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RESEARCH ARTICLE

ESTIMATION OF FLOW DEPTH AT GAULA BARRAGE, KATHGODAM USING 2D HEC-RAS HYDRAULIC MODEL

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ABSTRACT

The Gaula Barrage, which is situated at latitude 29°16′18′ N and longitude 79°32′51′ E over the Gaula River in Kathgodam, Nanital district, Uttarakhand, India is crucial for flood control and irrigation. For effective barrage operation and hydraulic planning, accurate flow depth estimation under various hydraulic conditions is crucial. In order to assess the impact of discharge, gate operation and Manning's roughness coefficient on maximum flow depth, a two-dimensional hydraulic model of the Gaula Barrage was created in the current study using HEC-RAS 6.5. Twenty-seven simulation scenarios were created by simulating three discharge conditions (500, 1500 and 3250 m³/s), three Manning's roughness coefficients (0.030, 0.035 and 0.040) and three gate operating circumstances (fully open, partially open and fully closed). The results showed that maximum flow depth increased with increasing discharge, increasing Manning's roughness coefficient and decreasing gate opening. The maximum flow depth of 11.747 m was observed under a discharge of 3250 m³/s, fully closed gate condition and Manning's roughness coefficient of 0.040, whereas the minimum flow depth of 3.521 m occurred under a discharge of 500 m³/s, fully open gate condition and Manning's roughness coefficient of 0.030. The study provides a reliable decision-support tool for irrigation and water resource authorities to optimize barrage gate operations and improve flood management strategies.

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INTRODUCTION

Water is one of the most vital natural resources and is essential in flood control, hydropower production, irrigation and environmental sustainability. A comprehensive understanding of hydraulic characteristics under various flow circumstances is necessary for the effective management of river systems. Flow depth is a crucial indication of river behavior among the several hydraulic parameters because it affects flow conveyance, sediment transport, hydraulic efficiency, floodplain inundation, and the integrity of hydraulic structures (Traore et al., 2015; Prasad et al., 2023). Since flow depth directly affects a barrage's hydraulic performance and safety, accurate flow depth estimation is crucial. It aids in establishing the freeboard requirements of hydraulic structures, measuring the appropriateness of channel capacity, assessing upstream ponding and backwater impacts and guaranteeing the safe passage of flood flows. A barrage is a gated hydraulic structure built across a river to control and redirect water for municipal water supply, agriculture and other advantageous purposes. Although they are more expensive than weirs, barrages provide superior control (Modi P.N., 1988). Barrages offer more operational flexibility than fixed weirs because their gates can be opened or closed based on water demand and river discharge. A barrage's hydraulic behavior is influenced by a number of variables, including as bed slope, channel roughness, inflow discharge, gate opening circumstances and channel shape. The distribution of flow depth in both upstream and downstream reaches is immediately impacted by changes in gate operation which also alter the flow pattern. Inadequate gate operation during high-flow conditions can lead to increased backwater effects, excessive upstream ponding and decreased hydraulic efficiency. In order to assess barrage performance and promote safe and effective management of water resources, it is crucial to analyze flow depth under various operating conditions (Khan and Mujumdar, 2021; Burele et al., 2022). The analysis of hydraulic structures and river hydraulics has significantly improved because of development in numerical modeling tools. By enabling engineers to simulate many hydraulic scenarios without requiring substantial field experimentation, mathematical models offer an economical and effective substitute for physical modeling. The Hydrologic Engineering Center-River Analysis System (HEC-RAS), created by the U.S. Army Corps of Engineers has emerged as one of the most popular software programs for river hydraulic analysis among the available hydraulic models (Brunner, 2016). The most recent two-dimensional (2D) features of HEC-RAS allow for more accurate depiction of spatial variations in flow depth by enabling realistic simulation of flow movement over complicated terrain and around hydraulic structures. HEC-RAS has been widely used in river engineering, floodplain mapping, barrage analysis and hydraulic design studies because of its computational efficiency, compatibility with Geographic Information Systems (GIS) and user-friendly interface (Karim, 2009; Khan et al., 2024). Prior research has mostly concentrated on dam-break analysis (Ramola et al., 2019). However, the thorough assessment of flow depth fluctuations brought about by various barrage gate operations has received very little attention, especially for Himalayan rivers. The Gaula Barrage which controls water for agriculture and flood control is situated at latitude 29°16′18′ N and longitude 79°32′51′ E over the Gaula River in Kathgodam, Nanital district, Uttarakhand. The hydraulic conditions surrounding the barrage vary significantly throughout the year due to seasonal variations in river discharge. In order to assess the change in flow depth under various hydraulic circumstances, a two-dimensional hydraulic model of the Gaula Barrage was created in the current study using HEC-RAS. Twenty-seven simulation scenarios were created by using three gate operation conditions-fully open, partially open and fully closed gates, three Manning's roughness coefficients (0.030, 0.035 and 0.040) and three discharge values (500, 1500 and 3250 m³/s) and then the simulated results were examined to compare the flow depth. The study's findings advance our knowledge of barrage hydraulics and offer helpful data for enhancing flood control, barrage operation and future hydraulic planning.

MATERIALS AND METHOD

Study Area: This study was carried out at the Gaula Barrage in Haldwani Tehsil, Nainital District, Uttarakhand, India, which was built across the Gaula River close to Kathgodam. The lower Himalayan hills in Uttarakhand are the source of the Gaula River, a perennial Himalayan river. Before joining the Ramganga River, a significant tributary of the Ganga, it passes through Kathgodam, Haldwani, Kichha, and Shahi.

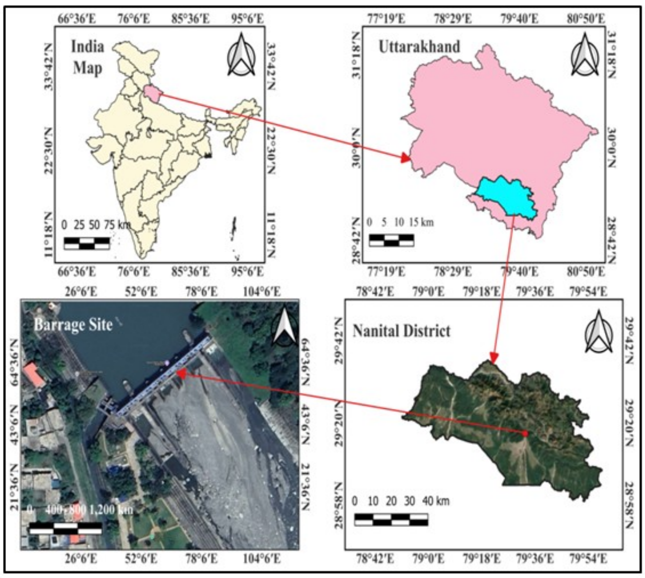

Figure 2.1: Map of Study Area.

In the Kumaon region, the river is a vital source of water for flood control, residential use and irrigation. There are significant seasonal changes in river discharge during the monsoon season and quick runoff because the surrounding watershed is primarily hilly. The Gaula Barrage, which is situated at latitude 29°16′18′ N and longitude 79°32′51′ E was completed in 1980 by the Uttarakhand government's irrigation department (Figure 2.1). The barrage has a design discharge capacity of 3250 m³/s, a total waterway length of 81 m and six radial gates, each measuring 11.50 m × 4.50 m. The two-dimensional (2D) HEC-RAS Version 6.5 hydraulic model was used in this work to assess the variance in flow depth under various discharges, Manning's roughness coefficient, and gate operation scenarios.

Model setup: The Gaula River hydraulic model was created using the two-dimensional (2D) HEC-RAS Version 6.5. The Gaula Barrage is situated inside the model domain, which was created for a 35-kilometer stretch of the Gaula River from the upstream reach at Jamrani Dam to the downstream reach near Anandpur-Khamia Block No. 1. Ten kilometers upstream and twenty-five kilometers downstream of the barrage is included in the model. The topography for the hydraulic model was created using FABDEM (Forest and Buildings removed Copernicus DEM), whereas HRC-RAS was used to create the river geometry, barrage arrangement and gate configuration.

Three representative discharges of 500, 1500 and 3250 m³/s representing low, medium and design flood conditions, respectively were simulated in order to assess the change in flow depth. There were three gate operation situations (fully open, partially open and fully closed) and three Manning's roughness coefficients (0.030, 0.035 and 0.040) taken into consideration for a total of 27 hydraulic simulation scenarios. Manning's n values were used for this study based on the United States Geological Survey's (USGS) standards for natural channels and flood plains. Since the Gaula Barrage reach has a natural gravel-cobble riverbed and the barrage construction only occupies a small section of the domain, a value in the range of 0.035-0.045 is more reasonable.

For the 2D flow area, a 40 m x 40 m computational mesh was created and suitable boundary conditions for upstream discharge and downstream normal depth were provided. The hydraulic response of the Gaula Barrage under various operating conditions was assessed by analyzing the simulated flow depth achieved from each scenario.

Numerical Model

2D Saint Venant's Equation

- Continuity Equation:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \quad (1)$$

- Momentum Equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{dy} + g\frac{\partial h}{\partial x} + gSf_x = 0 \quad (2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial h}{\partial y} + gSf_y = 0 \quad (3)$$

Where u = velocity of flow in x-direction, v = velocity of flow in y-direction, Sf_x and Sf_y = energy slopes in the x and y directions which include bed slopes and friction slopes.

RESULTS AND DISCUSSION

Observation Points: Three observation points were selected to evaluate the variation in flow depth across the barrage.

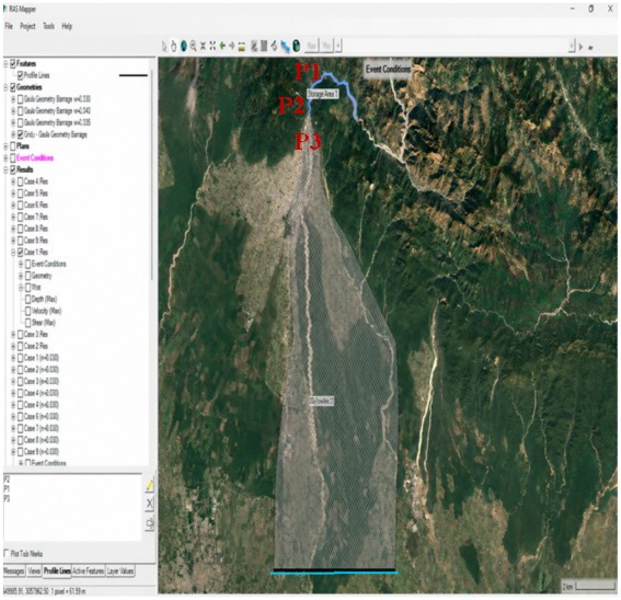

Figure 3.1. RAS Mapper showing observation locations

To measure the upstream hydraulic response, observation point P1 was situated next to Maa Sheetla Devi Mandir about 1 km upstream of the Gaula Barrage. In order to assess downstream flow conditions, observation point P2 was situated at the Gaula Barrage, while observation point P3 was situated about 1 km downstream of the barrage close to Ion Digital Zone, Haldwani. The two-dimensional hydraulic model created in HEC-RAS using the RAS Mapper is shown in Figure 3.1. The river channel, nearby floodplain and storage area, each represented by a computational mesh, make up the model domain. The spatial discretization needed to solve the two-dimensional Saint-Venant equations is supplied by the mesh. To guarantee an accurate depiction of the river alignment and computational bounds, the model geometry was superimposed on high-resolution satellite images. Variations in flow depth under various discharge, Manning's roughness and barrage gate operation conditions were then simulated using this hydraulic model. Variation of Flow Depth under Different Hydraulic Conditions Under various combinations of discharge, gate opening and Manning's roughness coefficient, the simulated maximum flow depth at the three observation stations (P1, P2, and P3) varied significantly, suggesting that all three factors affect the Gaula Barrage's hydraulic response. Table 4.1 demonstrates that the maximum flow depth was consistently recorded at the upstream observation point (P1), which is close to Maa Sheetla Devi Mandir. It varied from 3.521 m in Scenario S1 under a discharge of 500 m³/s, fully open gate operation, and Manning's roughness coefficient of 0.030 to 11.747 m in Scenario S27 under design discharge of 3250 m³/s, fully closed gates and n = 0.040, indicating an overall variation of 8.226 m. The results show that because more hydraulic head is needed to move the incoming flow through a constrained flow area, increasing discharge, increasing channel roughness and decreasing gate opening. This behavior progressively amplifies the upstream backwater effect and is consistent with the continuity equation.

Table 3.1 Maximum flow depth for different simulation scenarios

Scenario	Q (m^3/s)	Gate Condition	Manning's n	Maximum Depth (m)
S1	500	0.030	Open	3.521
S2	500	0.030	Partial	3.788
S3	500	0.030	Closed	4.080
S4	1500	0.030	Open	7.422
S5	1500	0.030	Partial	7.958
S6	1500	0.030	Closed	8.584
S7	3250	0.030	Open	8.760
S8	3250	0.030	Partial	9.729
S9	3250	0.030	Closed	10.868
S10	500	0.035	Open	3.650
S11	500	0.035	Partial	3.943
S12	500	0.035	Closed	4.262
S13	1500	0.035	Open	7.751
S14	1500	0.035	Partial	8.262
S15	1500	0.035	Closed	8.946
S16	3250	0.035	Open	9.107
S17	3250	0.035	Partial	10.189
S18	3250	0.035	Closed	11.328
S19	500	0.040	Open	3.848
S20	500	0.040	Partial	4.143
S21	500	0.040	Closed	4.481
S22	1500	0.040	Open	8.029
S23	1500	0.040	Partial	8.641
S24	1500	0.040	Closed	9.363
S25	3250	0.040	Open	9.482
S26	3250	0.040	Partial	10.625
S27	3250	0.040	Closed	11.747

Effect of Gate Operation on Flow Depth: As gate openings were reduced from fully open to fully closed condition, P1 showed the highest rise in flow depth among the three observation stations, as Table 4.2 and Figure 4.1 demonstrate. Under low discharge, the effect was comparatively minimal, but under increased discharge, it grew increasingly substantial. Maximum flow depth rise from 8.760 m under fully open gates to 10.868 m under fully closed gates at the design discharge of 3250 m³/s or almost 2.11 m. When the gates are closed, less effective flow area is available for discharge, which causes water to build up upstream and raises the hydraulic head. As a result, deeper flow conditions and more upstream ponding are caused by stronger backwater effects. The findings show that the best operational parameter for controlling flow depth during flood occurrences is gate operation.

Table 3.2 Maximum flow depth (n = 0.030)

	Discharge (m³/s)		
Gate Condition	500	1500	3250
Fully open	3.521	7.422	8.760
Partially open	3.788	7.958	9.729
Fully closed	4.080	8.584	10.868

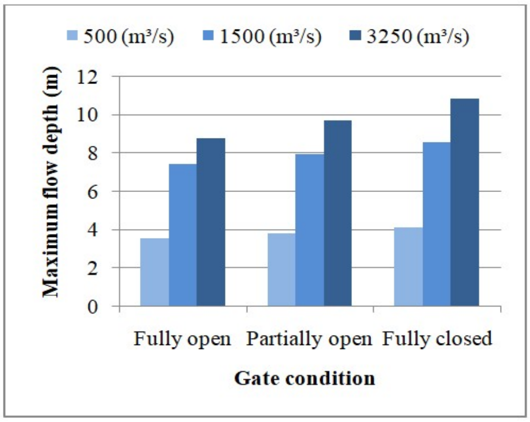

Figure 3.2. Effect of gate operation on maximum flow depth

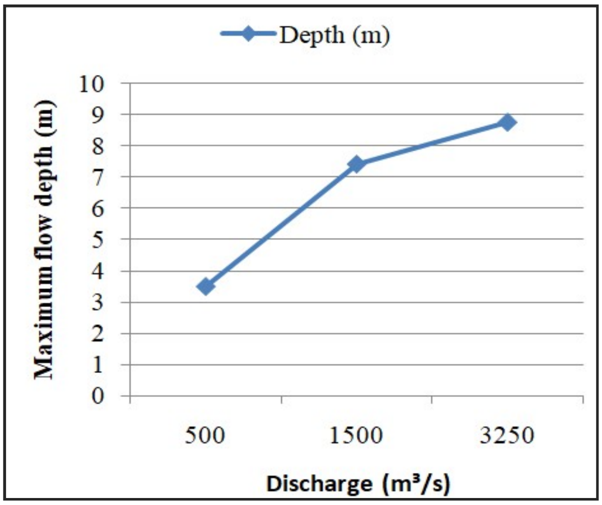

Figure 3.3. Effect of discharge on maximum flow depth

Table 3.4. Maximum flow depth (Fully open gate, Q = 3250 m^3/s**)**

Manning's Roughness	Depth (m)
0.030	8.760
0.035	9.107
0.040	9.482

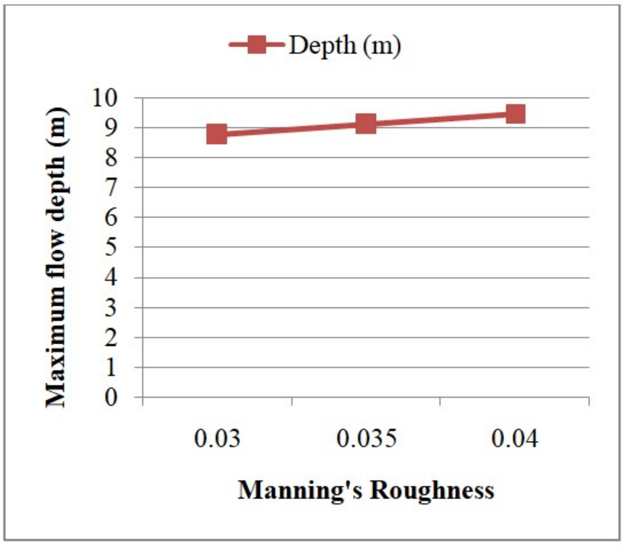

Figure 3.4 Effect of manning's roughness on maximum flow depth

Effect of Discharge on Flow Depth: There is a definite positive correlation between discharge and maximum flow depth as shown in Table 4.3 and Figure 4.2. The observation point P1, which is about 1 km upstream of the Gaula Barrage next to Maa Sheetla Devi Mandir recorded the highest flow depth for all discharge circumstances. The maximum depth rise from 3.521 m to 7.422 m when discharge increased from 500 m^3/s to 1500 m^3/s; a further increase to the planned discharge of 3250 m^3/s resulted in a depth of 8.760 m. The continuity principle, which states that a larger flow volume necessitates a greater flow area while the channel geometry stays same is the key factor controlling the growth in flow depth. In order to create enough hydraulic head to move the extra discharge through the barrage, the water level upstream rises. The increase between 500 and 1500 m^3/s is more noticeable than between 1500 and 3250 m^3/s, suggesting that under higher flow circumstances, some of the excess discharge can be accommodated by the available channel conveyance. However, the primary hydraulic loading factor influencing flow depth is still discharge.

Effect of Manning's Roughness Coefficient: As demonstrated in Table 4.4 and Figure 4.3, increasing Manning's roughness coefficient led to a progressive increase in maximum flow depth for all discharge circumstances. At observation point P1, which is about 1 km upstream of the Gaula Barrage next to Maa Sheetla Devi Mandir, the maximum depth rose from 8.760 m for n = 0.030 to 9.482 m for n = 0.040 under design discharge and fully open gate circumstances. Increased frictional resistance along the channel barrier due to higher roughness lowers flow velocity and increases energy losses. A higher hydraulic head is needed to maintain the same discharge, creating deeper flow conditions. Despite being constant throughout the simulations, the impact of roughness was less significant than that of discharge and gate operation.

CONCLUSIONS

The maximum flow depth at the Gaula Barrage under various hydraulic circumstances was assessed using HEC-RAS 6.5 along with the impact of gate operation, discharge, and Manning's roughness coefficient. The findings showed that when discharge increased, gate opening decreased and Manning's roughness coefficient increased, maximum flow depth increased. Under high-discharge conditions, gate operation had the biggest impact on flow depth of the three parameters, although Manning's roughness had a relatively lower effect. The design discharge of 3250 m^3/s, fully closed gate condition and Manning's roughness coefficient of 0.040 produced the highest simulated flow depth of 11.747 m, whereas the discharge of 500 m^3/s, fully open gate condition and Manning's roughness coefficient of 0.030 produced the minimum flow depth of 3.521 m. According to the open-channel hydraulics principles outlined by Modi (1988), larger upstream water depths are produced by increased flow resistance and flow area. This is consistent with the observed increase in flow depth with rising discharge, higher channel roughness, and decreased gate opening. These results show that HEC-RAS can be used for barrage hydraulic analysis.

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