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# Flood Hazard Assessment in Dhobi-Khola Watershed (Kathmandu, Nepal) using Hydrological Model

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## Abstract

*Flood, one of the main hazards in Nepal, requires an effective modelling to mitigate their impacts. Flood inundation models provide anestimation of flood extents and depths that are used in the preparation of hazard maps. Streams, like Dhobi-Khola in Kathmandu, with potential flood risks to infrastructures and settlements, are not studied to a level to predict and mitigate the flood hazards. This study assesses the flood vulnerable sites of Dhobi-Khola watershed and delineate theflood prone areas using hydrological HEC-HMS model and GIS application.The model was calibrated and validated in Bagmati River with discharge data of Gaurighat and rainfall data of Sundarijal stations. The model was then transposed to Dhobi-Khola watershed using hydrological data of Budhanilkantha station. The Slope-Area method of discharge measurementwas used to validate the model outputs in Dhobi-Khola using the field survey data. Final model outputswere used to predict the floods for different return periods using HEC-RAS model together with HEC-GeoRAS to generate flood inundation maps. Results indicate that the maximum flood depth can reach up to 5.24 m in 100 year return period (YRP) in Dhobi-Khola watershed. One site is inundated during the flood of 5 YRP and three sites in 10 to 20 YRPs. A total of five and seven sites is inundated during flood of 50 and 100 YRP, respectively. Vulnerabilityassessment showed two sites are very highly vulnerable and a site in low flood vulnerable due to low levee height, putting several households in the riverbanks and surrounding at the highest risk.*

**Keywords:** Flood Modelling, Inundation, Ungauged Watershed, Hazard Assessment.

## Introduction

**Flood Hazards:** Floods claim more than 20,000 lives every year and affect about 75 million people world-wide, mostly through pushing them into homelessness[1]. South Asian countries have a long history of floods[2]. Flood hazards are common in Nepal making it one of the most vulnerable countries in the world. It is one of the major natural hazards in terms of fatality and economic loss facing by the country every year. The historical data show that the country witnessed major floods in the Tinau (1978), Koshi (1980), Tadi (1985), and Sunkoshi (1987) Rivers, and Kulekhani area (1993) that alone claimed the life of 1,336 people. Recently, Koshi flood (2008) affected about 2,00,000 people in the eastern Nepal[2]. A maximum daily rainfall of 540 mm was recorded in Tistung of Makawanpur District on 19 July 1993. This has been the highest daily maximum rainfall ever recorded in Nepal[3]. Urban flooding in Nepal was much lightened up when the capital city Kathmandu got flooded badly with 27 people dead/missing in 2002[4]. The massive downpour of 22-23 July 2002 in Kathmandu valley was the highest recorded rainfall in 3 decades. During the period, the rainfall station at Thankot recorded 300 mm in 24 hours, whereas the last highest rainfall was 173.2 mm recorded in July 1954 in Indian Embassy, Kathmandu[5]. Extreme rainfall along with the encroachment of flood plain and squeezing of natural width of river channel converted high flow into catastrophic floods in Kathmandu Valley. On 23 July 2002, the flood overtopped the natural banks of rivers at many locations within the valley[4].

Flood can adversely affectthe economic growth of the country by damaging the agriculture and other related economies[6].Urban flood hazards are not only due to extreme rainfalls, but equally from human activities at flood plains and improper government policy[4]. Flow regimes of Nepal's river are largely determined by seasonal precipitation; they are characterized by high fluctuations between the peak flows during the summer monsoon months (June to September) and low flows during the rest of the monthin the year (October to May). Most effects of the floodscan be experienced in the downstream than the upstream of the basin. Mainly in rainy season, the Kathmandu valley has been threatened by quite unprecedented flooding of abnormal magnitude and damage. Apparently, this is for the large part, due to torrential or heavy rains falling for long days on the upstream basin. The rains have caused most rivers to swell and overflow or breach their courses, submerging the surrounding 'flat' fields or floodplains, which are mostly located in the downstream.

**Hydrological Modelling in Nepal:** The use of hydrological modelling for water resource study is being frequent nowadays and its efficient uses are becoming the suitable tool for water resource management planning and decision-making. Many hydrological models are available and in used. For the ungauged basins, the hydrological modelling can be best applied for an estimation and prediction of hydrological components based on available data[7].

In Nepal, several river basins have no hydrological measurement gauge. Initially, most of the hydrological models are developed specifically for the assessment of hydropower potential. Water and Energy Commission Secretariat (WECS) had used a linear regression model to estimate the flow duration statistics for the ungauged catchments[8]. These flow duration statistics enables to assign exceeding probabilities and assess the dependability of a given water flow. A hydrological model based on recession curve behaviour for estimating dry season flow in ungauged basins was applied and studied in the Nepal Himalaya and Northern India[8] to predict the average volume of water in an annual recession period.

A study conducted by Shrestha and Alfredsen[9] in the Sanghutal watershed of Likhu-Khola, a tributary of Sun Koshi River in eastern Nepal, used HBV hydrological model to generate flow time series and other hydrological variables. The calibrated model was then used to generate runoff for other ungauged catchment, at the intake site of the Likhu Hydro-Electric Project. A stream flow modeling of Bagmati River basin using the satellite based rainfall data and weather forecast was done in the Geospatial Stream Flow Model (Geo-SFM) developed by the US Geological Survey[10].The daily estimates of rainfall and evapotranspiration were derived from weather model and also the observed ground rain gauge stations. It had well predicted the daily stream flow at the Pandhera Dovan hydrometric station. The International Water Management Institute (IWMI)in Nepal did a study on the hydrology and the impact of climate change, of the Koshi River basin using SWAT (Soil Water Assessment Tool)model to simulate the hydrology and to calculate sub-basin wise water balances in the Koshi River basin[11]. Similarly, a small watershed (Jhiku Khola) was used for simulating the hydrological behaviour by using the WaSim model (Water balance Simulation model). Some other studies[12-16] attempted to understand the glacio-hydrological dynamics in Nepal using various hydrological models.

**Flood modelling**: Problem related to flooding have greatly increased and there is a need for effective modelling and understanding of the problem to help mitigate the worst effects of flood disasters and the need for development of a system to understand the threatened areas. Model simulation can provide flood depth and extent. The understanding of flooding will help in flood hazard assessment and will give insights into various ways of dealing with the hazard and disaster problems[6]. Tributaries like Dhobi-Khola in Kathmandu, with potential flood risks to floodplain, infrastructures and settlements, are not studied to the level; for example, flood hazard analysis that can help decision making in disaster mitigation. The flood hazard analysis helps to determine the high flood risk zones in advance, which helps to take mitigation measures effectively and efficiently[17]. This study is designed to assess the flood vulnerable sites of Dhobi-Khola watershed and mapping of disaster prone areas using hydrological models. However, it is not always easy to decide on the most appropriate flood modelling method forspecific tasks[18]. Even if, different models are applied in hydrological simulation, the HEC-HMS model is not applied in ungauged basin in Nepal. In this study, we use this model to simulate flood in ungauged watershed, like Dhobi-Khola.

**Study Site:** The Dhobi-Khola, a tributary of Bagmati River in Kathmandu Valley (Figure-1), originates from Shivapuri Hill on the north of the valley. This tributary stretches about 17.81 km and covers an area of 30.74 km$^2$ by its watershed[19]. The watershed lies between the 27.40° to 27.50°N and 85.20° to 85.25°E and flows from a height of about 2,732 m above MSL[10]. The Dhobi-Khola, fed by springs and monsoon rainfall, receives most of the runoff water due to the south-west monsoon rainfall, making the watershed vulnerable to frequent floods. A number of tributaries join the river as it flows downstream and passes through the valley to meet the Bagmati River at Buddhanagar. This river has been suffering from unmanaged urbanization and industrialization. The growing population pressure on the watershed of the river are resulting the destruction of natural river processes[20]. Further, the flash floods in the Dhobi-Khola adversely affects the agricultural lands and settlements nearly river banks in the Kathmandu valley.

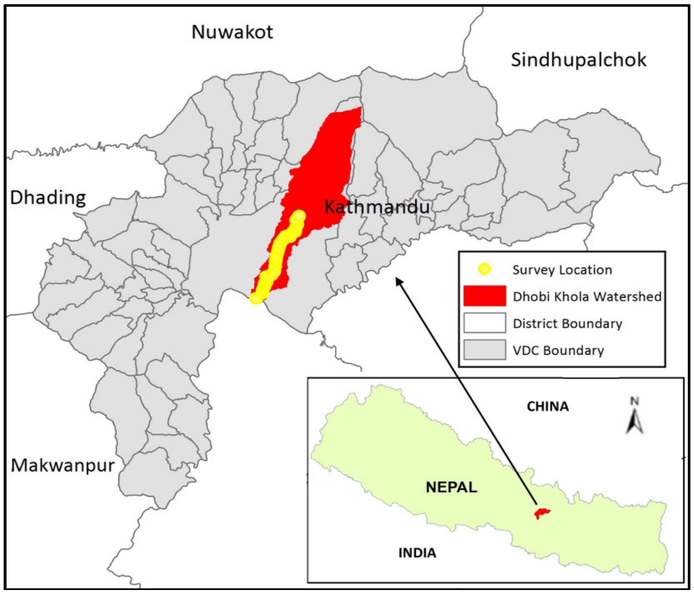

**Figure-1**
**Location of study area, the Dhobi-Khola watershed, in the map of Nepal**

## Materials and Methods

**Data Collection:** i. Hydro-meteorologicaldata: We used daily rainfall data from Sundarijal stations (index: 1074 and 1077), Budhanilkantha station (index: 1071), and daily discharge data from Gauri ghat gauging station (index: 530) for 1994-2008 (Table-1), acquiring from the Department of Hydrology and Meteorology (DHM), Government of Nepal. ii. Spatial data: The spatial data consisted of high-resolution (0.5 m) satellite image of Geo-Eye II (2012), the Digital Elevation Model (DEM), and other GIS layers. These data were obtained from Genesis consultancy Pvt. Ltd in Kathmandu[21] for this study. iii. Field data collection: Fieldworks for the River cross-section survey and discharge measurements were undertaken from 29 May to 3June, 2014. The bridges were used to measure the river cross-section, however, in some cases the measurement locationswas shifted to a nominal distance to address the field constraints due to lack of bridge in the river. A total of 27 river cross-sections were measured along the Dhobi-Khola River. The depth of the River was measured at every 1 m across the river cross-section to calculate the average discharge. Further, 28 GPS pointswere taken from the sites to estimate the elevation for slope calculation. A Garmin GPS having accuracy of ±3 m was used for this purpose. The River water discharges were measured at 3 locations in Dhobi-Khola using the float method to validate the predicted discharge.

**Data Analysis:** River features such as bank lines, flood plain lines, and river centerline were extracted from the satellite image. The DEM and TIN were prepared from digital contour lines. Contour data was in 1:2,000 scales with a contour interval of 2 m. The slope was calculated by as a difference of elevation values of the River (higher elevation – lower elevation) and divided by the distance between two sites for calculation of discharge by the Slope-Area method. Different Manning’s value (n) according to the environmental conditions of the River was used. Finally, the river discharge was calculated by multiplying the area by velocity of the river water in each cross-section.

**HEC-HMS:** The Hydrologic Engineering Centers - Hydrologic Modelling System (HEC-HMS), a physically based, semi-distributed rainfall-runoff model developed by the US Army Corps of Engineers, was used to simulate the rainfall-runoff processes of a watershed to a given hydro-meteorological input[22]. The model can simulate rainfall-runoff and routing process of the watershed system in both natural and controlled conditions[23]. The HEC-HMS 3.5 was used in this study.

Flood prediction at ungauged reaches is an important task in designing river engineering and hydraulic structures and remains a fundamental challenge for hydrologists[24]. Regionalization transfers hydrological information from one or more gauged basins to geographically non-continuous regions and hydrological neighbourhood ungauged basin of interest[25]. At ungauged basins, the hydrological regionalization is usually applied as a reliable method for the estimation of the hydro-climatic variables at different return periods[26]. The benefit of a HEC-HMS model as compared to other model is that once the model is calibrated in a gauged basin, it can be used to predict future events in ungauged basin under slightly changed conditions whereas the other model would have to be completely reformulated[7]. Since Dhobi-Khola watershed is a non-gauged watershed, gauged basins with similar hydromorphometry, land cover and climatic values should be used to interpolate the data. For basins with a gauged station close to their outlet, this discharge could be estimated by using HEC-HMS model and the output is interpolated to Dhobi-Khola watershed for predicting the flood.

**Clark Unit Hydrograph Approach for Gauged Bagmati Watershed:** The rainfall and discharge data taken from the DHM were used to calibrate and validate the HEC-HMS model. The HEC-HMS model was set up for the Bagmati Watershed. The sub-basin of area 40.343 km$^2$ above Gaurighat station was considered for modelling as it has the required discharge and rainfall data. It is calibrated and validated with Clark Unit Hydrograph method. The validated model was then applied for Dhobi-Khola watershed to generate flow data using the Snyder Unit Hydrograph Method.

**Table-1**
**Hydro-meteorological stations data**

| Station Index | Location | Latitude (°) | Longitude (°) | Altitude (m) | Data |
|---|---|---|---|---|---|
| 1074 | Sundarijal, Kathmandu | 27.46 | 85.25 | 1490 | Rainfall |
| 1077 | Sundarijal, Kathmandu | 27.45 | 85.25 | 1360 | Rainfall |
| 1071 | Budhanilkantha, Kathmandu | 27.47 | 85.22 | 1350 | Rainfall |
| 530 | Gaurighat, Kathmandu | 27.41 | 85.15 | 1300 | Discharge |

**Snyder Unit Hydrograph Approach for Ungauged Watershed:** For Snyder Unit Hydrograph Method, the required hydrograph parameters are Lag time and Peak coefficient that is calculated for each ungauged sub-basin. Basin geometry such as sub basin area, slope and longest flow path and sub-basin centroid are the primary parameters needed for Snyder Unit Hydrograph and estimating other parameters for developing the model.

Based on that basin geometry the lag time and peak coefficient were calculated. Assuming the ungauged sub basins are hydrological homogeneous with the calibrated gauged sub-basin, the model is then applied for simulating discharge using the Snyder unit hydrograph method. The peak discharge data for different return periods are then calculated with the model output data for Dhobi-Khola River using Gumball Method. The calibrated model, then gave the flow data of watershed areas using Snyder Method.

The model parameters were calibrated and validated on an event-basis using the rainfall runoff data available. Using a calibrated and validated HEC-HMS model for the watershed discharges in the main river and tributaries corresponding to the rainfall of different return periods (2, 5, 10, 20, 50, 100) were estimated.

**HEC-RAS:** The Hydrological Engineer Center – River Analysis System (HEC-RAS) is well-tested and in use by the National Weather Service for hydraulic modelling as a part of the Community Hydrologic Prediction System[27]. However, this model makes many simplifications, including that flow can be represented by a mean velocity in a cross section, that the water surface is horizontal across the cross section, that vertical acceleration and complex floodplain flows can be neglected, and that Manning's equation can be used to approximate uniform flow[28]. The HEC-RAS 4.1.0 was used for inundation mapping along with HEC-GeoRAS 10, an extension of ArcGIS 10 software in this study. The flow outputs of the HEC-HMS are the input data for the HEC-RAS model that provides inundation areas. Finally, inundation maps were prepared for 2, 5, 10, 20, 50, 100 year return periods (YRP). Flood inundation models are a major tool for mitigating the effects of flooding. They provide predictions of flood extent and depth that are used in the development of spatially accurate hazard maps[29]. The output of the hydraulic simulation can be transferred to GIS software to generate flood layer for various scenarios[30]. Further analysis such as flood damage assessment can be carried out for planning and design purpose.

Application of HEC-RAS is used to obtain flood extent and depth. The HEC-RAS is a 1D flow model in which the stream morphology is represented by a series of cross-sections indexed by river station. Each cross-section is defined by a series of lateral and elevation coordinates that are typically obtained from the DTM. Implementation of HEC-RAS requires inputs which come from three basic categories of data; i. Geometric data ii. Basin characteristics and iii. Flow data. After completing the set up of the system with the requisite model parameters and variables, a calibration run was performed using the peak discharge value corresponding to the 50 YRP flood event. The initially used Manning's 'n' values were varied to give the downstream boundary condition. The HEC-RAS model simulation results were exported to the HEC-Geo RAS for further processing and visualization of flood extents. The results of this simulation are then checked against flood extent delineated from the satellite data.

**Flood Hazard Assessment and Hazard Ranking:** Flood hazard assessment is the estimation of overall adverse effects of flooding. It depends on many parameters such as depth of flooding, duration of flooding, flood wave velocity, and rate of rise of water level. One or more parameters can be considered in the hazard assessment[6]. In the present study in Dhobi-Khola watershed, the depth of flooding (or Inundation depth; D) was considered for vulnerability ranking (Table-2) and corresponding levee height (H) was considered for Exposure ranking (Table-3). These two criteria (a. Vulnerability and b. Exposure) were assessed for hazard ranking (Table-4). The intensity of flood hazard is always given by a relative scale, which represents the degree of hazard and called a hazard rank. A smaller score was assigned for a low hazard (Table-5).

**Table-2**
**Vulnerability index for depth of flooding**

| **Inundation depth (D)** | **Vulnerable category** | **Vulnerable rank** |
|---|---|---|
| (0 <D ≤ 2.1m) | No | 0 |
| 2.1<D≤2.5m | Low | 1 |
| 2.5<D≤3.0m | Medium | 2 |
| 3.0m<D | High | 3 |

**Table-3**
**Hazard index for depth of flooding**

| **Height (H)** | **Exposure category** | **Exposure rank** |
|---|---|---|
| (0<H≤ 2.1m) | High | 3 |
| 2.1<H≤3.5m | Medium | 2 |
| 3.5<H≤4.8m | Low | 1 |
| 4.8m<H | No | 0 |

**Table-4**
**Hazard scoring with different vulnerability and exposure scores**

| Hazard | Vulnerable (D) | | | | | |
|---|---|---|---|---|---|---|
| Exposure (H) | | 0 | 1 | 2 | 3 | Total |
| | 3 | 3 | 4 | 5 | 6 | 18 |
| | 2 | 2 | 3 | 4 | 5 | 14 |
| | 1 | 1 | 2 | 3 | 4 | 10 |
| | 0 | 0 | 1 | 2 | 3 | 6 |
| | Total | 6 | 10 | 14 | 18 | 48 |

**Table-5**
**Hazard index for different scores**

| Score | Hazard Category |
|---|---|
| 0 | NH (No Hazard) |
| 1 | VLH (Very Low Hazard) |
| 2 | LH (Low Hazard) |
| 3 | MH (Medium Hazard) |
| 4 | HH (High Hazard) |
| 5 | VHH (Very High Hazard) |
| 6 | EHH (Extremely High Hazard) |

## Results and Discussion

**Model calibration:** The model was first calibrated and validated in the Bagmati River basin that has similar character with the Dhobi-Khola watershed. The data from 1994 to 2003 (10 years) were used for calibration of the HEC-HMS model. Figure-2 indicates an example of the calibration result for 1995 in the Bagmati River basin. Figure-3demonstrates that the observed peak values for 10 years were almost similar to the peak values of the model outputs. The difference of the mean of all the peak value is 0.453%.

The model calibrated by changing the parameters, like time of concentration, storage coefficient, and manning roughness coefficient[31]. Previous studies[8,32] suggested that calibration performance should be less than 5% root mean square error (RMSE). In this study, the RMSE was found to be around 5 % and the mean difference between observed and modelled values was 0.45%, indicating that the acceptable performance of the model calibration.

**Model validation:** The model is validated by 5 years data from 2004–2008 with the rainfall data of Sundarijal (average of stations 1074 and 1077) and discharge data of Gaurighat station (530) using the calibrated parameters. The validation result is presented in Figure-4. According to Reshma et al.[31], for validation the average of minimum three events average must be taken. In this study, averaging the values of all calibrated events carried out validation of three events.

Figure-4 indicates that the peak computed value 16.2 m$^3$s$^{-1}$and peak observed value 15.8 m$^3$ s$^{-1}$. The difference of observed and simulated discharge peak was 2.53%. Similarly, the mean difference was calculated as 4.48%. In a similar research, Roy et al.[33] found the percentage error 4.39 to 19.47% in peak and net difference of observed and simulated time series peaks. This indicates that for sub-basins, the model performance can be acceptable, if the simulation results are ±20% of accuracy. In our case, the difference of observed and simulated discharge peak mean was 5.3%, the maximum difference occurred in 7.21% in 2005 which suggested that the model performance is much reliable.

**Model Transpose to Dhobi-Khola:** The validated model in the Bagmati basin was transposed to Dhobi-Khola watershed using 20 years (1994-2013) period of precipitation data from Budhanilkantha station. Snyder method was used to run the model in Dhobi-Khola. Figure-5 shows the peak discharge of Dhobi-Khola from 1994 to 2013 period. The peak flows were the highest (24.8 m$^3$ s$^{-1}$) in 2012 and the lowest (10.9 m$^3$ s$^{-1}$) in 2007 with average peak value 15.49 m$^3$s$^{-1}$.

From the calculation of discharge at different cross-section different discharge values obtained are shown in Table 6. For the validation, Slope-Area method was used to calculate the discharge in different cross-section that yielded the mean discharge of 14.75 m$^3$s$^{-1}$. The mean discharge values obtained from the simulation of the HEC-HMS model and the Slope-Area method were almost similar, suggesting that the HEC-HMS model application was valid for Dhobi-Khola watershed for computation of peak discharge values.

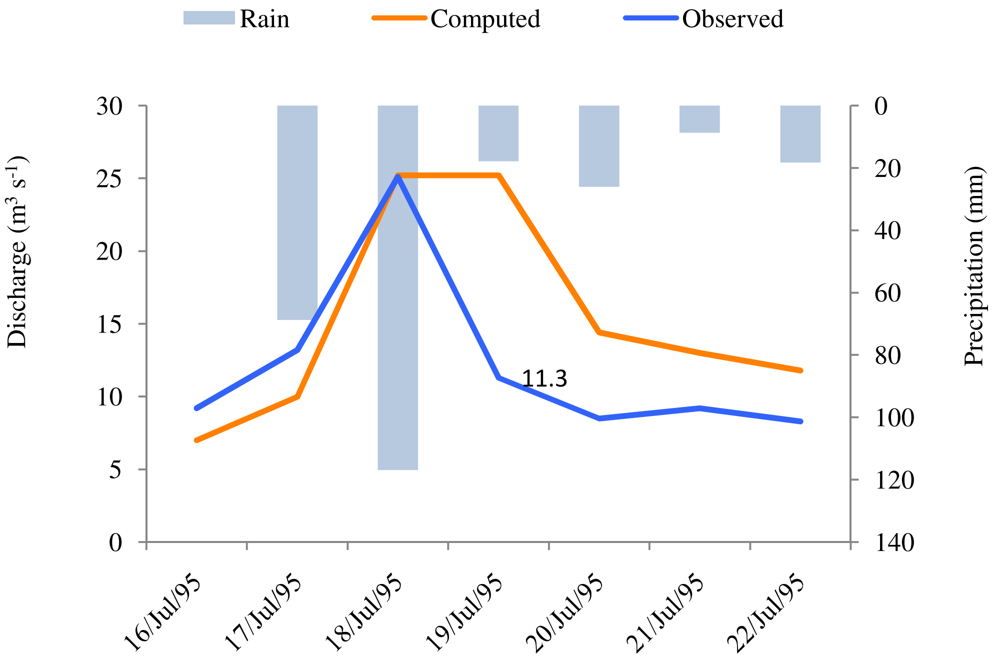

**Figure-2**
**Model calibrated result of HEC-HMS for year 1995.**

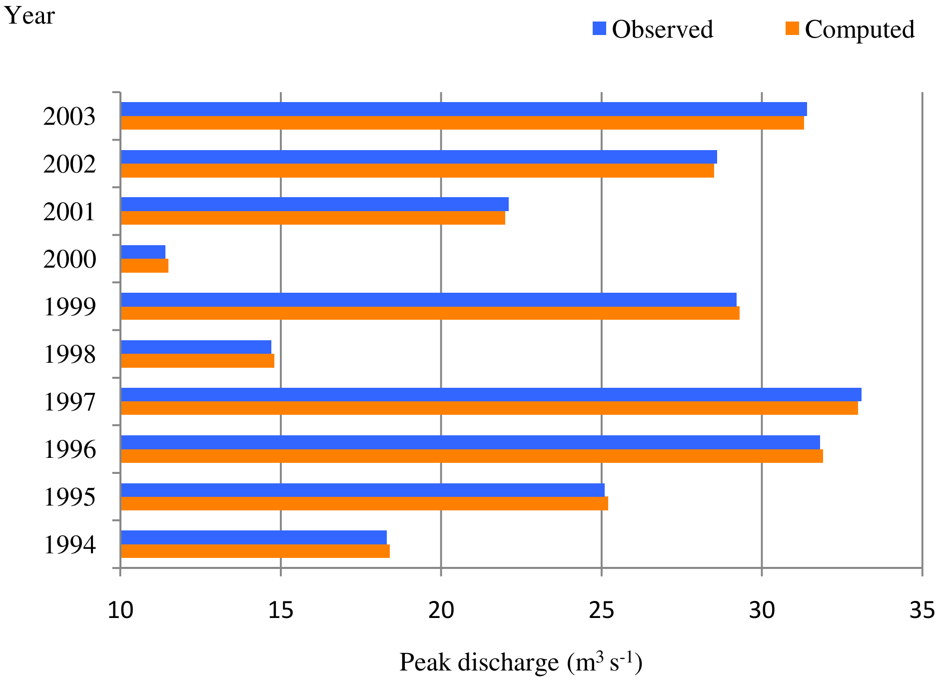

**Figure-3**
**Comparison of observed and computed flood peaks**

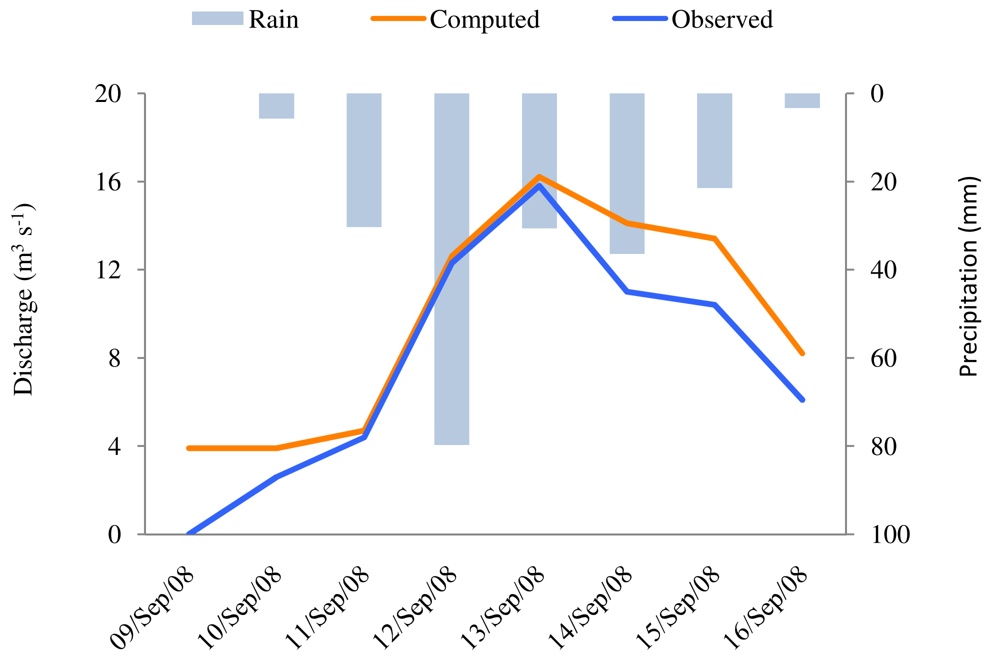

**Figure-4**
**Model validation result of HEC-HMS for 2008**

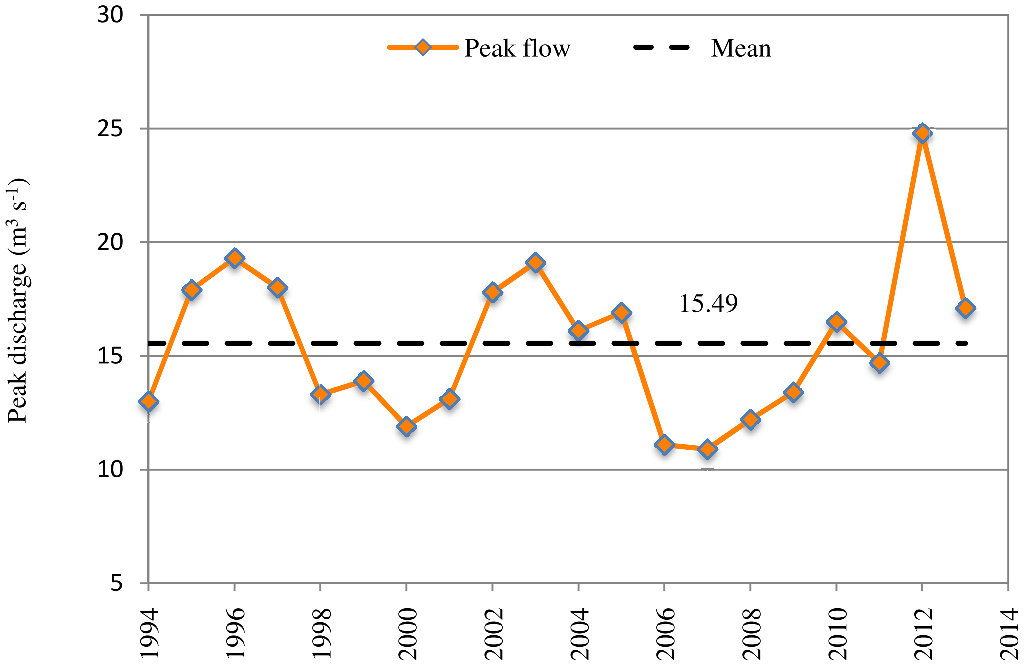

**Figure-5**
**Peak discharge of Dhobi-Khola from 1994-2013 using HEC-HMS model**

**Table-6**
**Peak discharge value from Slope-Area method**

| Sites | Discharge ($m^3 s^{-1}$) |
|---|---|
| 1 | 15 |
| 2 | 14 |
| 3 | 10 |
| 4 | 14 |
| 5 | 11 |
| 6 | 8 |
| 7 | 18 |
| 8 | 15 |
| 9 | 17 |
| 10 | 12 |
| 11 | 18 |
| 12 | 14 |
| 13 | 16 |
| 14 | 17 |
| 15 | 15 |
| 16 | 14 |
| 17 | 12 |
| 18 | 13 |
| 19 | 15 |
| 20 | 17 |
| 21 | 18 |
| 22 | 16 |
| 23 | 18 |
| 24 | 17 |
| 25 | 15 |
| 26 | 14 |
| 27 | 18 |
| Mean | 14.75 |

Using above peak discharge value of the HEC-HMS model, Gumball method is used to calculate the different YRP floods (Figure-6). The floods, thus calculated for the different return period in Dhobi-Khola watershed are the basic input for the HEC-RAS model.

Similarly, the peak values from the observed discharge of Dhobi-Khola were calculated. Figure-6 shows that the modelled and observed peak discharges at Dhobi-Khola are similar. So, we could say that the model outputs were good to construct the inundation map. These outputs were an input for HEC-RAS model as a hydrological parameter.

**Hydrodynamic Modeling:** As explained in the methodology, the cross-sections were generated using HEC-Geo RAS using field data. After this, flow plan defined by providing discharge data for different YRP to the selected cross-sections from upstream to downstream. Once the water surface profiles were calculated, the results were exported to GIS format for post-processing. In the post-processing phase, the HEC-RAS results were imported into HEC-GeoRAS platform and data layers have been set up with a given input of TIN and flow data to generate the water surface, flood plain boundary, and flood inundation map for different YRP viz. 2, 5, 10, 20, 50, and 100 of Dhobi-Khola (Figure-7).

**Inundation Mapping:** The inundation maps provide crucial information about the vulnerability of the areas.

In the 2 YRP flood, no sites lies in the higher hazard category. One site (#6) was seen in high vulnerable category, but in hazard ranking that the site moved to medium hazard due to the presence of high levee height. Inundation does not occur at the site, but may get trouble with water logging since there are some low elevated areas around.

In the 5 YRP flood, the maximum depth was 4.04 m from the base of the river. Water depth above 2.14m was seen in 5 locations. If we observe the corresponding height of the levees and the width of the flood plain, only one location found to be inundated. In this location, corresponding river depth was found to be 2.37m and bank height was 2.1m. This area can be inundated during the 5 YRP flood. No sites were found in VHH and EHH category. But, one site (#6) is so critical that the utmost care should be taken in rainy season since this may get inundated in the 5 YRP flood.

In the 10 YRP flood, 8 sites had higher inundation water depths, but if observed the corresponding height of the levees, then only 3 sites will get inundated as those locations had the depth of the river more than the levee height. Two sites (#6 and #23) have the levee height less than the flood depth and thus, more exposed to flood. In hazard assessment, two sites lie in VHH category, one in HH, and 4 sites in MH category. Since the chance of recurrence of the 10 YRP flood is high, so these above mention sites should be managed properly in order to prevent loss of life and property.

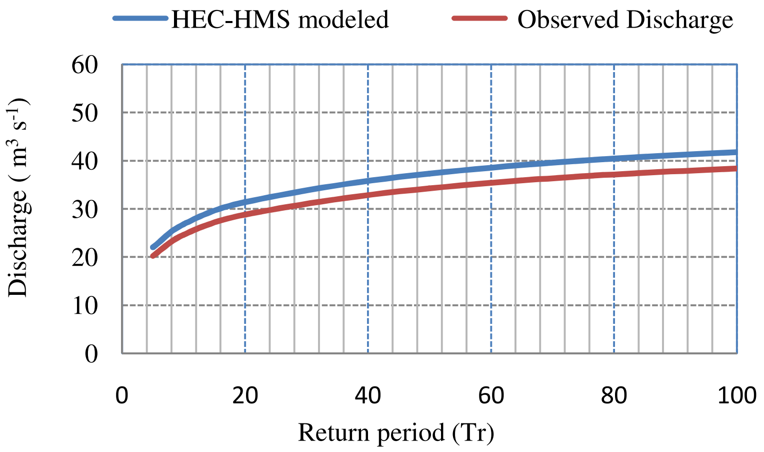

**Figure-6**
**Observed and modeled flows in different return period of flood in Dhobi-Khola**

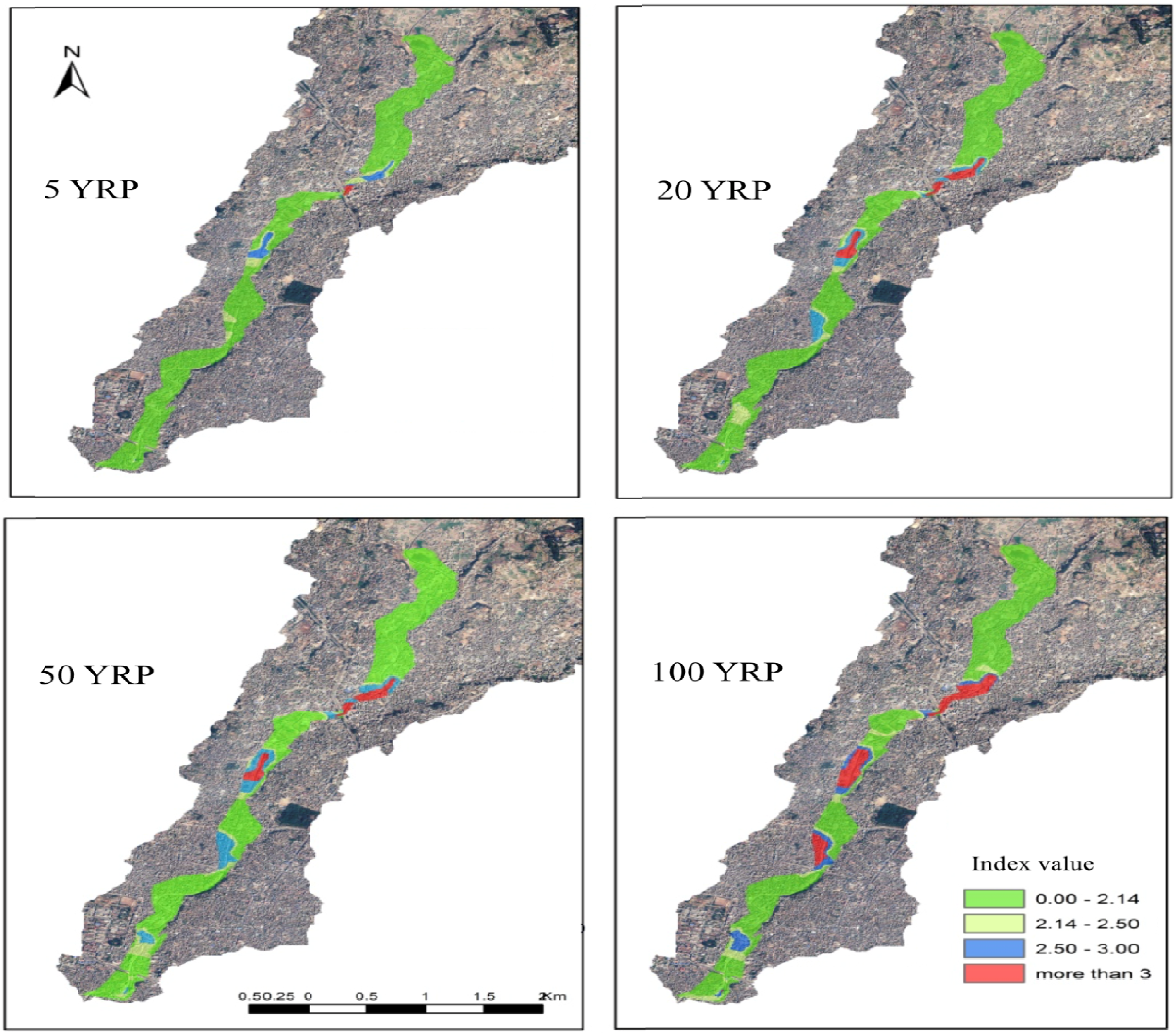

**Figure-7**
**Inundation and vulnerability maps for 5, 20, 50, and 100 years return period (YRP) flood**

**Table-7**
**Categorization of Dhobi-Khola sites into vulnerability classes in different YRP flood.**

| Depth (D) of flooding, m | Vulnerable category | Return period | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2 | 5 | 10 | 20 | 50 | 100 |
| (0 < D ≤ 2.1 m) | No | 26 | 22 | 19 | 19 | 17 | 13 |
| 2.1 < D ≤ 2.5 m | Low | 1 | 1 | 3 | 2 | 2 | 6 |
| 2.5 < D ≤ 3.0 m | Medium | | 3 | 2 | 3 | 3 | 1 |
| 3.0 m < D | High | | 1 | 3 | 3 | 5 | 7 |

**Table-8**
**Categorization of Dhobi-Khola sites into exposure classes.**

| Bank height (H) m | Exposure category | No of Sites |
|---|---|---|
| 0 < H ≤ 2.1 m) | High | 1 |
| 2.1 < H ≤ 3.5 m | Medium | 19 |
| 3.5 < H ≤ 4.8 m | Low | 7 |
| 4.8 m < H | No | 0 |

**Table-9**
**Categorization of Dhobi-Khola sites to different hazard classes in different YRP flood.**

| Hazard category | YRP | *2* | *5* | *10* | *20* | *50* | *100* |
|---|---|---|---|---|---|---|---|
| VLH | Number of sites | 8 | 7 | 6 | 6 | 6 | 5 |
| LH | | 17 | 17 | 14 | 14 | 12 | 12 |
| MH | | 2 | 1 | 4 | 3 | 1 | 2 |
| HH | | 0 | 2 | 1 | 2 | 5 | 4 |
| VHH | | 0 | 0 | 2 | 2 | 2 | 3 |
| EHH | | 0 | 0 | 0 | 0 | 1 | 1 |

In the 20 YRP flood, 9 sites had water depths above 2.14m. Those sites should be taken in more consideration for prevention of flood inundation. In hazard category, two sites each lie in VHH and HH, and 3 sites in MH, but the inundation occurs in two sites due to low levee height. Levee height should be increased in these locations in order to prevent inundation.

A study conducted by Irwin et al.[21] demonstrated that major flooding was foreseen in Dhobi-Khola with estimated 5,312 buildings to be affected by inundation with at least 5 buildings up to 5 m depth in 50 YRP flood. According to the present study, in 50 YRP, the flood height will reach 5.05m from the base of the river and water depth above 2.14m can be seen in 10 sites out of surveyed 27 sites. By observing the corresponding heights of levees 5 sites will get inundated. In term of hazard category, one site lies in EHH, two sites in VHH, and three sites lie in HH category. These all sites should be protected in order to prevent the loss of life and property.

During 100 YRP flood, Irwin et al.[21] reported that more impacts of inundation can be expected in Dhobi-Khola affecting about 5,425 houses, in which 79 houses inundated up to 2-5m. The present study shows that in 100 YRP, the flood depth may increase up to 5.24m and 12 sites lie in many hazardous categories. Of which 7 sites may get inundated in present condition. In terms of hazard category, one site lies in EHH, three in VHH and 4 in HH categories. All these sites should be improved. Though the levees are constructed on these sites, these levees are not capable enough to withstand 100 YRP flood.

Two major settlements along the river – i. Sukumbashitole, a place upstream of Gopi Krishna hall and ii. Anamnagar are at greater risk of flood hazards since those areas are low land and settlements are just adjacent to the river[34] (Figure-7). This study found these sites as flood hazard areas since the site near Gopi Krishna Hall falls under EHH category and former site falls under VHH category. Though some sites were ranked in low hazard criteria, but inundation could be observed at these sites (#23 in 10, 20 YRP flood, #14 in the 100 YRP flood). So, these areas should not be neglected just by considering the ranking of hazard.

In addition to the hazard categorization, the potential risk of flood hazards to households located in the nearly riverbanks and surroundings are evaluated. Table-10 presents the number of households affected under different vulnerability categories.

## Conclusion

The flood hazard assessment helps to determine the high flood risk zones in advance, which helps to take mitigation measures effectively and efficiently. In this study, we calibrated and validated the HEC-HMS model in the Bagmati River basin and applied to simulate flood depth. The model performance wassatisfactory, indicating its potential application in the estimation of the flood in ungauged basin. The modelled discharge was 15.85 $m^3s^{-1}$ and the discharge from Slope-Area method was found 14.75 $m^3 s^{-1}$. The flood intensity at different YRP was ranging from 14.85 $m^3s^{-1}$in the 2 YRP to a maximum of 41.79$m^3 s^{-1}$inthe 100 YRP, respectively.

The inundation mapsare generated using vulnerability category for resembling return period in HEC-GeoRAS. Among 27 sites 10 lies in low exposure, 16 sites in medium exposure, and 1 site in high exposure area. Similarly, in ranking vulnerable sites, were categorized, one site was categorized in low vulnerable category and 26 sites in no vulnerable category for the 2 YRP flood. Further, three sites are categorized in medium, 1 low, and 23 in no vulnerable category forthe 5 YRP flood. For 10 YRP floods, one high, four medium, three low, and nineteen no vulnerable category. For 20 YRP flood, 2 high, 3 medium, 3 low, and 19 no vulnerable category are observed and for 50 YRP flood, 5 High, 3 medium, 2 low and 17 no vulnerable category are found. For 100 YRP flood, 6 high, 2 medium, 5 low, and 14 no vulnerable category observed. Though some sites were ranked in low hazard criteria, inundation could be observed in those sites (site 23 in 10, 20YRP flood, site 14 for 100 YRP flood), so those sites should not be neglected just by looking into the hazard ranking.

As stated by different study related to Bagmati some sites that are near Anamnagar, Thapagaun, below Bhatkekopul, behind Sukedhara which fall under the High Hazard, Very High Hazard, Extremely High Hazard category. These sites need detail study including other social and economic parameters. Since the current levee height are not satisfied in 8 locations which cannot withstand in the 100 YRP flood. So, the levee height should be reconstructed with detail hydro-engineering survey in order to prevent future inundation. We highlight that in order to communicate and conduct more research this basin needs gauging site.

**Table-10**
**Estimated numbers of households under different vulnerability types in Dhobi-Khola watershed**

| Vulnerability Range | Vulnerability Category | Vulnerable # of households in different YRP | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2 | 5 | 10 | 20 | 50 | 100 |
| < 0.1 | No Vulnerable | 31371 | 31238 | 31191 | 31162 | 31135 | 31114 |
| 0.1 to 2.1 | Low Vulnerable | 3257 | 3156 | 3046 | 2955 | 2823 | 2674 |
| 2.1 to 2.5 | Vulnerable | 29 | 202 | 273 | 209 | 240 | 323 |
| 2.5 to 3 | Medium Vulnerable | 4 | 60 | 118 | 254 | 276 | 209 |
| Above 3 | High Vulnerable | 1 | 6 | 34 | 82 | 188 | 342 |
| *Grand Total* | | *34662* | | | | | |

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