

Hydraulic modelling of extreme flood event of semi-arid river basin

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Abstract

Floods are among the severe weather disasters that cause catastrophic damage to surroundings and adversely impact populations. This study aims to create a one-dimensional (1D) hydraulic model using HEC-RAS for the Rel River in Banaskantha, Gujarat, India. The model has been developed for the extreme flood event of July 2017. A total of hundred cross-sections have been used as geometric data. The peak discharge of 3355 m³/s and the river slope has been applied as upstream and downstream boundary conditions. The model has been calibrated and validated using observed water depth at the Railway bridge and Highway bridge. Critical cross-sections have been identified using the 1D hydraulic model. Eight out of the hundred cross-sections were safe for a flood discharge of 3355 m³/s. The villages at high flood risk are identified for this discharge. To mitigating floods, the construction of a retaining wall or levees is recommended to protect these villages. This study can help a disaster management strategy for the cities and town in the River's vicinity.

Introduction

Flood is the most frequent, recurrent, and widespread hazardous event in the world. Flood is the most incredible natural disaster that affects several parts of the world, including developing and developed countries (Demir and Kisi 2016). Due to floods, many property and infrastructure are damaged, and thousands of human lives are lost every year. Losses and hazards can be minimized by providing consistent information on flood hazards to the community through flood mapping. After Bangladesh, India is one of the most flood-affected countries globally, accounting for one-fifth of the world's flood-affected deaths. Approximately 0.4 million km², or nearly one-eighth of India's physical area is flood-prone (Patel and Dholakia 2010). Extreme precipitation and human intervention are the main reasons for floods in urban areas (Patel and Srivastava 2013). Drastic climate change is the main reason for accelerating and intensifying the hydrological system, leading to a high frequency of floods and an increase in the magnitude of floods (Kvočka et al. 2015; Shaikh et al. 2020).

The Hydraulic Engineering Center-River Analysis System (HEC-RAS) one-dimensional (1D) hydraulic model is widely used for flood analysis. The HEC-RAS tool is available in the public domain, which is one of its most significant advantages. The assumption made in 1D hydraulic modelling is that all water movements are in the longitudinal direction only. The representation of the 1D model is such that the terrain appears as a cross-section arrangement that helps to flow simulation. Estimates of the water depth and average velocity at each cross-section are required. Surveyed cross-sections are the primary data required for the development of a 1D hydraulic model in the HEC-RAS. If surveyed cross-sections are unavailable for analysis, a cross-section can be extracted from Google Earth Pro. The quality of the cross-section extracted from Google Earth Pro is inferior to that of a surveyed cross-section. Such an extracted cross-section can be used for preliminary analysis but not for design purposes (Rusli et al. 2014; Yamazaki et al. 2017). Several studies have been conducted in 1D hydraulic modelling in recent years (Masood and Takeuchi 2012; Parhi et al. 2012; Patel et al. 2018; Timbadiya et al. 2014a; Tunas and Maadji 2018).

The semi-arid Rel River Basin located in the northern part of Gujarat in India is the study area. In July 2017, the northern part of Gujarat received 559.4 mm of rain due to the simultaneous activation of the low-pressure regions across the Arabian Sea and Bay of Bengal (India Meteorological Department 2017). The reported rainfall was 65% higher than the average annual rainfall of Gujarat. The rainfall received in 2017 was the highest rainfall observed in the study region for the last 112 years (France-Presse 2017). On 24 July 2017, Banaskantha (northern Gujarat) received 267% of its average annual rainfall (Umarji 2017). According to the rainfall record of the Government of Gujarat, the Dhanera taluka of Banaskantha district received 235 mm of rainfall within six h (Skymet Weather Team 2017), which caused severe flooding and resulted in the loss of more than 4000 animals, 17 human lives, INR 1.54 billion worth of crops, and INR 934.06 million worth of infrastructure (1 USD = approximately 70 INR) (The Indian Express 2017).

The main objective of this study was to develop the 1D hydraulic model. The aim was to identify losses in urban and rural areas separately to help the administration. The 1D hydraulic model simulated well for the cross-section where the stream is perfectly defined. But with wider cross-sections and lower elevated terrain where the stream shape is not perfect, the 1D hydraulic model could not perform well.

Study Area

The Rel River originates from the Keshua village of Rajasthan and passes through the Dhanera town of Banaskantha district in Gujarat. The Rel River ends in the desert of Kutch (**Fig. 1**). The peculiarity of the river is that it flows for a distance from its source and then disappears into the desert of Kutch before it joins another river or ocean. The Rel River is a virgin river, and the area of its basin is 612 km². The maximum and minimum elevation of the Rel basin is 782 and 125 m, respectively. The average bed slope of the river is 0.00256. The river consists of an inline structure called the Jetpura weir in Rajasthan. A stage-discharge station (SDS) is situated at the Dhanera–Thavar highway bridge, located 40 km downstream of the Jetpura weir and controlled by the Government of Gujarat. Dhanera town is located in the Banaskantha district of north Gujarat. The Rel basin has a latitude of 24° 23' – 24° 45' N and longitude of 71° 59' – 72° 30' E. Dhanera has a population of 230000 as per the 2011 census (www.censusindia2011.com). The average annual precipitation in Dhanera is 600 mm. Dhanera

has experienced major floods in 1977, 1992, 2015, and 2017. A total of 435 and 365 mm of precipitation was reported at the Bapla rain gauge station on 24 and 25 July 2017, respectively. Water entered Dhanera and its surrounding villages due to this excess rainfall. A total of 17 human lives and INR 2.5 billion worth of property were lost in the 2017 flood. **Fig. 2** depicts the line diagram of the study area.

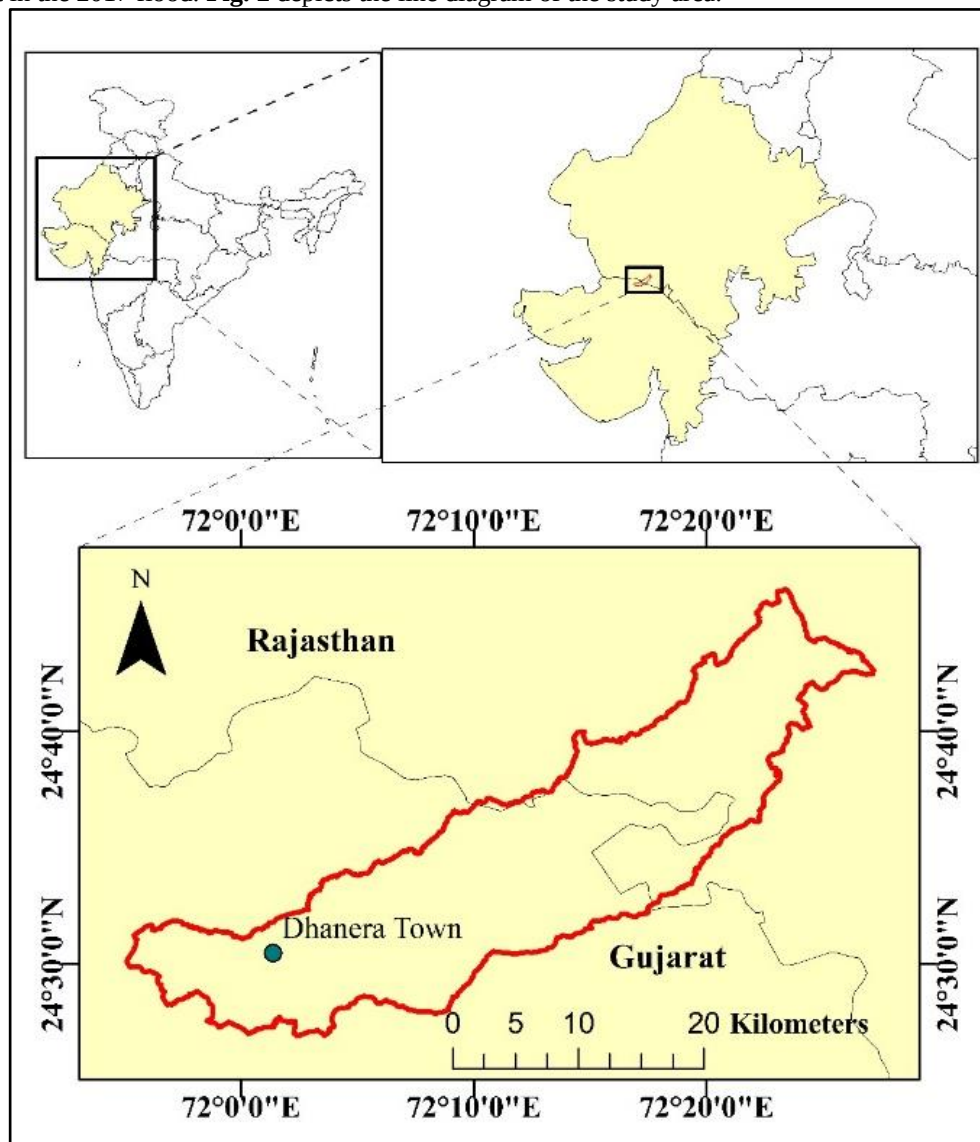


Fig.1 Index map of the study area

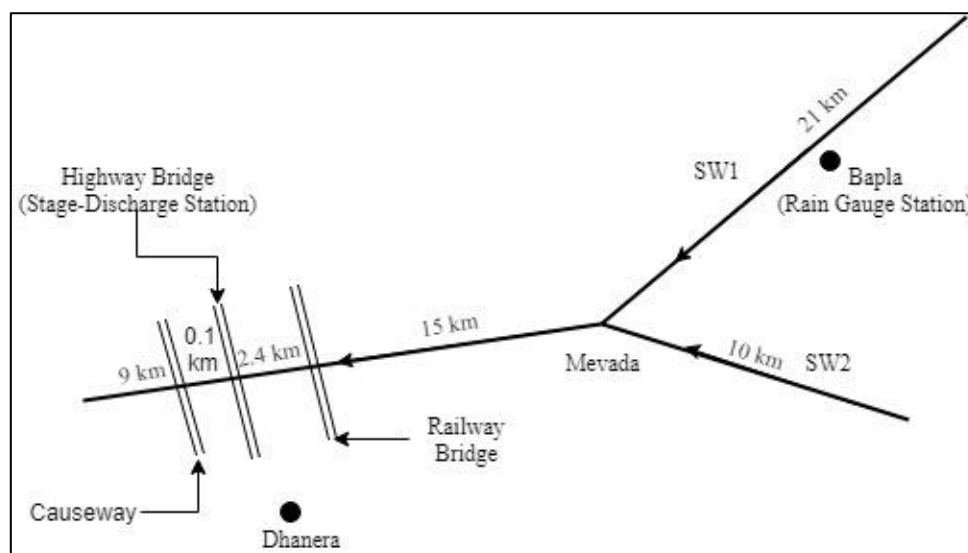


Fig. 2 Line diagram of Study area

Data collection

The key input parameters include the cross-section of the channel, reduced level of the bank, bed slope, and flood hydrograph. Of the 100 cross-sections used, 47 were surveyed, and the others were derived from Google Earth Pro. The surveyed cross-sections had a 100-m interval, and these sections were collected from the Irrigation Division, Deesa, after the 2017 flood event. The cross-sections derived from Google Earth Pro had a non-uniform interval. Cross-sections 10–56 were surveyed, and cross-sections 1–9 and 57–100 were derived from Google Earth Pro. The hourly discharge data at the highway bridge for the flood event of 2017 were collected from the river gauging section in Palanpur.

Methodology

Water surface levels were measured from one cross-section to another by evaluating the repeated energy equation. This process is known as the standard step methodology (Brunner et al. 2015). The energy equation is written as follows:

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e \quad (1)$$

where Z_1 and Z_2 = the channel invert's elevation, Y_1 and Y_2 = the water depth at cross-sections, V_1 and V_2 = the average velocities (total flow/total area), a_1 and a_2 = velocity weighting coefficients, g = gravitational acceleration, and h_e = loss of energy head.

The information required in the HEC-RAS is the river geometry, upstream and downstream boundary conditions, and Manning coefficient (Hameed and Ali 2013; Timbadiya et al. 2014b). HEC-RAS models use three types of data, namely geometry information, flow data, and plan information. Geometry data includes information on the length, shape, and cross-sections of the river basin. A total of 100 cross-sections were used to cover 57 km of the tributaries (**Fig. 3**). The Manning coefficient varies between 0.027 to 0.050 $\text{m}^{-1/3}\text{s}$ depending on the material and bed type in the river basin (Subramanya 2016).

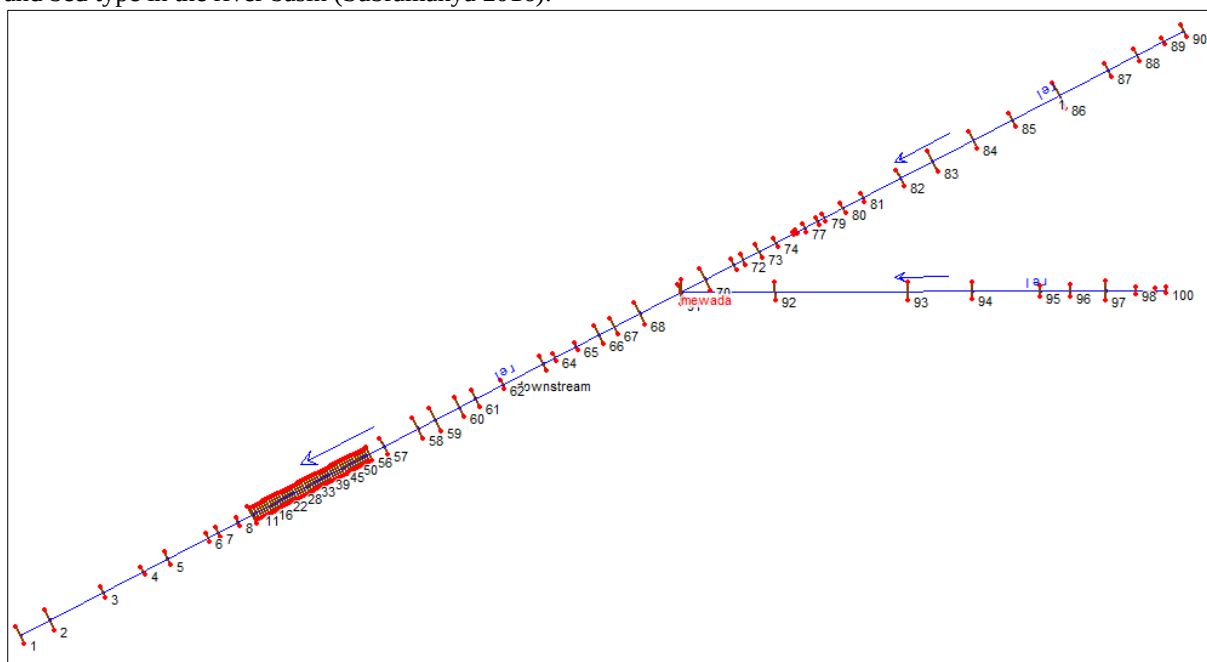


Fig. 3 Schematic layout of the river with a cross-section

In this study, for steady flow analysis, the peak discharges observed during the July 2017 flood were used as the upstream boundary conditions. The normal depths (bed slope of tributaries) were used as input data for the downstream boundary condition (Brunner 2016).

Results and analysis

If the WSE is higher than the bank elevation, the cross-section is considered critical. Only eight of the 100 cross-sections were safe, and 92 cross-sections were critical for a discharge of 3355 m^3/s during the July 2017 flood. For each cross-section, the WSE, minimum channel elevation, energy gradient elevation, energy gradient slope, channel velocity, flow area, and Froude numbers were calculated. **Fig. 4** illustrates the longitudinal profiles of cross-sections 1–70 of Rel River and the ground level, left overbank, right overbank, and WSE. **Fig. 5** illustrates cross-section 42, which was safe during the July 2017 flood, and **Fig. 6** illustrates cross-section 19, which was unsafe (critical) during the July 2017 flood. Two reference locations were used to validate the output of the 1D hydraulic model, namely the railway bridge and highway bridge. The discharge was recorded at the highway bridge, Dhanera. The discharge was measured at the river gauging section in Palanpur. A well-developed SD curve was available for this site. The Gujarat government marked the highest flood level (HFL) after July 2017 flood at the railway bridge, Dhanera. The comparison between the observed and simulated WSE at the two locations is presented in Table 2. At the railway bridge, the observed and simulated WSEs were 137.72 and 137.9 m, respectively. The percentage error was 0.13%. At the highway bridge, the observed and simulated WSEs were

134.81 and 134.4 m, respectively. The percentage error was -0.30% . The simulated results closely agreed with the observed results, which confirms the suitable performance of the 1D model. Khattak et al. (2016) and Demir and Kisi (2016) have also achieved similar results.

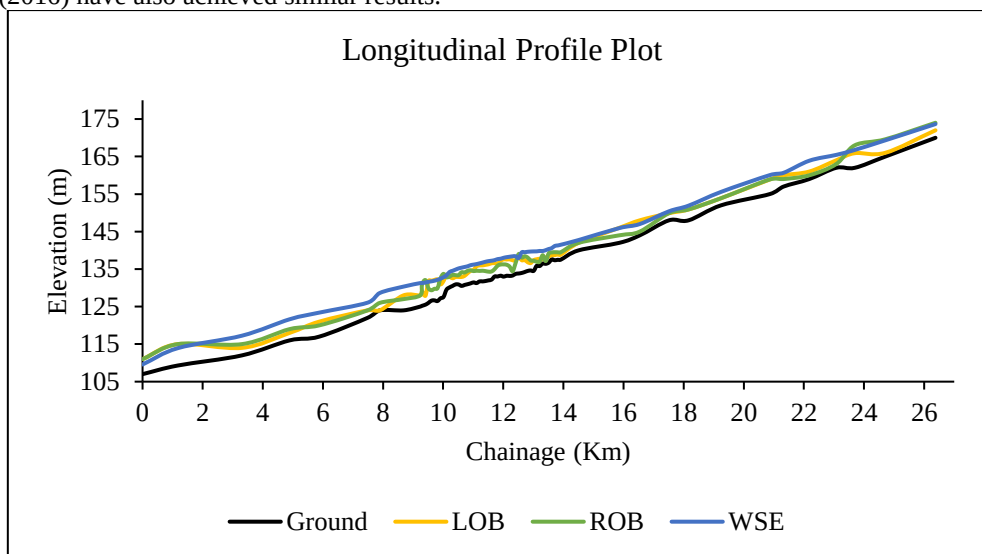


Fig. 4 Longitudinal profile of Rel river (C/S 1 to C/S 70)

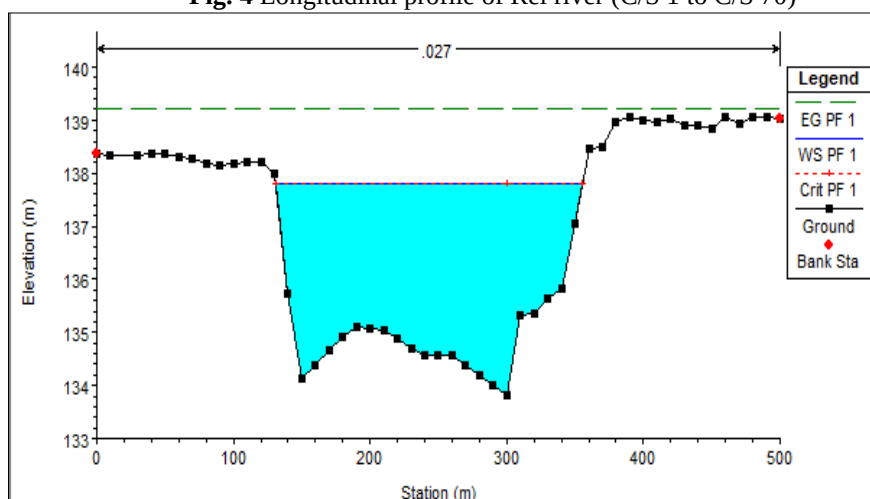


Fig. 5 Cross-section 42 (Safe)

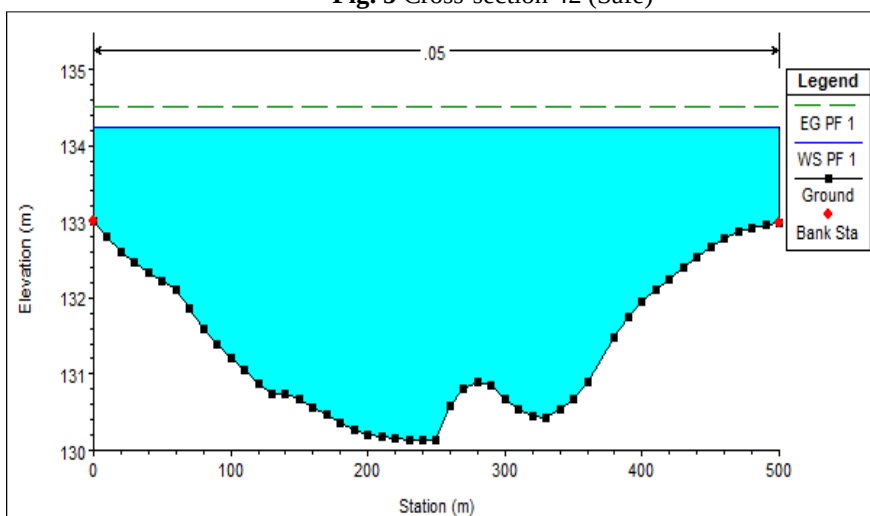


Fig. 6 Cross-section 19 (Critical)

Table 1 Comparison of Water Surface Elevation (WSE) after calibration of model

Location	Observed WSE	Simulated WSE	Error
Railway Bridge	137.72 m	137.9 m	+0.13%
Highway Bridge	134.81 m	134.4 m	-0.30%

Previous researchers for 1D hydraulic modelling also achieved similar outcomes. Masood and Takeuchi (2012) performed 1D hydrodynamic modelling for mid-eastern Dhaka, Bangladesh. The modelling showed that the maximum depth is 7.55 m, and the affected area is more than 50%. Timbadiya, Patel and Porey (2014) studied the 1D hydraulic model for two flood events in the lower Tapi River (India) and suggested that the predicted flood level was computationally acceptable. Patel, Mehta and Yadav (2018) carried out a 1D hydraulic model for 11 km of the lower part of the Ambica River (India) with 359 surveyed cross-sections to estimate the level of the flood. The results of their study found inundations of both the right and left banks. Tunas and Maadji (2018) assessed flood control structure performance using HEC-RAS 1D hydrodynamic model on Palu River, Indonesia. They identified the critical cross-section and water carrying capacity of river for a 25-years return period.

Conclusion

Critical sections were identified in this study. The carrying capacity of the Rel River at Dhanera is significantly less. Therefore, high-magnitude discharge causes flooding in various low-lying areas of the river basin. Good agreement was observed between the observed depth and the simulated WSE. As a precautionary measure, levees must be built at low-lying cross-sections to increase the River's capacity to carry high-magnitude discharge safely. The developed model accurately provided the River breach and the flood depth in several villages in the Rel River Basin.

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