Estimation of flood influencing characteristics of watershed and their impact on flooding in data-scarce region

Vikas Kumar Rana and Tallavajhala Maruthi Venkata Suryanarayana

The Maharaja Sayajirao University of Baroda, Vadodara, Gujarat, India

ABSTRACT
The research is focused on the integrated use of satellite remote sensing, Geographic Information System (GIS), and extensive field observation techniques for a better understanding of the impacts of watershed characteristics on hydrological processes and floods. It aims to create a methodology for assessing flood hazards and risk on a regional and local scale so that protective measures can be designed. Floods have occurred in the study area for many years, causing serious damage to infrastructure and civic structures. The present study evaluates the linear, aerial and relief morphometric parameters using the Cartosat-1 digital elevation model (30 metres) along with the curve number for assessing the flood influencing characteristics of the Vishwamitri River’s sub-watersheds. The study prioritizes five sub-watersheds as high, medium, and low based on their flood influencing characteristics and compound value, as a result, needs the highest priority for flood mitigation measures. The sub-watersheds I and IV of Vishwamitri watershed have been categorized into high priority, sub-watersheds II and V into moderate priority, and sub-watershed III into low priority. The geologic stage of development and erosion proneness of the watershed is quantified by hypsometric integral bearing value as 0.04, indicating the landscape to be in monadnack phase in landscape evolution indicative of a marked old stage in the basin’s evolution. Moreover, the ability of the rain-on-grid model at the watershed scale to simulate flood events and predict flood-prone areas, considering multiple rain gauge data, which will facilitate more accurate flood inundation where ground-based observational data are unavailable is shown.

1. Introduction

Flood hazard and flood risk maps are the main components of flood risk management around the world. A large part of the world’s population lives on flood-plains and depends directly or indirectly on these flood-plains for shelter and livelihoods. Floods produce dangerous environments that are especially vulnerable to humans. If the floodplains were unoccupied and unused, there would be no chance of flooding to the city. It is the human contact with the floodplain and the resulting exposure to the flood threat that causes the risk of flooding. In the last few decades, there has been an increase in the frequency of natural cataclysmic hazards, especially those caused by water, due to climate change (Choubin et al. 2019; Halgamuge and Nirmalathas 2017; Danumah et al. 2016; Hall et al. 2015; Holmes, Schwein, and Shadie 2012).

The quantitative study of the morphometric features of watersheds is of considerable importance in the prediction of flood behaviour. The watershed hydrological response can be connected to the physiographic features of the watershed (Romshoo, Bhat, and Rashid 2012). The morphometric watershed analysis offers important aspects of watershed characterization with a detailed description of the drainage scheme. Morphometric parameters such as watershed area, watershed perimeter, stream order, stream length, basin length, ruggedness number, form factor, circulatory ratio, compactness index, drainage density, drainage frequency, bifurcation ratio, drainage texture, relief ratio and lemniscate ratio have been used to establish a primary hydrological diagnosis and to prioritize sub-watersheds according to their flood potential (Masoud 2016; Bhat et al. 2019). (Bhat et al. 2019) evaluated the flood influencing factors in the upper Jhelum basin, they delineated the upper Jhelum basin into ten sub-basins, followed by extraction of drainage network and morphometric parameters using ASTER DEM and topographic maps in Geographic Information System. The overall flood potential was determined based on the compound value obtained for all morphometric parameters of each sub-basin. Lately, (Sridhar and Ganapuram 2021) used morphometric analysis and fuzzy analytical hierarchy process to prioritize the sub-watersheds of the Peddavagu watershed of the Krishna
River basin according to the degree of erosion. Several researchers have successfully used morphometric parameters to estimate the flash flood susceptibility of the watersheds (Mahmood and Rahman 2019; Wani, Ali, and Ali 2018; Bisht et al. 2018; Prasad and Pani 2017; Bannari et al. 2017).

Ungauged watersheds with scarce information on soil, geology, geomorphology and hydrology, morphometric analysis is an excellent alternative to understanding the underlying factors that regulate the hydrological behaviour (Altaf, Meraj, and Romshoo 2013). Traditional methods have generally been used for the morphometric characterization of watersheds in the past (Magesh and Chandrasekar 2014; Ozdemir and Bird 2009). However, the assessment of watershed morphometry has become more reliable, speedy and economically productive with the advancement of the geographic information system, high-resolution Digital Elevation Models (DEMs), and remote sensing techniques (Ahmed et al. 2010). After rainfall, water behaviour is determined by the morphometric characteristics of the basin. However, not only the morphometric properties but also the infiltration potential of rocks and soils, vegetative interception, the soil's preceding moisture state, and land use properties of the surface of the watershed are used to assess the rainfall portion available for surface runoff. As a result, for ungauged watersheds or where data are not available, several researchers use runoff modelling to gain an inclusive understanding of the hydrological response of the watershed (Karmokar and De 2020). Several methods, like Soil Conservation Service (SCS) – Curve Number method, Cook’s method, and unit hydrograph method, have been developed by engineers to estimate the discharge for an ungauged watershed (Gioti et al. 2013; Wakode et al. 2013; Elkhrachy 2015; Sudhakar, Anupam, and Akshay 2015; Abuzied et al. 2016; Iosub et al. 2020).

Flood inundation modelling plays an important role in obtaining knowledge on the spatial distribution of flood patterns (such as water depth and flow velocity) (Kim et al. 2014). This will include details on the nature of the danger, any risks to public safety and possible financial losses. It may also be used to support emergency response actions and mitigation policies for future flood events (Asselman et al. 2009; Thakur et al. 2017). In recent years, the hydrodynamic modelling of flood events has been greatly enhanced due to the advancement of increasingly accurate computational tools, effective computing power and innovative topographic survey techniques.

Generally, fluid motion and fluid dynamics are defined by solving mathematical equations based on the principles of the conservation of mass and momentum (Fassoni-Andrade et al. 2018). 2D models that solve full shallow water equations, although they are data-intensive and have high computational demand, are stated to have the ability to simulate the timing and period of inundation with high accuracy (Dasallas and Lee 2019; Costabile et al. 2015). In flood control programs, simulation of the water levels, release, flood forecasting and flood-prone areas are becoming more prominent. As a result, hydrological modelling has since become an important part of water resource management (Malik and Pal 2020). The latest HEC-RAS 5.0.7 is increasingly studied in the literature since this model is popular with water engineers dealing with flood risk problems. Recently, (Costabile et al. 2020) assessed the performance of HEC-RAS Version 5.0.7 for watershed-scale 2-D hydrodynamic rainfall-runoff simulations and concluded that HEC-RAS can be considered in rainfall-runoff simulations as a reliable model for discharge hydrograph computation. (Ongdas et al. 2020) showed the application of HEC-RAS for flood hazard map generation for the Yesil (Ishim) River in Kazakhstan. They simulated different flood scenarios on the River Yesil (Ishim) and also compared different mesh sizes (25, 50 and 75 m), the obtained results indicated no significant difference in model performance. (Quirogaa et al. 2016) highlighted the strong performance of the flood scale simulated by HEC-RAS compared to the satellite picture of the Bolivian Amazon flood. The combined version 1-D/2-D of HEC-RAS demonstrated that, together with the high accuracy of topographic data, observed events can be replicated in the water basin (Voizinaki et al. 2017).

In this study, we have evaluated watershed characteristics that make the downstream areas of the watershed prone to flooding. This leads to the integration of scientifically approved methodologies with new technologies combining morphometric analysis and hydraulic models along with the land-use dynamics of the watershed. The hydraulic behaviour of the Vishwamitri River affects an important area of the watershed since it flows through the urban areas. Floods have occurred in the study area for many years, causing serious damage to infrastructure and civic structures. On a local scale, applied research is critical to design effective preventive measures and plan disaster mitigation measures. It is worth mentioning that very few studies have considered the effect of the land-use dynamics on the flood-prone area of the watershed while conducting morphometric analysis. They considered morphometric parameters for analysing the prioritization of sub-watersheds using only the digital elevation model (DEM). We have incorporated the effect of land use land cover and soil type using curve number method.

We adopted a comprehensive and novel approach considering curve number with the help of the Support
Vector Machine classified land use and land cover map using Principal Component Analysis (PCA) based approach along with morphometry because a single or limited set of parameters cannot accurately represent the flood hazard potential of any sub-watershed. Each of the linear, aerial and relief morphometric parameters along with the curve number are considered for assessing the flood influencing characteristics of the Vishwamitri River's sub-watersheds, as LULC and soils have a direct relationship with runoff generation in the watershed. Moreover, the ability of the rain-on-grid model at the watershed scale to simulate flood events and predict flood-prone areas, considering multiple rain gauge data, which will facilitate more accurate flood inundation where ground-based observational data are unavailable is shown. As there is a significant lack of local-level information in the data-scarce region on rating curves and inundation mapping. The framework provided may effectively allow early warning systems to perform better during support decision-making so that protective measures can be designed to reduce fatalities and economic losses due to inundation hazards.

2. Study area

The present study was conducted in the Vishwamitri Watershed in Vadodara district, Gujarat. Vadodara district is located at the south of the Tropic of Cancer in the transition zone of heavy rainfall areas of South Gujarat and arid areas of North Gujarat plains. It has a subtropical climate with moderate humidity and forms a part of the great Gujarat plain. The eastern portion of the district is hilly terrain with several ridges, plateaus, and isolated relict hills with an elevation of 150–481 m above the mean sea level. The Vishwamitri River originates from the hills of Pavagadh, 43 km northeast of Vadodara. The Vishwamitri River has a channel length of around 70 km, of which, 58 km flows through the Vadodara district. It meets the Dhadhar River at Pingalwara in the Vadodara district. (Figure 1) shows the geographical location of the study area.

The European Space Agency’s Sentinel–2 Multispectral Imager measures the reflected solar spectral radiances in 13 spectral bands ranging from the visible to the shortwave infrared bands (Pahleven et al. 2017). The primary purpose is to monitor

![Figure 1. Geographic location of the study area.](image-url)
Table 1. Data characteristics of Cartosat DEM and Sentinel–2 data used in the study.

| Acquisition technique       | Spatial resolution | Projection |
|-----------------------------|--------------------|------------|
| Cartosat DEM                | 1 arc-second or 30 metres | WGS84     |
| Sentinel-2                  | Band 2-Blue        | 10 m       |
|                             | Band 3-Green       | 10 m       |
|                             | Band 4-Red         | 10 m       |
|                             | Band 5-Vegetation Red Edge | 20 m |
|                             | Band 6-Vegetation Red Edge | 20 m |
|                             | Band 7-Vegetation Red Edge | 20 m |
|                             | Band 8-NIR         | 10 m       |
|                             | Band 8A-Narrow NIR | 20 m       |
|                             | Band 11-SWIR       | 20 m       |
|                             | Band 12-SWIR       | 20 m       |

Vegetation, water bodies, cropland, urban areas and land use and land cover (LULC) change at local, regional, national and global scales. Sentinel–2A and –2B can together revisit the same region every five days with data acquisitions available in Level 1 C processing.

Ten Sentinel–2 bands were used in the study. The data characteristics of Cartosat DEM and Sentinel–2 data used in the study are given in (Table 1). Bands 1, 9 and 10 at 60 m resolution are dedicated mainly to atmospheric corrections and cirrus-cloud screening. As they do not contain surface information, those these bands were omitted after the pre-processing phase from the analysis.

According to the classification based on soil texture, seven types of HSG (Hydrologic Soil Group), (USDA 1986), soils are found in the Vishwamitri watershed (Figure 2). Typic Ustifluvents and Fluventic Haplustepts correspond to HSG group A, Udic Haplustepts corresponds to HSG group B, Chromic Haplusterts and Typic Haplustepts correspond to HSG group C and Lithic...
Haplustepts and Vertic Haplustepts corresponds to HSG group D. The most dominating soil, Chromic Haplusterts (HSG group C), covers 48.94% of the total watershed area. HSG-A has the lowest runoff potential (typically contains more than 90% sand and less than 10% clay), HSG-B has moderately low runoff potential (typically contains between 10 and 20% clay and 50 and 90% sand), HSG-C has moderately high runoff potential (typically contains between 20 to 40% clay and less than 50% sand) and HSG-D has high runoff potential (typically contains more than 40% clay and less than 50% sand).

3. Methodology

The methodology used in the study is presented in (Figure 3). Drainage was created from the Cartosat-1 30 m digital elevation model in the GIS environment. The Arc Hydro tools were used for the generation of drainage, which is more rational and consistent compared to the manual approach. To remove small imperfections in the DEM data for proper determination of flow direction and flow accumulation grids, the fill sink tool was used. DEM sinks were identified and filled. A sink is a cell in DEM that does not have an associated drainage value. The direction that water will flow from that particular cell is based on the underlying topography of the landscape. A raster of the flow direction from each pixel to its downslope neighbours is created by the flow-direction tool. Flow accumulations locate cells with a high flow where streams and channels are to be expected. The accumulated flow as the accumulated weight of all pixels flowing into each downslope pixel in the output raster is calculated by the flow accumulation tool. A stream network was delineated by applying a threshold value to the flow accumulation raster. The point on the surface at which water flows out of an area is called the outlet or the pour point. Each cell has an outlet point called a pour point that indicates the location where water would naturally flow out of the cell. Pour points must be located in cells with a high cumulative flow. (Figure 4) shows the methodology adopted for watershed delineation. The area of the derived

![Diagram of methodology](image-url)
watershed is calculated by calculating the geometry of the watershed polygons in the GIS environment. Using the mathematical formulas given in (Table 5), morphometric analysis of the parameters, namely, stream order, stream length, bifurcation ratio, relief ratio, drainage density, drainage frequency, drainage texture, form factor, length of overland flow, ruggedness number, circulatory and elongation ratio, area, perimeter and basin lengths of all five sub-watersheds is carried out. Single or limited parameters cannot present the comprehensive picture of the flood hazard potential of any sub-watershed, and hence, each of the linear, aerial and relief morphometric parameters along with curve number is taken into consideration for assessing the flood influencing characteristics of the five sub-watersheds of the Vishwamitri watershed (Table 7), as these parameters have a direct but variable relationship with flood runoff. Therefore, influencing value or rank (highest weightage 5 and least 1) is given to each sub-watershed based on the nature of the selected parameter (Table 8). Prioritization was achieved through the allocation of weights to the individual indicators contributing to flood runoff and a compound value \( C_v \) was calculated for final prioritization. \( C_v \) is derived by calculating the average of ranks assigned to the individual parameters. The sub-watershed with the highest \( C_v \) is contributing most to flood runoff, as a result, needs the highest priority for flood mitigation measures, whereas sub-watershed with lowest \( C_v \) is contributing least to flood runoff thereby in low priority. Thus an index of high, medium and low priority was produced.

The hypsometric analysis is useful to understand the geomorphometric stage of a River basin and to assess factors forcing the basin evolution (Markose and Jayappa 2011). By graphing the relative area along the abscissa and relative elevation along the ordinate, the hypsometric curve is obtained. The relative area is obtained as a ratio between the area above a particular contour and the total area of the watershed encompassing the outlet. The relative elevation is calculated as the ratio between the height of a given contour \( h \) from the base plane and the maximum basin elevation \( H \) (up to the remote point of the watershed from the outlet) (Sarangi et al. 2001; Lama and Maiti 2019). The curve obtained provides a measure of the distribution of land mass volume remaining below or above a basal reference plane. The area under the hypsometric curve (Hypsometric integral (HI)) indicates the erosion process dynamics in a watershed. The shape of the hypsometry curve shows the evolutionary stage of a basin. As illustrated in (Figure 5) the curves with convex shapes are related to young basin morphologies while basins with concave curved shapes are more mature basins.

Hypsometric Integral (HI):

\[
HI = \frac{[Elev_{mean} - Elev_{min}]}{[Elev_{max} - Elev_{min}]}
\]

where,

\( Elev_{mean} = \) average elevation of the catchment
\( Elev_{min} = \) minimum elevation within the catchment

Figure 5. Hypsometric curves – young, mature and old stages – showing toe, head and body.
Elev_{max} = \text{maximum elevation within the catchment}

This work intends to examine the findings of situations for which no observed data or very limited data, related to flooded areas and discharge, are available. This is the typical situation in small watersheds that, very often, are ungauged catchments for which it is not possible to have data for model calibration and validation. In circumstances like these, the reliability of the commercial or open source applications should be measured using a state-of-the-art research model that is developed for benchmarking purposes. For these reasons, we have considered an observed storm event (30–07–2019 to 03–08–2019) for modelling. This period of storm event witnessed the stronger than normal cross-equatorial flow and active monsoon conditions over major parts of the watershed during last week of July to the first phase of August in the year 2019. For rainfall-runoff simulations at the watershed scale, the runoff was evaluated with the well-known SCS-CN method, the potential maximum soil retention is calculated using the following formula:

\[
S = \frac{25400}{CN} - 254
\]  

(2)

where \( S \) is in mm, and \( CN \) is the curve number (dimensionless).

SCS-CN assumes that, for a single storm event, potential maximum soil retention is equal to the ratio of direct run-off to available rainfall. This relationship, after algebraic manipulation and inclusion of simplifying assumptions, results in the following expression:

\[
\text{DailyRunoff} (\text{mm}) = \frac{(P - l_0)^2}{(P + S - l_0)} = \frac{(P - \lambda S)^2}{P + (1 - \lambda) S} \quad \text{for} \ P > \lambda S
\]  

(3)

\( Q \) = direct run-off depth
\( P \) = total rainfall
\( l_0 \) = initial abstraction
\( l_0 \) and \( S \) can be related using the following equation:

\[
l_0 = \lambda S
\]  

(4)

\( \lambda = 0.2 \) was assumed in the original SCS-CN model.

The Hydrologic Engineering Center’s Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) is an extension to ESRI’s ArcGIS software that computes the curve number and other loss rate parameters based on various soil and land use/land cover databases. HEC-GeoHMS is used to create the curve number with the help of the Support Vector Machine classified land use and land cover map using PCA based approach and soil map containing hydrological soil groups (Rana and Suryanarayana 2020b). Sentinel–2 Level 1 C data were processed from Top-of-Atmosphere Level 1 C to Bottom-of-Atmosphere Level 2A using QGIS desktop 3.6.1. QGIS desktop 3.6.1 is a free and open-source cross-platform desktop geographic information system application that supports viewing, editing, and analysis of geospatial data. QGIS desktop 3.6.1 interface was used with Semi-Automatic Classification Plugin (SCP), developed by (Congedo 2016), to convert the Sentinel–2 MSI data to reflectance values and for dark object subtraction atmospheric correction (DOS1) of the data. After atmospheric correction, ten bands (2–8, 8A, 11 and 12) were composited and clipped to the study area. The processed data were georeferenced to the WGS 84 UTM 43 N projected coordinate system. The PCA technique was used to reduce the number of bands or dimensions necessary for classification. Dimension reduction leads to a reduction in the computation costs without compromising the desired variability in the data. PCA is a statistical procedure that transforms the input bands (with correlated variables) orthogonally from an input multivariate attribute space to a new multivariate attribute space (having linearly uncorrelated variables) whose axes are rotated with respect to each other. Transformation or dimensionality reduction of the data in the analysis compresses data by eliminating noise, redundancy and irrelevant information. The linearly uncorrelated variables in the new multivariate attribute space are called principal components. The first principal component (PC1 derived from the first eigenvector) is the direction in space along which projections have the largest variance. The subsequent principal component (PC2) is the direction that maximizes variance among all directions orthogonal to the previous principal component. The supervised classification Support Vector Machine (SVM) algorithm is applied on principal components of Sentinel–2 cloud-free data for classifying the data into seven major land use and land cover classes namely water, built-up, mixed forest, cultivated land, barren land, fallow land with vertisols dominance, and fallow land with inceptisols dominance (Table 2). SVM operates on the principle of statistical learning theory, called structural risk minimization, which minimizes an upper bound on the generalization error. It aims at reaching the minimum of the upper bound on the error.

| Land use/land cover | Description |
|---------------------|-------------|
| Built up            | Residential area, industrial area, roads, pavements, settlements |
| Water               | Ponds, lakes, River, permanent open water |
| Vegetation          | Trees, vegetation, mixed forest, sparsely vegetated parks, cultivated land crop |
| Baresoil            | Fallow land with vertisols dominance, fallow land with inceptisols dominance, earth and sand land in-fillings, and the remaining land cover types |
probability of the classifier by achieving a trade-off between the training set and the capacity. The basic approach in support vector machines is to identify a hyper-plane that produces an optimal separation between the two classes. SVM classification with a hyperplane that maximizes the separating margin between the two classes. The algorithm defines the multidimensional space in such a way that the gap between class clusters is as large as possible. The hyperplane is developed using a subset of the data called the training data set and the generalizing ability of the developed hyper-plane is validated using an independent subset called testing data set. If the training dataset is not linearly separable, a kernel method is used to simulate a non-linear projection of the data in a higher-dimensional space, where the classes are linearly separable (Oommen et al. 2008).

The key element of a quantitative accuracy assessment is the creation of a confusion matrix. The confusion matrix is represented by a table that shows the correspondence between the classification result and a reference image assigned to a particular category, which is relative to the actual category as indicated by the reference data. The accuracy and quality of the reference data should be at least one order better as compared to the data to be evaluated. DigitalGlobe’s WorldView-4 data (Product Id: 1ba34688-3ee0-41e4-9187-de68fdb075df-inv) with 31 cm resolution was used for the accuracy assessment. The accuracy assessment was done by overall accuracy, producer’s and user’s accuracies, and Kappa coefficient. Overall accuracy indicates the quality of the map classification, producer’s accuracy indicates the quality of the classification of training set pixels and user’s accuracy indicates the probability that a value predicted to be in a certain class is really in that class. The kappa coefficient value measures the agreement between classification and truth values. A kappa value of unity represents a perfect agreement, whilst a value of zero represents no agreement or expected by chance:

\[
\text{Overall accuracy} = \frac{\text{Total number of correctly classified pixels}}{\text{Total number of reference pixels}} \tag{5}
\]

\[
\text{Producer's accuracy} = \frac{\text{Number of correctly classified pixels in each category}}{\text{The number of training set pixels of the corresponding category}} \tag{6}
\]

\[
\text{Users accuracy} = \]

\[
\text{Kappa coefficient} = \frac{\text{Observed agreement} - \text{Expected agreement}}{1 - \text{Expected agreement}} \tag{8}
\]

A logical condition is defined in ArcGIS to generate the curve number raster file from the raster files of hydrologic soil group and land use and land cover using TR-55 table (Feldman 2000). The tables provide estimates of the Curve Number as a function of hydrologic soil group, cover type, treatment, hydrologic condition, antecedent runoff condition and impervious area in the catchment. Selected Curve Number values for the study area are given in (Table 3).

The most popular and most used model in both the scientific literature and in practice amongst the software packages using physically oriented equations. The Hydrologic Engineering Centre-River Analysis System (HEC-RAS) was developed by the U.S. Army Corps of Engineers. In the latest release version (5.0.7), the HEC-RAS model is complemented by new modules, which include complete 2-D calculations based on 2-D fully dynamic equations and 2-D diffusion wave equations that ignore inertial conditions. It also provides the possibility of 1-D/2-D combined simulations, which aim to combine both a full

| LULC                     | Sub-classes of LULC | HSG- A | HSG- B | HSG- C | HSG- D |
|--------------------------|---------------------|--------|--------|--------|--------|
| Water                    | Water               | 100    | 100    | 100    | 100    |
| Cultivated land          | Cultivated land     | 64     | 75     | 82     | 85     |
|                          | crop 1              | 71     | 80     | 87     | 90     |
|                          | crop 2              | 74     | 83     | 88     | 90     |
| Barren land              | Barren land         | 77     | 86     | 91     | 94     |
| Fallow land (Vertisols)  | Fallow land 1       | 76     | 85     | 90     | 93     |
|                          | dominated           |        |        |        |        |
|                          | Vertisols           |        |        |        |        |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
| Fallow land (Inseptisol) | Fallow land 1       | 74     | 83     | 88     | 90     |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
|                          | dominated           |        |        |        |        |
| Mixed forest             | Mixed forest        | 36     | 60     | 73     | 79     |
| Built up                 | Built up            | 89     | 92     | 94     | 95     |
| Mixed builtup 1          |                      | 83     | 89     | 92     | 93     |
| Mixed builtup 2          |                      | 89     | 92     | 98     | 98     |
2-D and a full 1-D. The numerical simulation of the flood event was undertaken using HEC-RAS-v-5.07 using 2D shallow water equations:

\[
\frac{\partial H}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = r
\]  (9)

\[
\frac{\partial p}{\partial t} + \frac{\partial (p^2)}{\partial x} + \frac{\partial (pq)}{\partial y} = -\frac{n^2 pg}{h^2} \left( p^2 + q^2 \right) - gh \frac{\partial H}{\partial x} + pf
\]  

\[+ \frac{\partial}{\partial x} (h \tau_{xx}) + \frac{\partial}{\partial y} (h \tau_{xy}) \]  (10)

\[
\frac{\partial q}{\partial t} + \frac{\partial (pq)}{\partial x} + \frac{\partial (q^2)}{\partial y} = -\frac{n^2 qg}{h^2} \left( p^2 + q^2 \right) - gh \frac{\partial H}{\partial y} + qf
\]  

\[+ \frac{\partial}{\partial x} (h \tau_{xy}) + \frac{\partial}{\partial y} (h \tau_{yy}) \]  (11)

where \(H(x, y, t) = z(x, y) + h(x, y, t)\) is the surface elevation (m), \(z\) is the cell elevation in the cartesian coordinates \(x, y\), \(h\) is the water depth (m), \(p = h + u^2 + v^2\) and \(q = h + u \cdot v\) are the specific flow in the \(x\) and \(y\) directions (m² s⁻¹), \(u\) and \(v\) are the velocities in \(x\) and \(y\) respectively, \(r\) is the net rain rate (m), \(g\) is the gravity acceleration (m² s⁻¹), \(n\) is the Manning’s roughness coefficient (s m⁻¹³), \(\rho\) is the water density (kg m⁻³), \(\tau_{xx}, \tau_{xy}\), and \(\tau_{yy}\) are the components of the stress tensor and \(f\) is the Coriolis parameter (s⁻¹). When the diffusive wave is selected, the inertial terms in Equations (10) and (11) are neglected. The 2D diffusion wave equations were preferred in the present study due to their faster computing time and higher stability properties (Brunner 2016). The above equations are solved with an implicit finite-volume scheme. The area of the model is divided into grid cells, where each cell uses the underlying terrain data with less loss in resolution (sub grid model). For each cell and cell face, HEC-RAS generates a detailed hydraulic property table (such as elevation-volume relationship, elevation-area, etc.). As regards the boundary conditions, we have not specified the upstream boundary condition due to the nature of the simulation. The boundary of the model is generally characterized by a closed boundary (watershed ridge line) except where an open line boundary condition with normal depth is drawn at the downstream section of the watershed to allow outflows from the watershed, which means uniform flow condition. Based on the modelled results for the storm event, an inundation map is prepared for Vadodara city which is further assisted by field sites visit.

4. Results

Watershed morphometry reveals lumped or semi-distributed watershed features. Watershed hydrology is highly influenced by its morphometry. Runoff potential is directly related to a variety of morphometrical parameters including drainage density, drainage frequency, mean bifurcation ratio, drainage texture and elongation ratio (i.e. the greater the values of these parameters are, the greater the watershed’s runoff potential and vice versa). Morphometric parameters were directly calculated from the Cartosat-1 30 m DEM by using Arc-hydro tools. Morphometry of Vishwamitri watershed and sub-watersheds (Figure 6), and its hydrological importance is discussed in detail below.

4.1. Basic parameters

The basin length (\(L_b\)) is the longest length of the watershed from the head waters to the point of confluence. The basin length determines the shape of the watershed. High basin length indicates elongated watershed. The computed \(L_b\) for the Vishwamitri watershed using Arc-hydro tool is 66.232 km. Another significant parameter is the area of the watershed (\(A\)), the computed Vishwamitri watershed area is 1289.39 km². Perimeter of watershed (\(P\)) is the outer boundary of the watershed that enclosed its area and used as watershed size and shape indicator. The computed perimeter for the Vishwamitri watershed using GIS software is 279.44 km.

4.2. Linear, aerial and relief morphometric parameters

Stream order (\(S_o\)): Stream ordering is a method of assigning a numeric order to links in a stream network. It is defined as a measure of the stream’s position in the hierarchy of tributaries. There are different systems available for ordering streams. Based on the system of stream order (Strahler 1964), the watershed has been designated as a fifth-order watershed in (Figure 7). The stream order increases when streams of the same order intersect. Therefore, the intersection of two first-order links will create a second-order link, the intersection of two second-order links will create a third-order link, and so on. The intersection of two links of different orders, however, will not result in an increase in order. For example, the intersection of a first-order and second-order link will not create a third-order link but will retain the order of the highest ordered link. In the present investigation, the maximum frequency is observed in the first-order streams (Table 4). More number of first-order streams is observed in the hilly region of the study area, which points towards terrain density and compacted nature of the bedrock lithology.
Stream Length ($L_u$): The total length of individual stream segments of each order is the stream length of that order. Generally, the total length of stream segments is the maximum in first-order streams and decreases with an increase in the stream order. Streams of relatively short lengths represent areas of...
Table 4. Computed stream order, stream number, stream length and bifurcation ratio.

| Stream order ($S_o$) | Stream number ($N_o$) | Stream length ($L_o$) | Bifurcation ratio ($R_b$) |
|----------------------|------------------------|------------------------|--------------------------|
| 1                    | 85                     | 294.5                  | 2.1                      |
| 2                    | 39                     | 124.7                  | 1.3                      |
| 3                    | 30                     | 88.1                   | 3                        |
| 4                    | 10                     | 33.0                   | 2                        |
| 5                    | 5                      | 16.7                   |                          |
| Total                | 169                    | 557.1                  | Mean 2.1                 |

Table 5. Computation of basic, linear, relief and shape morphometric parameters of Vishwamitri watershed.

| Morphometric parameters | Formulae | Units | Calculated values |
|-------------------------|----------|-------|-------------------|
| Basin length ($L_b$)    | $\Sigma u\cdot A$ | Km | 66.232 |
| Area (A)                | Area of watershed | Km$^2$ | 1289.39 |
| Perimeter (P)           | Length of the watershed boundary | Km | 279.44 |
| Stream order ($S_o$)    | Hierarchical rank (Strahler Scheme) | Dimensionless | 5 |
| Stream length ($L_o$)   | $L_o = L_1 + L_2 + \ldots + L_n$ | Km | 557.1 |
| Stream number ($N_o$)   | $N_o = N_1 + N_2 + \ldots + N_n$ | Dimensionless | 169 |
| Bifurcation ratio ($R_b$) | $R_b = \Sigma N_o + 1$; $R_b$ was computed as the ratio between the number of streams of any given order to the number of streams in the next higher order | Dimensionless | 2.12 |
| Mean Bifurcation Ratio (Rbm) | $Rbm = \text{Average of bifurcation ratios of all orders}$ | Dimensionless | 0.43 |
| Drainage density (D_d)  | $D_d = \Sigma u\cdot A$; The ratio between the total stream length of all orders to the area of the basin | (km/km$^2$) | 0.13 |
| Drainage frequency (F_d) | $F_d = \Sigma u\cdot A$; The ratio between total number of streams and area of the basin | (no./km$^2$) | 0.011 |
| Drainage texture (T_d)  | $T_d = \Sigma u\cdot P$; Where, $P = \text{Perimeter (km)}$ | (no./km) | 0.034 |
| Relief ratio ($R_r$)    | $R_r = H/L$; Where, $R_r = \text{Relief ratio}; H = \text{Total relief of the basin in Kilometre}; L_b = \text{Basin length}$ | Dimensionless | 0.032 |
| Ruggedness number ($R_r$) | $R_r = B_0 \times D_0$; Where, $B_0 = \text{Basin relief}; D_0 = \text{Drainage density}$ | Dimensionless | 0.29 |
| Form factor (F_r)       | $F_r = A/L_0^2$; The ratio of the basin area to the square of the basin length | Dimensionless | 0.21 |
| Circularity ratio ($R_c$) | $R_c = 4\pi A/P^2$; Where, $R_c = \text{Circularity ratio}; \pi = \text{'Pi' value that is 3.14}; A = \text{Area of the basin (km$^2$)}; P = \text{Perimeter (km)}$ | Dimensionless | 0.61 |
| Elongation ratio ($R_e$) | $R_e = (2L_0)^2 \times \sqrt{(A/m)}$; Where, $Re = \text{Elongation ratio} A = \text{Area of the basin (km$^2$)}; \pi = \text{'Pi' value that is 3.14}; L_0 = \text{Basin length}$ | Dimensionless | 1.16 |
| Length of overland flow ($L_o$) | $L_o = 1/(D_o \times 2)$; Where, $D_o = \text{Drainage density}$ | Km | 1.16 |

steep slopes and finer texture, while longer lengths of the stream are generally indicative of low gradients. The mean and total stream length of each stream order is tabulated in (Table 4).

**Bifurcation Ratio ($R_b$):** The bifurcation ratio is the ratio of the number of the stream segments of given order $N_o$ to the number of streams in the next higher-order ($N_o + 1$). $R_b$ is an important parameter to affect the peak of the runoff hydrograph (Jain and Sinha 2003). High $R_b$ values indicate instantaneous discharge and the possibility of flash flooding during extended rainy hours (Rakesh et al. 2000). However, $R_b$ does not precisely remain constant between stream orders because of variations in watershed geometry, lithology, and tectonics. The flat terrains have low $R_b$ values, whereas mountainous or highly dissected terrains have values from 3 to 5 (Horton 1945; Strahler 1957). In the present study, the mean bifurcation ratio ($R_{bm}$) for the overall watershed is 2.12. The low $R_{bm}$ value for the Vishwamitri watershed suggests a delayed hydrograph peak. The lower values of $R_{bm}$ are an indicator of the watersheds, which have undergone fewer or less structural disruptions and the drainage pattern has not been distorted because of structural disturbances (Nag 1998). The higher value of $R_b$ indicates highly dissected terrain, mature topography with a higher degree of drainage integration and higher discharge potential (Eze and Efiong 2010). In particular, the high $R_b$ value of sub-watershed SW 1 indicates an early hydrograph peak with a high potential for flash flooding during the storm events among all the sub-watersheds. It is usual to use the weighted mean $R_b$ value to characterize a watershed using a more representative value in a situation when the values of $R_b$ differ for sequential stream orders. For this reason, the weighted mean $R_b$ of the study watershed was calculated as follows:

$$\text{Weighted mean bifurcation ratio (WRB)} = \frac{R_{b1}N(u_1) + R_{b2}N(u_2) + R_{b3}N(u_3) + R_{b4}N(u_4)}{\text{Total number of stream segments}}$$

Where,
$R_{b1}$ = bifurcation ratio between first and second order  
$R_{b2}$ = bifurcation ratio between second and third order  
$R_{b3}$ = bifurcation ratio between third and fourth order  
$R_{b4}$ = bifurcation ratio between fourth and fifth order  
$N(u_1)$ = total number of streams involved in $R_{b1}$ computation  
$N(u_2)$ = total number of streams involved in $R_{b2}$ computation  
$N(u_3)$ = total number of streams involved in $R_{b3}$ computation  
$N(u_4)$ = total number of streams involved in $R_{b4}$ computation

The weighted mean bifurcation ratio (WRB) for the watershed of Vishwamitri is 3 indicates that geological structures (tectonic activity) exert very low influence on the pattern of streams.

**Drainage density ($D_d$):** Drainage density of the watershed is calculated by dividing the total length of streams of all orders by the drainage area of the watershed to indicate the closeness of spaces between channels. In other words, it provides the quantitative value for the average length of all channels for the whole watershed. The measurement of drainage density provides a numerical measurement of landscape dissection and runoff potential (Reddy, Maji, and Gajbhiye 2004). The $D_d$ of Vishwamitri watershed is 0.43 km/km². The $D_d$ of sub-watersheds ranges from 0.35 to 0.5. Drainage density has been classified with the following value ranges (km/km²), i.e. very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8) (Sukristiinyati, Maria, and Lestiana 2018). A high value of $D_d$ indicates a relatively high density of streams, high runoff, a quick stream response, and consequently, a low infiltration rate. By contrast, the low drainage density of a watershed implies low runoff and takes a longer time to peak. The low class of $D_d$ shows a poorly drained watershed with a slow hydrologic response. Besides, the low class of $D_d$ has a resistant permeable subsurface material, dense vegetation cover, and low relief.

**Drainage frequency ($F_s$):** Drainage frequency is defined as the total number of streams per area unit. The result (Table 7) shows that $F_s$ is maximum in sub-watershed SW III (0.19/km²), followed by SW II and SW V (0.15/km²), SW IV (0.14/km²) and SW I (0.10/km²). The discharge from SW I takes a longer time to peak because of low runoff rates due to the lesser number of streams. Overall, the results of $F_s$ reflect early peak discharge for sub-watersheds in order of their decreasing drainage frequency value, resulting in flash floods. $F_s$ for Vishwamitri watershed is 0.13/km².

**Drainage Texture ($R_n$):** Drainage texture is defined as the total number of stream segments of all orders in a River watershed to the perimeter of the watershed. According to (Smith 1950), the drainage texture has been classified into very coarse (<2), coarse (2–4), moderate (4–6), fine (6–8) and very fine (>8). According to this classification, the Vishwamitri watershed has a very coarse drainage texture (0.6 km⁻¹). Also, The $R_n$ value for Vishwamitri sub-watersheds ranges from 0.14 to 0.35. Hydrologically very coarse texture watersheds have large basin lag time periods (Altaf, Meraj, and Romshoo 2013).

**Relief ratio ($R_r$):** The relief ratio is called the maximum relief of the horizontal distance parallel to the main drainage line along the longest dimension of the watershed. It is a good indicator of the intensity of water flows from a catchment slope. It is the measurement of the overall steepness of a watershed. The high $R_r$ implies shorter lag time and the watershed attains higher peak discharge and flow velocities. With increasing relief, steeper hill slopes and higher stream gradients, the time of concentration of runoff decreases, thereby increasing flood peaks (Bhatt and Ahmed 2014). The $R_r$ for the Vishwamitri watershed is 0.01, indicating overall nearly flat terrain or lower slope values. The $R_r$ values for the sub-watersheds range between 0.00 and 0.02. The SW III, SW IV and SW V having 0 $R_r$ indicating a flat terrain with a longer basin length and their influence on the flood is very less. While sub-watersheds SW I and SW II have relatively high values of $R_r$ and contribute more water in a short period of time and cause floods in the lower region of the watershed.

**Ruggedness number ($R_n$):** The ruggedness number is expressed as the product of watershed relief and drainage density. High $R_n$ occurs in those watersheds which have steep and long slopes and fine texture, thus, is highly susceptible to erosion and increased peak discharge. The slope is another important indicator of runoff, which provides a general representation of relief ruggedness within the watershed. The calculated $R_n$ value of Vishwamitri watershed is 0.32. The low $R_n$ value of Vishwamitri watershed due to low relief and a lesser degree of terrain complexity, causing less water flow. In the upper Vishwamitri watershed, SW I and SW II have relatively high $R_n$ values, indicating that they have high relief, fine texture and possibilities of high surface flow (Table 7). Moreover, these sub-watersheds are susceptible to erosion and producing increased peak discharge. The SW III, SW IV and SW V have the lowest $R_n$ values because of low relief and a lesser degree of terrain complexity causing less water flow.

**Form factor ($F_f$):** Form factor is the ratio of the area of the watershed and square of the watershed length. $F_f$ represents the shape or outlines of a watershed and is useful in predicting the flow intensity of a catchment.
and has a direct link to peak discharge. High $F_r$ values occur in the watersheds having the potential to produce high peak flows in a short duration and low $F_r$ values are vice versa. For a perfectly circular watershed, the form factor value would always be greater than 0.78. The smaller the value of the form factor, the more elongated will be the watershed. The low $F_r$ value of 0.29 of Vishwamitri watershed reveals that the shape of the watershed is elongated, it has less side flow for shorter duration and high main flow for longer duration. $F_r$ of sub-watersheds of the Vishwamitri watershed is given the (Table 7). The $F_r$ values for the sub-watersheds range between 0.1 and 0.3, indicate the elongated shape of sub-watersheds.

**Circularity ratio ($R_c$):** Circularity ratio is the ratio between the areas of a watershed to the area of the circle having the same circumference as the perimeter of the watershed. The $R_c$ values can attain a maximum of 1.0 where the outline of the watershed is approaching near circularity. A numerically low $R_c$ indicates an elongated shape, while higher values are expression of approach to near circularity. Elongated watersheds are characterized by longer lag times and lower peak discharge. In study area, the overall $R_c$ value of Vishwamitri watershed is 0.21 and, for sub-watersheds, it range from 0.07 and 0.2. The $R_c$ values suggest the elongated shape of the Vishwamitri watershed and its sub-watersheds.

**Elongation ratio ($R_e$):** It is defined as the ratio of the diameter of a circle with the same area as that of the watershed to the maximum basin length. The $R_e$ values vary from 1 for circular watersheds and 0 for elongate watersheds. High $R_e$ values occur for circular watersheds, considered highly hazardous because they yield peak flow in a short period of time compared to low $R_e$ in elongated watersheds (Masoud 2016). These values can be grouped into three categories, namely, circular ($>0.9$), oval (0.9–0.8), less elongated 0.8–0.7) and elongated (<0.7) (Lama and Maiti 2019). The overall $R_e$ value of the Vishwamitri watershed is 0.61 and, for sub-watersheds, it ranges from 0.37 and 0.62.

**Length of Overland Flow ($L_o$):** Length of overland flow is a length of water over the ground before it gets concentrated into certain stream channels. There are three classes of $L_o$ i.e. low value (< 0.2), moderate value (0.2–0.3) and high value (>0.3). The low $L_o$ value shows high relief and short flow paths, which are more susceptible to flash flooding. Meanwhile, a high $L_o$ value implies gentle slopes and long paths of flow. $L_o$ value for the overall watershed is 1.43 and, for sub-watersheds, it ranges from 1 and 1.43. The SW I has the lowest value of $L_o$, which means it is more susceptible to flash flooding.

### 4.3. Hypsometry analysis

The hypsometry and the HI are used in classical conceptual geomorphometric models of landscape evolution as follows: (i) for HI above 0.60 the area is considered young; (ii) for HI ranging between 0.35 and 0.60 the area is in a steady-state balance or mature phase and (iii) HI below 0.35 characterizes a Monadnock phase in landscape evolution. Vishwamitri watershed is certainly indicative of a marked old stage in the basin’s evolution (Figure 8), meaning that the watershed has reached the equilibrium in the longitudinal profiles of the River. This is further attested by a very low hypsometric integral (HI = 0.04). A low value of HI occurs in terrains characterized by isolated relief feature standing above extensive level surfaces (Pike and Wilson 1971).

The hypsometric analysis is important to analyse as an erosional process directly affects the morphometric of the watershed. Based on the hypsometric analysis the Vishwamitri watershed is stable or in the old stage of the erosional process, the computed flood influencing parameters and calculated compound value of the watershed will hold true until there is a major structural disturbance that occurred due to tectonic activity. If the HI value were high, the computed flood influencing parameters and calculated compound value of the Vishwamitri watershed would need to be calculated again to compensate for the changes that occurred due to the erosional process of the young watershed.

### 4.4. Land use/land cover

The pattern of land usage influences the runoff of any watershed. A more accurate LULC map (Figure 9) is necessary for calculating hydrological elements. Image processing techniques can generate images that show some characteristics, especially cover types such as areas with vegetation, bodies of water, bare soils, etc. Land use and land cover classes were selected based on knowledge about the study area. Seven major land use and land cover classes were identified, viz., Water, Built-up, Mixed forest, Cultivated land, Barren land, Fallow land with Vertisols dominance, and Fallow land with Inceptisols dominance. The classification was conducted using PCA-based approach using Sentinel–2 bands. Training data for each land use and land cover class were collected as a group of pixels. Stratified random sampling was used to obtain the testing data. The overall classification accuracy of land use/land cover map was 76%. Major portion of the study
area (about 35%) is agricultural land (cultivated land, fallow land with vertisols dominance and fallow land with inseptisol dominance) followed by sparsely vegetated (19%), mixed forest (14%), Built up (12%), barren land (5%) and water bodies (2%). The results of the accuracy assessment are given in (Table 6).

4.5. Compound value and weightage

Based on the integration of each flood influencing parameter and calculated compound value, the SW I and IV of Vishwamitri watershed have been categorized into high priority, SW II and V into moderate
Table 6. Accuracy assessment results.

| Land use/land cover | Sub-classes of land use/land cover | Producer’s accuracy | User’s accuracy |
|---------------------|------------------------------------|---------------------|----------------|
| Water               | Water                              | 1.00                | 1.00           |
| Vegetation          | Cultivated land Crop 1             | 0.80                | 0.57           |
|                     | Mixed forest                       | 0.33                | 0.25           |
|                     | Cultivated land Crop 2             | 0.60                | 0.67           |
|                     | Sparsely vegetated                 | 0.88                | 0.88           |
| Baresoil            | Barren land                        | 0.50                | 0.43           |
|                     | Fallow land 1 Vertisols dominance  | 0.60                | 0.86           |
|                     | Fallow land 2 Vertisols dominance  | 1.00                | 0.60           |
|                     | Fallow land 1 Inseptisol dominance | 1.00                | 0.67           |
|                     | Fallow land 2 Inseptisol dominance | 0.75                | 1.00           |
| Built up            | Built up                           | 0.86                | 1.00           |
|                     | Mixed builtin 1                    | 1.00                | 1.00           |
|                     | Mixed builtin 2                    | 0.56                | 1.00           |
| Kappa coefficient   | 0.74                               |                     |                |
| Overall accuracy    | 76.00                              |                     |                |

Table 7. Flood influencing characteristics of the five sub-watersheds of the Vishwamitri watershed.

| Sub-watershed ID | I   | II  | III | IV  | V   |
|------------------|-----|-----|-----|-----|-----|
| Form factor (F)  | 0.166 | 0.154 | 0.108 | 0.304 | 0.208 |
| Circulatroy ratio (R_i) | 0.159 | 0.141 | 0.067 | 0.199 | 0.106 |
| Elongation ratio (R_e) | 0.459 | 0.442 | 0.371 | 0.622 | 0.515 |
| Drainage density (D_i) | 0.500 | 0.403 | 0.497 | 0.418 | 0.349 |
| Drainage texture (R_t) | 0.203 | 0.228 | 0.139 | 0.353 | 0.217 |
| Relief ratio (R_R) | 0.017 | 0.020 | 0.001 | 0.002 | 0.001 |
| Ruggedness number (R_q) | 0.362 | 0.293 | 0.015 | 0.024 | 0.011 |
| Weighted bifurcation ratio (WRB) | 3.643 | 2.119 | 3.155 | 3.213 | 3.205 |
| Length of overland flow (L_o) | 1.000 | 1.240 | 1.005 | 1.195 | 1.431 |
| Drainage frequency (F_s) | 0.102 | 0.150 | 0.189 | 0.138 | 0.151 |
| Curve number (C_n) | 81.972 | 83.060 | 81.197 | 81.846 | 83.607 |

4.6. 2D Hydraulic modelling for flood hazard assessment

HEC-RAS 5.0.7 only supports a single representative rainfall record. Consequently, a single representative daily rainfall record was created. Thiessen polygon of rain gauge stations is shown in (Figure 10). For M stations, the average precipitation P is calculated as

\[ P = \frac{1}{M} \sum_{i=1}^{M} P_i \]

The ratio \( \frac{A}{A_i} \) is called the weightage factor for each station. Precipitation data, Thiessen weightage factor, and calculations of Thiessen mean for storm event occurred on 30–07–2019 to 03–08–2019 are shown in (Tables 9 and 10).

Low CN values indicate low runoff potential while larger numbers indicate an increased runoff potential. The calculated curve number is also termed CN II or AMC II (Antecedent Moisture Condition II). The calculated curve number can be adjusted to dry moisture conditions (called AMC I) and high moisture conditions (called AMC III) by using adjusting factors. The calculated weighted curve number of the Vishwamitri watershed for AMC I, AMC II and AMC III are 68.99, 84.04 and 92.50, respectively. Empirical equations of daily runoff for Vishwamitri watershed for AMC I, AMC II and AMC III conditions are:

Table 9. Precipitation data and Thiessen weightage factor.

| Rain gauge station | Thiessen polygon area (Km²) | Thiessen weightage factor(fraction of total area) | Station reading (mm) on 30–07–2019 | Station reading (mm) on 01–08–2019 | Station reading (mm) on 02–08–2019 | Station reading (mm) on 03–08–2019 |
|--------------------|-----------------------------|-----------------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Padra              | 92                          | 0.07                                          | 6                                 | 78                                | 8                                 | 18                                 |
| Savid              | 178                         | 0.14                                          | 14                                | 36                                | 80                                | 4                                 |
| Vadodara           | 504                         | 0.39                                          | 37                                | 499                               | 32                                | 34                                |
| Waghodia           | 512                         | 0.40                                          | 8                                 | 126                               | 12                                | 22                                |
Table 10. Calculation of Thiessen mean.

| Rain gauge station | Weighted station rainfall (mm) on 30–07-2019 | Weighted station rainfall (mm) on 31–07-2019 | Weighted station rainfall (mm) on 01–08-2019 | Weighted station rainfall (mm) on 02–08-2019 | Weighted station rainfall (mm) on 03–08-2019 |
|--------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|
| Padra              | 0.43                                      | 5.57                                      | 0.57                                      | 1.29                                      | 1.93                                      |
| Vadodara           | 14.52                                     | 195.77                                    | 12.55                                     | 13.34                                     | 39.62                                     |
| Waghadia           | 3.18                                      | 50.14                                     | 4.78                                      | 8.75                                      | 25.87                                     |
| Thiessen mean of the station | 20.06                                   | 256.46                                    | 28.97                                     | 23.93                                     | 79.59                                     |

\[ Q_{\text{mm}} = \frac{(P - 22.83)^2}{(P + 114.16 - 22.83)} \text{ for AMCI} \]

\[ Q_{\text{mm}} = \frac{(P - 9.64)^2}{(P + 48.23 - 9.64)} \text{ for AMCI II} \]

\[ Q_{\text{mm}} = \frac{(P - 4.11)^2}{(P + 20.59 - 4.11)} \text{ for AMCI III} \]

The estimated daily runoff for the period 30–07-2019 to 03–08-2019 using weighted CN is given in (Table 11). Variation of curve number across the Vishwamitri watershed for AMC II condition is shown in (Figure 11).

Due to the unavailability of the cloud-free optical data or Synthetic Aperture Radar data and discharge data at the outlet of Vishwamitri watershed for the storm event. The validation of the inundation map was done by field visits for Vadodara city. The simulation shows good performance when comparing the simulation results with actual field data. Simulated peak flood for the storm event at Kalaghoda Bridge is shown in (Figure 12). The simulated result shows the peak flood of 884.729 m³/sec at Kalaghoda Bridge on 01–08-2019. Flood frequency analysis of observed flood peak data from (1996 to 2013) at Kalaghoda Bridge using Gumbel’s method shows that the simulated peak discharge has a return period close to 25 years (872.69 m³/sec). The magnitude of flood for different return periods calculated and is shown in (Table 12). Ward numbers 2, 5, 6 and 8 were severely affected by the flood, and the percentage of the area inundated in these wards varies from 35.69% to 39.86% (Table 13).
and Figure 13), and the average depth of inundation in these wards range from 1.66 m to 2.66 m. Ward numbers 4, 7, 10 and 12 were moderately affected by the flood and percentage of the area inundated in these wards varies from 16.34% to 21.92%, and the average depth of inundation in these wards range from 1.85 m to 2.75 m. Ward numbers 1, 3, 9 and 11 were marginally affected by the flood, and the percentage of the area inundated in these wards varies from 0.56% to 3.54%, and the average depth of inundation in these wards range from 0.62 m to 1.61 m. Flood hazard assessment, by means of flood mapping and identification of flood risk areas, is a crucial element in the formulation of any flood management strategy. In order to generate categories of flood hazards, the water depth for each flood extent was classified according to Japanese criteria by the Ministry of Land Infrastructure and Transportation (MLIT) (Table 14) (Quirogaa et al. 2016). The criteria suggest five categories of flood hazards: H1 – very low hazard (water depth < 0.5 m); H2 – low hazard (water depth between 0.5 and 1 m); H3 – medium hazard (water depth between 1 and 2 m); H4 – high hazard (water depth between 2 and 5 m); H5 – extreme hazard

![Figure 11. Variation of curve number across the Vishwamitri watershed for AMC II condition.](image)

Table 12. Magnitude of flood for different return period calculated using Gumbel’s flood frequency method.

| Return period (years) | Flood discharge (Cumecs) |
|-----------------------|--------------------------|
| 15                    | 752.69                   |
| 25                    | 872.69                   |
| 35                    | 951.73                   |
| 50                    | 1033.16                  |

Table 13. Inundation statistics for the Vadodara city.

| Ward no. | Ward name  | Ward area km² | Min depth (m) | Max depth (m) | Range (m) | Mean Depth (m) | Inundated area (km²) | Percentage of area Inundated |
|----------|------------|---------------|---------------|---------------|-----------|----------------|-----------------------|-----------------------------|
| 1        | Nyay Mandir| 1.12          | 0.048         | 2.05          | 2.00      | 0.62           | 0.01                  | 0.56%                       |
| 2        | Harni      | 13.73         | 0.002         | 12.26         | 12.26     | 1.97           | 5.46                  | 39.79%                      |
| 3        | Waghodia   | 9.39          | 0.001         | 4.05          | 4.04      | 1.30           | 0.13                  | 1.38%                       |
| 4        | Pratap Nagar| 15.20       | 0.002         | 12.06         | 12.06     | 2.40           | 3.33                  | 21.92%                      |
| 5        | Raopura    | 7.08          | 0.008         | 11.23         | 11.22     | 2.54           | 2.53                  | 35.69%                      |
| 6        | Akota      | 22.83         | 0.001         | 13.00         | 13.00     | 1.66           | 8.59                  | 37.64%                      |
| 7        | Fatehgunj  | 22.47         | 0.005         | 13.19         | 13.19     | 2.75           | 3.67                  | 16.34%                      |
| 8        | Tin Rasta  | 4.55          | 0.029         | 17.25         | 17.22     | 2.66           | 1.81                  | 39.86%                      |
| 9        | Ajwa       | 10.87         | 0.008         | 5.10          | 5.10      | 1.61           | 0.39                  | 3.54%                       |
| 10       | Subhanpura | 9.61          | 0.001         | 8.87          | 8.87      | 1.85           | 1.86                  | 19.31%                      |
| 11       | Vasna      | 14.88         | 0.015         | 5.09          | 5.08      | 1.36           | 0.20                  | 1.37%                       |
| 12       | Makarpura  | 28.84         | 0.006         | 10.42         | 10.41     | 1.87           | 4.86                  | 16.86%                      |
According to flood hazards categories, 55.65% of total flood extent are located in the very low hazard class (H1) followed by H4 – high hazard class (17.73% of total flood extent), H3 – medium hazard class (14.69% of total flood extent), H2 – low hazard class (7.26% of total flood extent), H5 – extreme hazard class (4.65% of total flood extent).

5. Conclusion

Morphometric parameters are ideal for providing fundamental data for drawing conclusions that concern the effect of River morphology on the flood situation. In countries like India, high maintenance costs and the requirement for skilled operators make providing gauge stations to each watershed probably expensive. As remote sensing data are widely used in mathematical watershed models to simulate and evaluate the existing and proposed management scenarios, the runoff curve numbers estimated from remotely sensed parameters, such as land use and land cover and soil data, in combination with observed rainfall, predicted runoff and peak flow, may result in high accuracy of hydrological modelling. The morphometric parameters derived from the Cartosat-1 digital elevation model (30 metres)
helped to understand the hydrological behaviour of various sub-watersheds of the Vishwamitri watershed. Based on the integration of each flood influencing parameter and calculated compound value, the SW I and IV of Vishwamitri watershed have been categorized into high priority, SW II and V into moderate priority, and SW III into low priority. The hydrodynamic-based surface runoff computations in rainfall-runoff simulation at the catchment scale show the application of the hydrodynamic model HEC-RAS for identifying the inundation areas, in regions with very limited or no ground-based observational data. A significant advantage of the framework is considered to be its ability to produce results using only good quality topographical and land use and soil data. In this way, the technique will yield results for ungauged catchments. The integrated analysis of morphometric, land cover and topographic analysis for characterizing the hydrological behaviour of the Vishwamitri watershed, as shown in this study, maybe the sensible alternative until the automated observation network is built in such areas. For validating and calibrating the hydrological simulation models, the availability of the discharge data is crucial.

| Flood hazard | Flood depth (m) | Hazard classes | Hazard description |
|--------------|----------------|----------------|--------------------|
| H1           | <0.5           | Very low       | Flood does not pose hazard to people and on-foot evacuation is not difficult. |
| H2           | 0.5–1          | Low            | Flood water poses hazard for infants and on-foot evacuation of adults becomes difficult; evacuation becomes more complicated. |
| H3           | 1–2            | Medium         | Flood depth can drown people; people may be safe inside their homes. |
| H4           | 2–5            | High           | People are exposed to flood hazard even inside their homes and evacuate towards the roof of their homes is suggested. |
| H5           | >5             | Extreme        | Built-up structures like homes may get covered by the flood; people may get drowned even if they evacuate towards the roof of their homes. |

Table 14. Flood hazard classification based on water depth according to the MLIT.

Figure 13. Inundation map of Vadodara city with sites visit.
Therefore, the establishment of a network of hydro-meteorological and River discharge stations in the basin to facilitate better prediction of the flooding process is of the utmost importance.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

**ORCID**

Vikas Kumar Rana [http://orcid.org/0000-0002-9229-2041](http://orcid.org/0000-0002-9229-2041)  
Tallavajhala Maruthi Venkata Suryanarayana [http://orcid.org/0000-0002-6201-5676](http://orcid.org/0000-0002-6201-5676)

**References**

Abuzied, S., M. Yuan, S. Ibrahim, M. Kaiser, and T. Saleem. 2016. “Geospatial Risk Assessment of Flash Floods in Nuweiba Area, Egypt.” *Journal of Arid Environments* 133: 54–72. doi:10.1016/j.jaridenv.2016.06.004.

Ahmed, S. A., K. N. Chandrashekarappa, S. K. Raj, V. Nischitha, and G. Kavitha. 2010. “Evaluation of Morphometric Parameters Derived from ASTER and SRTM DEM—a Study on Bandihole Sub-watershed Basin in Karnataka.” *Journal of the Indian Society of Remote Sensing* 38 (2): 227–238. doi:10.1007/s12524-010-0029-3.

Altal, F., G. Meraj, and S. A. Romshoo. 2013. “Morphometric Analysis to Infer Hydrological Behaviour of Lidder Watershed, Western Himalaya, India.” *Geography Journal* 14.

Asselman, N., J. T. Maat, A. D. Wit, G. Verhoeven, S. Frazão, M. Velickovic, and P. Bates. 2009. “Flood Inundation Modelling.” *Executive summary, Report* , (T08-08), 01.

Bannari, A., A. Ghadeer, A. El-Battay, N. A. Hameed, and M. Rouai. 2017. “Detection of Areas Associated with Flash Floods and Erosion Caused by Rainfall Storm Using Topographic Attributes, Hydrologic Indices, and GIS.” In *Global Changes and Natural Disaster Management: Geo-information Technologies*, edited by Pirasteh S., Li J, 155–174. Cham: Springer. https://doi.org/10.1007/978-3-319-51844-2_13

Bhat, M. S., A. Alam, S. Ahmad, H. Farooq, and B. Ahmad. 2019. “Flood Hazard Assessment of Upper Jhelum Basin Using

---

**Figure 14.** Classification of flood hazards based on MLIT water depth for Vadodara city.
Morphometric Parameters." *Environmental Earth Sciences* 78 (2): 54. doi:10.1007/s12665-019-8046-1.

Bhatt, S., and S. A. Ahmed. 2014. "Morphometric Analysis to Determine Floods in the Upper Krishna Basin Using Cartosat DEM." *Geocarto International* 29 (8): 878–894. doi:10.1080/10106049.2013.868042.

Bisht, S., S. Chaudhry, S. Sharma, and S. Soni. 2018. "Assessment of Flash Flood Vulnerability Zonation through Geospatial Technique in High Altitude Himalayan Watershed, Himachal Pradesh India." *Remote Sensing Applications: Society and Environment* 12: 35–47. doi:10.1016/j.rsase.2018.09.001.

Brunner, G. W. (2016). "HEC-RAS River Analysis System 2D Modeling User’s Manual." US Army Corps of Engineers—Hydrologic Engineering Center, 1–171.

Choubin, B., E. Moradi, M. Golshan, J. Adamowski, F. Sajedi-Hosseini, and A. Mosavi. 2019. "An Ensemble Prediction of Flood Susceptibility Using Multivariate Discriminant Analysis, Classification and Regression Trees, and Support Vector Machines." *Science of the Total Environment* 651: 2087–2096. doi:10.1016/j.scitotenv.2018.10.064.

Congedo, L. 2016. "Semi-automatic Classification Plugin Documentation." doi:10.13140/RG.2.2.29474.02242/1.

Costabile, P., C. Costanzo, D. Ferraro, F. Macchione, and G. Petaccia. 2020. "Performances of the New HEC-RAS Version 5 for 2-D Hydrodynamic-based Rainfall-runoff Simulations at Basin Scale: Comparison with a State-of-the-Art Model." *Water* 12 (9): 2326. doi:10.3390/w12092326.

Costabile, P., F. Macchione, L. Natale, and G. Petaccia. 2015. "Flood Mapping Using LIDAR DEM. Limitations of the 1-D Modeling Highlighted by the 2-D Approach." *Natural Hazards* 77 (1): 181–204. doi:10.1007/s11069-015-1606-0.

Danumah, J. H., S. N. Odai, B. M. Saley, J. Szarzynski, M. Thiel, A. Kwaku, L. Y. Akpa, and L. Y. Akpa. 2016. "Flood Risk Assessment and Mapping in Abidjan District Using Multi-criteria Analysis (AHP) Model and Geoinformation Techniques," (cote D’ivoire). *Geoenvironmental Disasters* 3 (1): 1–13. doi:10.1186/s40677-016-0044-y.

Dasallas, L. and S. Lee. 2019. "Topographical Analysis of the 2013 Typhoon Haiyan Storm Surfing Flood by Combining the JMA Storm Surge Model and the FLO-2D Flood Inundation Model." *Water* 11 (1): 144. doi:10.3390/w11010144.

Elkhrrachy, I. 2015. "Flash Flood Hazard Mapping Using Satellite Images and GIS Tools: A Case Study of Najran City, Kingdom of Saudi Arabia (KSA)." *The Egyptian Journal of Remote Sensing and Space Science* 22 (2): 261–278. doi:10.1016/j.ejrs.2015.06.007.

Eze, E. B. and J. Efong. 2010. "Morphometric Parameters of the Calabar River Basin: Implication for Hydrologic Processes." *Journal of Geography and Geology* 2 (1): 18.

Fassoni-Andrade, A. C., F. M. Fan, W. Collischon, A. C. Fassoni, and R. C. D. D. Paiva. 2018. "Comparison of Numerical Schemes of River Flood Routing with an Inertial Approximation of the Saint Venant Equations." *RBRH* 23. doi:10.1590/2318-0331.0318170069.

Feldman, A. D. 2000. *Hydrologic Modeling System HEC-HMS: Technical Reference Manual*. US Army Corps of Engineers, USA: Hydrologic Engineering Center.

Giotti, E., C. Rigas, K. Kalogeropoulos, and C. Chalkias. 2013. A GIS-based Flash Flood Runoff Model Using High Resolution DEM and Meteorological Data." *EARSel eProceedings* 12 (1): 33–43.

Halgamuge, M. N., and A. Nirmalathas. 2017. "Analysis of Large Flood Events: Based on Flood Data during 1985–2016 in Australia and India." *International Journal of Disaster Risk Reduction* 24: 1–11. doi:10.1016/j.ijdrr.2017.05.011.

Hall, J., B. Arheimer, G. T. Aronica, A. Bilbashi, M. Boháč, O. Bonacci, ... G. Blöschl. 2015. "A European Flood Database: Facilitating Comprehensive Flood Research beyond Administrative Boundaries." *Proceedings of the International Association of Hydrological Sciences* 370: 89–95. doi:10.5194/phils-370-89-2015.

Holmes, R. R., Jr, N. O. Schwein, and C. E. Shadie. 2012. "Flood Risk Awareness during the 2011 Floods in the Central United States: Showcasing the Importance of Hydrologic Data and Interagency Collaboration." *Leadership and Management in Engineering* 12 (3): 101–110. doi:10.1061/(ASCE)LM.1943-5630.0000181.

Horton, R. E. 1945. "Erosional Development of Streams and Their Drainage Basins; Hydrophysical Approach to Quantitative Morphology." *Geological Society of America Bulletin* 56 (3): 275–370. doi:10.1130/0016-7606(1945)56[275:EOSAT]2.CO;2.

Iosub, M., I. Minea, O. E. Chelariu, and A. Ursu. 2020. "Assessment of Flash Flood Susceptibility Potential in Moldavian Plain (Romania)." *Journal of Flood Risk Management* 13 (4): e12588. doi:10.1111/jfr3.12588.

Jain, V., and R. Sinha. 2003. "Evaluation of Geomorphic Control on Flood Hazard through Geomorphic Instantaneous Unit Hydrograph." *Current Science* 85 (11): 1596–1600.

Karmokar, S., and M. De. 2020. "Flash Flood Risk Assessment for Drainage Basins in the Himalayan Foreland of Jalpaiguri and Darjeeling Districts, West Bengal." *Modeling Earth Systems and Environment* 6 (4): 2263–2289. doi:10.1007/s40808-020-00807-9.

Kim, B., B. F. Sanders, J. E. Schubert, and J. S. Famiglietti. 2014. "Mesh Type Tradeoffs in 2D Hydrodynamic Modeling of Flooding with a Godunov-based Flow Solver." *Advances in Water Resources* 68: 42–61. doi:10.1016/j.adwatre.2014.02.013.

Lama, S., and R. Maiti. 2019. "Morphometric Analysis of Chel River Basin, West Bengal, India, Using Geographic Information System." *Earth Science India* 12 (1): 1–23. doi:https://doi.org/10.31870/ESI.12.1.2019.01.

Maghes, N. S., and N. Chandrasekar. 2014. "GIS Model-based Morphometric Evaluation of Tamiraparani Subbasin, Tirunelveli District, Tamil Nadu, India." *Arabian Journal of Geosciences* 7 (1): 131–141. doi:10.1007/s12051-012-0742-z.

Mahmod, S., and A. U. Rahman. 2019. "Flash Flood Susceptibility Modeling Using Geo-morphometric and Hydrological Approaches in Panjokra Basin, Eastern Hindu Kush, Pakistan." *Environmental Earth Sciences* 78 (1): 43. doi:10.1007/s12665-018-8041-y.

Malik, S., and S. C. Pal. 2020. "Application of 2D Numerical Simulation for Rating Curve Development and Inundation Area Mapping: A Case Study of Monsoon Dominated Dwarkeswar River." *International Journal of River Basin Management* 1–11. doi:10.1080/15715124.2020.1738447.

Markose, V. J., and K. S. Jayappa. 2011. "Hydrometric Analysis of Kali River Basin, Karnataka, India, Using Geographic Information System." *Geocarto International* 26 (7): 553–568. doi:10.1080/10106049.2011.608438.

Masoud, M. H. 2016. "Geoinformatics Application for Assessing the Morphometric Characteristics’ Effect on Hydrological
Response at Watershed (Case Study of Wadi Qanunah, Saudi Arabia),” Arabian Journal of Geosciences 9 (4): 280. doi:10.1007/s12633-015-2300-y.

Nag, S. K. 1998. "Morphometric Analysis Using Remote Sensing Techniques in the Chaka Sub-basin, Purulia District, West Bengal." Journal of the Indian Society of Remote Sensing 26 (1–2): 69–76. doi:10.1007/BF03007341.

Ongdas, N., F. Akiyanova, Y. Karakulov, A. Muratbayeva, and N. Zinabdin. 2020. "Application of HEC-RAS (2D) for Flood Hazard Maps Generation for Yesil (Ishim) River in Kazakhstan.” Water 12 (10): 2672. doi:10.3390/w12102672.

Oommen, T., D. Misra, N. K. Twarakavi, A. Prakash, B. Sahoo, and S. Bandopadhyay. 2008. “An Objective Analysis of Support Vector Machine Based Classification for Remote Sensing.” Mathematical Geosciences 40 (4): 409–424. doi:10.1007/s11004-008-9156-6.

Ozdemir, H., and D. Bird. 2009. "Evaluation of Morphometric Parameters of Drainage Networks Derived from Topographic Maps and DEM in Point of Floods," Environmental Geology 56 (7): 1405–1415. doi:10.1007/s00254-008-1235-y.

Pahlevan, N., S. Sarkar, B. A. Franz, S. V. Balasubramanian, and J. He. 2017. "Sentinel-2 MultiSpectral Instrument (MSI) Data Processing for Aquatic Science Applications: Demonstrations and Validations.” Remote Sensing of Environment 201: 47–56. doi:10.1016/j.rse.2017.08.033.

Pike, R. J., and S. E. Wilson. 1971. "Elevation-relief Ratio, Hypsometric Integral, and Geomorphic Area-altitude Analysis.” Geological Society of America Bulletin 82 (4): 1079–1084. doi:110.1130/0016-7606(1971)82[1079:ERHIAG]2.0.CO;2.

Prasad, R. N., and P. Pani. 2017. "Geo-hydrological Analysis and Sub Watershed Prioritization for Flash Flood Risk Using Weighted Sum Model and Snyder’s Synthetic Unit Hydrograph.” Modeling Earth Systems and Environment 3 (4): 1491–1502. doi:10.1007/s40808-017-0354-4.

Quirogaa, V. M., S. Kurea, K. Udoa, and A. Manoa. 2016. "Application of 2D Numerical Simulation for the Analysis of the February 2014 Bolivian Amazonia Flood: Application of the New HEC-RAS Version 5.” Ribagaua 3 (1): 25–33. doi:10.1016/j.ribja.2015.12.001.

Rakesh, K., A. K. Lohani, K. Sanjay, C. Chattered, and R. K. Nema. 2000. "GIS Based Morphometric Analysis of Ajay River Basin Upto Srarath Gauging Site of South Bihar." Journal of Applied Hydrology 14 (4): 45–54.

Rana, V. K., and T. M. V. Suryanarayana. 2020a. “GIS-based Multi Criteria Decision Making Method to Identify Potential Runoff Storage Zones within Watershed.” Annals of GIS 26 (2): 149–168. doi:10.1080/19475683.2020.1733083.

Rana, V. K., and T. M. V. Suryanarayana. 2020b. “Performance Evaluation of MLE, RF and SVM Classification Algorithms for Watershed Scale Land Use/land Cover Mapping Using Sentinel 2 Bands.” Remote Sensing Applications: Society and Environment 19: 100351. doi:10.1016/j.rsase.2020.100351.

Reddy, G. P. O., A. K. Maji, and K. S. Gajbhiye. 2004. "Drainage Morphometry and Its Influence on Landform Characteristics in a Basaltic Terrain, Central India–a Remote Sensing and GIS Approach.” International Journal of Applied Earth Observation and Geoinformation 6 (1): 1–16. doi:10.1016/j.jag.2004.06.003.

Romshoo, S. A., S. A. Bhat, and I. Rashid. 2012. “Geoinformatics for Assessing the Morphometric Control on Hydrological Response at Watershed Scale in the Upper Indus Basin.” Journal of Earth System Science 121 (3): 659–686. doi:10.1007/s12040-012-0192-8.

Sarangi, A. K., K. Bhattacharya, A. Singh, and A. K. Singh. 2001. “Use of Geographic Information System (GIS) in Assessing the Erosion Status of Watersheds.” Indian J Soil Conserv 29 (19): F195.

Smith, K. G. 1950. “Standards for Grading Texture of Erosional Topography.” American Journal of Science 248 (9): 655–668. doi:10.2475/ajs.248.9.655.

Sridhar, P., and S. Ganapuram. 2021. "Morphometric Analysis Using Fuzzy Analytical Hierarchy Process (FAHP) and Geographic Information Systems (GIS) for the Prioritization of Watersheds.” Arabian Journal of Geosciences 14 (4): 1–29. doi:10.1007/s12517-021-06539-z.

Strahler, A. N. 1957. "Quantitative Analysis of Watershed Geomorphology.” Eos, Transactions American Geophysical Union 38 (6): 913–920. doi:10.1029/TR038i006p00913.

Strahler, A. N. 1964. "Part II. Quantitative Geomorphology of Drainage Basins and Channel Networks.” In Handbook of Applied Hydrology: McGraw-Hill, 4–39. New York: McGraw-Hill.

Sudhakar, B. S., K. S. Anupam, and O. J. Akshay. 2015. "Snyder Unit Hydrograph and GIS for Estimation of Flood for Un-gauged Catchments in Lower Tapi Basin, India.” Hydrology: Current Research 6 (1): 1.

Sukristiyanti, S., R. Maria, and H. Lestiana. 2018, February. "Watershed-based Morphometric Analysis: A Review.” In IOP conference series: earth and environmental science, Vol.118, 12–28. Bandung, Indonesia: IOP Publishing.

Thakur, B., R. Parajuli, A. Kalra, S. Ahmad, and R. Gupta. 2017. "Coupling HEC-RAS and HEC-HMS in Precipitation Runoff Modelling and Evaluating Flood Plain Inundation Map.” In World Environmental and Water Resources Congress 2017, 240–251. Sacramento, California: American Society of Civil Engineers

USDA, U. Department of Agriculture. 1986. “Urban Hydrology for Small Watersheds. Technical Release 55” Natural Resource Conservation Service, Conservation Engineering Division. Washington, DC Accessed 7 2003 ftp://ftp.wcc. nrcs.usda.gov/downloads/hydrology_hydraulics/tr55/tr55. pdf

Vozinaki, A. E. K., G. G. Morianou, D. D. Alexakis, and I. K. Tsanis. 2017. “Comparing 1D and Combined 1D/2D Hydraulic Simulations Using High-resolution Topographic Data: A Case Study of the Kollias Basin, Greece.” Hydrological Sciences Journal 62 (4): 642–656. doi:10.1080/02626667.2016.1255746.

Wakode, H. B., D. Dutta, V. R. Desai, K. Baier, and R. Azzam. 2013. "Morphometric Analysis of the Upper Catchment of Kosi River Using GIS Techniques.” Arabian Journal of Geosciences 6 (2): 395–408. doi:10.1007/s12517-011-0374-8.

Wani, M. B., S. A. Ali, and U. Ali. 2018. "Flood Assessment of Lolab Valley from Watershed Characterization Using Remote Sensing and GIS Techniques.” In Hydrologic Modeling, edited by V. P. Singh, 367–390. Singapore: Springer.