



# Assessing the past and adapting to future floods: a hydro-social analysis

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## Abstract

Floods are extreme events affecting millions of people worldwide and causing loss worth billions. The magnitude and frequency of floods are likely to increase with altered climate, and developing countries tend to suffer the most because of low resilience and adaptive capacity. This research aimed to analyze existing and preferred future flood adaptation strategies in a flood-prone West Rapti River (WRR) Basin of Nepal, using hydrological analysis and flood modelling, and a social survey of 240 households (HHs) and several focus group discussions (FGDs). The specific objectives were to (1) understand the rainfall-flood behaviour of the basin in a simplistic way, (2) carry out flood modelling to generate inundation maps for informing the local people, and (3) identify flood adaptation strategies based on people's perception. Flood inundation maps are generated for four scenarios based on return periods: scenario I (2 years), scenario II (20 years), scenario III (50 years), and scenario IV (100 years). Results show that the southern parts of three rural municipalities (Duduwa, Narainapur, and Rapti Sonari) get inundated almost every year irrespective of the flood magnitude. This information was presented to local communities before administering the HH survey and FGDs so that they could make informed decisions. During the survey, the preference of people's adaptation strategies for the four flood scenarios was explored and prioritized. Our findings suggest that peoples' thoughts and preferences for adaptation strategies changed with exposure to flood magnitudes. For example, "bamboo mesh with sand filled bags"—simplest and least expensive adaptation strategy—was preferred for a less severe flood while a complex and expensive technique "reservoir/flood regulating structures" was preferred for a devastating flood scenario. Thus, this study has highlighted firstly, the importance of inundation maps to understand and inform the local people about floods and their impacts; and secondly, the value of information to the people enabling them to make informed decisions. The novelty of this empirical study lies in a multi-disciplinary assessment framework which integrates scientific information, stakeholder knowledge, and local people's perceptions of flood risks and adaptation strategies for the future. Such an approach of hydro-social analysis has the potential for replication in flood-prone regions globally, with similar bio-physical and socio-economic conditions.

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**Keywords** Adaptation strategies · Flood scenarios · HEC-RAS · Hydro-sociality · Inundation mapping · Linear regression

## 1 Introduction

Water-related hazards have the largest share among all natural disasters globally and floods are extreme events which affect millions of people worldwide causing loss worth billions (Jain et al. 2018; Towner et al. 2019). There is significant concern that the associated global loss will increase under future climate (Keighley et al. 2018; Sharma et al. 2019). It is extremely difficult to obtain a direct correlation between climatic variability and flood events. While the effects of climatic variability are global, developing countries tend to suffer the earliest and the most because of high vulnerability to climatic stress (Rahman et al. 2018). South Asia is one of the most sensitive regions because of its low resilience and adaptive capacity to deal with the adverse impacts of climate risks (Singh et al. 2020; Disse et al. 2020). Studies have tried to evaluate the impacts of climate change on water resources, particularly floods at regional and basin scales (Ali et al. 2019; Basak et al. 2015). Research shows that the magnitude and frequency of floods are likely to increase with an altered climate (Zhang et al. 2014). This implies that adequate provisions are needed to adapt to increasing flood risk and to minimize physical and welfare losses for households in flood-prone areas (Dangol and Carrasco 2019).

Flooding is a recurrent phenomenon in the southern plains of Nepal. Recent floods have damaged physical infrastructure, caused difficulty in mobility, brought about water-borne diseases and health hazards, reduced crop production, and contributed to other social problems (Mishra and Sinha 2020; Talchabhadel et al. 2015). Recent studies project that the temperature over Nepal will increase, rainfall patterns will change both in intensity and magnitude with increased uncertainty in future floods (Dahal et al. 2020). This calls for the development of simple yet effective techniques for predicting floods to timely minimize their damage.

Hydrological models coupled with hydraulic models are established methods for flood studies which have been applied in a number of basins across the world at varying scales (DOWRI 2018; Echogdali et al. 2018; Kirkpatrick and Olbert 2020; Try et al. 2018). Hydrological models have been applied in Nepalese basins for analysing water availability (Pandey et al. 2020; Bharati et al. 2016; Dhami et al. 2018) and floods (Devkota and Gyawali 2015; Talchabhadel et al. 2015). DOWRI (2018) used HEC-RAS 1D to analyze the six most flood-prone basins of Nepal, including the West Rapti River (WRR) Basin, based on the results of which the proposed mitigation measures are currently being implemented by the Government of Nepal. Lintott (2017) used HEC-RAS 2D to analyze the effects of floods on physical infrastructure and evaluate initial design options for flood risk mitigation. However, the use of such models requires long-term, reliable, and quality-controlled (spatial and temporal) data. It is difficult to meet this requirement without resorting to a lot of assumptions in the case of most Nepalese basins. Moreover, with limited research in Nepal and thus, due to the lack of scientific evidence and information about adaptation and mitigation, the state is generally not able to identify and implement appropriate strategies (Bastakoti et al. 2016; Delalay et al. 2018; Devkota and Bhattarai 2016). Furthermore, the application of simple methods combining scientific as well as community-level inputs to quantify flood magnitudes and devise adaptation strategies has become very important in such data-scarce regions.

Additionally, studies have tested and applied simple regression-based techniques to understand the rainfall-runoff relationship (McIntyre et al. 2007; Roland and Stuckey 2008) in areas

with limited data. Regression analysis is a black box approach in which a mathematical relationship is created among the involved variables. It does not involve any physical processes in the calculation. However, such methods come in handy when extensive data are not available to carry out complex hydrological modelling which is believed to incorporate most physical processes although limitations and assumptions are inevitable. McIntyre et al. (2007) argue that the results of such regression analysis should be limited to the range of the training data and extrapolation beyond that is not advisable. Similarly, Roland and Stuckey (2008) mention that a longer data series is more likely to yield better relationships among the variables. The choice of the flood prediction method will have a direct implication on the adaptation measures.

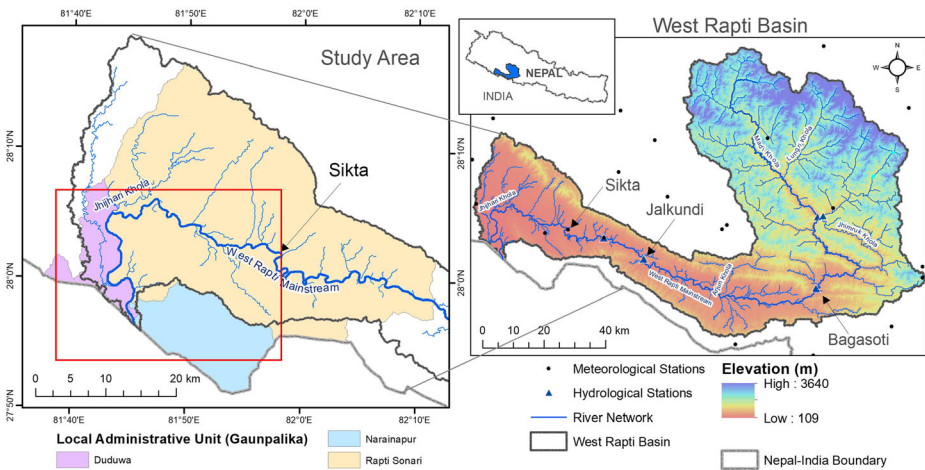
Generally, structural and non-structural measures are applied for flood mitigation. Structural measures include constructing infrastructure such as dams, embankments, flood walls, spurs, among others (Tran and James 2017). Non-structural measures are a combination of the multi-disciplinary type of interventions, for example, flood hazard zoning, watershed management, and afforestation. An assessment of both technical and social aspects is needed in order to provide a sound basis for the development of long-term flood adaptation strategies. Community participation is a way to empower stakeholders, giving them a more central role in the generation of knowledge and therefore increasing their capacity of resilience (Mai et al. 2020). Recent studies on the combined hydro-social approach have been carried out in Nepal in different basins (Devkota et al. 2017; Bastakoti et al. 2016) with encouraging outcomes. Studies have concluded that a participatory approach can lead to social learning (Devkota and Bhattarai 2016; Delalay et al. 2018).

The overarching goal of this study is to understand the flood behaviour and impacts along with perceived adaptation strategies in relation to different levels of exposure. The specific objectives are to (i) understand the rainfall-flood dynamics of the WRR Basin in a simplistic way and develop a regression-based relation for the same, (ii) carry out flood modelling to generate inundation maps for informing the local people of the possible flood impacts, and (iii) identify flood adaptation strategies based on people's perception. These have been achieved through the development of a vulnerable communities-centred multi-disciplinary assessment framework in which stakeholders were engaged with information obtained from hydraulic modelling. This work provides a collaborative assessment of the aspirations of local people as well as evidence-based outcomes to policy makers at the government level on information about future plausible flood scenarios and their likely impacts on the community. The novelty of this study is that it has integrated scientific information, stakeholder knowledge, and local people's perceptions of flood risk management. This work has developed an integrated science-policy framework in the flood adaptation sector with the WRR Basin as a case.

## 2 Materials and methodology

### 2.1 Study area

This study was carried out in the WRR Basin which lies in the south-western part of Nepal with its elevation ranging from 109 to 3640 m above sea level (masl) (Fig. 1). Most of the people living in this study area are of the indigenous communities among which 90% are dependent on agriculture for a subsistence livelihood. The population density of the area is about 160 per km<sup>2</sup> which is slightly more than the national figure of 157 per km<sup>2</sup>. Although not snow-fed, the



**Fig. 1** Location map of the study area. The red rectangle on the figure (left) indicates the extent of the hydraulic modelling as well as the area where social survey was carried out

WRR (mainstream river length of 365 km) is a major perennial river with its origin in the middle mountains of Nepal. The WRR flows southward up to Bagasoti, bends westward after that until the confluence with Jhijari River, and finally flows south again out of Nepal to India. The two major tributaries of WRR are Madi and Jhimruk. The drainage area of the WRR basin at the Nepal-India border is 6438 km<sup>2</sup>. The average annual basin rainfall is about 1500 mm (Talchabhadel et al. 2015). More than 80% of the rainfall with intense incessant instances occur during the four monsoon months—June through September. Such cloudburst events cause floods and inundate a large extent in the flat land near the Nepal-India border almost every year—a peculiar character of many monsoon-driven Nepalese rivers. Therefore, the WRR Basin was categorized as one of the top priority basins for flood management by the Government of Nepal (DOWRI 2018). The questionnaire survey was carried out in the lowermost part of the basin where 720 households (HHs) vulnerable to floods exist.

## 2.2 Methodology

This study is based on a two-tier approach which consists of hydrological and hydraulic analysis as the first tier followed by social analysis as the second. A simple multi-variate linear regression relation was derived to estimate the flood peaks based on limited observed daily precipitation and discharge data. HEC-RAS (1D) (USACE 2002) was used for hydraulic modelling to simulate floods of different return periods and consequently generate inundation maps. And finally, people's perceptions of the flood impacts were tested through an assessment of local knowledge of mitigation and adaptation.

### 2.2.1 Hydrological analysis and flood modelling

Precipitation is a highly stochastic phenomenon. A direct method for correlating precipitation and flood discharge is not available. Generally, an event-based hydrological model with high-resolution data is necessary to have a better understanding of the rainfall-runoff phenomenon (Pandey et al. 2020; Bharati et al. 2016; Devkota and Gyawali 2015). However, such high-resolution temporal climate and

spatial data are not available in the WRR Basin and hence hydrological modelling was not carried out. Rather, a simple rainfall-flood relationship was established which could be conveniently used to estimate flood peaks based on observed daily data and also be easily communicated to the authorities responsible for flood management in the area without skilled manpower. Precipitation, daily discharge, and instantaneous maximum discharge were correlated considering historical data of 32 years (1984–2015) at Bagasoti (Fig. 1). The time of concentration of the WRR Basin is less than 2 days. Moreover, the rainfall occurring during the previous day could have a significant influence on the discharge of the flood day. Therefore, a regression equation was derived considering 2-day accumulated basin rainfall, 2-day accumulated point rainfall, and 24-h discharge (of the flood day) as the independent variables and the instantaneous maximum (peak) discharge as the dependent variable. Details of the data used are given in the Supplementary Material (SM):S1 and S2.

The average daily runoff coefficient ( $C_R$ ) of the highest flood days, which we have been defined as the ratio of the daily basin precipitation to the average 24-h discharge at Bagasoti on the flood day, averaged over the period of observed year, was calculated using Eq. 1 (in compatible units) which is based on its definition as:

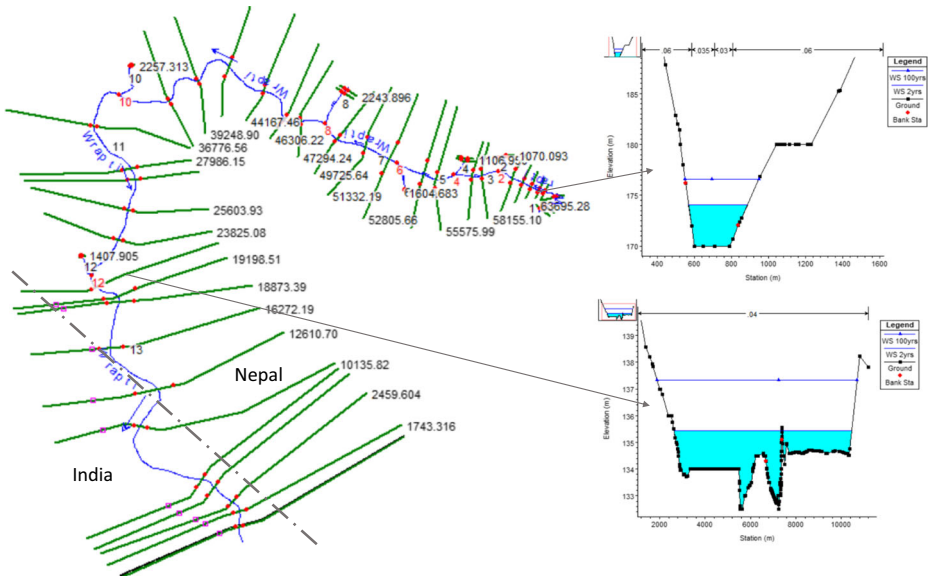
$$C_R = \frac{1}{n} \sum_{i=1}^n \frac{Q_{\text{point},24\text{hr},i}}{0.5R_{\text{basin,acc},i}} \times \frac{86400}{A \times 10^9} \quad (1)$$

where,

$C_R$	Daily runoff coefficient
$Q_{\text{point},24\text{hr},i}$	24-h discharge of the flood day for the $i$ th year at Bagasoti ( $\text{m}^3/\text{s}$ )
$R_{\text{basin,acc},i}$	Accumulated 2-day basin rainfall (mm) for the $i$ th year at Bagasoti
$A$	Catchment area at Bagasoti ( $= 3380 \text{ km}^2$ )
$n$	Number of observed flood years (32)

Flood modelling was carried out in HEC-RAS (1D) within a spatial extent comprising a flood-prone flat area downstream of Sikta up to the Nepal-India border in the WRR Basin (Fig. 1). SRTM<sup>1</sup> 3 arcsec digital elevation model (DEM) was corrected using Google imagery to precisely define the river channels of the study reach. Geometric data was extracted from the DEM. Details of the input data and model parameters are listed in SM:S3 and S4. Figure 2 shows the model schematic and typical upstream and downstream cross-sections. Observations from the Department of Hydrology (DHM), GoN, was used to pre-process the flow data at the Bagasoti gauging station. There is another gauging station named Jalkundi near Sikta but its data is unreliable and thus excluded in our study. Flood frequency analysis was carried out by fitting a Gumbel distribution to the observed annual instantaneous maximum flow data at Bagasoti from 1984 through 2015 to estimate the flood magnitudes of 2-, 20-, 50-, and 100-year return periods. The Gumbel distribution method is the most widely used probability distribution function for extreme values in hydrologic and meteorological studies for the prediction of flood peaks and maximum rainfalls. In the absence of other gauging stations downstream of Bagasoti, we had to rely on a regional method to estimate the additional incremental floodwater to the WRR mainstream to calculate the inflow at Sikta (upstream boundary for the HEC-RAS model). Modified WECS method (Sharma and Adhikari 2004), which is a widely applied method for flood studies in Nepal, was used for this purpose. Within

<sup>1</sup> [http://srtm.csi.cgiar.org/wp-content/uploads/files/srtm\\_5x5/ TIFF/srtm\\_53\\_07.zip](http://srtm.csi.cgiar.org/wp-content/uploads/files/srtm_5x5/ TIFF/srtm_53_07.zip) accessed 12 January 2020



**Fig. 2** HEC-RAS model schematic of the study area for two flood scenarios (2 years and 100 years), mainstream centerline with cross-section cut lines (left); sample cross-section at chainage 61,069 (top right); and 20,525 (bottom right)

the modelled reach, the additional contribution of the tributaries entering the main river was estimated using an area transpose method. The return period of these floods is directly correlated to the probability of occurrence and thus their severity. A 2-year return period flood (probability of occurring once every 2 years) is a regularly occurring flood: this has been considered scenario I. Similarly, a 20-year flood (probability of occurring once every 20 years) has a higher magnitude, is expected once in a while, and is likely to be more devastating than scenario I: this has been called scenario II. Furthermore, a 50-year period flood (probability of occurring once every 50 years) is a large flood with chances of significant damage—scenario III. And finally, a 100-year period flood (probability of occurring once every 100 years) is a very large flood with high likelihood of extensive damage to life and property: it has been modelled as scenario IV. The input flood discharges for the model are presented in Table 1 and the details of the contribution of the tributaries at the respective flow change locations are given in SM:S5.

In the absence of observed discharge or water level data in the modelled reach, the model was validated with a soft/indirect approach against the 2008 flood by determining inundation depths at various locations across the river stretch. These were then compared with water marks and depths reported by the local people during the field survey who remembered the extent and damage of the flood. Details of the validation are presented in SM:S6. The model was able to satisfactorily simulate the hydraulic processes within the study reach for flood analysis.

Water depths at different locations were extracted from the model in raster format and flood inundation maps prepared for all the modelled scenarios. It is imperative to understand the cumulative effect of depth and duration of inundation and the number of times an area is inundated in a given time frame to assess the severity of floods on the community. It



**Table 1** Adopted flood discharge and criteria for flood risk zoning

Location	Flood discharge (m <sup>3</sup> /s) of different return periods				Remarks
	2 years (scenario I)	20 years (scenario II)	50 years (scenario III)	100 years (scenario IV)	
Bagasoti	1739	4556	5565	6320	Calculated using Gumbel's method
Sikta	3442	8409	10,289	11,732	Additional discharge calculated using Modified WECS method
Criteria			Inundation <0.3 m	Impacts Manageable	Risk Low
There is less disturbance to daily human activities and little damage to crops or settlements			0.3–1.0 m	Tolerable	Moderate
Daily activities are impeded and there is damage to crops and settlements			> 1.0 m	Very difficult to tolerate and with long term impacts.	High
Daily activities are severely impeded, settlements are highly affected and there is significant damage to crops.					

is difficult to exactly quantify and apply a set of threshold values for these parameters for zonation. Keeping things simple for relative assessment, more is the inundation depth, the higher will be the disturbance to the people. Thus, the flood inundation map was categorized into three zones with depths less than 0.3 m, 0.3–1.0 m, and more than 1.0 m representing low, moderate, and high risks respectively (Table 1) based on a previous study (Devkota 2014).

## 2.2.2 Analysis of flood adaptation strategies

During the focus group discussions (FGDs), local people were asked to prepare a list of flood adaptation strategies they have been most commonly using over the past 20 years. They were further requested to identify five applicable techniques that are most relevant for the HH survey. A simple random sampling method with a proportion of HH numbers was adopted and a total of 240 HHs (over 25% of the total flooded HHs) were randomly interviewed for a semi-structured questionnaire survey. There were 720 HHs in the three flood risk zones—144 in high, 274 in moderate, and 302 in low. Stratified random sampling with the proportion of HH numbers was considered as a basis of allocating the sampling effort in each zone. Before administering the HH survey and FGDs, the questionnaire was pre-tested and the results from flood modelling were presented to the local communities so that they could make informed decisions. During the HH survey, the key person of each HH was requested to rank the selected flood adaptation strategies on a 1–5 scale, 1 being the least preferred and 5 the most preferred option (Maraseni and Xinquan 2011). For each strategy, frequency (F), relative frequency (RF), and cumulative relative frequency (CRF) of scores were calculated; strategies were then ranked on the basis of CRF for the most preferred (MoP), very preferred (VeP), and moderately preferred (MdP) levels based on the methodology developed by Devkota (2014). The adaptation strategies for each flood scenario were then ranked, based on total scores, from the overall preferred strategies. Furthermore, five FGDs were conducted in the flood-prone areas within the study domain. People who have had first-hand experience in the

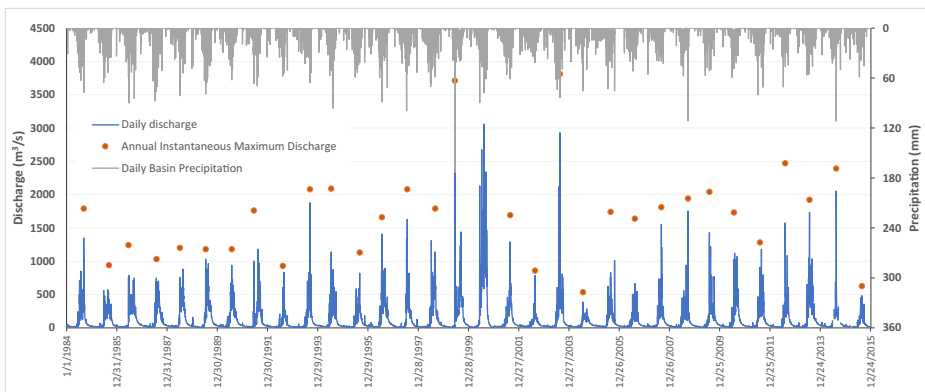
implementation of flood adaptation strategies, such as farmers, foresters, local authority secretaries, school teachers, and members of local non-government offices, were invited to participate in the FGDs resulting in the active participation of 71 respondents.

### 3 Results and discussion

Flooding has many disruptive effects on lives, livestock, physical damage to human settlements, and economic activities. Therefore, a detailed study on human-water systems is important to complement the temporal and spatial analyses of floods (Babel et al. 2020; Baldassarre et al. 2013; Sivapalan et al. 2011). Furthermore, predicting the hydrological phenomenon of an ungauged/partly gauged basin such as the WRR is always a big challenge especially for flood peaks.

#### 3.1 Rainfall-runoff analysis

The WRR Basin is very responsive to rainfall, particularly high rainfall events occurring during the monsoon season which generates high peak flood events (Fig. 3). The long-term annual average flow of WRR at Bagasoti was calculated to be 97 m<sup>3</sup>/s with the highest monthly flow of 295 m<sup>3</sup>/s occurring in August and the lowest flow of 10 m<sup>3</sup>/s in April. Approximately 75% of the flow occurs from June through September (average = 218 m<sup>3</sup>/s). It can be seen from Fig. 3 that daily flows are well above 1000 m<sup>3</sup>/s almost every year during the monsoon. In some years, daily flows have been observed to be as high as 2000 m<sup>3</sup>/s (for example in 1993 and 2014) and even up to 3000 m<sup>3</sup>/s (in 2000 and 2003). The observed annual instantaneous flood peaks are always greater than 1000 m<sup>3</sup>/s except for a few years (1992, 2002, 2004, and 2015). It can also be seen that out of the 32 years considered in this study, 19 years have an annual peak flood magnitude above 1500 m<sup>3</sup>/s. In some years (1999 and 2003), magnitudes above 3500 m<sup>3</sup>/s were observed. Additionally, earlier studies have shown that the lowermost part of the basin is at high risk of floods (Talchabhadel et al. 2015; Talchabhadel and Sharma 2014; Perera et al. 2015). These data highlight the need for serious flood adaptation planning especially in the lowermost part of the basin.



**Fig. 3** Daily discharge and rainfall pattern of Bagasoti (1984–2015) with annual instantaneous maximum discharge values (shown as red dots)



Devkota and Gyawali (2015) have put forward a simple equation for the Koshi Basin (Nepal) in which the peak floods have been correlated to daily flood values using varying coefficients for different return period floods. In a similar manner, this study has made use of additional parameters for developing a regression equation for the WRR Basin with a reasonably good fit. Based on the long-term (32 years) precipitation and flood data, a rainfall-flood regression formula was derived (Eq. 2).

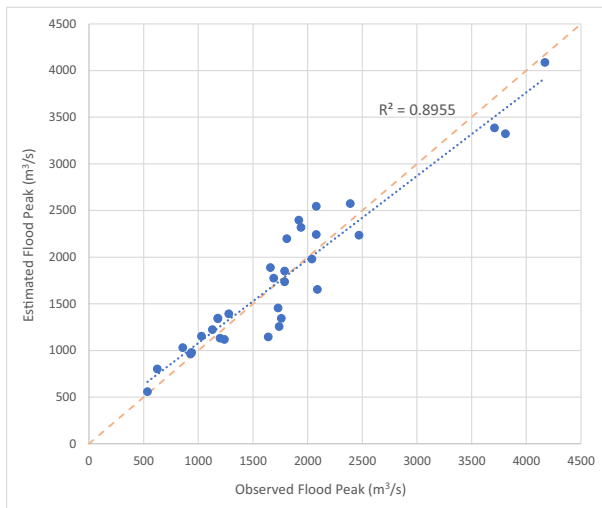
$$Q_{\text{inst,est}} = 323.73055 - 2.8297R_{\text{basin,acc}} + 0.34755R_{\text{point,acc}} + 1.27202Q_{\text{point,24hr}} \quad (2)$$

where,

$Q_{\text{inst,est}}$	Estimated instantaneous flood peak ( $\text{m}^3/\text{s}$ )
$R_{\text{basin,acc}}$	Accumulated 2-day basin rainfall (mm, calculated from daily precipitation surface, details provided in SM:S2)
$R_{\text{point,acc}}$	Accumulated 2-day point rainfall at Bagasoti (mm, calculated using precipitation surface)
$Q_{\text{point,24hr}}$	Observed 24-h discharge of the flood day at Bagasoti ( $\text{m}^3/\text{s}$ )

From Eq. 2, it can be seen that the coefficient for the observed 24-h discharge has a significant positive impact on the estimated flood peak. Surprisingly, the basin accumulated precipitation coefficient is inversely correlated with the flood peak while the accumulated point precipitation coefficient shows a positive correlation. In case of a dry year when the precipitation intensity and duration are quite low, Eq. 2 gives an estimated flood peak of about  $320 \text{ m}^3/\text{s}$  which is comparable to an observation of the year 2004. The scatter plot between observed and estimated values of the flood peaks is shown in Fig. 4. The coefficient of determination ( $R^2$ ) of 0.89 is a good indication of the accuracy and usability of the equation. Although the observed training data for Eq. 2 covers up to a 5-year return period only, it can be extended for higher return period floods if corresponding precipitation can be estimated or forecasted. This equation is not used for calculating the floods for modelling rather it has been developed as a simple method to predict the magnitude of flood peaks based on observed daily data at Bagasoti. This will be beneficial to the flood management authorities who lack skilled manpower for running complex hydrological models for flood estimation which is further limited by the availability of data. Although some real-time telemetry systems have been installed in the basin (Talchabhadel et al. 2015), their data is neither continuous nor reliable. This simple rainfall-flood relationship developed for the study area could also be very useful for calculating missing flood peak data in the historical time series (Perera et al. 2015). Moreover, it could be helpful in estimating or forecasting possible future floods using forecasted precipitation data, assuming all the other basin characteristics remain unaltered.

Using Eq. 1, the value of average  $C_R$  calculated was 0.81 at Bagasoti which is reasonable in the case of floods. The area upstream of Bagasoti has a steep terrain with an average slope of 0.020. The WRR Basin is dominantly rural with less very little impervious/built-up area (see SM:S7). Landuse map shows that about 38% of the area is agricultural land while 57% is covered by forest. However, during high precipitation and flood events, the soil gets fully saturated and the surface runoff as well as the total discharge is very high which is mainly driven by the steep slope and the narrow river channels with rocks and cliffs on the sides. Therefore, a high value of the runoff coefficient is observed.



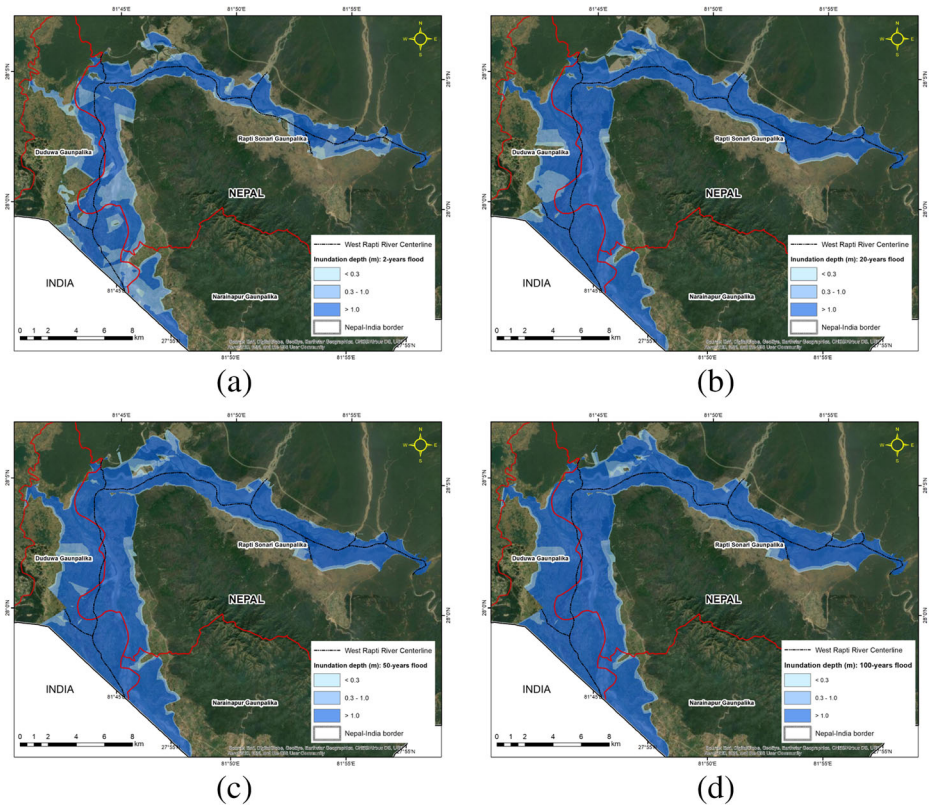
**Fig. 4** Scatter plot of the observed and estimated flood peak values by Eq. 2 for 32 years of historical flood data

### 3.2 Flood inundation mapping

It can be seen from Table 1 that the flood values are significantly high in the WRR Basin given its size: danger level (DL) of WRR at Kusum (drainage area: 5200 km<sup>2</sup>) corresponds to 2000 m<sup>3</sup>/s; DL of Karnali at Chisapani (drainage area: 42890 km<sup>2</sup>) corresponds to 10,000 m<sup>3</sup>/s; DL of Koshi at Chatara (drainage area: 54100 km<sup>2</sup>) corresponds to 8150 m<sup>3</sup>/s; and DL of Narayani at Narayanghat (drainage area: 31100 km<sup>2</sup>) corresponds to 10,000 m<sup>3</sup>/s (Gautam and Dulal 2013). This is mainly due to the high precipitation in its upper part which gets routed downstream quite fast. Sikta is the upstream boundary of the model while the Laxmanpur Barrage (in India) is its downstream boundary; however, the inundation mapping has been done for Nepal only. Other model parameters and constants have been taken from the literature (details in Supplementary Materials SM: S3, S4, and S5). The model was run in steady mode and the results were used to generate inundation maps and demarcate flood-prone areas.

Flood inundation maps corresponding to the four modelled scenarios were generated and the inundation raster was overlaid on the land use image<sup>2</sup> (Fig. 5). For each case, three zones were demarcated representing areas where inundation depth was (i) less than 0.3 m, (ii) between 0.3 and 1 m, and (iii) more than 1 m (Table 1). It can be seen that the flood-prone areas are mostly villages or cultivated land lying on the floodplain of the river with the average width of inundation around 7000 m near the Nepal-India border while around 2000 m in the upper reach near Sikta. Similar results have been reported from other river basins of Nepal (for example, DWIDP (2016), DOWRI (2018), and other parts of the world Gao et al. (2020), Pasquier et al. (2020), Ashley et al. (2020). Furthermore, due to the flat terrain near the Nepal-

<sup>2</sup> Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community available through [http://goto.arcgisonline.com/maps/World\\_Imagery](http://goto.arcgisonline.com/maps/World_Imagery)



**Fig. 5** Flood inundation map corresponding to floods of different return periods. **a** Scenario I: 2 years. **b** Scenario II: 20 years. **c** Scenario III: 50 years. **d** Scenario IV: 100 years

India border, these areas remain inundated for at least a day or two during high precipitation events as reported by Talchabhadel et al. (2015). The spatial distribution of flood with varying inundation depths (Fig. 5) shows that three rural municipalities, namely, Duduwa, Narainapur, and Rapti Sonari, were found to be inundated with varying levels for different magnitudes of floods. These are expected flooded areas at least with floods of a certain return period and thus, rather than designing and constructing heavy and expensive flood control structures, it would be beneficial for the people to realize the risk and practise living with floods taking necessary mitigating measures. This assessment provides decision makers with a basis for formulating disaster reduction strategies, appraisal of policy options, and prioritization and allocation of available resources for flood management.

Table 2 shows the municipality-wise area under inundation for different scenarios. It is obvious that the inundation area increases with the increase in flood magnitude. Furthermore, it can be seen that Duduwa Gaunpalika (rural municipality) is the most vulnerable to floods with 34% of the area being flooded even by a frequently occurring flood (scenario I) while 50.5% being flooded during an extreme flood event (scenario IV). Similarly, for Narainapur, which is almost double the size of Duduwa Gaunpalika, the area under floods varies from 7.7 to 9.5% for frequently occurring and extreme flood cases, respectively. In the case of Rapti Sonari (area = 1041.2 km<sup>2</sup>; 10 times of Duduwa), flood areas have been estimated to be

**Table 2** Rural municipality areas under inundation for different flood scenarios

Flood-affected rural municipality (Gaunpalika)	Total municipality area (km <sup>2</sup> )	Depth-wise inundated area (km <sup>2</sup> ) (percent of total municipality area)			
		Scenario I	Scenario II	Scenario III	Scenario IV
Duduwa	90.9	D1: 2.9 D2: 10.0 D3: 17.9 Total: 30.8 (34%)	D1: 1.8 D2: 8.6 D3: 33.3 Total: 43.7 (48%)	D1: 1.4 D2: 5.1 D3: 38.8 Total: 45.3 (50%)	D1: 0.8 D2: 3.9 D3: 41.2 Total: 45.9 (50.5%)
Narainapur	172.2	D1: 1.1 D2: 5.4 D3: 6.6 Total: 13.1 (7.7%)	D1: 0.4 D2: 1.2 D3: 13.7 Total: 15.3 (8.9%)	D1: 0.5 D2: 1.1 D3: 14.3 Total: 15.9 (9.2%)	D1: 0.4 D2: 1.1 D3: 14.9 Total: 16.4 (9.5%)
Rapti Sonari	1041.2	D1: 5.0 D2: 17.7 D3: 45.5 Total: 68.2 (6.5%)	D1: 3.8 D2: 8.4 D3: 74.1 Total: 86.3 (8.3%)	D1: 6.5 D2: 6.5 D3: 78.9 Total: 91.9 (8.8%)	D1: 6.2 D2: 6.5 D3: 82.5 Total: 95.2 (9.1%)

*D1*, inundation depth < 0.3 m; *D2*, inundation depth between 0.3 and 1.0 m; *D3*, inundation depth > 1.0 m

between 6.5 and 9.1% corresponding to floods of low to high magnitudes, maximum inundation in D3 category for all scenarios.

### 3.3 Flood adaptation strategies

During the survey, the inundation maps were presented to the participants and asked to rate their perceptions of different flood adaptation strategies for each of the four flood scenarios on a five-point scale. The most plausible adaptable strategies explored in the study were (i) bio-engineering: bio-engineering measures are an effective method applied to control mass wasting due to riverbank cutting by flowing water or preventing flood water entering adjoining lands (Chen 2020). Planting appropriate plants only with the right techniques or in combination with small-scale cost-optimized civil engineering structures such as check dams, reservoirs, gabion/earthen embankments, spurs, and other river training structures can be very effective for flood management in Nepal (Howell 1999). Our findings suggest that peoples' ways of thinking and their preferences for adaptation strategies changed with exposure to flood magnitudes.

Table 3 (scenario I) presents the survey results of how flood adaptation strategies are preferred for frequently recurring floods. "Bamboo mesh with sand filled bags" was the most preferred option (CRF = 90.5%). This was followed by "reservoir/flow regulating structure" (CRF = 88.6%), "gabion wall/spur" (CRF = 86.7%), and "making embankment including bio-fencing/river training" (CRF = 86.2%). "Bio-engineering" was the least preferred adaptation strategies among these structures for this flood situation. Likewise, the perception of respondents on flood adaptation strategies for flood is given in Table 3 (scenario II). "Bamboo mesh with sand filled bags" was most preferred (CRF = 93.6%), followed by "making embankment including bio-facing/river training" (CRF = 90.5%), "bio-engineering" (CRF = 86.2%) "gabion wall/spurs" (CRF = 85.7%), and "reservoir/flood regulating structure" (CRF = 64.2%).

**Table 3** People’s preference for flood adaptation strategies

Responses to scenario I		Bamboo mesh with sand filled bags			Reservoir/flood regulating structure			Gabion wall/spurs			Embankment with bio-facing /river training			Bio-engineering		
	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	
MoP	17	8.1	8.1	70	33.3	33.3	29	13.8	13.8	41	19.5	19.5	15	6.3	6.3	
VeP	92	43.8	51.9	51	24.3	57.6	81	38.6	52.4	75	35.7	55.2	82	34.2	40.4	
MdP	81	38.6	90.5	65	31	88.6	72	34.3	86.7	58	27.6	82.9	61	25.4	65.8	
LsP	18	8.6	99	20	9.5	98.1	25	11.9	98.6	32	15.2	98.1	61	25.4	91.3	
LeP	2	1	100	4	1.9	100	3	1.4	100	4	1.9	100	21	8.8	100	
Rank	I			II			III			IV			V			
Responses to scenario II		Bamboo mesh with sand filled bags			Embankment with bio-facing /river training			Bio-engineering			Reservoir/flood regulating structure					
	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	
MoP	18	8.6	8.6	32	15.2	15.2	18	8.6	8.6	36	17.1	17.1	21	8.8	8.8	
VeP	100	47.6	56.2	88	41.9	57.1	81	38.6	47.1	88	41.9	59	75	31.3	40	
MdP	78	36.4	93.6	70	33.3	90.5	82	39	86.2	56	26.7	85.7	58	24.2	64.2	
LsP	13	5.7	99.5	20	9.5	100	20	9.5	95.7	23	11	96.7	71	29.6	93.8	
LeP	1	0.5	100	32	15.2	15.2	9	4.3	100	7	3.3	100	15	6.3	100	
Rank	I			II			III			IV			V			
Responses to scenario III		Reservoir/flood regulating structure			Embankment with bio-facing /river training			Bamboo mesh with sand filled bags			Bio-engineering					
	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	
MoP	54	25.7	25.7	54	8.6	8.6	45	21.4	21.4	75	35.7	35.7	32	15.2	15.2	
VeP	89	42.4	68.1	89	47.6	56.2	74	35.2	56.7	53	25.2	61	73	34.8	50	
MdP	60	28.6	96.7	60	37.6	93.8	74	35.2	91.9	58	27.6	88.6	63	30	80	
LsP	6	2.9	99.5	6	5.7	99.5	15	7.1	99	22	10.5	99	30	14.3	94.3	
LeP	1	0.5	100	1	0.5	100	2	1	100	2	1	100	12	5.7	100	
Rank	I			II			III			IV			V			
Responses to scenario IV		Reservoir/flood regulating structure			Embankment with bio-facing /river training			Bamboo mesh with sand filled bags			Bio-engineering					
	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	F	RF	CRF	
MoP	157	74.8	74.8	71	33.8	33.8	84	40	40	39	18.6	18.6	82	39	39	
VeP	45	21.4	96.2	86	41	74.8	64	30.5	70.5	79	37.6	56.2	62	29.5	68.6	
MdP	2	1	97.1	42	20	94.8	50	23.8	94.3	75	35.7	91.9	46	21.9	90.5	
LsP	5	2.4	99.5	11	5.2	100	9	4.3	98.6	13	6.2	98.1	19	9	99.5	
LeP	1	0.5	100	0	0	0	3	1.4	100	4	1.9	100	1	0.5	100	
Rank	I			II			III			IV			V			

MoP, most preferred; VeP, very preferred; MdP, moderately preferred; LsP, less preferred; LeP, least preferred; F, frequency; RF, relative frequency (%); CRF, cumulative relative frequency (%)

Similarly, Table 3 (scenario III) shows the preference of the local people on structural flood adaptation strategies for a rarely occurring flood. “Reservoir/flow regulating structure”, “embankment protection with bio-facing/river training”, “bamboo mesh with sand filled bags”, “gabion wall/spur”, and “bio-engineering” ranked first to fifth, respectively, with CRF values ranging from 96.7 to 80.0% of the respondents. Likewise, “reservoir/flow regulating structure” was the most preferred adaptation strategy (CRF = 97.1%) for a very rare extreme flood, followed by “embankment protection with bio-facing/river training” (CRF = 94.8%), “bamboo mesh with sand filled bags” (CRF = 94.3%), “bio-engineering” (CRF = 91.9%), and “gabion wall/spur” (CRF = 90.5%) strategies (Table 3, scenario IV).

Socio-hydrological analysis has been used to explore the co-evolution of human-water systems (Sivapalan et al. 2011; Ali et al. 2019). In the study area, it is interesting to find out how local people deal with natural variations of the climate and how their adaption strategies change with exposure to climate extremes. Flood adaptation strategies for the four flood scenarios were identified and ranked through FGDs and respondents, respectively. Table 4 shows the overall summary of preferences for structural flood adaptation strategies. All potential structural measures, i.e. “bio-engineering”, “embankment/river training”, “bamboo mesh with sand filled bags”, “gabion wall spurs”, and “reservoir/flood regulating structure” received a score over 80%, showing people’s acceptance of a range strategies for flood protection. However, preferences for these measures changed with exposure to the flood scenarios.

Embankments of sufficient height and storage reservoirs of adequate capacity can contain the flood waters within the river (Gallena et al. 2014; Smith and McAlpine 2014). Since these structures protect the adjoining land mass where people farm and have their settlements, they are considered major and reliable flood control structures. “Gabion wall/spurs” are considered less effective structures and require stones of sufficient quantity. Furthermore, other measures can save adjoining lands from small floods.

Similarly, “bamboo mesh with sand filled bags” was the most preferred adaptation strategy for scenario I whereas “reservoir/flood regulating structure” obtained the highest rank as the most preferred adaptation strategy for scenario IV. It can be seen that “reservoir/flood regulating structure” is one of the most preferred adaptation measures for scenarios I, III, and IV. However, it was not preferred by the local people for scenario II because they do not consider it a cost-effective method compared to the damage caused by a 20-year flood. This indicates that people realized that the flood risks are likely to increase with climatic extremes and that the effectiveness of the adaptation strategies could vary significantly with the magnitude of the flood. It was found that the perceptions of flood adaptation strategies changed with information on different flood scenarios. The preferred adaptation strategies for smaller floods become less attractive when people comprehend that the flood problems could be more severe in the future. Major engineering structures such as embankments and flood-controlling

**Table 4** Changes in the preference of structural adaptation strategies with the exposure of different level of floods

Flood scenarios	Bio-engineering	Embankment/river training	Bamboo mesh with sand filled bags	Gabion wall/spurs	Reservoir/flood regulating structure
Flood scenario I	V (65.8)	IV (82.9)	I (90.5)	III (86.7)	II (88.6)
Flood scenario II	III (86.2)	II (90.5)	I (93.6)	IV (85.7)	V (64.2)
Flood scenario III	V (80.0)	II (93.8)	III (91.9)	IV (88.6)	I (96.7)
Flood scenario IV	IV (91.9)	II (94.8)	III (94.3)	V (90.5)	I (97.7)



reservoirs rate more highly as preferred choices with this realization regarding extreme floods. Therefore, the value of information on flood impacts of different probabilities is high. This information led people to choose better adaptation strategies to avoid catastrophic flood events. There is evidence that such large engineering structures are becoming a preferred option by many for future flood adaptation strategies (Dewan 2015; Jacobson 2020). “Construction of gabion wall/spurs” and “bamboo mesh with sand filling bags” are also effective in minimizing the effects of floods, soil erosion, and riverbank cuttings. However, both are temporary in nature and need regular maintenance. In addition, stone is not available in the lower part of the river basin (Perera et al. 2015); therefore, “gabion wall/spurs” strategies are not a preferred option for local people. Similarly, embankment protection with proper river training with bio-engineering technique is widely practised in many river basins. There are two main reasons for applying this method; first, the roots of trees hold the soil and reduce the velocity of water flow and second, people mainly use medicinal/multipurpose plants serving multiple purposes such as *Jatropha curcas*, *Azadirachta indica*, *Sapium insigne*, and *Vitex negundo*, and fodder plants like *Artocarpus lakoocha*, *Flemingia congesta*, *Bauhinia variegata*, and *Bauhinia purpurea* for bio-fencing (Aryal et al. 2020).

## 4 Conclusion

This research applies an integrated approach of hydro-social analysis of floods with a fusion of scientific and socio-economic knowledge. The rainfall-flood assessment and inundation mapping methods have theoretical contributions to flood studies mainly for ungauged basins. Rainfall was correlated to flood peak by proposing and validating a simple regression equation.  $R^2$  of 0.89 proved that the developed equation has potential for application with a high confidence level for estimating and forecasting future flood peaks based on projected precipitation data. However, limitations associated with linear regression is inherent. The average runoff coefficient of the WRR Basin at Bagasoti was calculated to be 0.81 based on historical flood events. Outputs of the flood model were used to prepare flood inundation maps which showed that the southern parts of three rural municipalities, namely, Duduwa, Narainapur, and Rapti Sonari, are inundated almost every year with varying levels for different magnitudes of floods. The flood model has areas of improvement especially regarding the calibration and validation of the results when observed data is available. The flood extent in these maps was categorized into three zones with low, moderate, and high risks respectively; these zones were found to be in good agreement with people’s perception. The inundation maps were shown to the participants in order to further inform them of the severity of future flood problems. This study found that peoples’ ways of thinking about particular adaptation strategies changed with exposure to flood scenarios. People had realized that the flood risks are likely to increase under extreme climatic conditions and that such risk can be reduced only through higher level adaptation strategies. The preferences of the adaptation strategies of the respondents shifted from a relatively lower level (for example, from “bamboo mesh with sand filled bags” for scenario I) to a more complicated and expensive adaptation strategy (for example, “reservoir/flood regulating structures” for scenario IV) as informed decisions. Furthermore, the more preferred strategies for flood adaptation today might become less attractive when people realize that the flood problems could become more severe in the future.

The process and results of this study highlight two things: the importance of visual aids to understand the magnitude of floods impacts; and the value of information about different flood levels and potential risk to enable people to choose appropriate adaptation strategies. This study

has contributed to the enrichment of the available knowledge base and a better understanding of people's perceptions of the exposure of climatic risk and its impact on floods. This research is special for the WRR Basin as it provides field-based evidence to policy makers and other key stakeholders to identify and prioritize areas for flood adaptation, to adopt appropriate policy and programs, and to allocate and justify scarce resources. Moreover, the overall approach and methodological framework for socio-hydrological analysis of this empirical study could be a model study for other similar catchments and developing countries with similar bio-physical and socio-economic conditions and most importantly, flood problems. Therefore, this novel approach of science-policy interaction research is expected to be applicable elsewhere in the world with similar settings.

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