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2D hydraulic modelling of diversion headworks under extreme flood conditions: A case study of Sunkoshi hydropower project

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Abstract

This study examines the hydraulic performance and operational vulnerabilities of the Sunkoshi Hydropower Plant in Nepal through two-dimensional (2D) hydraulic modeling. The objectives include analyzing flow dynamics under various operational conditions, optimizing gate management for flood resilience, and maintaining the minimum ecological flow required to ensure environmental needs. Employing historical hydrological data (1965-2012) from the Department of Hydrology and Meteorology, Nepal, and a high-resolution Digital Elevation Model (DEM), the study simulates flood scenarios (10 to 100–year return periods) and operational configuration of the barrage and intake gate with 2D HEC-RAS Modeling. The findings show that during extreme floods, water depths and velocities significantly surpass the design limits, increasing the risks of structural damage and environmental disruption. The findings highlight the necessity of adaptive gate operations, structural reinforcements, and ecological flow considerations to enhance resilience and sustainability. The methodology provides a replicable framework for such hydropower projects in mountainous regions, contributing to sustainable hydropower development.

1. Introduction

Hydropower projects are increasingly favored for their ability to balance ecological benefits with operational flexibility in flood-prone areas. These projects utilize a diversion headworks design that includes a weir and gated intake, allowing for controlled water diversion and upstream ponding, which is essential for managing extreme flow events. Two-dimensional hydraulic modeling plays a crucial role in capturing detailed flow behaviors around these structures, aiding in gate operation optimization and flood management [1]. While Run-of-River (RoR) systems depend on natural flow, they can disrupt ecosystems, leading to habitat degradation and water quality issues, which require mitigation strategies like environmental fluxes [2]. Additionally, dynamic water-level management is recommended to improve efficiency while maintaining environmental integrity [3]. Overall, integrating advanced modeling and ecological considerations is vital for the sustainable development of RoR hydropower projects [1][4].

The challenges associated with headworks design and operation are particularly acute in the Himalayan region. Rivers in this area are challenged by a combination of steep topography, fragile geology, and intense monsoonal rainfall, which drives exceptionally high sediment transport [5] that compromises hydraulic performance, reduces operational efficiency, and shortens infrastructure lifespan through the erosion of critical components [6]. Furthermore, the region is experiencing the impacts of climate change, including rising temperatures. Rising temperatures have accelerated glacier retreat, leading to increased meltwater runoff, which temporarily boosts water availability [7]. This phenomenon, coupled with shifting precipitation patterns, has resulted in a higher frequency and intensity of extreme flood events [8]. This has led to stressed aging infrastructure that may not withstand these new hydrological realities, necessitating urgent re-evaluation and adaptation strategies to mitigate risks [9].

Although the diversion weir represents the first line of defense in run-of-river systems, it becomes the most

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vulnerable component during extreme floods. Studies show that when floodwater surpasses design parameters, the diversion weir experiences complete submergence, fundamentally altering the hydraulic regime [10][11]. The flow dynamics undergo a dramatic transformation, characterized by turbulent, high-velocity water that exerts extreme pressure on both the weir structure and its foundation [12]. Laboratory investigations reveal that local scour downstream of energy dissipators represents one of the most critical degradation mechanisms affecting weir stability [13]. Studies indicate that scour depths can reach 1.5 meters or more during maximum discharge events, potentially undermining the structural foundation [13]. The intake structure, designed for specific flow diversion capacities, faces unprecedented challenges when confronted with sediment-laden water [14]. Undersluice gates, critical for sediment flushing operations, may become inoperable due to immense pressure and debris accumulation [15]. The scientific evidence demonstrates that the diversion headworks of the hydropower facilities represent complex, interconnected systems vulnerable to cascading failures during extreme flood events [11]. The combination of structural scour, debris loading, sediment overwhelm, and gate operations failure creates a multi-faceted challenge that often results in prolonged operational downtime and significant infrastructure damage. Understanding these mechanisms is crucial for developing more resilient hydropower infrastructure capable of withstanding increasingly frequent extreme weather events associated with climate change. The 2021 flooding in the Eifel region, especially the small town of Stolberg and Eschweiler in the Inde River catchment, which led to significant infrastructure damage, highlights the need for advanced modeling techniques that can predict the behavior of diversion headworks under such conditions [16]. Consequently, HEC-RAS is recognized as the industry-standard software for modeling complex flow behavior, particularly when simulations must incorporate hydraulic structures and their corresponding gate operations.

Since traditional one-dimensional (1D) hydraulic models rely on cross-sectional averaging and unidirectional flow assumptions, they are fundamentally inadequate for capturing complex, multidirectional flow dynamics around the headworks structures during major floods [18][19][20]. Critical features that are necessary for the precise prediction of sediment deposition and hydraulic performance in complex geometries, such as lateral velocity variations, recirculation zones, and secondary flow patterns, are not included in these models [21]. 1D models, which rely on the Saint-Venant equations, become particularly unreliable during flooding events when flow exhibits significant two-dimensional characteristics, leading to substantial errors in hydraulic analysis and design [22]. While significant studies are showing that 2D models provide more accurate flood extent and velocity predictions, simulate multi-directional flow, and capture lateral variations and recirculation zones [23][24]. There is a lack of comprehensive 2D modeling studies, especially focusing on the operational performance of diversion headworks in the Himalayas, which could inform retrofitting and operational strategies. Although 2D modeling has been effectively applied in many contexts, such as floodplain studies and dam-break scenarios [25][26], studies have focused more on general flood mapping rather than on in-depth, scenario-based hydraulic analyses of the headworks of operational plants [24].

Figure 1: The Jure landslide (2014) damaged the road and headwork of the Sunkoshi hydropower project [17]

This study presents a comprehensive hydraulic assessment of the headworks of the Sunkoshi Hydropower Plant, an ageing but critical diversion headworks facility in Nepal. The primary objective is to provide a robust, data-driven evaluation of the headworks' hydraulic performance, identify vulnerabilities related to modern flood magnitudes and sediment management, and evaluate potential design and operational improvements. This paper aims to inform future upgrades and support the long-term resilience of similar diversion headworks in the Himalayan region and beyond.

2. Study area

The Sunkoshi Hydropower project is situated in Sindhupalchowk District, Nepal, approximately 75-81 km northeast of Kathmandu at Khandichaur (27° 43' N - 27°44' N latitude and 85°55' E - 85°56' E longitude). The Sunkoshi River, a major feeder to the Saptakoshi River, is well-positioned to meet the capital with substantial power generation capacity. The project supplies around 15% of peak electricity demand to the central grid of the Integrated Nepal Power System.

Emerging from the Himalayan ridges, the Sunkoshi River exhibits significant seasonal flow variations. Monsoon season (June- September) is responsible for maximum annual discharge, with peak flows reaching about 3,000 m³/s, while dry season flows (October- May) average in-river about 120 m³/s coming from snowmelt. These flow patterns through hydrology records can be used to produce a flood event and the water surface profiles along the bank of the river. Events, like the Jure landslide of 2014 (Figure 1), which diverted a river in a significant flood event that caused destruction and halted power generation for 40 days, and historical events like monsoon floods of 1981 that disrupted road and agricultural infrastructure, emphasize the need for strong flood management [27]. Annually, monsoon floods occur, and climate change and other geographical factors further exacerbate this phenomenon due to historical records exhibiting spatial concerns.

The pattern of land use/land cover, which is present in the Sunkoshi River basin, includes grasslands with 37%, forests with 33%, bare lands with 19%, settlements with 4%, wetlands, crop-grown land, debris-covered glaciers, and clean glaciers with 1% each [28].

The Sunkoshi Hydropower Project began operating in January 1972 and has generated 3,259.5 GWh with a recent annual generation of 58.2 GWh (92.7% of its design capacity of 10.05 MW). It has contributed to the energy security of Nepal by reducing the reliance on fossil fuels. The Sunkoshi Hydropower projects help community economic security through employment and provision of services (Such as schools and health facilities). However, the 2014 landslide demonstrated the community's vulnerabilities related to disasters that resulted in displaced communities and disrupted livelihoods. This underscored the importance of disaster risk management and resilience-building strategies.

3. Material and methods

3.1. Hydrological data pre-processing and analysis

Hydrological input data, including annual maximum discharge and rainfall records, were sourced from [29]. Discharge data gaps were filled using the Prophet forecasting model in Python, while minor rainfall gaps were considered negligible.

Catchment delineation was performed using ArcGIS 10.8, based on a 12.5m resolution ALOS PALSAR DEM retrieved from [30]. The Sunkoshi River basin upstream of the headworks was divided into gauged and ungauged sub-catchments using data from the Bahrabise hydrological station. Catchment properties, including flow path length, centroid location, and elevation range, were extracted to support runoff and flood estimation. All the data and their sources with descriptions are presented in Table 1.

Design discharges for 10, 25, 50, and 100-year return periods were computed. For the gauged basin, statistical flood frequency methods (Weibull, Gumbel, Log Pearson III, and Log Normal) were applied. For the ungauged sub-basin, empirical approaches (Snyder's method, WECS/DHM, Fuller's, and Modified Dicken's formulae) were used. Rainfall distribution across the ungauged area was estimated using Thiessen polygon analysis. The combined peak discharge, used as the design flood, informed headworks and canal flow design.

3.2. Topographic survey and DEM development

A high-resolution topographic survey of the headworks area was conducted using a Stonex Total Station, with key structural features and river cross-sections recorded. Ground control points were geo-referenced and verified using GPS and satellite imagery. In areas with limited access, non-prism surveying techniques were used.

All spatial datasets were projected to WGS 84 UTM Zone 45N. Using ArcGIS, survey points were interpolated to create a Triangulated Irregular Network (TIN), which was then converted into a 2m resolution raster DEM. This DEM captured structural and terrain features necessary for accurate hydraulic modeling. Alignment between DEM elevations and original cross-sections was verified to ensure topographic fidelity.

3.3. Overall methodology

The study employed a structured multi-phase approach integrating hydrological analysis, topographic data processing, and two-dimensional hydraulic modelling in HEC-RAS to assess flow behaviour at the Sunkoshi hydropower headworks. The methodology encompasses five primary stages presented on Figure 2, Topographic survey and DEM creation, 2D flow model configuration in HEC-RAS, Model calibration and validation, and Simulation scenario analysis.

3.4. 2D hydraulic model development in HEC-RAS

The hydraulic model was developed using HEC-RAS 6.5, employing a 2D unsteady-flow domain encompassing the Sunkoshi headworks, intake structures, settling basin, and approach canal. A refined, unstructured computational mesh was constructed with cell sizes ranging from 0.5m × 0.5m (in high-gradient zones near gates and piers) to 2m × 2m (in low-gradient regions), balancing accuracy and computational efficiency.

Table 1: Available data and their sources

Data Type	Source	Description
Hydrological and Meteorological Data	Department of Hydrology and Meteorology (DHM), Kathmandu, Nepal	Historical annual maximum discharge data (1965-2012) and daily rainfall records (1947-2024) for flow analysis.
Topographic Data	Field survey data collected with a Stonex Total Station	Used to create a high-resolution DEM for 2D modelling.
DEM	ALOS PALSAR (12.5m resolution) via the ASF Data Search platform	Additional DEM data for catchment delineation using GIS environment.
Structural Dimensions	Field survey measurements; Sunkoshi Hydropower Plant management	Detailed measurements and design specifications of headworks components.

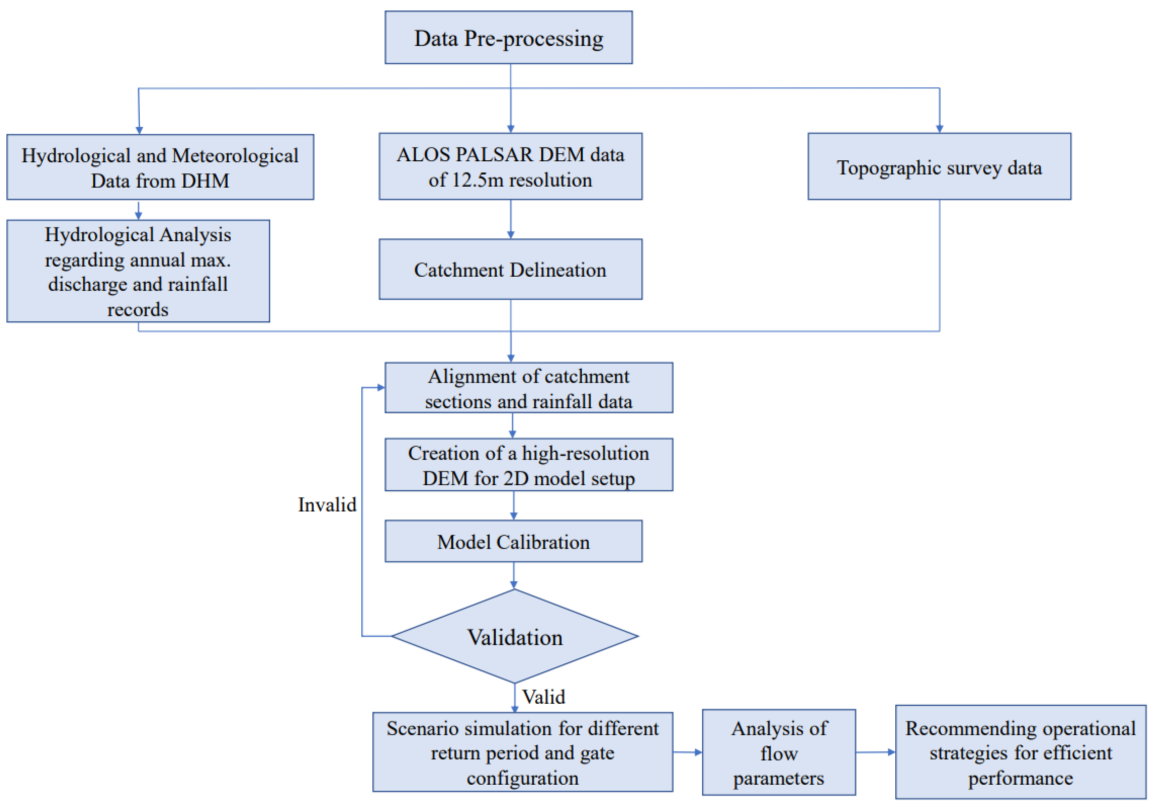

Figure 2: Comprehensive methodological flowchart

An average Manning's roughness coefficient of 0.033 (0.03 to 0.035) was assigned across the domain to represent riverbed and structural surfaces [31]. Internal 2D area connections were used to model hydraulic structures, including the barrage and intake. Terrain modification was performed to model the settling basin and canal based on the field-survey data. Gate hydraulics were simulated using default HEC-RAS coefficients, with operational states (open, partially open, closed) defined per scenario.

The upstream boundary condition was prescribed with both design discharges of 1,079.36 m³/s (10-year return period) to 2,857.46 m³/s (100-year return period), which are moderate and extreme floods, respectively. The downstream boundaries employed a normal depth condition based on the calculated slope of 0.015 for the river and 0.001 for the settling basin and canal. Initial water surface elevations were set using default HEC-RAS estimates, with a warm-up duration of 500-time steps to ensure numerical stability. The diffusive wave solver was selected for improved performance under gradually varied flow conditions. A fixed computational time step of 0.2 seconds was used, with outputs stored at 1-hour intervals for analysis.

3.5. Model calibration and validation

Calibration was performed using observed water surface profiles and flow records at the Sunkoshi headworks. Model parameters, including Manning's roughness and gate operation states, were iteratively adjusted to match simulated and observed water levels. Validation was conducted using historical flood data, including the 2014 Jure landslide-induced flood event, cross-referenced with field and NEA operational records. Sensitivity analyses were carried out to assess the model's responsiveness to boundary and structural condition changes.

3.6. Simulation scenarios

Two categories of simulation were executed:

- **Flood scenarios:** Extreme flood events corresponding to 10-, 25-, 50-, and 100-year return periods were simulated to evaluate flow behaviour, hydraulic jumps, recirculation patterns, and structural vulnerability. Results informed assessments of scour risk and sediment ingress near critical components.
- **Operational scenarios:** Simulations were conducted for various barrage gate configurations (fully open, closed, and partially open) while keeping intake gates fully open across all scenarios. These analyses evaluated intake performance and flow distribution under both design and extreme conditions.

4. Results

4.1. Flood frequency analysis

The catchment area of the Sunkoshi Hydropower Project was delineated using ArcGIS 10.8 with a 12.5m resolution Digital Elevation Model (DEM) from Alos Palsar. The total catchment area is 2,492.24 km^2, with 95% (2,364.64 km^2) (Figure 3) being gauged and monitored by the Bahrabise hydrological station and 5% (127.603 km^2) being ungauged (Figure 4). The elevation ranges from 763 m at the outlet to 7,916 m at the highest point, with an average slope of 15–30% (Figure 5). Approximately 78% of the area has slopes greater than 15%, and more than 35% have slopes exceeding 30%, indicating a highly steep basin that contributes to high flow velocities and sediment transport. The hydrological analysis provided flood discharge estimates for different return periods.

To estimate the design discharges of the gauged section of the catchment, the Log-Pearson Type III distribution was selected, which would give the best fit to the annual maximum series of discharges, and for the ungauged sub-basin peak flows B.D Richards Method was chosen, which involves rainfall intensity, spatial distribution and time of concentration principles. Table 2 provides the sum of the contributions of both the gauged and the ungauged basins as the total design flood of each return period.

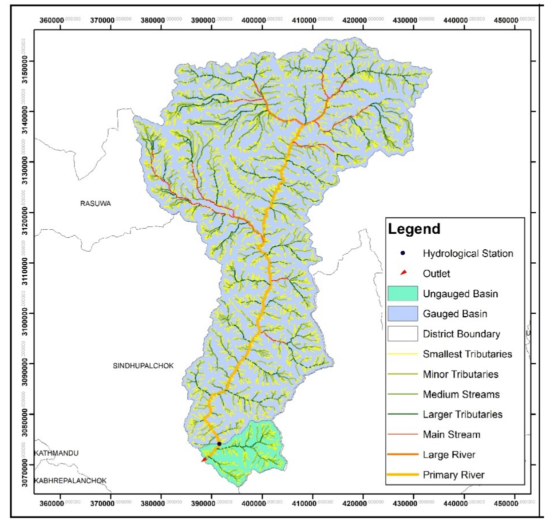

Figure 3: Catchment Area

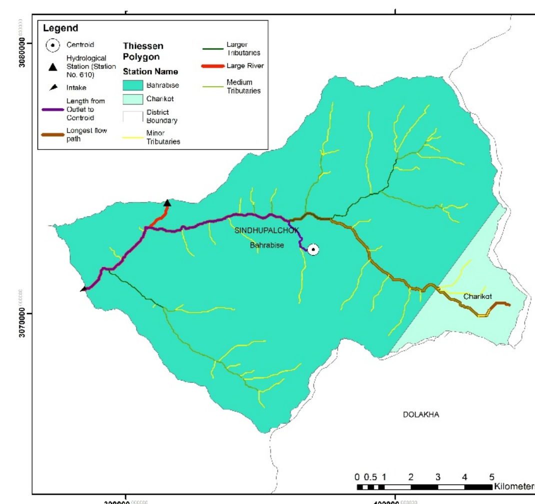

Figure 4: Ungauged catchment map

4.2. Topographical survey

A detailed topographic survey was conducted using a Stonex total station and GPS. The survey covered the headworks area, including the barrage, intake, settling basin, and approach canal, providing precise coordinates

Table 2: Flood discharge estimates for entire catchment area

Return Period (Years)	Gauged Discharge (m^3/s)	Ungauged Discharge (m^3/s)	Total Discharge (m^3/s)
10	888.169	191.189	1079.36
25	1357.816	241.777	1599.59
50	1859.778	280.878	2140.66
100	2536.565	320.891	2857.46

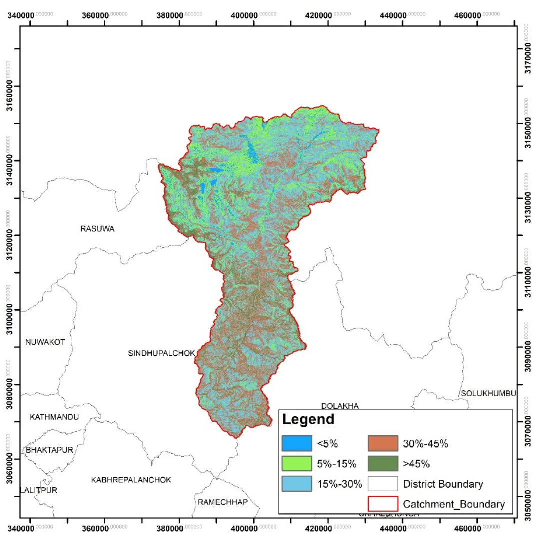

Figure 5: Slope map of catchment

and elevations for these structures and the surrounding terrain. The DEM shown in Figure 6 was created using Triangulated Irregular Network (TIN) interpolation, ensuring accurate representation of the complex topography.

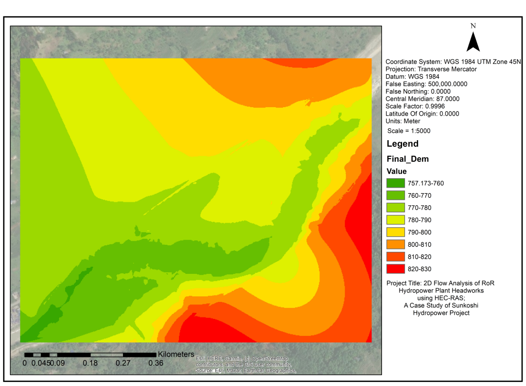

Figure 6: Digital elevation from survey points

4.3. Model optimization

A 2D hydraulic model was created in HEC-RAS using the high-resolution DEM and structural data from the survey. The computational mesh shown in Figure 7 was set with cell sizes of 0.5 m × 0.5 m near critical zones (e.g., barrage, intake, canal) and 4 m × 4 m in less critical areas to balance detail and computational efficiency. Manning's roughness coefficient was uniformly set to 0.033. The model included hydraulic structures such as the barrage (4 radial gates, 11.5 m wide, 7 m high), under sluice (2 radial gates, 5 m wide, 7.1 m high), and intake (3 sluice gates, 6.5 m wide, 6 m high), with user-defined gate operations for different scenarios (e.g., fully open, fully closed, partially open).

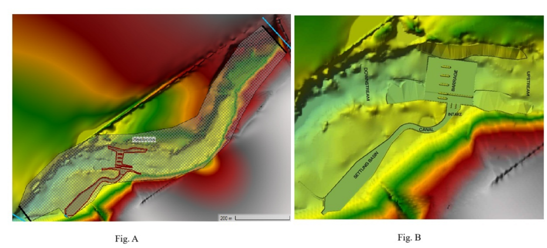

Figure 7: Snapshots of the model showing Mesh and Boundary condition lines (A) and structures modeled by performing terrain modification (B)

4.4. Hydraulic condition under multiple scenarios

The two-dimensional (2D) flow simulations conducted using the HEC-RAS provided detailed insights into the hydraulic performance of the headworks of the Sunkoshi Hydropower Plant under various operational scenarios and flood conditions. The simulations were based on a computational model using a two-dimensional unstructured mesh and dependent on linearity between the computational model. The experimental boundary conditions and initial parameter data utilized to reflect the return period of a flood wave of 10, 25, 50 and 100 years along major pathways in hydrodynamic processes in the approach canal, the main river channel and the settling basin. The scenarios considered both open and closed barrage configurations, as detailed in the methodology section of this study.

4.4.1. Velocity distribution

The velocity distributions along the approach canal, river, and settling basin were analysed to understand flow patterns under different flood scenarios and barrage operations. In the concrete-lined approach canal, the maximum permissible mean velocity ranges from 3.8 m/s to 7.4 m/s [32]. However, flood scenarios exhibited significantly higher velocities. For the 100-year flood with the barrage open and intake open (F100_BO_IO) [1], velocities peaked above 30 m/s near the entrance (stations 0–20 m) and stabilized at 18–21 m/s along most of the canal (stations 40–120 m). For the 50-year (F50_BO_IO) and 25-year (F25_BO_IO) floods with the barrage open, maximum velocities reached 18–19 m/s and 15–16 m/s, respectively (Figure 8). Barrage closure further increased velocities; for example, in the 10-year flood with the barrage closed and intake open (F10_BC_IO), velocities were approximately 13–15 m/s, compared to below 10 m/s in the open barrage scenario (F10_BO_IO). High-turbulence zones were observed at the canal entrance, particularly in higher flood scenarios.

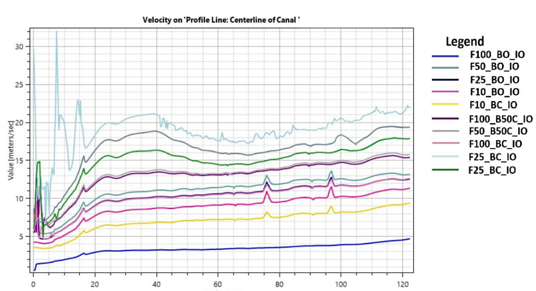

Figure 8: Maximum velocity distribution along canal centerline

Along the river centerline (Figure 9), a pronounced velocity spike of approximately 21 m/s was recorded at the barrage location (station ~60 m), indicative of a hydraulic jump. Upstream velocities were highest in the F100_BO_IO scenario, reaching 12–13 m/s, which decreased to approximately 9 m/s immediately before the barrage. Barrage closure reduced upstream velocities to 5–8 m/s due to backwater effects. Downstream of the barrage, velocities stabilized between 4 and 10 m/s, with open barrage scenarios maintaining higher velocities (6–10 m/s) compared to closed scenarios (4–7 m/s).

In the settling basin (Figure 10), entrance velocities

[1]F100_BO_IO means the flood frequency F for the return period of 100 years with barrage opened (BO) and intake opened (IO)

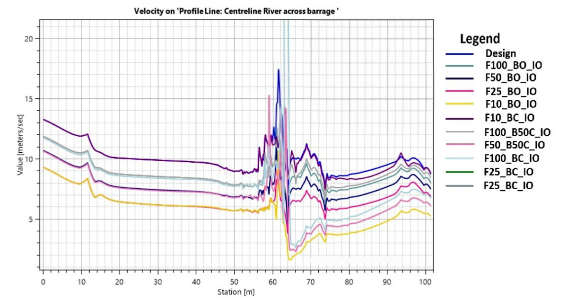

Figure 9: Maximum velocity distribution along river centerline

peaked at over 22 m/s in the F100_BO_IO scenario, creating high-turbulence zones unsuitable to settle sediments. Velocities decreased progressively, stabilizing at 3–5 m/s at the exit (station 120–140 m). Open barrage scenarios exhibited higher velocities with oscillations, suggesting recirculation zones that could reduce settling efficiency. Velocities at different station(m) from intake are presented in Table 3.

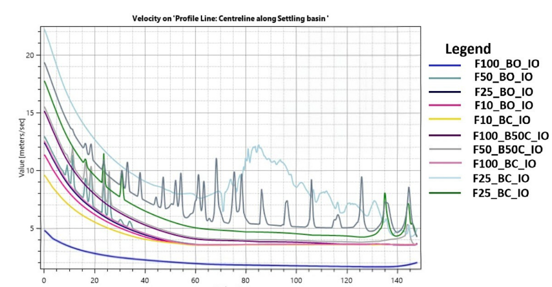

Figure 10: Maximum velocity along settling basin centerline

Table 3: Summary of peak velocity observed in approach canal for each scenario

Scenario	Peak Velocity (m/s)	Location (Station)
F100_BO_IO	>30	0–20 m
F50_BO_IO	18–19	0–20 m
F25_BO_IO	15–16	0–20 m
F10_BC_IO	13–15	0–20 m
F10_BO_IO	<10	0–20 m

4.4.2. Volume accumulation

Volume accumulation was assessed to evaluate changes in water storage across the approach canal and river centreline for various scenarios. In the approach canal (Figure 11), all flood scenarios showed a progressive volume loss, with the F100_BC_IO scenario experiencing the most significant reduction, approximately 6,000,000 m³ by the end of the simulation (6 hours). Barrage-closed scenarios exhibited steeper volume decrease rates compared to open scenarios, with higher flood magnitudes (F50 and F100) resulting in greater losses.

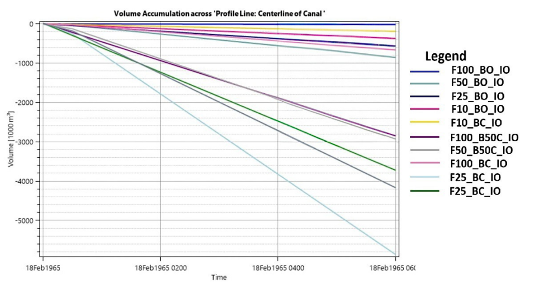

Figure 11: Volume accumulation along approach canal

Along the river centreline (Figure 12), positive volume accumulation was observed upstream, indicating storage. The F50_BC_IO scenario accumulated approximately 11,000,000 m³, nearly three times higher than its open barrage counterpart (F50_BO_IO). Closed barrage scenarios showed faster accumulation rates, while open scenarios exhibited more gradual increases. Volume of water accumulated over period of time for different scenarios are presented in Table 4.

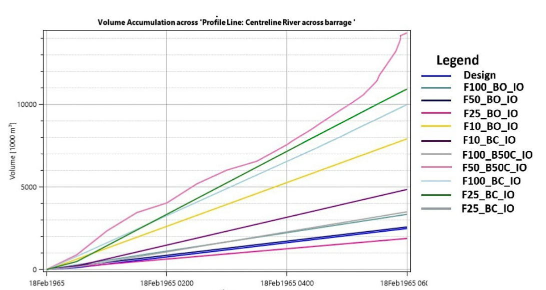

Figure 12: Volume accumulation in river across barrage

Table 4: Volume accumulation data for selected scenarios along the river centreline

Scenario	Accumulated Volume (thousand m^3)	Location
F50_BC_IO	∼11,000	Upstream
F50_BO_IO	∼4,000	Upstream
F25_BO_IO	∼3,000	Upstream
F25_BC_IO	∼10,000	Upstream

4.4.3. Water depth and surface elevation

Depth profiles (Figure 13) and water surface elevations (Figure 14) were examined to assess hydraulic behaviour along critical flow paths. In the approach canal (Figure 13), the F100_BO_IO scenario produced the highest depths, approximately 9.5 m upstream, decreasing to about 8 m downstream, while F10 scenarios ranged from 4.5 to 5.5 m. Barrage closure reduced depths by approximately 1–1.5 m compared to open scenarios. Summary of water depth at different locations of the approach canal is provided in Table 5.

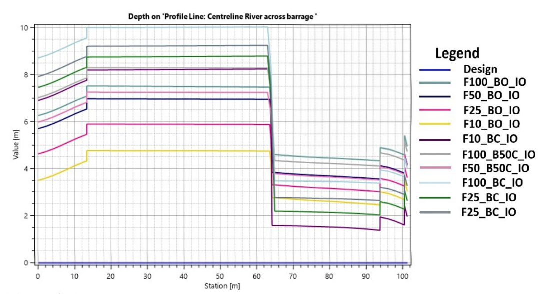

Figure 13: Depth variation along river centerline across barrage

Along the river centreline (Figure 13), a hydraulic jump at station 60 m resulted in depths dropping from 8–10 m upstream to 1.5–4 m downstream, with a corresponding WSE drop of approximately 5–6 m. The F100_BO_IO scenario achieved maximum upstream depths of about 10 m and a WSE of 774 m. Barrage closure increased upstream depths by 1–2 m.

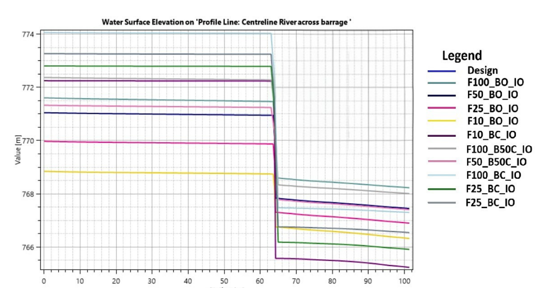

Figure 14: Water surface elevation along river centerline across barrage

In the settling basin (Figure 15), depths in the F100_BO_IO scenario were highest, around 7.5 m upstream, decreasing to 5.5 m downstream, with all flood scenarios surpassing the design depth of 4 m by at least 0.6 m. Open barrage scenarios generally exhibited higher depths than closed ones.

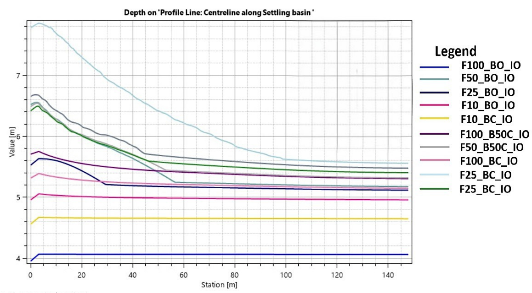

Figure 15: Depth variation along the settling basin centerline

Table 5: Summary of the maximum water depths in the approach canal for each scenario

Scenario	Maximum Depth (m)	Location
F100_BO_IO	9.5	Upstream
F50_BO_IO	∼8–9	Upstream
F25_BO_IO	∼7–8	Upstream
F10_BO_IO	4.5–5.5	Upstream
F10_BC_IO	3.5–4.5	Upstream

4.4.4. Flow regulation and sediment transport

The interplay between velocity, depth, and sediment dynamics was analysed to assess sediment transport and deposition potential. In the approach canal, peak velocities of 30–32 m/s in the F100_BO_IO scenario near stations 10–20 m stabilized to 18–20 m/s, promoting sediment deposition between stations 20–40 m. In the settling basin, entrance velocities of up to 22 m/s in the F100_BO_IO scenario decreased to 3–5 m/s at the exit but exceeded the optimal settling velocity of 1.0 m/s, indicating potential inefficiencies in sediment removal. The hydraulic jump at the barrage (station 6̃0 m) caused significant depth reductions from 8–10 m to 1.5–4 m, increasing turbulence and posing risks of scour and erosion.

Volume accumulation data further highlighted hydraulic challenges. In the approach canal, the F100_BC_IO scenario showed a volume loss of approximately 6,000,000 m³, with steeper reductions in closed barrage scenarios. In the settling basin, the F100_BC_IO scenario lost approximately 10,500 thousand m³ over 6 hours, reflecting intense hydraulic conditions. Along the river centreline, scenarios such as F25_BO_IO accumulated 3̃,000,000 m³ upstream, while closed barrage scenarios (e.g., F50_BC_IO, F25_BC_IO) accumulated 11,000 and 10,000 thousand m³, respectively.

5. Discussion

The 2D hydrodynamic analysis of the diversion headworks of the Sunkoshi Hydropower plant in Nepal puts emphasis on the fundamental hydraulic functionality of the system and the operational issues that it is subjected to in rivers with sediments. The main issue identified is poor performance under extreme flood conditions (water depth and flow greatly exceeding design conditions, caused by the river environment), which is compromising operational capability and structural performance.

According to Penche et al. [33], peak velocities in the approach canal and settling basin range from 1-4.5 m/s, but during the simulation of the 100-year return period flood, keeping both barrage and intake open, velocities in the approach canal and settling basin range from 15-20 m/s and 6-8m/s, respectively. These elevated velocities create vulnerabilities for less sediment deposition, making the settling basin non-functional and increasing the potential for scour, erosion, and structural damage. Similarly, the water depths in the canal reached 9.5m and 7.5m in the settling basin, exceeding the design depth of 6m in the settling basin, which may lead to overtopping and excessive hydraulic loads. These findings underscore the requirements for robust design considerations to adapt to extreme floods in Himalayan Hydropower plants.

The simulated design case of reaching canal velocity of 30 m/s and canal depth of 9.5 m during a 100-year flood demonstrates the need to have adaptive operational strategies. In particular, the maximization of gate activities (partial or complete closures) may help to decrease downstream velocities and off-peak upstream ponding, which alleviates hydraulic risk due to extreme flood occurrences. Closing the barrage during the floods will decrease the downstream velocities but also result in ponded upstream storage, which can affect upstream ecosystems and infrastructure. Therefore, we can develop a list of operating strategies to ensure adaptive barrage operations while still maintaining the desired balance between flood management and generation demand. Studies on optimizing Hydropower plants, choosing the appropriate turbine types and configurations, may provide operators with greater operational flexibility under more variable flow conditions, such as in Sunkoshi, where there is a considerable amount of seasonal flow variability.

This study's 2D HEC-RAS modelling approach offers a solid framework for assessing hydraulic performance in a variety of hydropower projects. For other Hydropower plants, the methodology's dependence on scenario-based simulations and high-resolution DEMs can be standardized, particularly in regions with complex topographies like the Andes and Alps. As an illustration of how HEC-RAS can be applied to comparable problems, the Thakot Hydropower Project used it to optimize sediment management [34]. The broad application can be ensured by practicing standardization over model setup using high-resolution digital elevation models (DEMs) and adaptive mesh sizes to capture terrain variations and refinement regions over structures. These practices align with HEC-RAS best practices, emphasizing accurate terrain representation and model validation. Comparative Studies, such as those between HEC-RAS and IBER 2D, confirm reliability in simulating complex flow dynamics, making it suitable for hydropower applications [35]. The dependency on statistical flood estimates introduces uncertainties due to limited observed data. To improve the accuracy of the model, future studies could incorporate real-time hydrological data. Additionally, incorporating climate change scenarios could improve predictions of future flood risks, given increasing hydrological variability in mountainous regions [36]. Developing successful cases, such as Thakot, advanced tools like HYPER could be explored for long-term performance analysis [34].

A critical research gap in using 2D hydraulic analysis to address the vulnerabilities in the design of the hydropower headworks in a mountainous region can be addressed by this study. Future research is suggested to include the emerging climate baseline forecasts, especially CMIP6 ensembles of SSPs and modified wet/dry cycles, to better assess the risk of flood and make diversion headworks more resilient [37]. The applicable framework offers insights for robust design and sustainable operation, advancing hydropower engineering worldwide. This study promotes the switch to renewable energy while maintaining ecological integrity by tackling both technical and environmental issues. By integrating technical and environmental considerations, it provides a foundation for informed decision-making and sustainable practices in the hydropower sector. In conclusion, this study emphasizes the critical role of advanced hydraulic modelling in addressing the multifaceted challenges of such hydropower plants in mountainous regions.

6. Recommendations

To improve the stability of the diversion headworks of the Sunkoshi Hydropower Plant to extreme flood events, simulated velocities of 30m/s and depths of over 9.5m, the suggestion will be to reinforce the barrage foundations with riprap and geotextiles. Also, the approach canal walls are to be raised by 2-3 m and energy dissipating structures have to be provided to contain the flow velocities within reasonable limits and the capacity of the settling basin should be raised by 20-30 percent by the introduction of additional baffle walls. Operationally, dynamic gate sequencing (opening gates 50-70 percent under moderate flood conditions) should be adopted through real-time monitoring in order to help with the flushing of sediments. It is advisable to have biannual under sluice flushes to ensure the integrity of intake during the monsoon seasons and the environmental flow requirements of 10-15 percent of the mean annual discharge should be imposed. The phased and simulation-supported interventions should be able to help lengthen the service life of the infrastructure and adapt to the increasing hydrological variability linked to climate change.

7. Conclusion

The study offers an extensive two-dimensional (2D) flow analysis of the headworks of the Sunkoshi Hydropower Plant of Nepal's first Run-of-River (RoR) hydropower installation using HEC-RAS modelling, and filling urgent gaps in the understanding of complex flow interactions and infrastructure resilience related to aging hydropower infrastructure. The headworks and hydropower plant are in the steep Himalayan floodplain with high sediment concentrations, and the research examined flood resilience and sustainability, using advanced hydraulic modelling and scenario-based evaluation methods.

The results demonstrate considerable vulnerabilities during extreme flooding events, exceeding design parameters for velocity and depth, thus affecting operational efficiency and infrastructure integrity. Specifically, during the 100-year flood condition with the barrage and intake open, the velocities were up to 30 m/s in the approach canal, and 22 m/s in the settling basin, indicating design velocities as low as 1-4.5m/s. The water depth of 4 m also exceeded the maximum design water depth by up to 1.5 m in the canal. These findings demonstrate the need for more flexible gate management and added structural reinforcement to reduce flooding impacts while maintaining some level of power generation.

Next, the study promotes the need for consideration of environmental aspects in operational actions by utilizing habitat flows of 10-15% of the mean annual discharge to avoid sediment starvation to downstream habitats. The move to 2D HEC-RAS models offers significant improvements from traditional 1D models since they provide a better representation of flow dynamics and offer a model pathway that could be replicated for other similar programs in the mountain landscape. However, the authors also reported limitations in the study, such as the absence of data for sediment transport and geography-specific considerations on the outcomes of the study, which may limit broader applications. Future studies should include a consideration of complete datasets (including an understanding of sediment transport), climate change long-term impacts, and consider using real-time monitoring systems to assist with operational decision-making.

In summary, this study makes a valuable contribution to the understanding of the technical context of RoR hydropower plants and enhances the broader story of sustainable development of energy in areas that are sensitive to environmental factors. Through the clarification of the relationships of hydraulic performance, environmental stewardship, and resilience in infrastructure, the study offers meaningful information to policymakers, engineers, and operators hoping to operate hydropower systems more effectively with the least impact on the surrounding environments. The study's results and methodology can support improved design and management practices to develop hydropower infrastructure in difficult terrains around the world and ensure sustainability.

8. Limitations

- Lack of proper observed DHM data for calibration and validation.
- Less detailed topography in upstream areas due to the difficult terrain structure, which made surveying challenging with the heavy equipment.
- The absence of DHM data gaps in the boundary condition; the data predicted may fail to provide simulation accuracy.
- Gates were assumed to operate with constant openings, which may not reflect actual conditions.

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