Flood Hazard Assessment using Hydro-geospatial Technique: A Case Study of River Chenab from Qadirabad to Trimmu in Pakistan

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***Abstract*—HEC-RAS flood flow model with flood inundation mapping through HEC-GeoRAS were applied to compute flood peak attenuation and mapping of flood inundation areas and flood depths in floodplains of Chenab River in Pakistan from Qadirabad to Trimmu, a reach length of 209 km. Input river cross-sections to HEC-RAS model were collected from field survey and partly extracted from DEM SRTM 30 m resolution using HEC-GeoRAS. An exceptionally high flood of 2014 and a very high flood of 2006 were considered for model calibration and verification. The results of model calibration and verification of HEC-RAS show high correlation coefficients thus assuring high model accuracy. Results of HEC-RAS model were exported to ArcGIS to perform flood inundation mapping and consequently flood hazard assessment. Flood inundation extent and depth maps were computed for floods of return periods of 25, 50, 100 and 200 years respectively. The effectiveness of the existing flood control infrastructure was evaluated in terms of flood depths and inundation areas. The novel contribution of this study is the flood hazard assessment using two different criteria: one on people safety and another on flood depths and extents. The two criteria were applied to evaluate flood hazard to people and deficiency of existing flood control embankments. Recommendations for further improvement are given.**

Keywords—* *flood control effectiveness; hazard mapping; hazard assessment; Chenab River; Pakistan

I. INTRODUCTION

Pakistan is a flood prone country. Floods occur frequently mainly due to heavy concentrated rainfalls in monsoon season, mostly augmented by the snowmelt, in the catchment areas of major and other rivers. Floods of various magnitudes caused disorder in vast areas of almost all parts of the country [1]. The Indus basin which is the largest river basin has more than 138 million populations where irrigated agriculture is a major source of livelihood [2]. The Chenab River is the second largest river of the Indus river basin (Fig.1). It has experienced floods of various magnitudes, for example, in 1973, 1977, 1988, 1992, 1995, 1996, 1997, 2006, 2013 and 2014. In each of these floods, the overall damages to both the public and private properties were enormous. Whenever River Chenab overflowed, major cities and surrounding villages on both sides of the river were severely affected by floods.

The first objective of this study is to perform flood modeling of the 209 km reach of Chenab River using the HEC-RAS model. The river reach is from Qadirabad Barrage to Trimmu Barrage. The recent flood periods in 2006 and 2014 were considered in the model simulation. The second objective is to assess flood hazards using two different hazard assessment criteria under the conditions with and without flood control infrastructures under various flood return periods.

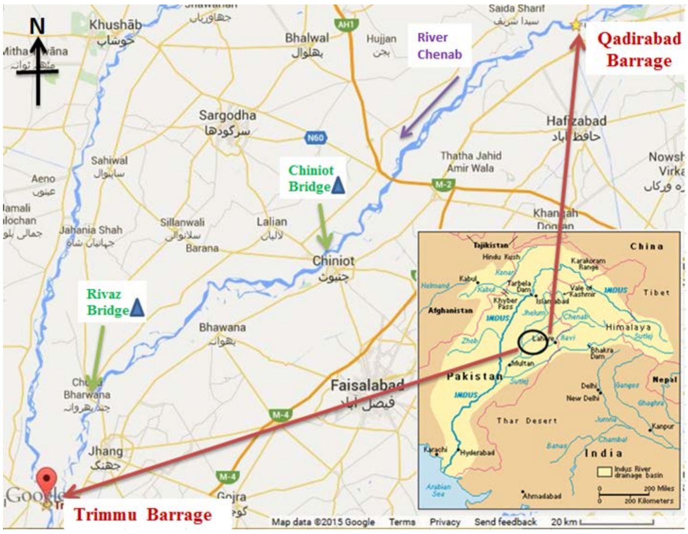

Fig.1 Map of Chenab River from Qadirabad Barrage to Trimmu Barrage, Chiniot and Rivaz Bridges

II. STUDY AREA

Qadirabad and Trimmu are two barrages, located 209 km apart, on the River Chenab. Qadirabad Barrage has a design capacity of 25,481 m^3/s while that of Trimmu Barrage is 18,262 m^3/s. The study area comprises of a selected river reach starting from Qadirabad Barrage to Trimmu Barrage. There are two gauging stations in the study reach, one at Chiniot Bridge and another at Rivaz Bridge. Fig. 1 shows the study area with the locations of Qadirabad Barrage, Trimmu Barrage, Chiniot Bridge and Rivaz Bridge. Nine existing flood bunds or flood control infrastructures were constructed along river sides.

III. METHODOLOGY

The methodology comprises of 1) data collection and analysis, 2) flood frequency analysis, 3) flood modeling, 4) assessing effectiveness of flood control infrastructure and 5) flood hazard assessment.

3.1 Data Collection

The following data were collected and analyzed namely:

a) historic flooding events in the study reach; b) Chenab River annual flood peaks in Qadirabad-Trimmu reach from 1983-2015; c) daily outflow data at Qadirabad Barrage for upstream model boundary condition and daily stage data at Trimmu Barrage for downstream boundary condition; d) input cross sections from field survey and that extracted from DEM SRTM 30 m resolution using digitization in HEC- GeoRAS. Field surveyed cross sections were available only for about 60% of study reach at about 4 km apart. Remaining cross sections were based on digitized verified DEM obtained by comparing field surveyed elevations with SRTM DEM elevations and applying correction [4]; e) Stage-discharge rating curves at Qadirabad and Trimmu Barrages; f) locations and geometry of 9 existing flood bunds shown in Fig.2 and their lengths and heights given in Table 1.

TABLE 1 SALIENT FEATURES OF FLOOD CONTROL BUNDS [1]

Name of Flood Bund	Length (km)	Top Width (m)	Avg. Top Level (m msl)
1.Humber Flood	25.146	6.096	198.75
2.Pindi Bhattian	44.348	6.096	218.64
3.Kot Najja Flood	40.386	6.096	218.64
4.Chiniot Flood	30.023	6.096	218.64
5.Muhammad Wala	7.62	7.62	218.64
6.Thatta Mahla- Rivaz	15.545	6.096	154.34
7.Thatta Mahla Loop	3.505	6.096	154.34
8.Jhang	19.507	7.62	154.34
9.Massan Disty	20.631	6.096	159.45

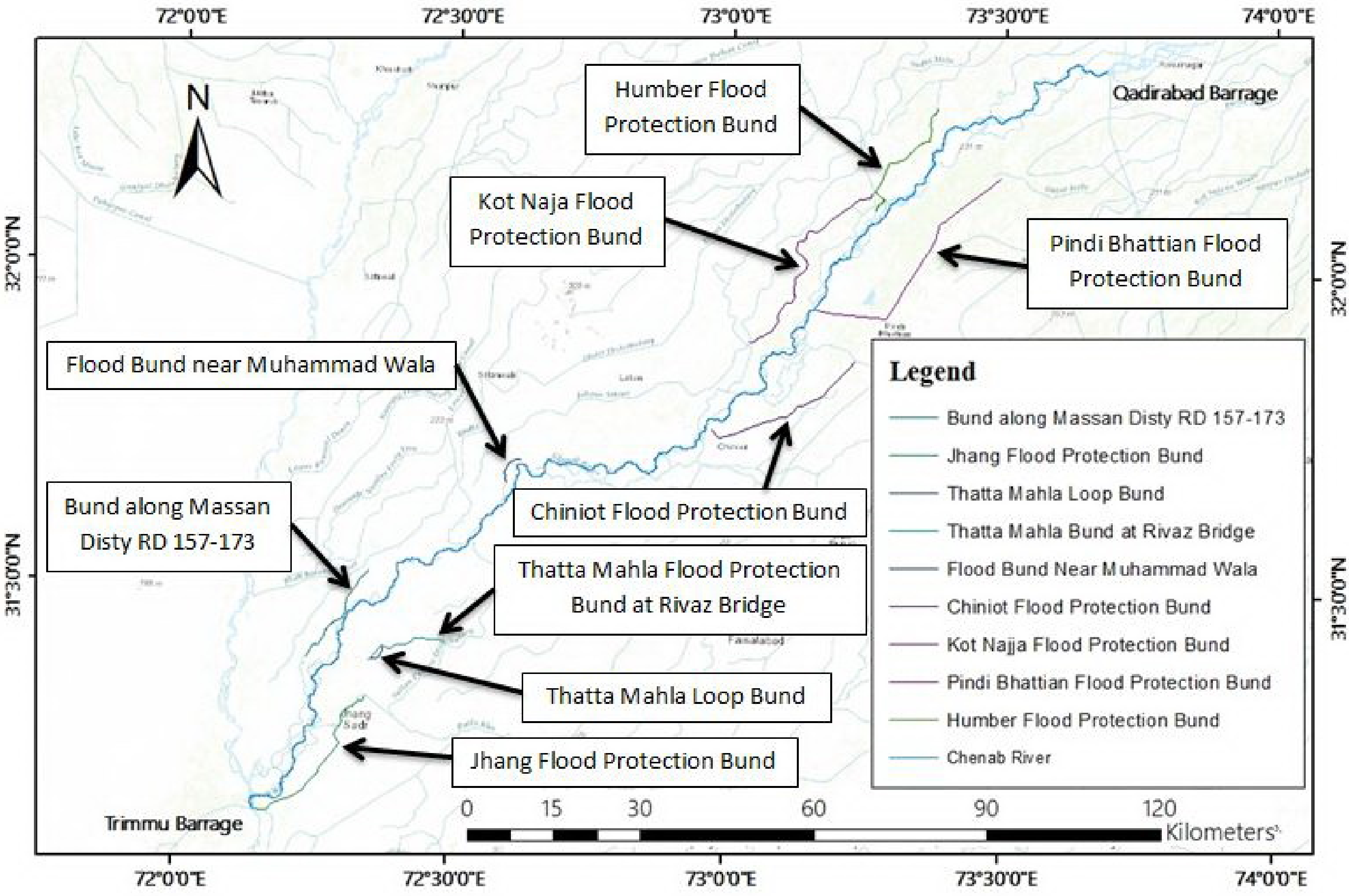

Fig.2 Locations and names of the nine flood bunds

3.2 Flood Frequency Analysis

Gumbel flood frequency distribution on the observed peak discharges at the Qadirabad barrage under full gate opening from 1983-2015 was done to obtain the flood peak discharges of 25, 50, 100 and 200 year return periods. The flood hydrograph of each return period was obtained by multiplying the peak discharge from frequency analysis to the average normalized flood hydrograph which has the normalized peak equal to 1. The average normalized flood hydrograph is constructed by averaging the normalized hydrographs of many past floods. The normalized flood hydrograph is obtained by dividing the discharges by its peak discharge. The flood hydrographs of various return periods are shown in Fig.3

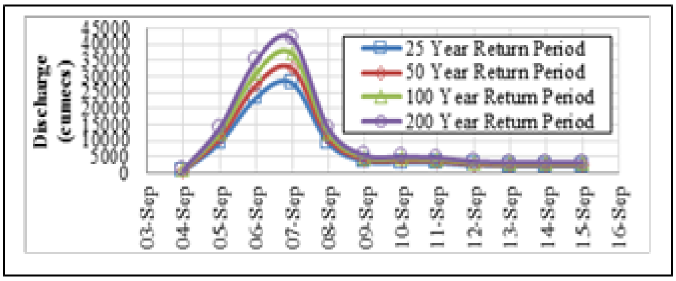

Fig.3 Constructed flood discharge hydrographs at Qadirabad of various return periods

IV. HEC-RAS Model Calibration and Verification

The HEC-RAS flood flow model [3] was used for modeling flow in Chenab River and its flood plains from Qadirabad Barrage to Trimmu Barrage. The river cross-section data and flood plain elevations from field measurements and DEM were input to HEC-RAS. Due to flat topography of the flood plains, the river flood level was assumed to be horizontal across the river and its flood plains on its left bank and right bank. The model configuration is shown in Fig.4.

4.1 Initial and Boundary conditions

The initial flow condition along the river reach was assumed to be steady flow at a constant upstream discharge at the beginning according to the Manning equation [5]. The model upstream boundary condition was the flow hydrographs of the measured discharge at Qadirabad Barrage. The downstream boundary condition was the measured stage hydrograph just upstream of the Trimmu Barrage. The lateral inflows between Qadirabad Barrage and Trimmu Barrage (Fig.4) were very small compared to very large river flood magnitudes and hence neglected.

4.2 Calibration of Model Results

In the calibration, the observed and simulated stage hydrographs in 2014 from 5 to 15 September at Chiniot Bridge and Rivaz Bridge were compared. The Manning's n coefficient 'n' was initially assumed based on literature [5] and the site conditions. The final values of Manning n was determined by trial and error calibration. After several trials, Manning's n was found equal to 0.029 for the main channel and 0.047 for floodplains. Fig.5 shows that the observed and simulated

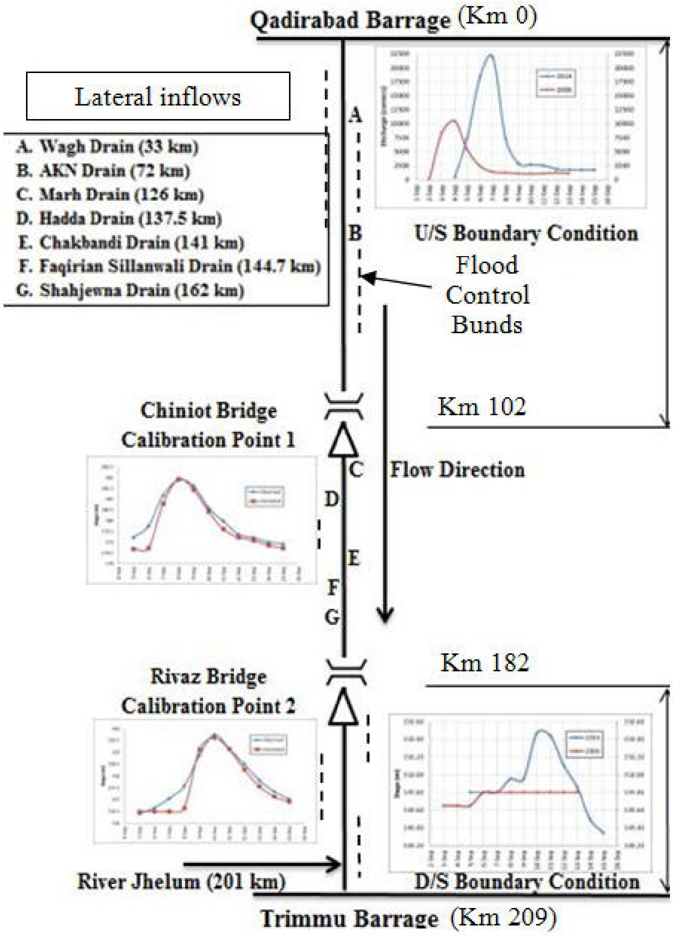

Fig.4 Configuration of HES-RAS Model for the Chenab River Reach from Qadirabad Barrage to Trimmu Barrage

hydrographs agree satisfactorily well with a correlation coefficient of 0.97 and Nash and Sutcliffe coefficient of 0.86.

4.3 Verification of Model Results

The model is verified for the 2006 flood from 3 to 14 September. The observed and computed stage hydrographs at the Chiniot Bridge and Rivaz Bridge were compared by keeping Manning n's from the model calibration unchanged. Fig. 6 shows an example of model verification at Chiniot Bridge with satisfactory agreement. The correlation coefficient was 0.97, and Nash and Sutcliff coefficient was 0.79.

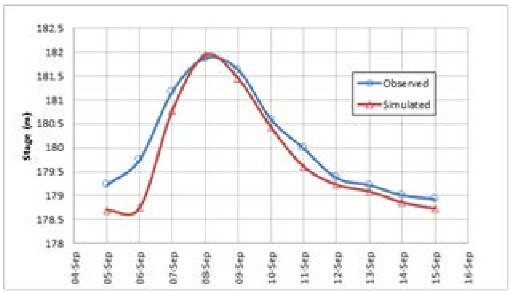

Fig. 5 Results of model calibration at Chiniot Bridge, 2014

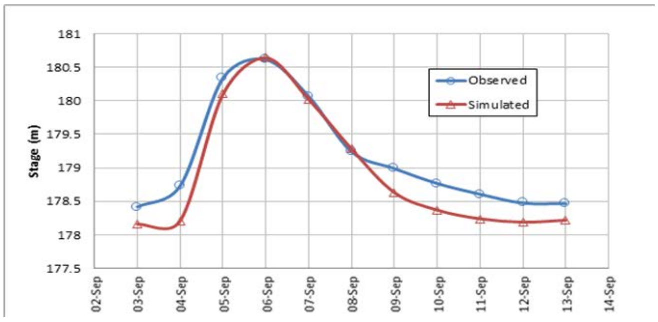

Fig.6 Results of model verification at Chiniot Bridge, 2006

V. Assessing Effectiveness of Flood Control Infrastructure

In assessing the effectiveness of the existing flood control infrastructure, the HEC-RAS model simulations were performed for different scenarios with and without flood control. This was done by entering generated flow hydrographs for different return period floods as upstream boundary conditions and water levels generated through extension of the downstream stage-discharge rating curve, against the peak discharge values of different return periods as downstream boundary conditions.

Model simulations were done for the cases with and without Flood Control Infrastructure to find out their effectiveness. The results of HEC-RAS model were exported to Arc-GIS through its tool HEC-GeoRAS which were further analyzed to generate flood maps in the form of flood inundation area and depth maps. Comparisons were done to assess the effectiveness of flood control infrastructure on the basis of inundation depths and flooding areas

VI. Flood Hazard Assessment

In assessing flood hazard assessment, two criteria are used namely ESCAP criterion [6] and DEFRA criterion [7]. The ESCAP flood hazard criterion is based on flood inundation depth only. By classifying flood depth based on the assigned critical depths of 0.8, 1.0 and 3.5 m according to ESCAP criterion, a flood hazard map was prepared in which flood depth was classified in four different intervals namely: 0.0-0.81 m as low, 0.82-1.00 as medium, 1.01-3.50 as high and from 3.51-higher as very high respectively.

The criterion of DEFRA considers flood hazard to people (FHR) as a function of depth and velocity:

$$FHR = d\,(v + 0.5) + DF \qquad (1)$$

Where d = depth of flooding (m), v = velocity of flow (m/s) and DF = debris factor (equal to 1 if d > 0.25m otherwise 0). The hazard to people was calculated and plotted as map using ArcGIS based on DEFRA criterion below (Table 2).

TABLE 2 DEFRA CRITERIA FOR FLOOD HAZARD TO PEOPLE [7]

Flood hazard rating = d(v+0.5)	Degree of Flood Hazard	Description
<0.75	Low	Caution (Flood zone with shallow flowing water or deep standing water)
0.75-1.25	Moderate	Dangerous for some (i.e. children, flood zone with deep or fast flowing water)
1.25-2.5	Significant	Dangerous for most people (Danger: flood zone with deep fast flowing water)
>2.5	Extreme	Dangerous for all (Extreme danger: flood zone with deep fast flowing water)

VII. Results on Flood Control Effectiveness, Flood Hazard and Discussions

7.1. Assessing Effectiveness of Flood Control Infrastructure

From the model computation of flood conditions with the existing flood control infrastructure, the simulated maximum depths in the floodplains for 25, 50, 100 and 200 year return floods were 11.73, 12.58, 13.46 and 14.46 m respectively. For the case without the flood control infrastructure, the model computed results shown that there was an increase by about 8-10% in inundation depth and flooded area more than the case with flood control infrastructure for the 25, 50 and 100 year floods. For the 200 year flood, there was no significant difference in inundation area and depth for the cases with and without the flood control infrastructure. Hence the overall effectiveness of the flood control infrastructure is ensured only for the floods of 100 year return period and smaller. For the floods larger than the 100 year flood, e.g. the 200 year flood, the effectiveness of the flood control infrastructure is not ensured.

Detailed investigation was made on individual effectiveness of each component of the existing flood control infrastructure, i.e. the nine flood bunds or embankments [13]. The results shown that out of the nine existing flood embankments, four of them are not safe against the flood larger than the 100 year flood. These embankments were Thatta Mahla, Thatta Mahla

Loop, Jhang and Massan Disty respectively. The computations shown that for the 200 year flood, these bunds were overtopped by flood depths of 2.77, 2.77, 1.40 and 2.94 m respectively. These four bunds need to be raised and strengthened in order to ensure safety against the heavy floods. In assessing flood hazard assessment, two criteria were used namely ESCAP criterion [6] and DEFRA criterion [7]. The ESCAP flood hazard criterion is based on flood inundation depth only by classifying flood depth based on the assigned critical depths of 0.8, 1.0 and 3.5 m. DEFRA criterion considers both depth and velocity in assessing flood hazard to people.

7.2. Flood Hazard Assessment

After assessing the effectiveness of the existing flood control bund infrastructure, the HEC-RAS model simulations were performed for different scenarios. Figs. 7 and 8 show the flood hazard maps according to ESCAP and DEFRA criteria for the 100 year flood with the presence of the flood control infrastructure. The protected flood plain areas behind by the flood bunds are shown as geometric-shape flood free areas in both figures. The results show that for the 25-, 50-, 100- and 200- year floods, both assessment criteria give the increasing trends of hazard to people and properties and the existing flood control bunds. For the ESCAP criterion, mostly the hazard level in the flood plains was low and moderate for the 25 year flood, medium and high for the 50 and 100 year floods, high and very high for the 200 year flood. For the DEFRA criterion, the flood hazard to people was low for the 25 year flood, moderate for the 50 year flood, moderate and significant for the 100 year flood and extreme for the 200 year flood.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Flood inundation along the flood plains of 209 km reach of the Chenab River, Pakistan from Qadirabad Barrage to Trimmu Barrage was simulated by using HEC-RAS flood flow model. The novelty of this study is the application of two assessment criteria namely ESCAP and DEFRA to assess the flood hazard impacts with and without the existing flood control infrastructure. The ESCAP criterion considers flood hazard based on magnitudes of flood depth but does not consider flood velocity. While the DEFRA criterion considers both depth and velocity in assessing the flood hazard to people on their safety and their life. The ESCAP criterion is better used to assess flood hazard impacts due to inundation depth only and ignore the impact due to flood velocity. While the DEFRA criterion is better used to assess the flood impact on people only; due to both flood depth and velocity. The purposes of ESCAP and DEFRA criteria are different but when used together they provide useful assessment in estimating the effectiveness of the flood control structures in reducing flood hazard on the safety of flood control infrastructures and on the people. The effectiveness of the nine existing flood control bunds have been assessed and found that five of them were effective in controlling the flood plain inundation for the flood return periods up to 200 years. The other four bunds were not fully safe for the floods of 100 years and more. The four flood bunds are at the following locations namely; Thatta Mahla, Thatta Mahla Loop, Jhang and Massan Disty. They must be increased in heights and strengthened to ensure safety against the floods of 100 years and more.

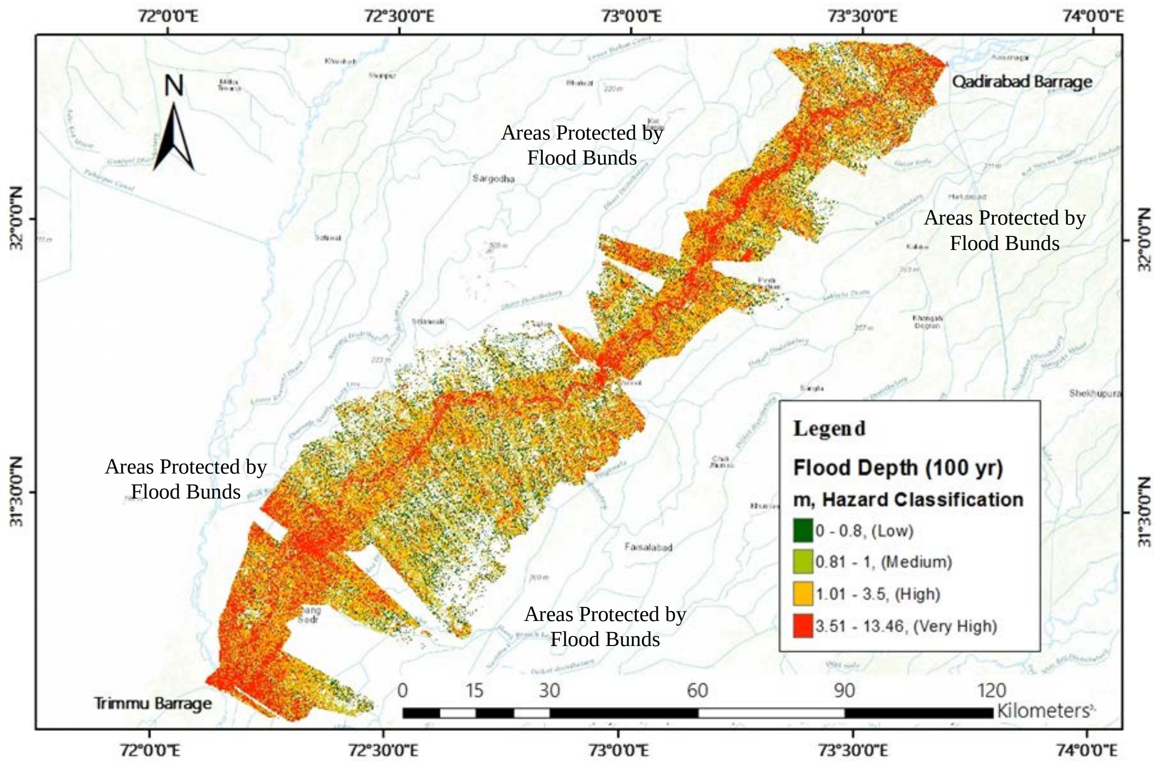

Fig.7 Flood hazard map for 100-year return period flood using ESCAP assessment criterion

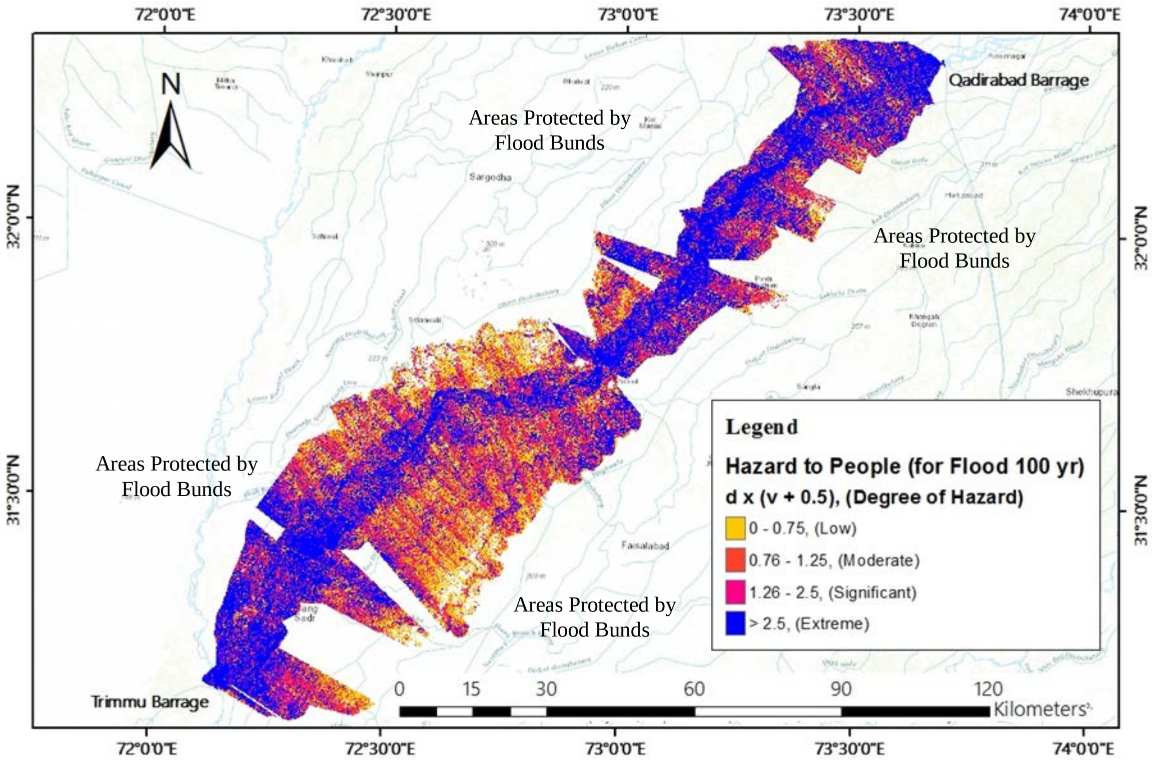

Fig.8 Flood map of hazard to people for 100-year return period flood using DEFRA assessment criterion

The following recommendations are given:

-The missing river cross sections in the study reach should be field-surveyed in the future rather than extracting from STRM DEM data

-Flood hazard and risk assessment should be further accomplished by incorporating various land-uses, land cover,

demographic data, private properties and public infrastructures, etc. [8], [9] and [10].

-Other flood hazard assessment methods should be considered, for example, multi-hazard loss estimation or HAZUS-MH of FEMA, USA[11]; and national flood-risk management guidelines of National Flood Risk Advisory Group of Australia [12].

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