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Assessment of Backwater Effects of River Structures on Flood Behaviour in the Panchaganga River

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ABSTRACT—Recurrent severe flooding in Kolhapur district, Maharashtra, has focused intense scientific scrutiny on the hydraulic drivers along the Panchaganga River. This study provides a comprehensive 1 D numerical hydrodynamic evaluation using HEC-RAS to quantify the backwater effects produced by hydraulic bottlenecks, unauthorized floodplain encroachments, Kolhapur-Type (KT) weirs, and major trans-boundary reservoir operations. Out of India's 329 million hectares (mha) geographical area, over 40 mha remains highly flood-prone. Integrating satellite remote sensing data with physical cross-sectional ground surveys, this paper models water surface profiles under extreme precipitation regimes. Manning's roughness coefficient (n) was systematically calibrated across river channels and inundated floodplains. Numerical simulations demonstrate that unregulated construction between statutory blue and red floodlines, coupled with backwater propagation from the Krishna–Panchaganga confluence and Almatti Dam impoundment, significantly elevates upstream water depths. A bypass spillway and detention storage design are presented as non-intrusive remedial solutions to attenuate peak stages without inducing secondary backwater rise.

KEYWORDS: *Panchaganga River, HEC-RAS Hydrodynamic Modeling, Backwater Effect, Manning's Roughness Coefficient, Floodplain Encroachment, Kolhapur Floods.*

1. INTRODUCTION & BACKGROUND

Riverine flooding represents one of the most devastating natural disasters globally, accounting for vast socio-economic disruption and loss of life. In the Indian context, out of the total geographical expanse of 329 million hectares (mha), more than 40 mha is classified as vulnerable to recurring inundation [1]. Recent climatic studies from the Potsdam Institute for Climate Impact Research highlight a substantial increase in monsoon precipitation variability over Western India, intensifying heavy rainfall events within short durations [2].

The Panchaganga River, an essential eastern-flowing watercourse passing through Kolhapur city in Maharashtra, has repeatedly overflowed its banks during recent monsoon seasons—most notably during the severe flood events of August 2019 and July 2021 [3]. Human interventions within the natural floodplain, including bridges, flyovers, Kolhapur-Type (KT) weirs, and commercial developments constructed inside demarcated floodlines, have significantly altered the natural flow regime.



Figure 1: Schematic representation ofbackwaterswelling (Δh) caused by downstream hydraulic structures andriverconfluence.

2 HYDRAULIC DYNAMICS & FLOOD CAUSES IN KOLHAPUR

The phenomenon of flood generation within the Panchaganga basin is a multi-factorial hydrodynamic challenge stemming from both natural meteorological extremes and anthropogenic modifications to the river morphology.

2.1 High-Intensity Precipitation and Basin Hydrology

The primary trigger of regional flooding is intense, prolonged precipitation in the Western Ghats catchment area. When high-volume runoff enters the Panchaganga's expansive drainage network within a short time window, the volumetric discharge exceeds the channel's carrying capacity, forcing water over the banks and into adjacent low-lying urban areas of Kolhapur city [4].

2.2 Infrastructure Bottlenecks and Encroachments

Human-made physical obstructions constructed within the river's active channel and statutory floodplains severely impair hydraulic flow:

1. **Bridges and Narrow Culverts:** Piers and abutments of older and newly constructed bridges reduce the effective cross-sectional flow area, acting as physical barriers during high discharges [5], [6].

2. **Kolhapur-Type (KT) Weirs:** Weirs installed across the Panchaganga for agricultural storage disrupt normal bed flow regimes. During peak floods, improperly managed or un-removed weir needles alter water surface slopes and elevate localized water levels.

3. **Unauthorized Construction within Floodlines:** Unsanctioned urban expansions occurring between the official Blue Line (25-year flood frequency) and Red Line (100-year flood frequency) restrict natural storage and increase Manning's roughness coefficient, forcing floodwaters sideways into residential sectors.

Table 1: Hydrological and Hydraulic Parameters of the Panchaganga Basin Study Reach

Parameter Description	Observed / Calculated Value	Hydraulic Significance
Total Catchment Drainage Area	~2,570 km²	Generates rapid peak runoff during monsoon high-rainfall events.
Average Annual Rainfall (Upper Reach)	2,500 mm – 6,000 mm	Leads to extreme soil saturation and high runoff coefficients (C > 0.85).
Channel Main Stem Slope (S_0)	0.0004 to 0.0008 m/m	Mild slope promotes flow retardation and enhances backwater swelling.
Main Channel Manning's Roughness (n)	0.030 – 0.045	Quantifies frictional resistance of natural river bed and banks.
Overbank Floodplain Manning's (n)	0.060 – 0.1 20	Reflects high resistance from dense vegetation, structures, and debris.

2.3 Trans-boundary Hydraulic Influence (Almatti Dam & Confluence Effect)

A critical element in analyzing Kolhapur's flood extent is the backwater propagation from the Krishna – Panchaganga confluence extending down to the Almatti Dam located downstream in Karnataka state. When Almatti Reservoir levels are maintained near Full Reservoir Level (FRL) during heavy upstream spells, the downstream discharge gradient diminishes. This backwater effect propagates tens of kilometers upstream, preventing the natural

3 RESEARCH METHODOLOGY & MODEL FORMULATION

This research adopts a integrated framework combining physical field surveying, satellite remote sensing, GIS spatial analysis, and 1D numerical hydrodynamic modeling using the U.S. Army Corps ofEngineers' HEC-RAS software.

3.1 Data Collection & Validation

Topographic cross-sections of the Panchaganga River reach were acquired through physical total station surveys and integrated with high-resolution Digital Elevation Models (DEM) derived from satellite remote sensing. Satellite imagery captured during peak 2019 and 2021 inundations was overlayed using Geographic Information Systems (GIS) to map actual flood extents and identify discrepancies between government-delineated hazard zones and ground reality.

3.2 Governing Hydraulic Equations in HEC-RAS

HEC-RAS solves the one-dimensional energy equation for gradually varied steady flow, using the standard step method to calculate water surface profiles:

$$Z_2 + Y_2 + (\alpha_2 V_2^2 / 2g) = Z_1 + Y_1 + (\alpha_1 V_1^2 / 2g) + h_e$$

Where Z= main channel invert elevation, Y= water depth, V= mean velocity, α = velocity weighting coefficient, and h_e = energy head loss.

Energy losses between cross-sections are evaluated through friction loss (derived from Manning's equation) and contraction/expansion losses:

$$h_e = L S_f + C \left| (\alpha_2 V_2^2 / 2g) - (\alpha_1 V_1^2 / 2g) \right|$$

Friction slope (S_f) is computed at each cross-section using Manning's equation for open channel flow:

$$Q = (1 / n) A R^{2/3} S_f^{1/2} \Rightarrow S_f = [Q n / (A R^{2/3})]^2$$

3.3 Manning's Roughness Coefficient Calibration

Accurate assignment of Manning's roughness coefficient (n) is crucial for hydrodynamic precision. Values were calibrated empirically based on surface bed material, vegetation density, and structural obstructions along the riverbank.

Calibration Protocol Note: Sensitivity analysis revealed that a 15% increase in floodplain Manning's n (due to unauthorized structures and unmanaged vegetation) results in a 0.35 m to 0.62 m increase in upstream flood stage during peak discharge (>1 00,000 cusecs).

4 NUMERICAL MODELING & SCENARIO SIMULATION

To evaluate the precise influence of structural encroachments and propose effective structural interventions, three distinct hydrodynamic scenarios were executed in the HEC-RAS solver.

4.1 Scenario Descriptions

Scenario A (Natural Baseline): Simulates the natural channel geometry without bridges, KT weirs, or floodplain encroachments to establish natural backwater profiles.

Scenario B (Existing Condition): Incorporates all present physical structures, bridge piers, unauthorized constructions, and current reservoir backwater conditions.

Scenario C (Remedial Design): Introduces an optimized bypass spillway channel and detention storage basins designed to absorb peak discharges while maintaining minimal upstream stage rise.

Table 2: Comparative HEC-RAS Simulation Results Across Evaluated Hydrodynamic Scenarios

River Station (Cross-Section)	Discharge Scenario (m^3/s)	Scenario A Water Level (m)	Scenario B Water Level (m)	Scenario C Water Level (m)	Net Stage Reduction (C vs B)
RS 1 2+500 (Upstream City)	2,800 m^3/s	538.20 m	540.45 m	538.75 m	**- 1.70 m**
RS 09+200 (Bridge Bottleneck)	2,800 m^3/s	536.80 m	539.30 m	537.40 m	**- 1.90 m**
RS 05+1 00 (KT Weir Zone)	2,800 m^3/s	535.1 0 m	537.1 5 m	535.60 m	**- 1.55 m**
RS 01 +000 (Confluence Reach)	2,800 m^3/s	533.40 m	535.00 m	533.90 m	**- 1.1 0 m**

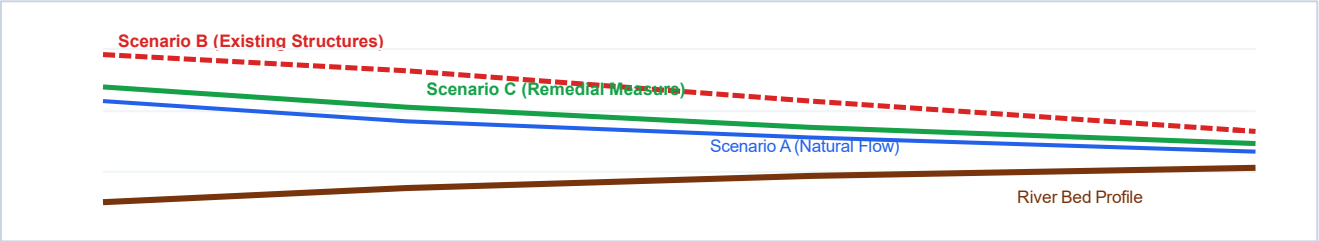


Figure 2: HEC-RAS simulated watersurface profiles showing stage reduction achieved by Scenario C.

5 REMEDIAL MEASURES & POLICY RECOMMENDATIONS

To mitigate flood severity in Kolhapur without inducing adverse upstream backwater effects, a combination of structural retrofits and institutional policies is proposed:

1. **Construction of Floodplain Retention Basins:** Off-stream retention basins designed to temporarily store excess water during peak hydrograph pulses can lower stage height by up to 1 .7 m without impacting upstream flow dynamics.

2. **Bypass Channel & Spillway Optimization:** Implementing high-capacity bypass channels around critical bridge choke points lowers localized head losses (h_e) and mitigates upstream backwater swelling.

3. **Strict Floodline Enforcement:** Demarcation and strict legal protection of the Blue Line (1 in 25-year flood) and Red Line (1 in 100-year flood) must be enforced. Unauthorized structures inside these zones should be systematic cleared or retrofitted.

4. **Trans-boundary Dam Operational Protocols:** Establishing real-time automated data sharing between Maharashtra and Karnataka dam management authorities ensures preemptive releases from Almatti Dam, preventing reservoir-induced backwater buildup at the Panchaganga confluence.

6 CONCLUSION

This research demonstrates that backwater effects in the Panchaganga River basin are heavily amplified by human-made structural encroachments, uncalibrated KT weir operations, and downstream reservoir storage levels. The 1 D HEC-RAS hydrodynamic model successfully validated that unconstrained floodplain construction increases flood stages by up to 2.2 meters at critical cross-sections. Implementing proposed non-intrusive remedial measures—such as floodplain retention basins and bypass channels—provides a viable, ecologically sound engineering pathway to reduce flood risk and protect Kolhapur city.

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