International Journal of Latest Engineering and Management Research (IJLEMR)
ISSN: 2455-4847
www.ijlemr.com || Volume 09 – Issue 08 || August 2024 || PP. 61-69

1D-Flood Hazard Mapping and Analysis Using HEC-RAS Modelling, A case study of the Seti River, West Central Nepal

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Abstract: With jolts of climate change, dubious rainfall, melting of glaciers, Nepal in last couple of years has been liable to natural disasters spawning loss of lives, possessions and economic losses. Flooding, is a major issue in Nepal that needs to be prioritized calls for more action to study, analyze and prevent it. The Seti River has been periodically enduring flood events and much less thought has been given to it, though some studies has been conducted previously. This study is perpetrated to add effort towards it. The study uses long term precipitation for rainfall analysis using Hazen, California and Weibull while discharge to reckon flood frequency prediction employing Gumbel, Weibull and Log Pearsons Type III method. The HEC-RAS uses Gumbel flood values to produce one dimensional flood maps for return period of 2,10,50,100 years and Arc-GIS is used for hazard and risk analysis. The result unveils positive correlation between flood discharge, rainfall and inundation area over different return period with expected flood exceeding the channel capacity over the years. Installation of early warning system in rivers, potential dangerous glacial lakes and community-based disaster management has been suggested for preparedness, response and recovery from such catastrophes.
Keywords: Arc-GIS,Flood hazard maps,Flood Risk, HEC-RAS.

1. INTROCUCTION

Flood in Nepal has always been an entity of concern as whenever monsoon arrives destruction of lives and properties occur each year. The Seti River being a glacier fed river even poses more risk for Glacial Lake outburst flood (GLOF), landslide damming, debris flow, flash floods etc. The impact of climate change has been a catalyst igniting such hazards in higher frequencies over the years. Morphometric, geological, hydrological and hydrometeorological are major considerable factor for increased vulnerability regarding flood. Pokhara being a second largest city with heavily urbanized valley alongside the river while boasting highest precipitation in the country with a mean rainfall of 5700 mm per annum[1]is not only a threat in the monsoon but episodes of GLOF, landslide damming and breach may occur during other dry periods. May 5th, 2012 has been evidence of such outburst costing 72 souls, wrecking properties and changing river morphology [2] with estimated cause by the detachment of a portion of rock from edge of Annapurna IV massif and estimated flow of 8,400m^3/s [3]. In this research the HEC-RAS and Arc-GIS has been employed for concocting flood hazard maps with flood frequency and rainfall analysis. Associated risk calculation combines assessment of flood depth and land use to procure effects and analyze probable future hazard zones to estimate their size and frequency to achieve better understanding of flood dynamics. Therefore, intent of this research is to estimate discharge, rainfall prevalence and provide flood hazard map of the Seti River with two significant affluent the Mardi khola and the Madi River.

2. GEOLOGICAL SETTING OF THE STUDY AREA

The Seti River basin is shaped by sequences of the Higher Himalaya, Lesser Himalaya, Tibetan Tethys Sediments and Quaternary deposits. The Annapurna Detachment Fault (ADF) delineates boundary amid the Tethyan Sedimentary Sequence and the Greater Himalayan Metamorphic Sequence[4]. The Tibetan Tethys sediments lay open embracing greatly distorted limestone, schist and sandstone[5] while Higher Himalayan Crystalline i.e., the Tibetan slab embody silicates and magmatic gneisses, meddle by leucogranite[6] which is confined at bottom by MCT (Main Central Thrust).The lesser Himalaya is confined to south by Main Boundary Thrust (MBT) and to north by MCT which is discerned as Upper Lesser Himalaya depicting Eoproterozoic and Lower lesser Himalaya portrayal of middle Proterozoic[7, 8] exposing dominant sedimentary with low- grade metamorphic rocks and presence of augen gneiss, granites, amphibolites and occasional volcanic rocks [6]).The Seti River basin also boast Quaternary deposits and has been investigated[9–11]which portrays presence of compact, consolidated unstratified to weakly stratified heterogenous mixture of boulders, pebbles and fines held clasped by the impure cementing materials[12].The substantial part of gravels and boulders are contrived of Central crystalline gneisses, Dhaulagiri and Nilgiri Limestones, granites, Schists and quartzites[12].

3. STUDY AREA

The basin area embodies west central Nepal incorporating three districts Kaski, Tanahun and Lamjung of Gandaki Province covering an area of 2944.59 sq. km. Geologically study area lies in vicinity of the Lesser Himalayas, the Higher Himalayas and the Tibetan Sedimentary Zones with Pokhara valley being an intermontane basin. The glacier fed streams originate from foothills of the Mount Annapurna IV and the Mount Machhapuchhre eventually emerging as a major left tributary of the Trishuli River. The study area is bounded between the (27°40′–28°40′N, and 83°40′–84°40′E). The Seti River traverses ~358 km along the Central Himalaya region to meet the Trishuli River at Devghat[13] with the Mardi, Yamgdi, sardi, Kali, Bijayapur, Kotre, and Madi rivers being major tributaries.

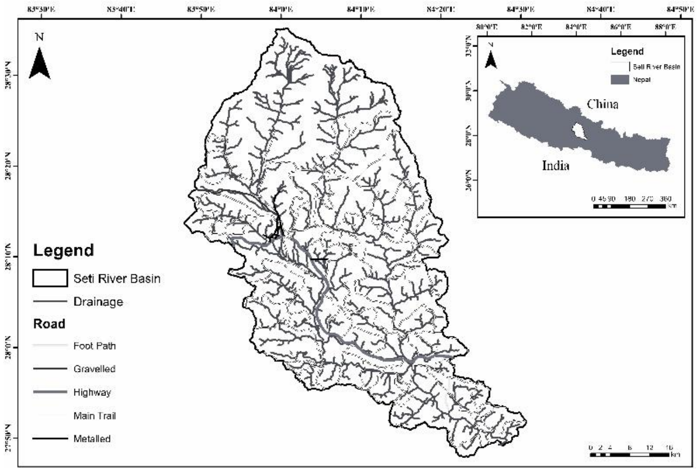


Figure 1:Location and accessibility road network of the study area.

4. METHODOLOGY

The two different aspects were employed in this study which includes statistical analysis i.e. (i) flood frequency and (ii) rainfall analysis while modelling approach was taken using HEC-RAS for flood inundation and Arc-GIS for hazard mapping.

4.1 Rainfall Analysis

For execution to statistically analyze rainfall, the rainfall data (>30 years) acquired from DHM (Department of Hydrology and Meteorology,2024) [14]from seven-weather observatory inside watershed area was used to calculate the total annual rainfall, maximum annual rainfall and rainfall return. Hyetograph was produced using the total annual maximum rainfall for geographical analysis of precipitation within the watershed area. The rainfall return analysis was done to calculate maximum rainfall return period using the Hazen, California and Weibull methods.

Weibull method:

$$T=\frac{(n+1)}{r}$$

California method:

$$T=\frac{n}{r}$$

Hazen method:

$$T=\frac{n}{(r-0.5)}$$

Where T signify recurrence interval in years, n and r denotes number of years and rank for the rainfall respectively.

4.2 Flood Frequency Analysis

To analyze Flood frequency, discharge data of 20 years (2000-2019) of the Seti River, the Mardi Khola and the Madi River was obtained from DHM (Department of Hydrology and Meteorology,2024)[14]. The discharge for 2, 10,50 and 100 years was calculated for the Seti River and its two major tributaries the Mardi Khola and Madi River respectively. As all the three rivers are gauged rivers, the Gumbel, Log Pearsons Type III and Weibull empirical methods were employed which are expressed as:

Gumbel method

$$XT = \bar{X} + K*\sigma x$$

where, σx typify standard deviation of the sample.
And, K depict frequency factor expressed as:
$K = Yt - \overline{\overline{Yn}}/Sn$

Yt is reduced variate, $\bar{Y}n$ and Sn are favored using Gumbel's extreme volume distribution table weighed leaning on sample size (n).
Log Pearsons Type III Method:
$\log x = \overline{logx} + K\sigma_{\log x}$

Where, x defines flood value with specified probability, $\overline{logx}$ represents average of log x flood values, K is defined as frequency factor which is a function of the skewness coefficient and return period where σ is standard deviation of $log\ x$ values.
Weibull Method

$$P = \frac{m}{(n+1)}$$

Where, m represent rank, P is the probability and n signify number of years of record.
P given by the expression:

$$P = \frac{1}{T}$$

Where T denotes return period.

4.3 Flood Hazard Mapping

For inundation mapping, HEC-RAS 6.4.1 was used for modelling 1-D influx for diverse return year as calculated in flood frequency. Project file was created using digital elevation model in the first step. After DEM file was setup using RAS mapper, geometry of the river was created which includes preparation of river center line, flow path, flood plain delineation and cross-sections for reach of the river and its tributaries. The manning's n values were than imported as per the land use type and was infused with geometry of the terrain in HEC-RAS. The values of n=0.03 was used for river channel while n=0.04 was used for the flood plains. Afterpreparation of geometry, flow data was assigned to the four floods return profile and boundary conditions was assigned. Plan was created for simulation of steady flow and was executed. A steady flood flow analysis was performed and flood inundation maps were computed. The produced inundation maps of different return period were exported as raster files with flood extent, velocity, depth and imported to Arc-GIS which were reclassified on basis depth for different flood event.

The hazard analysis was based on approach taken by[15]which extends flood risk as an upshot of flood hazard and susceptibility to flooding. Depth maps, low (0-0.4m), medium (0.4-0.8m), high (0.8-1.8m), very high (1.8-3m) and extremely high (>3m) were used to observe the extent of hazard while depth hazard maps were intersected with land use map for extracting area inundated by flood events to calculate vulnerable areas prone to flooding.

5. RESULTS

5.1 Rainfall Analysis

From the rainfall data of 7 stations inside watershed area, aggregate annual precipitation was computed and maximum precipitation of each station was used to produce hyetograph of the basin for spatial analysis of rainfall throughout the basin area.Also, rainfall frequency analysis was done to calculatemaximum precipitation for the prevalence of 2 years, 10 years, 50 years and 100 years using the Weibull, Hazen and California method for trend analysis over the different period of time.

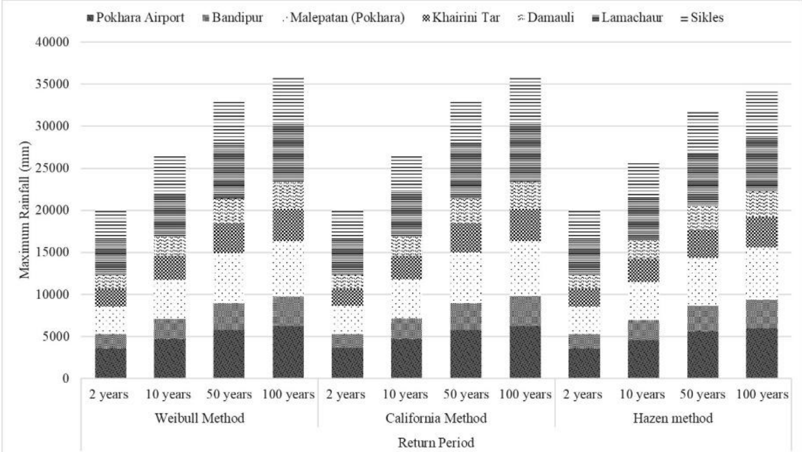


Figure 2:Rainfall analysis using Weibull, Hazen and California methods of the basin.

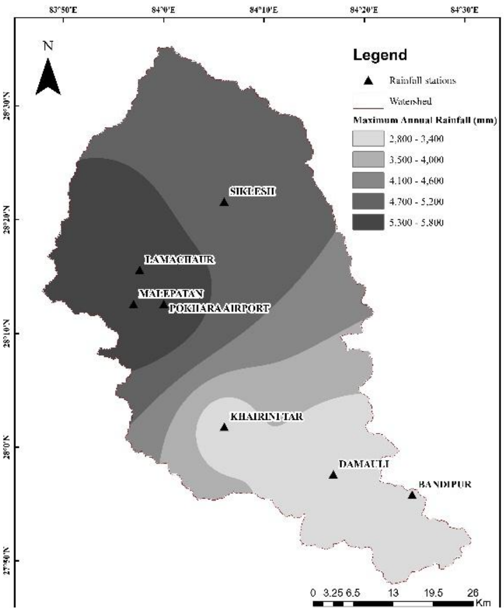


Figure 3:Annual maximum precipitation distribution in the watershed.

5.2 Land Cover Analysis

The land use map of the basin was extracted with ICIMOD dataset 2019, 30m*30m Spatial resolution[16] by clipping watershed area. The basin is extravagantly exploited by human activities in central part of the basin where most of the built- areas and the croplands are present. Forest dominates basin with 57.27 %, Cropland 19.20 %, grassland 7.60%, other wooden land 7.71% with glacier 2.68 % and snow 2.31% and rest making up 3.23% of the total area.

Table 1:Land use classification with area covered.

Land Cover Class	Area(km^2)	Percentage (%)
Waterbody	20.232	0.68
Glacier	78.9156	2.68
Snow	68.0571	2.31
Forest	1685.561	57.27
Riverbed	10.0224	0.34
Built-up area	17.7426	0.60
Cropland	565.236	19.20
Bare soil	0.0927	0.0031

Bare rock	46.1349	1.56
Grassland	223.6995	7.60
Other wooded land	227.1798	7.71

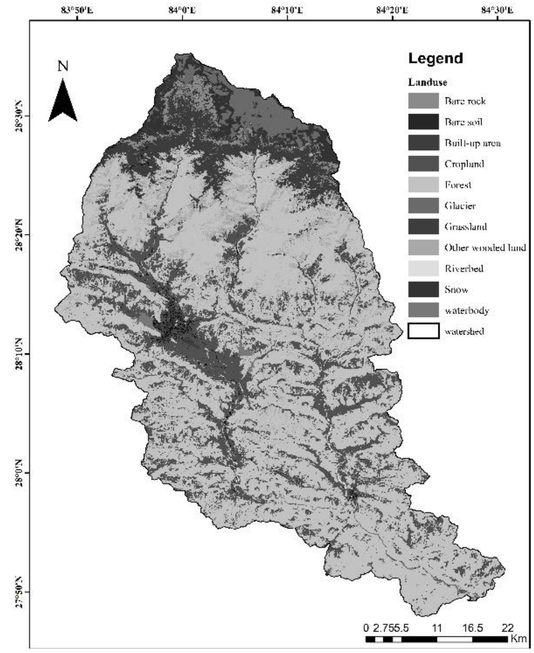


Figure 4:Land use map of the Seti River basin.

5.3 Flood Frequency Analysis

Flood flow using discharge data of 20 years' time period (2000-2019) was used to calculate maximum instantaneous discharge for prevalence of 2 years, 10 years, 50 years and 100 years. Gumbel, Weibull and Log Pearsons type III distribution has been used in this research.

Table 2:Flood frequency analysis by Gumbel, Weibull and Log Pearsons Type III methods for the Seti River and Gumbel method for the Mardi Khola and the Madi River.

T (Return period)	Seti River			Madi River	Mardi Khola
	Gumbel, Q(m^3/s)	Weibull, Q(m^3/s)	LogP3, Q(m^3/s)	Gumbel, Q(m^3/s)	Gumbel, Q(m^3/s)
2	936.3539	850.4757	816.832	435.54	78.21
10	2158.023	2138.509	1753.266	695.23	131.61
50	3229.059	3426.542	3253.585	923.09	178.43
100	3681.844	3981.268	4170.768	1019.38	198.22

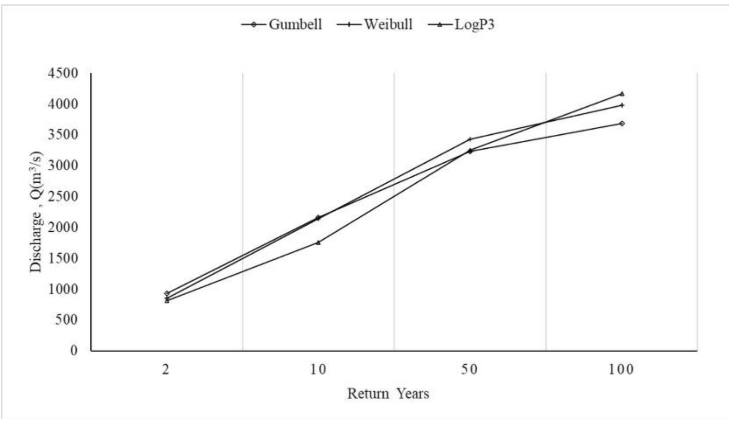


Figure 5:Flood frequency comparison by Gumbel, Weibull and Log Pearsons Type III methods for the Seti River.

5.4 Flood hazard Mapping

Flood hazard maps were produced for 2 years, 10 years, 50 years, and 100 years using maximum instantaneous discharge from different return year using Gumbel Method in HEC-RAS. The inundation was classified according to depth into different hazard zones. The Seti River section from the Mirsa to Devghat was taken for flood hazard mapping along with its two major tributaries, the Mardi Khola and the Madi River.

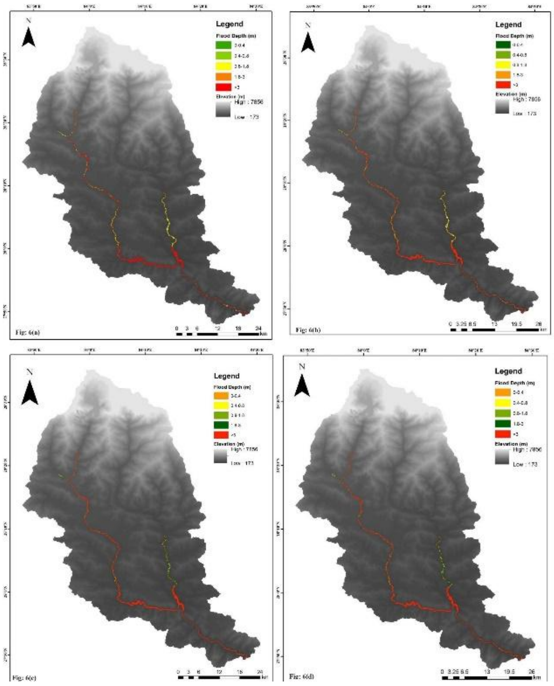


Figure 6:Flood Hazard map, Fig 6(a)2 years, Fig6(b)10 years, Fig 6(c)50 years and Fig 6(d)100 years prevalence.

The inundation simulation shows gradual increasing trend over different return periods with inundation area of 27.08 km^2 for 2 years, 29.84 km^2 for 10 years, 31.48 km^2 for 50 years and 32.07 km^2 for 100 years return period.

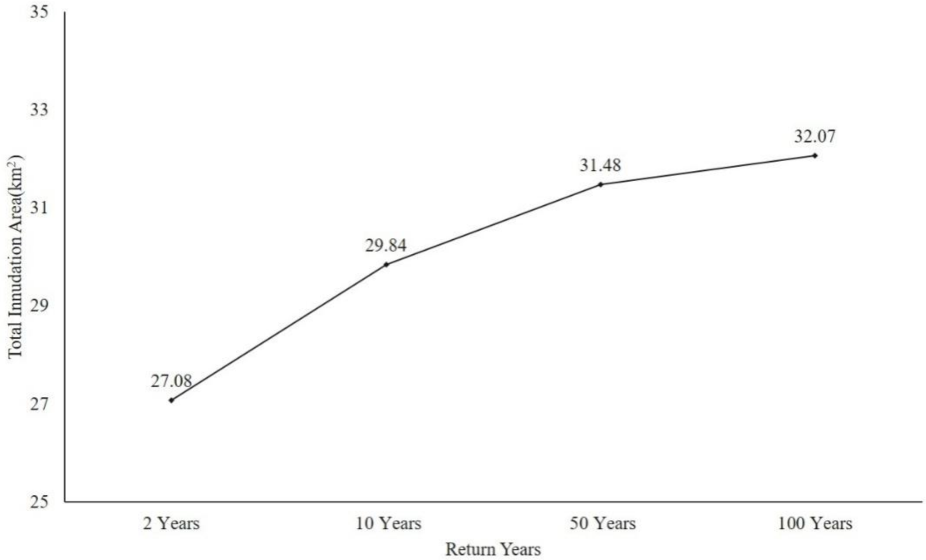
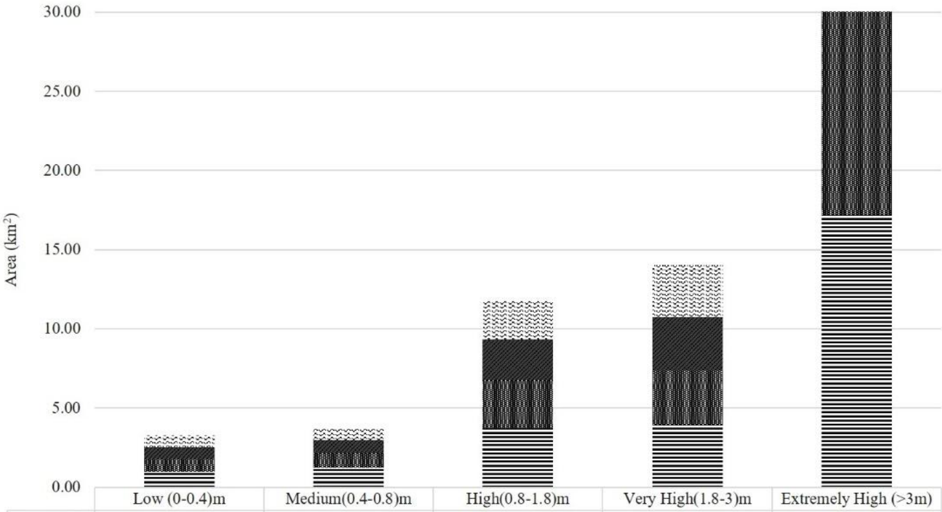


Figure 7:Total flood inundation area for different return years.

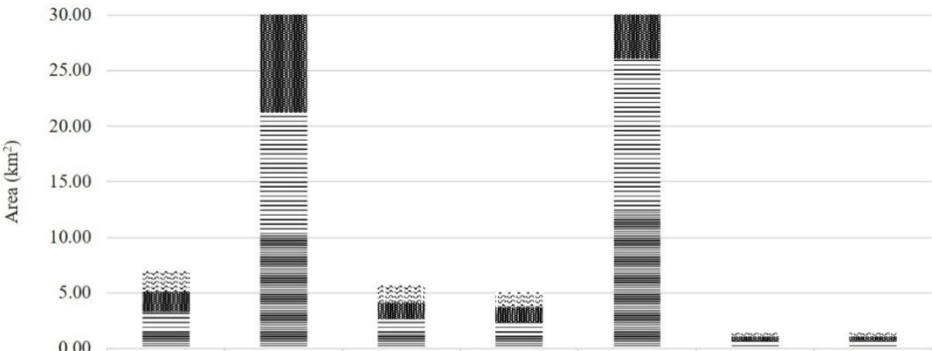


	Low (0-0.4)m	Medium(0.4-0.8)m	High(0.8-1.8)m	Very High(1.8-3)m	Extremely High (>3m)
100 Years	0.74	0.77	2.45	3.29	24.81
50 Years	0.76	0.83	2.55	3.36	23.99
10 Years	0.78	0.94	3.04	3.45	21.63
2 Years	1.00	1.22	3.73	3.94	17.20

Flood Depth(m)

Figure 8:Flood hazard classification based on depth.

In this study, on the basis of flood depth, the low (0-0.4) m shows inundation of 3.27 km^2, medium (0.4-0.8) m shows 3.76 km^2, high (0.8-1.8) m shows 11.77 km^2, very high (1.8-3) m shows 14.04 km^2 and extremely high(>3m) shows 87.63 km^2 total inundation area over four different return period years.



	Waterbody	Forest	River Bed	Built-up Area	Cropland	Grassland	Other Wooden land
100 Years	1.86	11.58	1.52	1.36	14.95	0.39	0.41
50 Years	1.82	11.42	1.48	1.34	14.65	0.38	0.40
10 Years	1.71	10.98	1.38	1.25	13.79	0.36	0.37
2 Years	1.55	10.24	1.25	1.09	12.29	0.32	0.33

Land Cover

Figure 9:Flood vulnerability analysis based on land use type.

Analysis with merger of flood depth and land use provides with vulnerability analysis of different land use type of basin area. The most vulnerable areas include cropland with inundation of 12.29 km^2, 13.79 km^2, 14.65 km^2 and 14.95 km^2 for 2 to 100 years return period. Similarly, second most vulnerable is forest with inundation of 10.24 km^2, 10.98 km^2, 11.42 $km^2$and 11.58 km^2 for 2 to 100 years return period. The third most vulnerable being the major issue in Nepal is inundation of built-up area with inundation of 1.09 km^2, 1.25 km^2, 1.34 km^2, and 1.36 km^2 inundation over return period of 2 to 100 years. All of the land use type shows positive trend with increase in inundation area with increase of return period proving their vulnerability towards flood.

6. DISCUSSIONS

Rainfall analysiswas performed via hyetograph to analyze geographical distribution of rainfall throughout basin area. Maximum annual precipitation was then employed to calculate rainfall prediction over different return period using Gumbel, California and Hazen Method. Flood discharge for 2 years, 10 years, 50 years and 100 years was computed using Weibull, Gumbel and Log Pearsons type III for the Seti River and Gumbel method was used solely for its two major tributaries the Mardi Khola and the Madi River. The Seti River using Gumbel method recorded a discharge flow of 936.35 m^3/s, 2158.02 m^3/s, 3229.06 m^3/s, 3681.84 m^3/s for return year of 2 ,10, 50 and 100 years respectively. Similarly for the Mardi Khola 78.21 m^3/s, 131.61 m^3/s, 178.43 m^3/s, 198.22 m^3/s and for Madi River 435.54 m^3/s, 695.33 m^3/s, 923.09 m^3/s, 1019.38 m^3/s for prevalence of 2 to 100 years respectively. The flood analysis shows a gradual increase in instantaneous discharge with increase of return period to predict overflow of channel capacity with eventual evidence of past mega floods centuries back foreseen by Pokhara gravels[17]. Flood hazard maps were produced with use of Gumbel flood frequency analysis discharge value for periods of 2,10, 50,100 years using steady flow analysis in HEC-RAS and processed using Arc-GIS for map preparation. Flood inundation maps show a gradual increase in inundation area with increasing return year proving positive correlation with similar approach taken[18] for mapping. The total inundation of 27.08 km^2, 29.84 km^2, 31.48 km^2 and 32.07 km^2 for the return years of 2, 10 ,50 and 100 years respectively observed. The maps present a maximum inundation of cropland followed by inundation of forest, waterbody, river bed and built-up areas. The inundation of vulnerable cropland, forest and built-up area shows a gradual increase in vulnerability over the years. Being a glacier fed river and also being watershed gifted with highest rainfall in the region, the river has been prone to flooding over past years. Flooding due to glacial lake outburst, landslide damming, high precipitation over short duration are the major factors. Past events reflect turbulent history of flooding, deposition of debris along valley following earthquakes in 1100, 1255 and 1344 C. E[19]with recent episode on May 5th 2012, a sudden outbreak of a portion of rock form the Annapurna Mountain causing damming of river and subsequent flooding[3]led to loss of souls and ruination. Flood frequency analysis and flood hazard map shows vulnerability of landscapes and built-up area, hydropower projectsprone to future inundation and wrecking with settlements along banks requiring serious relocation[20].

7. CONCLUSIONS

The Seti River basin boasts highest rainfall in northwestern region exceeding above 5200mm up to 5800mm annually. Statistical analysis of Rainfall and flood frequency stipulate gradual proliferate with mounting return periods. Flood hazard map connote incremental in inundation area with swell in return years as total deluge terrain was calculated to be 27.08 km^2 for 2 years, 29.84 km^2 for 10 years, 31.48 km^2 for 50 years and 32.07 km^2 for 100 years. Most vulnerable area by flooding is represented by cropland with inundation of 12.29 km^2, 13.79 km^2, 14.65 km^2 and 14.95 km^2 for 2 to 100 years return period followed by second most vulnerable being forest with inundation of 10.24 km^2, 10.98 km^2, 11.42 $km^2$and 11.58 km^2 for 2 to 100 years return period. Built-up area along river banks is also prone with inundation of 1.09 km^2, 1.25 km^2, 1.34 km^2, and 1.36 km^2 over period of 2 to 100 years increasing with every return period. The necessity of early warning systems for rivers and glacial lakes in basin for potential early flood warning with evacuation of people from river bank areas. Flood hazard control with cooperation of local communities managing river banks from potential erosion through employing civil structures with incorporation of bio-engineering. Meticulous disaster management planning with community-based preparedness, response and recovery to tackle climate change, natural hazard such as GLOF, flood, drought etc.

8. RECOMMENDATIONS

1. Use of unsteady flow modelling approach should be pondered for simulation citing unsteady state of flow of natural rivers and streams.
2. High precision topographic and bathymetry data of higher resolution should be incorporated for better accuracy in developing geometry and simulation of flood modelling.
3. Installation of early flood warning system in the Seti River, the Mardi Khola, the Madi River and in potentially dangerous glaciers such as, Sabache glacier as well as investigation of stability of other potentially dangerous glaciers for GLOF events.
4. The ongoing construction projects mainly hydropower projects along the Seti River should incorporate intense security and safety majors in case of catastrophic flood, GLOF’s events.

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