric surveys are necessary to obtain reliable river cross-section data.
6. The model (based on HEC-RAS) has been built for the main channel and does not include tributaries that may contribute to significant flows during floods.
7. To increase the lead time of flood warning, the rainfall intensity-duration threshold for the initiation of flooding needs to be assessed at the watershed level. Due to lack of spatially representative sub-daily rainfall data for the study watersheds, rainfall intensity-duration thresholds could not be assessed in this study.
8. For some of the watersheds, including Tila Karnali, West Seti, Thuligaad, hydrological stations are not present near the upstream boundary; a well-defined rating curve is not available; and a field visit was not conducted in these watersheds. Likewise, flow data series of four watersheds show a poor network of hydrological gauge stations, so the WECS/DHM

regional flood frequency formula was used to estimate peak flows. Hence, historical highest flood level data could not be obtained and imposed a limitation on the corresponding maximum flood hazard maps of these seven watersheds.

7. CONCLUSIONS

Flood hazard maps were prepared for different return periods, including 2-year, 5-year, 10-year, 25-year, 50-year, 100-year, and 200-year. Similarly, other important flood maps, including warning level, danger level, and maximum flood level hazard maps, were also prepared. The flood inundation depths have been presented at five intervals: less than 15 cm, 15 cm-30cm, 30 cm-60 cm, 60 cm-100 cm and greater than 100 cm.

Based on site observations and consultations with local communities, the draft flood hazard maps were updated and final maps prepared at a scale of 1:50,000. The information generated in the flood hazard maps can be very useful for the following purposes:

i) Flood early warning in the watersheds;
ii) Risk sensitive land use planning at the municipality level;
iii) Urban development planning;
iv) Community-based flood risk management; and
v) Enhancing risk knowledge and raising awareness about flood risks.

8. RECOMMENDATIONS

Based on the information collected and our findings, we present a set of general recommendations for all the watersheds, and then site-specific recommendations for six watersheds that have significant exposure to flood risk.

8.1 GENERAL RECOMMENDATIONS

To improve flood hazard map results and products:

- Obtain detailed and reliable flood hazard maps by adopting the freely available SRTM 30m for the purpose of developing flood warning analysis appropriate for mountain watersheds. However, for Tarai watersheds, fine resolution DEM with around ±1m vertical accuracy may be necessary. Likewise, for the design of flood control structures, land use planning, and flood proofing regulation, fine-resolution DEM is required.
- Generate high-quality cross-section data through topographic and bathymetric survey for accurate and reliable flood hazard mapping.
- Maintain and monitor hydrological and meteorological stations on a regular basis to record adequate time series data for flood frequency analysis.
- Collect detailed topographic and bathymetric data to complement extreme water level and flood wave height information for accurate flood hazard mapping for highest flood level (HFL).

To disseminate and share flood hazard maps:

- Provide capacity building training on the application of the maps in flood disaster preparedness and early warning system (EWS) development to downstream local community living in flood risk areas and to flood responders and stakeholders, including Paani representatives, the Nepal Red Cross Society (NRCS), and ward level disaster management committee.
- Utilize the DHM's institutional network and resources available at the regional and watershed levels to list and update the communities potentially affected by warning and danger level floods. This information is available from DHM's flood forecast division, which provides flood forecast products during the monsoon season.
- Provide flood hazards maps and related products to the Emergency Operation Centers (EOC) in flood-vulnerable communities at the ward, local, municipal and district levels.
- Strengthen the capacity of local government to prepare and implement risk-mitigation activities by sharing and using the flood hazard maps.

To prepare for flood events and utilize EWS:

- Carry out a detailed, comprehensive and integrated assessment by considering hydrological phenomenon in a watershed for effective EWS development both in perennial and seasonal rivers. These assessments should include determination of rainfall threshold, determination of lead time, analysis of flood risk in terms of vulnerability, exposure and adaptive capacity in downstream areas, and rainfall-runoff analysis that considers all hydrological characteristics of a watershed.
- Establish operational flood EWS. While simple technologies for real-time water level monitoring may be feasible for community-based flood EWS, these types of sensors do standards of the World Meteorological Organization (WMO), and DHM may not integrate these stations into its network.
- Include the flood hazard map information and results in Disaster Preparedness and Response Plans (DPRPs) at the local level.
- Prepare immediate response plans with flood protection measures in those communities threatened by warning and danger level floods.
- Raise awareness of local stakeholders (local government and communities) about the need for EWS and flood response plans.
- Alert likely affected settlements in the watersheds (especially downstream communities and stakeholders) that need instant evacuation during the time of warning.
- Develop safe evacuation routes and shelters for affected communities during flood events.
- Provide a sensitization program on the uses of flood hazard maps to the response task force and flood rapid response team in the municipalities.
- Develop two-way communication for EWS at the community level during the rainy season and link vulnerable communities/groups both upstream and downstream with livelihood activities and capacity building in the watershed.

To reduce risk, enhance mitigation and increase resilience:

- Adopt an integrated flood risk management approach (e.g., develop river protection measures and wet/dry flood proofing strategy, develop flood spill out mechanisms, include flood proofing in build building code).
- Construct embankments sufficiently beyond the active flood plain region (~500 m away), considering at least a 100-year return period flood for long-term development planning and infrastructure development in flood prone regions.
- Adopt mechanisms and suitable measures for living with flood risk (e.g., flood proofing in house construction, road construction, bridge design and construction). Consider appropriate flood protection measures in the areas of high hazards as a measure of immediate response.
- Carry out effective conservation measures such as afforestation, check dams, bioengineering activities, and agro-forestry (e.g., fruit trees and seasonal vegetable species) in the catchment areas to reduce intensity of the sediment load and flood.
- Integrate flood hazard map information in urban planning to adopt integrated flood management practices to reduce urban flood risks.
- Disseminate the flood hazard maps to the affected community through the concerned municipality/rural municipality by adopting public media (e.g., hoarding boards, local FM radio, Facebook, mobile based apps, public announcements, posters, and pamphlets).
- Ensure the implementation of risk reduction measures to save the life of gauge readers by providing life insurance, job guarantees, and lifesaving tools during high flood measurement events.
- Adopt information generated by the flood hazards map (i.e., several inundation depths of flooding at different periods of time downstream) for building construction, flood proofing provisions in building codes, infrastructure development, and urban planning.

8.2 SPECIFIC RECOMMENDATIONS

Jhimruk

- Incorporate information from the flood hazard map in development activities, especially in the Detailed Project Report (DPR) of the proposed smart city development in Jhimruk watershed.
- Update the gauging station at Madi Khola.
- Keep regular monitoring of flow below the dam and inform the downstream community.
- Adopt the use of public siren to disseminate warning information in the watershed.

Lower Karnali

- Take immediate diplomatic action to reduce the inundation risk towards Nepal due to back-water flooding caused by the Kailashpur Dam on the Nepal-India border. The most affected areas are Daulatpur, Gangapur, Jhhariya Phanth, Shankarpur, Lahure Tole, Lachiyapur, and Kholteniyapur.
- Monitor and regulate sand and gravel mining in both channels of the Karnali River. Haphazard extraction of river-based resources scours the river bed, leading to more deposition and inundation downstream.

- Establish an EWS system for the watershed in collaboration with DHM. Most settlements downstream in the watershed are under significant threat to floods.
- Take immediate action to clear sediment from Budi Kulo so flood water can pass more easily during monsoon.

Lower Mahakali

- Assess flood risk and develop EWS in the seasonal river network of the watershed, especially in the Kundura River, Sadani River, and Khannya Khola. These seasonal rivers pose a greater threat to Bhimdatta Municipality than the Mahakali.
- Adopt the information of the flood hazard maps into an Urban Development Strategy.
- Develop a link between the Local Emergency Operation Center (LEOC) and DHM to develop EWS on small rivers originating from the Siwalik range.
- Give special attention to monitor haphazard extraction of sand mining downstream of the barrage that causes increased risk of floods to downstream communities.
- Develop a mechanism to provide advance notice of water spill-out from the barrage so that flood risk can be reduced to vulnerable communities, especially women, who usually work in groups sand mining downstream from the barrage.
- Consider the flood hazard maps during the design and construction of houses in the municipality to reduce urban drainage problems caused by blockage of river flow.
- Coordinate with India operation of the barrage to reduce inundation in the watershed due closure of the Tanakpur barrage.

Middle Karnali

- Use flood hazard maps in the smart city development in Rakam district to provide a detailed risk assessment.
- Develop effective and reliable dissemination of warning information to communities through different means of communications, especially in the Rakam area downstream.

Middle Rapti

- Include major tributaries (seasonal rivers) in hydraulic modeling and flood risk mapping to represent their impact in the watershed.
- Carry out detailed topographic surveys at regular time intervals to delineate actual flood plains and demarcate actual political boundaries of the adjacent municipalities, where the Rapti River determines the border of two municipalities, since the river course changes rapidly downstream in the watershed.
- Construct flood mitigation structures along the banks of the Rapti River to reduce the exposure of settlements residing on the floodplain.

Rangun

- Adopt flood hazard risk reduction measures with a rehabilitation program in major seasonal rivers, especially in Puntura River, which is one of the major tributaries in the watershed.
- Provide all hazard maps in large scale to the municipalities (especially to Parshuram Municipality).
- Provide capacity building programs to gauge readers in the Rangun watershed about the monitoring of water levels to educate them about the telemetry water level monitoring

system and link them with the downstream community to create a more effective EWS service in the watershed.

- Organize awareness programs using flood hazard maps (especially in Parshuram Municipality).

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ANNEXES

Annex 1: Questionnaire for stakeholders' consultation

1. Here is the flood hazard map. It shows that these communities are in flood risk (low, medium, high). Do you think this is correct?
2. Have you experienced/witnessed flood in your locality/area? If yes, when?
3. How much was the depth of flooding/highest flood level?
4. Did you feel the impact of floods?
5. Is there is a flood early warning system in your area?
6. Do you know warning & danger level?
7. What is the flood danger level for your locality?
8. Have you ever received an early warning in advance of a flood?
9. How appropriate are these for women/disabled? Are there any challenges or barriers to women/disabled using these?
10. What is the highest water level in the River in upstream and its impacts in downstream?

Annex 2: List of KIIs interviewed

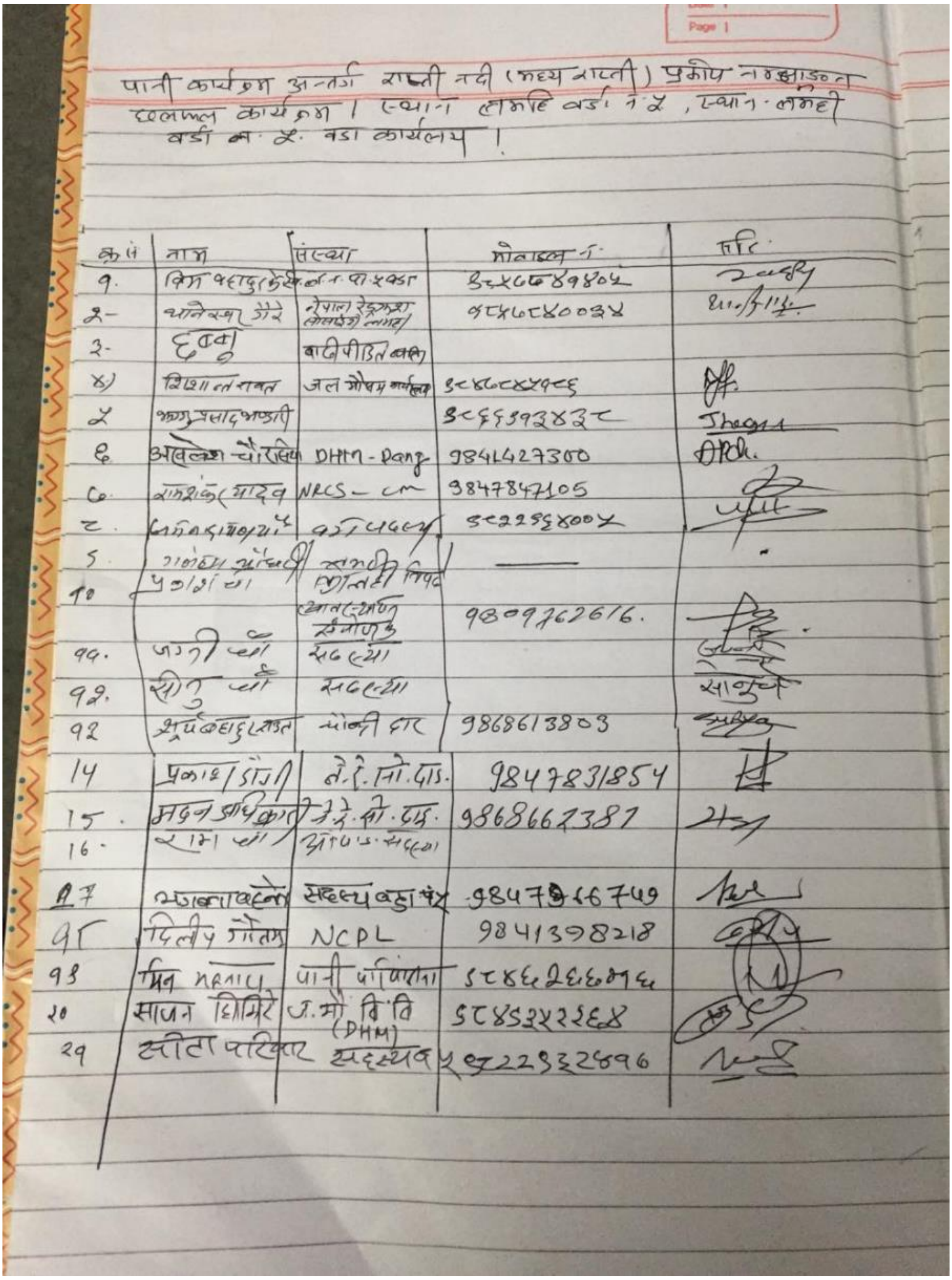
NAME	WATERSHED	LOCATION(PLACE)	WARD	ORGANIZATION	CONTACT NO.
Antaram Cahudhary	Middle Rapti	Lamahi	4		9818611468
Sushila Chaudhary		Bagaswoti			9809575148
Kirshan Kumar Cahudhary		Bangarapur, Rapti	6	Community Disaster Management	9847848421
Sugendra Raj Chaudhari		Gadhawa	2	Night Community disaster and climate susceptibility committee	9829560553
Shanti Devi Yadav		Gadhawa	2		9809703753
Ram Dev Tahru		Gadhawa	2		
Anjita Chaudhary		Gadhawa	2	NRCS	9808611684
Hom Bahadur Chaudhary		Gadhawa	2		9809535720
Sita Kumari Chaudhary		Kanchi, Gadhawa		Volunteer	9806262409
Shiva Prasad Adhikari		Kanchi, Gadhawa		Ex.Ward member	9809548837
Kit Bahadur Gurung	Lower Karnali	Rampur	7		9822422085
Bishan Dev Bhatta	Lower Mahakali	Bhimdatta Municipality			
Devaki Singh	Rangun	Kainpani, Jogbuda	12		
Pashupati Dhami		Kainpani, Jogbuda	12		9848983396
Lal Bahadur Bista		Kainpani, Jogbuda	12	Leader social worker	9848846684
Dev Raj Timilsina	Middle Karnali	Rakam		Health post	

Rana Bahadur Majhi		Rakam			9848199348
Mahendra Kumar Rawal		Rakam	4		9861803157
Madan Karki		Rakam	4		9868981617
Wapendra Sunuwar		Rakam	4		9868948871
Raj Majhi		Rakam	4		9844703303
Kiran Majhi		Rakam	4		
Bhupendra Sijapati					9868264642
Sushil Rasaili					9860099079
Rabindra Rana Magar	Jhimruk	Dobang	4		9812814382 9801004429
Bhupendra Prassad Adhikari					9844956215
Sharad Basnet			3		9857836718
Ram Mani Acharya		Chernata			9847982725

Annex 3: Different return period (2, 5, 10, 25, 50 and 200 year) flood hazard maps of Middle Rapti Watershed

Please refer to the folder attached separately for all maps in this Annex.

Annex 4: List of Participants during field consultation



Page 1

पानी कार्यक्रम अन्तर्गत राप्ती नदी (मध्य राप्ती) प्रकोप नक्साङ्कन छलफल कार्यक्रम। स्थान लमही वडा नं ५, स्थान लमही वडा नं. ५ वडा कार्यालय।

क्र.सं	नाम	संस्था	मोबाइल नं.	सहि.
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३.	[illegible]	बाढीपीडित [illegible]		
४.	[illegible] रावत	जल मौसम कार्यालय	[illegible]	
५	[illegible] प्रसाद भण्डारी		[illegible]	
६	अखिलेश चौरसिया	DHM - Dang	9841427300	
७.	राजशंकर यादव	NRCS - CM	9847847105	
८.	[illegible]	[illegible]	[illegible]	
९.	[illegible]	[illegible]	—	
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15.	मदन अधिकारी	ने.रे.सो.दाङ	9868662387	
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१९	[illegible]	पानी परियोजना	[illegible]	
२०	साजन घिमिरे	ज.मौ.वि.वि (DHM)	[illegible]	
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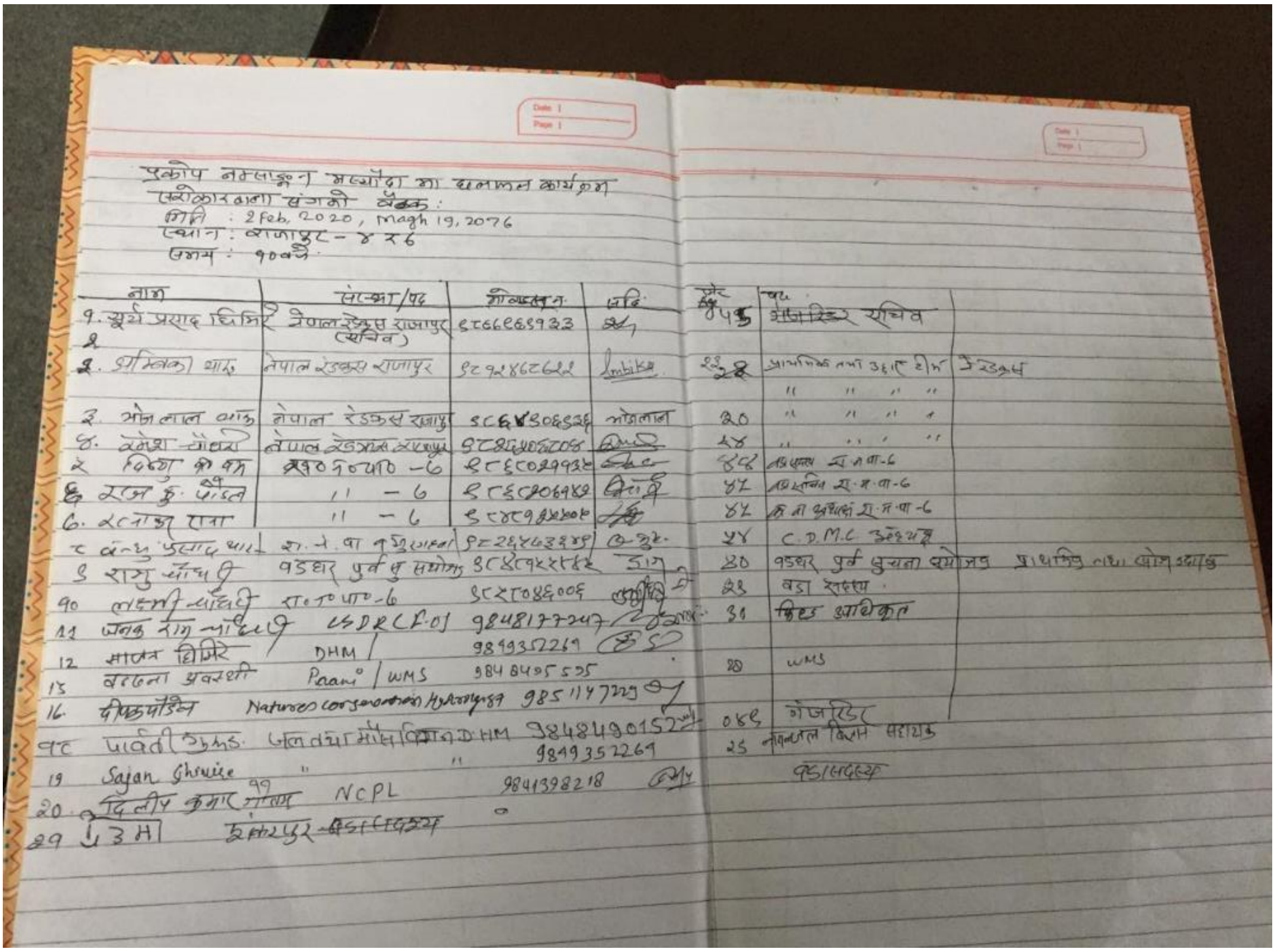

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मिति: 2 Feb, 2020, Magh 19, 2076
स्थान: राजापुर - ४ र ६
समय: १० बजे

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12 माधव घिमिरे	DHM	9849352269	[illegible]	28	WMS
13 वन्दना अवस्थी	Paani / WMS	9848495595			
16 दीपक पौडेल	Nature Conservation Hydrologist	9851147729	[illegible]	०८६	गेजरिडर
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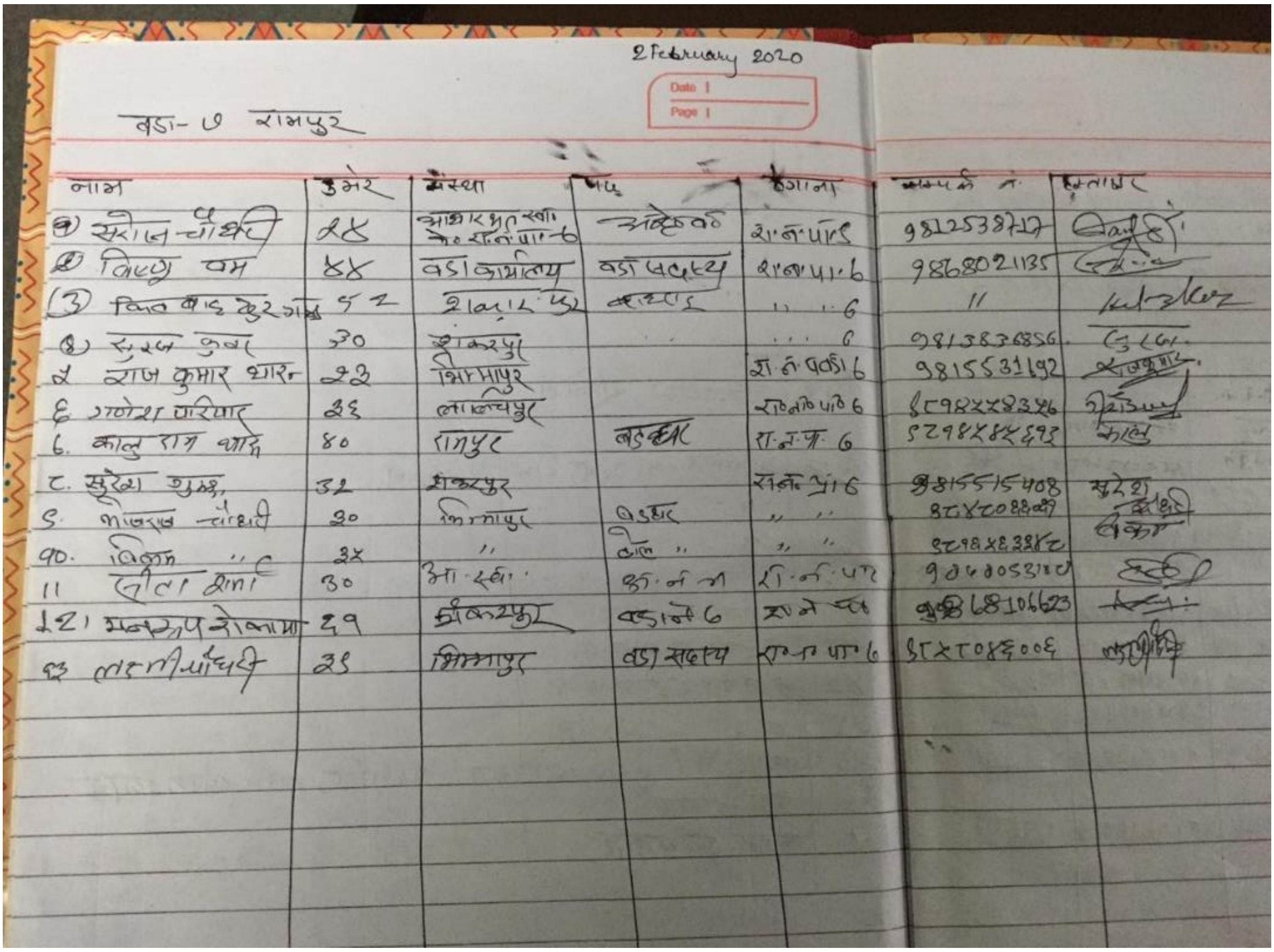

2 February 2020

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वडा- ७ रामपुर

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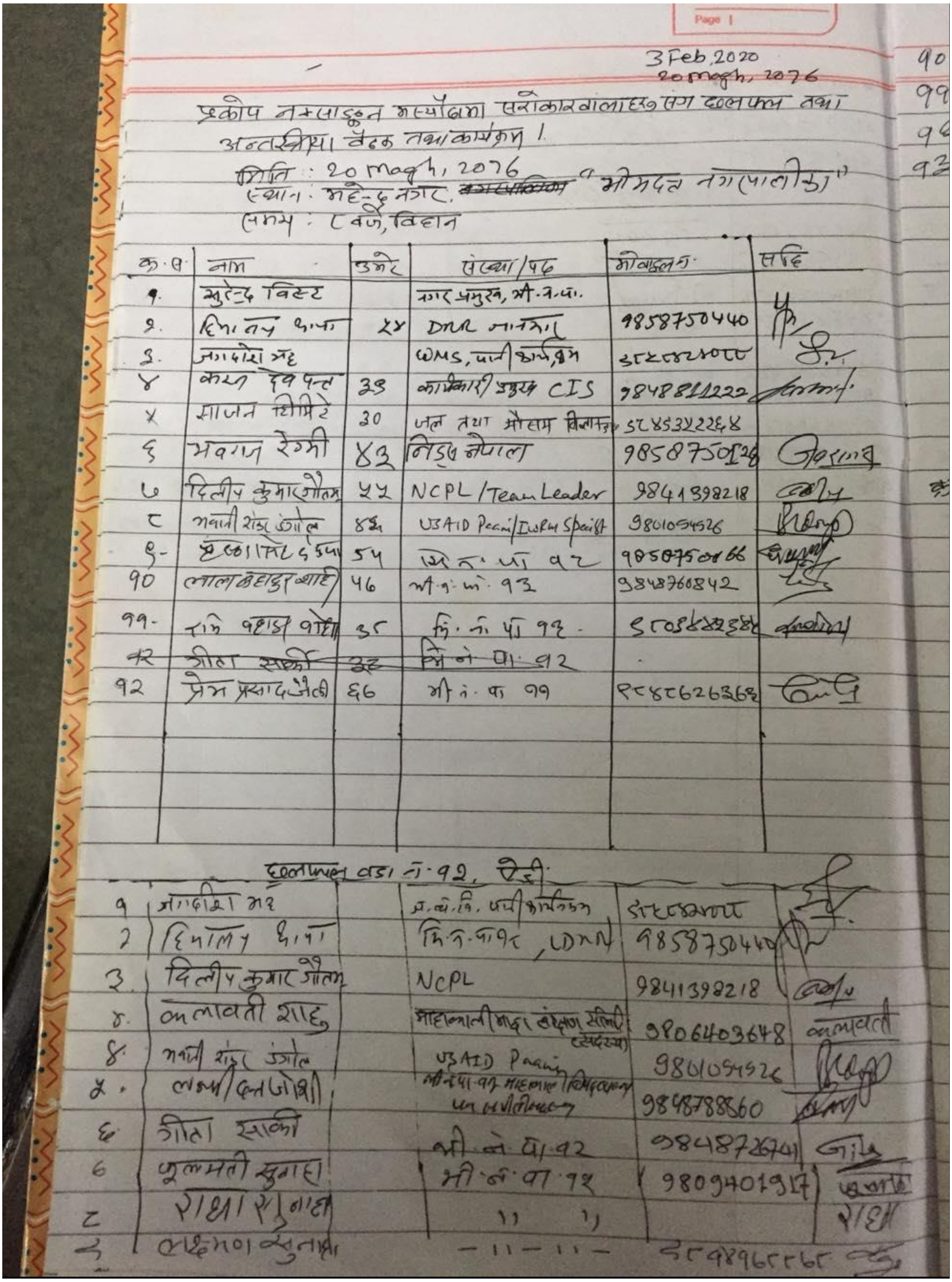

3 Feb, 2020
२० माघ, २०७६

प्रकोप नक्साङ्कन मस्यौदामा सरोकारवालाहरुसंग छलफल तथा अन्तरक्रिया बैठक तथा कार्यक्रम ।

मिति : २० magh, 2076
स्थान : महेन्द्रनगर, ~~नगरपालिका~~ "भीमदत्त नगरपालिका"
समय : ८ बजे, बिहान

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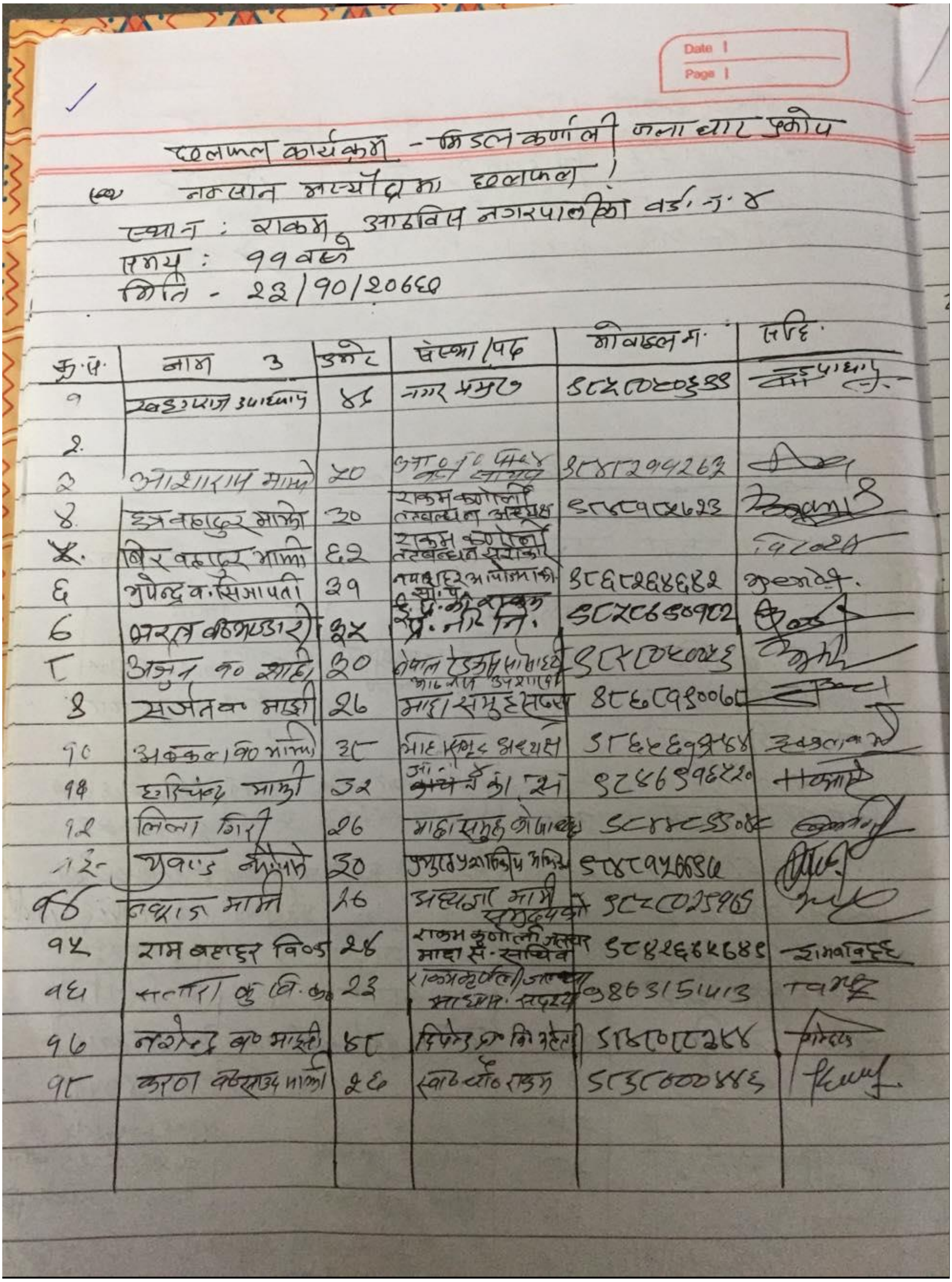
छलफल वडा नं. १२, पेडी

क्र.सं.	नाम	संस्था/पद	मोबाइल नं.	सहि
१	जगदीश भट्ट	प्र.का.नि. पानी कार्यक्रम	९८५८७४२४०८८	[signature]
२	हिमालय थापा	जि.स.का., DNR	9858750440	[signature]
३	दिलीप कुमार गौतम	NCPL	9841398218	[signature]
४	कलावती शाह	महाकाली माछा संरक्षण समिति (सदस्य)	9806403648	कलावती
५	भवानी शंकर ज्ञवाली	USAID Paani	9801054526	[signature]
५	लक्ष्मी दत्त जोशी	भी.न.पा. १२ महाकाली सिंचाई [illegible]	9848788560	[signature]
६	गीता सार्की	भी.न.पा. १२	9848726741	गीता
७	फूलमती सुनाहा	भी.न.पा. १२	9809401917	फूलमती
८	राधा सुनाहा	" "		राधा
९	लक्ष्मण सुनाहा	-"-	९८४८९६८८६८	[signature]



छलफल कार्यक्रम - मिडल कर्णाली जलाधार प्रोजेक्ट
नक्सान सम्बन्धमा छलफल
स्थान : राकम, आठबिस नगरपालिका वडा नं. ४
समय : ११ बजे
मिति - २३/१०/२०७६

क्र.सं.	नाम थर	उमेर	संस्था/पद	मोबाइल नं.	सहि
१	खड्गराज उपाध्याय	४५	नगर प्रमुख	९८४८०२०३३३	[illegible]
२					
३	आशाराम माझी	४०	[illegible]	९८४८२११२६३	[illegible]
४	इन्द्रबहादुर माझी	३०	राकम कर्णाली तटबन्धन अध्यक्ष	९८४८१८८६२३	[illegible]
५	बिर बहादुर माझी	६२	राकम कर्णाली तटबन्धन सदस्य		[illegible]
६	भूपेन्द्र ब. सिसापती	३१	नयाँ सहर आयोजना सो.पु.	९८६८२६४६६४	[illegible]
७	भरत अधिकारी	३५	इ.प्र.को राकम प्र.नीरी	९८२८६९०१०२	[illegible]
८	अर्जुन व. शाही	३०	नेपाल टेलिकम सो.पु.	९८४८०५००२६	[illegible]
९	सर्जित ब. माझी	२६	माझी समुह सचिव	९८६०९९००६०	[illegible]
१०	अक्कल ब. माझी	३८	माझी समुह अध्यक्ष	९८६४६९४४४	[illegible]
११	हरिचन्द्र माझी	३२	आर्य ठे. को. सं.	९८४६९१६८८०	[illegible]
१२	लिला गिरी	२६	माझी समुह कोषाध्यक्ष	९८४४८९०८४	[illegible]
१३	युवराज नौडियाल	३०	प्रकृति संरक्षण अभियान	९८४८१५८६६९८	[illegible]
१४	लक्ष्मण माझी	४६	अध्यक्ष माझी समुदाय	९८४८०२५९६५	[illegible]
१५	राम बहादुर विष्ट	४८	राकम कर्णाली जलधार माझी सं. सचिव	९८४२६६५६४९	[illegible]
१६	सन्तारा कुमारी वि.क.	२३	राकम कर्णाली जलधार माझी सदस्य	९८६३१५१४१३	[illegible]
१७	नरेन्द्र ब. माझी	४८	[illegible]	९८४८०८८२४४	[illegible]
१८	करण बहादुर माझी	२८	[illegible]	९८३८०००४४६	[illegible]

Photos from field consultations

Photo 1: Consultation meeting in the Lower Karnali watershed

Photo 2: Consultation meeting in the Middle Rapti watershed

Photo 3: Consultation in the Middle Karnali watershed

Photo 4: Consultation in the Rangun watershed

Photo 5: Consultation in the Jhimruk watershed

Photo 6: Consultation in the Lower Mahakali watershed

Photo 7: Consultation meeting in Bhimdatta Municipality

Photo 8: Local man showing historical flood inundation mark

Photo 9: Local woman indicating historical mark of inundation flood depth in the Middle Rapti watershed