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Designing for Resilience: An Integrated Engineering Framework for Irrigation Infrastructure in Climate Vulnerable Himalayan Basins

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ABSTRACT

Designing resilient irrigation infrastructure under hydrological uncertainty is a critical challenge in climate-vulnerable, sediment-laden Himalayan basins. This study develops an integrated engineering framework through comprehensive assessment of Nepal's Bagmati River at Pandhera Dobhan, combining forty-one years of discharge data (1979–2019), historical and contemporary sediment records (1990–2024), and seasonal water quality monitoring. The Log-Normal distribution provided the best fit for flood frequency analysis (χ^2 goodness-of-fit, $p < 0.05$), yielding a 100-year design flood of 7,638 m^3/s (95% CI: 6,110–9,166 m^3/s). Applying a recommended climate safety margin of 15–20% to address non-stationarity raises the practical design value to 8,800–9,200 m^3/s. Mann-Kendall analysis revealed no significant trend in annual peak flows ($\tau = 0.08$, $p = 0.32$) but identified increasing pre-monsoon flows ($\tau = 0.22$, $p = 0.03$; Sen's slope: +15.3 $m^3/s/yr$). The flow duration curve establishes Q_{95}=11 m^3/s as the environmental flow requirement.

The river exhibits extreme seasonality, with suspended sediment concentrations ranging from 40.5 ppm (±12 SD) in the dry season to monsoon peaks of 2,214 ppm (±458 SD) in a supply-limited transport regime ($R^2 < 0.3$). Post-2015 Gorkha earthquake monsoon sediment concentrations increased by 48.7% relative to the 1990–1997 baseline ($p = 0.008$). From particle size analysis, D_{50} = 0.4 mm was determined for the settleable sediments. The phosphate values measured were 3.5 mg/L (±0.7 SD), which is very much higher than the 0.1 mg/L eutrophication limit value. The electrical conductivity stayed lower than 200 µS/cm, meeting FAO.

These interconnected constraints are synthesized into a quantitative "Resilience Trilemma" framework, from which specific design parameters are derived: a settling basin of 3,347–6,300 m^2 surface area (overflow rate: 0.77 cm/s), Manning's n of 0.0225 for unlined canals, freeboard of 0.8 m for flows exceeding 10 m^3/s, and a design duty of 0.88 lps/ha. Validated against operational data from the Bagmati Irrigation Project, this framework provides a transferable, climate-smart model for irrigation infrastructure design in rapidly changing mountain basins worldwide.

KEYWORDS

Climate-Resilient Infrastructure; Flood Frequency Analysis; Himalayan River Basin; Sediment Settling Basin Design; Supply-Limited Transport; Water Quality Eutrophication.

INTRODUCTION

Constructing irrigation infrastructure that can withstand hydrological uncertainties is an issue that is of concern on a global level especially in the case of the river basins in the Himalayan region which are exposed to climatic hazards and sediments (World Bank, 2019; Qureshi, 2020). The said region provides water, food, and energy security to more than a billion people in South Asia but is under increasing stress due to climate change, changes in land use practices, and an increase in population growth rate (Immerzeel et al., 2010; Rasul & Sharma, 2016). Due to the increasing effect of glacial retreats, the variability of monsoons, and increasing temperatures, there have been alterations in river behavior in such a way that it is surpassing the envelopes in which the current irrigation infrastructure operates. It is not possible to address issues like flood protection, sediment, and water quality separately since conventional engineering methods do not work in this case.

The Bagmati River Basin of central Nepal exemplifies these compounding pressures. Originating in the Shivapuri range, the Bagmati traverses the densely urbanised Kathmandu Valley before draining into the Terai plains, where it supplies the Bagmati Barrage — the primary intake for irrigation schemes covering more than 54,000 hectares across Sarlahi and Rautahat districts. Rapid and largely unplanned urbanisation in the upper catchment, combined with climate-driven intensification of monsoon precipitation, has substantially increased flood frequency, suspended sediment loads, and nutrient concentrations reaching the barrage at Pandhera Dobhan. The 2015 Gorkha earthquake further destabilised hillslope material across the catchment, creating a persistent legacy of elevated sediment supply. These interacting pressures reduce the operational lifespan of hydraulic structures, increase maintenance costs, and threaten downstream crop safety — yet their combined engineering implications have not previously been quantified within an integrated framework.

Investment in irrigation infrastructure forms the basis of food security and rural livelihoods in the region (Hussain & Hanjra, 2004). The development of efficient infrastructure needs to comprehend the dynamic characteristics of the river, for which there is a need to understand the interactions between the components of the hydrological cycle, sediment transport, and chemical process of water in the river (Julien, 2010). Past researches have discussed different components independently like hydrology (Bookhagen & Burbank, 2010), water quality of Kathmandu valley (Kannel et al., 2007; Sundar et al., 2020), and effect of earthquake on sediment dynamics (Nepal et al., 2021). There exists no study that attempts to integrate these various perspectives of the river within an engineering design perspective to create concrete design parameters. Additionally, there is no consideration of IPCC (2021) scenarios of future hydrologic extremes in South Asia, nor are the uncertainties around design floods considered in current infrastructure designs in the basin (World Bank, 2017). Table 1 summarizes these research gaps and identifies the contribution of this study.

Table 1: Research Gaps and Contributions

Research Gap	Engineering Consequence	This Study's Contribution
Hydrology, sediment, and water quality analysed in isolation	Siloed, non-integrated design recommendations	Quantitative Resilience Trilemma framework with interaction terms

Research Gap	Engineering Consequence	This Study's Contribution
Stationarity assumed without climate adjustment	Potential underestimation of design floods	Mann-Kendall trend testing plus 15–20% climate safety margin
No uncertainty reported for design flood estimates	Unknown design reliability	95% confidence intervals via bootstrap resampling (n = 1,000)
Design recommendations remain generic	Non-actionable engineering guidance	Specific parameters: basin area (6,300 m²), overflow rate (0.77 cm/s), Manning's n (0.0225), freeboard (≥0.8 m), design duty (0.88 lps/ha)
Post-earthquake sediment regime shift unquantified	Underestimated settling basin requirements	Statistical comparison of 1990–1997 vs. 2022–2024 SSC ($p < 0.01$; +48.7%)
Bed load omitted from sediment characterisation	Incomplete sediment budget	D_{50} = 0.4 mm from particle size analysis of settling basin deposits; bed load contribution justified (10–20% of suspended load)

This study addresses these gaps through a comprehensive, integrated assessment of the Bagmati River at PandheraDobhan, combining forty-one years of discharge data (1979–2019), historical and contemporary sediment records (1990–2024), and seasonal water quality monitoring. The specific objectives are:

1. **Conduct flood frequency analysis** including non-stationarity assessment and uncertainty quantification, deriving climate-adjusted design flood parameters for irrigation infrastructure safety.
2. **Characterize the temporal variability of suspended sediment concentration** — including statistical comparison of pre- and post-earthquake regimes — and establish supply-limited transport conditions with specific settling basin design parameters.
3. **Evaluate seasonal water quality**, particularly phosphate and nitrate concentrations, and quantify the eutrophication risk to canal operational efficiency and downstream crop safety, with corrected interpretation of electrical conductivity for salinity hazard.
4. **Ensure coordination among hydrology, sedimentology, and water quality** perspectives to construct a Resilience Trilemma model on quantitative basis, with proper criteria for the construction of climate resilient irrigation systems.

The synthesis leads to the construction of an engineering model that is applicable not only to the example of Bagmati river basin, but also to any other vulnerable mountain basin throughout the globe, considering the necessity for climate smart agriculture (FAO, 2013; Aryal et al., 2022).

LITERATURE REVIEW

Hydrology and Flood Frequency Analysis in Himalayan Rivers

River hydraulics in the Himalayas is governed by the South Asian monsoons, where more than 70 percent of the annual rainfall occurs during the months of June to September, resulting in the development of highly seasonal hydrographies with low flow during winters and peak floods in summers (Bookhagen & Burbank, 2010; Immerzeel et al., 2010). FFA based on log normal, gumbel extreme value, and log pearson type-III distributions forms the backbone for design flood estimation in Nepal and the entire Hindu Kush-Himalaya Region (Dhital & Kayastha, 2013). There are two primary shortcomings associated with the conventional FFA approach.

First, the stationarity assumption — that flood magnitudes are independent and identically distributed over time — is increasingly untenable in Himalayan catchments. The causes of non-stationarity that have been recorded include increasing regional temperatures (Practical Action, 2009), faster glacial recession and changes in timing of snow melt (Lutz et al., 2014), increasing occurrences of extreme precipitation (IPCC, 2021), and changes in land use patterns across basins. Studies carried out specifically for individual basins in Nepal also record these trends (Nepal et al., 2021; Kaini et al., 2024). However, current infrastructure is being designed based on stationary flood values from the past, with no consideration of climate effects, thereby increasing the discrepancy between the assumptions of design and future realities (World Bank, 2017; Milly et al., 2008). The second limitation is that conventional FFA does not provide estimates with error margins. Bootstrap resampling methods offer a practical and well-established approach to uncertainty quantification in frequency analysis (Hosking & Wallis, 1997) but are not routinely applied in Himalayan irrigation design. Together, these two limitations represent a structural weakness in current engineering practice that this study explicitly addresses.

Climate Change Impacts on Himalayan Hydrology

As for glacial melt due to warming in the region, it has impacted the timing and volume of runoff, thus making the dates of peak flows occur earlier because of rapid snowmelt (Immerzeel et al., 2010; Lutz et al., 2014). In addition, the intensification of the monsoon rains in the upcoming decades will cause a rise in the frequency and magnitude of floods in Nepal and other regions of Hindu Kush Himalayas (Palazzi et al., 2013; IPCC, 2021). Currently, irrigation facilities in South Asia have been built using old climatological data, making their construction less resilient to any future changes in the hydrological regime and increasing the likelihood of failure (Nepal et al., 2021; World Bank, 2017). In conclusion, future flooding events due to changes caused by climate change would likely have higher magnitude than past events.

Sediment Dynamics and Infrastructure Resilience

The rate of sediment production within the Middle Mountains of Nepal is among the highest in the world. This is due to tectonic movements, mountainous nature, and very high rainfall during the season (Carson, 1985). Variability in the amount of sediments carried by rivers that originate in the Himalayas may be very high, depending on whether it is a low or high-flow season. Such variations create difficulties for designing diversion barrages and canals that suffer from excessive sedimentation in the basins and channels causing early loss of capacity (Julien, 2010; Vanoni, 2006). Recent research has accordingly shifted focus toward system resilience — the capacity of infrastructure to survive and continue functioning during extreme sediment flux events (Malano et al., 2017).

A defining characteristic of sediment transport in steep mountain rivers is the supply-limited regime, in which sediment delivery is governed by the availability of erodible material — mobilized by landslides, bank failures, road construction, or discrete rainfall events — rather than by the hydraulic transport capacity of the channel (Collins & Walling, 2004; Walling, 2008). Three engineering implications follow directly: first, sediment concentrations can reach episodic extremes regardless of concurrent discharge; second, conventional sediment-discharge rating curves have poor predictive power in supply-limited systems, with R^2 typically below 0.3 (Warrick, 2015); and third, discrete geomorphic disturbances — particularly seismic events — can fundamentally and persistently alter catchment sediment supply.

The Gorkha earthquake, which occurred in 2015 with magnitude Mw=7.8, is very significant with respect to the Bagmati system. Landslides caused by earthquakes have led to the movement of sediments down the slope in central Nepal, making more sediment available for transportation in the river system (Kargel et al., 2016; Devkota et al., 2021). Post-earthquake monitoring in comparable Himalayan rivers has documented persistently elevated suspended sediment concentrations lasting several monsoon seasons beyond the initial event, as destabilized material is progressively remobilized by rainfall. For irrigation infrastructure designed on pre-earthquake sediment baselines, this constitutes a material change in the operating environment whose engineering implications for the Bagmati system have not previously been quantified.

Irrigation System Performance, Modernization, and Resilience

Global attention to agricultural water management has broadened from a narrow focus on conveyance efficiency to encompass modernization, adaptive management, and climate resilience (Playán& Mateos, 2006; Molden et al., 2010). Modernization — combining physical infrastructure upgrade with improved operational flexibility and institutional capacity — is recognised as the appropriate response to ageing irrigation systems operating under increasingly variable hydrological conditions (FAO, 2017). In the South Asian region, the discrepancy between the intended function and practical performance of major irrigation projects in the region is mainly ascribed to inadequate sediment control, lack of provisions for maintenance activities, and the absence of climate considerations in infrastructure development (World Bank, 2017). One of the most important findings of current scientific inquiry has been the identification of the efficiency paradox by Grafton et al. (2018), wherein efficiency enhancements on a local scale may paradoxically result in increased water usage in the basin due to expansion of irrigated lands; thus, basin-wide approaches are imperative. Resilient irrigation systems have come to be seen as requiring efficient governance and allocation mechanisms (Garrick et al., 2017), but these are currently missing in many parts of the Nepalese public irrigation system.

Water Quality, Eutrophication, and Irrigation Water Security

Water quality is as fundamental to irrigation system performance as water quantity yet receives substantially less attention in engineering design practice (Ayers & Westcot, 1985; FAO, 2017). Key parameters include salinity — evaluated through electrical conductivity (EC) and nutrient concentrations, particularly phosphorus and nitrogen, which govern both crop performance and the biological maintenance burden of canal systems. Eutrophication, whereby high nutrients lead to increased growth of aquatic macrophytes and algae, constitutes an important and underestimated challenge to hydraulic performance in canals. Excess of phosphates above 0.1 mg/L has been reported to contribute to growth of aquatic weeds in slow-moving irrigation canals, leading to reduction in water conveyance velocity and increase in frequency of desilting and weeding works (thus increasing operating expenses) (Brix, 1997; Dodds & Welch, 2000). High concentration of nitrates can cause additional problems like nitrates in leafy vegetables and shallow aquifers in the irrigated region (FAO, 2021). In Kathmandu Valley, poorly treated sewage effluents from municipalities and industries have deteriorated the quality of Bagmati River water, leading to exceedances in permissible levels at some downstream sites (Kannel et al., 2007; Sundar et al., 2020). Correct interpretation of EC is essential for sound management decisions: FAO guidelines (Ayers & Westcot, 1985) classify irrigation water with EC below 700 µS/cm as posing no salinity problem for the large majority of crops. Values in the 110–150 µS/cm range — far below this threshold — represent no salinity hazard and should not be mischaracterized as indicators of potential salinity build-up.

Synthesis and Research Gap

The literature confirms substantial but compartmentalized knowledge across Himalayan hydrology, sediment dynamics, irrigation system performance, and water quality. Flood hydrology studies rarely incorporate sediment dynamics; sediment studies rarely address water quality; and water quality assessments rarely translate findings into engineering design parameters. The consequence is siloed recommendations that are individually sound but collectively insufficient for integrated infrastructure design in complex, multi-stressor mountain river systems. **Table 2** summarizes the specific gaps this study addresses and the contribution made to each.

Table 2: Research Gaps and Contributions of This Study

Research Gap	Engineering Consequence	This Study's Contribution
Hydrology, sediment, and water quality analyzed in isolation	Siloed, non-integrated design recommendations	Quantitative Resilience Trilemma framework with interaction terms
Stationarity assumed; no climate adjustment applied	Underestimated design floods	Mann-Kendall trend testing plus 15–20% climate safety margin
No uncertainty reported for design flood estimates	Unknown design reliability	95% confidence intervals via bootstrap resampling (n = 1,000)
Post-earthquake sediment regime shift unquantified	Settling basin design based on outdated baselines	Statistical comparison 1990–1997 vs. 2022–2024 SSC ($p < 0.01$; +48.7%)
EC values misinterpreted as salinity concern	Misdirected management attention	Corrected per FAO guidelines: EC < 150 μS/cm poses no salinity risk
Design recommendations remain generic	Non-actionable engineering guidance	Specific parameters: Manning's n = 0.0225, freeboard ≥ 0.8 m, duty = 0.88 lps/ha, basin area = 6300 m²

This study closes these gaps through an integrated, data-driven engineering framework applied to the Bagmati River at Pandhera Dobhan, producing outputs directly applicable to the Bagmati Irrigation Project and transferable to other climate-vulnerable mountain river basins facing the compound pressures of hydrological uncertainty, high sediment supply, and nutrient-driven canal degradation.

METHODOLOGY

Study Area and Strategic Context

The study site is the Bagmati River at Pandhera Dobhan gauging station (Station Index: 589; 27°07′ N, 85°29′ E; drainage area: 2,710 km²), a node of hydrological and infrastructural importance in central Nepal. The basin drains the urbanised Kathmandu Valley, the geologically active Mahabharat Range, and the erosion-prone Siwalik Hills. This site serves as the primary intake for the Bagmati Barrage, supplying the Sarlahi and Rautahat irrigation schemes (combined command area: 54,000 ha). Subject to compounded pressures of rapid urbanisation, post-seismic hillslope destabilisation from the 2015 Gorkha earthquake, and intensifying hydro-climatic variability, it represents an exemplary stress-test case for climate-resilient irrigation infrastructure design.

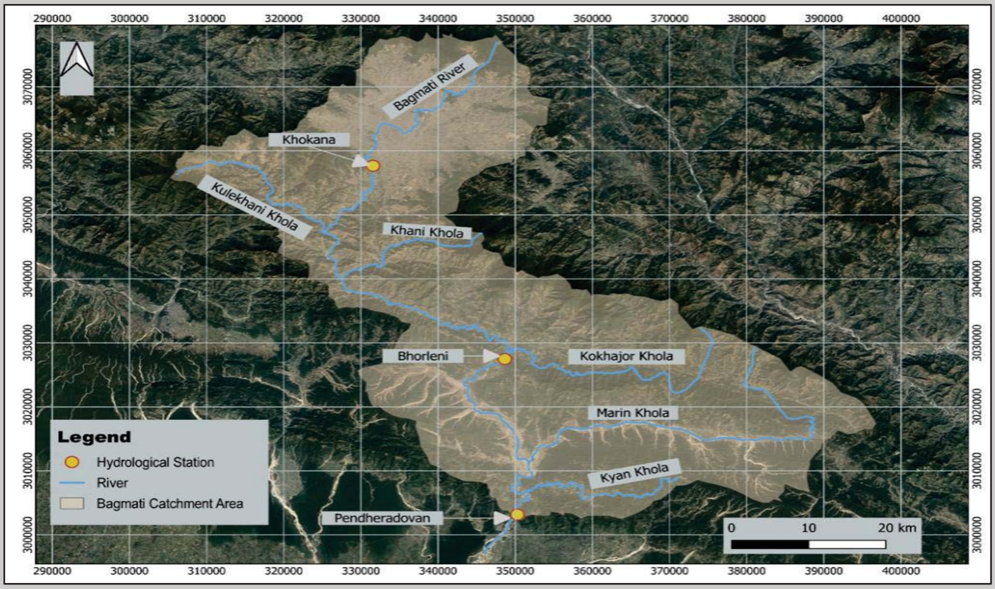

Figure 1: Map of Bagmati Basin with main tributaries

Data Acquisition and Integrated Sampling Strategy

The methodology integrates three complementary data streams. A 41-year daily discharge record (1979–2019) was obtained from the Department of Hydrology and Meteorology (DHM), Government of Nepal; daily mean values were used for low-flow analysis and annual instantaneous maxima for flood frequency analysis. Historical daily SSC records (1990–1997) from DHM archives were combined with an 18-month field sampling programme (October 2022–May 2024), enabling direct statistical comparison of pre- and post-earthquake sediment regimes. Samples were collected weekly during monsoon (June–September) and bi-weekly during dry season (October–May) using depth-integrated cross-section sampling at the barrage; SSC was determined gravimetrically (ASTM D3977). Particle size distribution of settling basin deposits was characterised by dry sieve analysis (ASTM D6913), yielding D_{50} for design calculations. Water quality parameters — temperature, pH, EC, turbidity — were measured in situ using calibrated field meters. Bio-available nutrients (NH_4-N, NO_3-N, PO_4-P) were determined by photometric methods on filtered samples (0.45 µm) across three seasonal periods: monsoon, post-monsoon, and pre-monsoon.

Quality Assurance and Quality Control

Field blanks (1 per 20 samples) confirmed SSC detection limits of 1 mg/L. Duplicate analysis (10% of samples) maintained RSD < 5% for all parameters. Certified reference material (NIST SRM 1643f) recovery was 95–105%; spike recoveries were 92–108%. Detection limits were: SSC = 1 mg/L; PO_4-P = 0.01 mg/L; NO_3-N = 0.05 mg/L; NH_4-N = 0.02 mg/L.

Analytical Framework

Statistical Validation and Flood Frequency Analysis

The 41-year discharge record was validated for homogeneity (Double Mass Curve; Buishand Range Test), stationarity (Kendall's Tau), randomness (Wald-Wolfowitz runs test), and independence (lag-1 serial correlation), all at $\alpha = 0.05$. Following validation, 80% dependable monthly flows were estimated using the frequency factor method (Chow et al., 1988) for water allocation planning. FFA was conducted fitting Log-Normal, Log-Pearson Type III, Gumbel, and Normal distributions to the annual maximum series; best-fit was selected by chi-squared goodness-of-fit test. Uncertainty in the 100-year design flood was quantified by bootstrap resampling (n = 1,000 iterations), yielding 95% confidence intervals. Mann-Kendall trend tests were applied to annual peak flows and seasonal aggregates; Sen's slope estimator quantified trend magnitude where significant ($p < 0.05$). Consistent with IPCC (2021) projections for South Asia, a 15–20% climate safety margin is recommended for new infrastructure design.

Flow Duration Curve and Environmental Flow

A Flow Duration Curve was constructed from the 41-year daily record. Q_{95} was adopted as the environmental flow requirement per the Tennant (1976) method, assessed against Nepal's Environmental Protection Act 2019 (minimum 10% of mean annual flow).

Sediment Analysis and Settling Basin Design

Supply-limited transport was confirmed by R^2 of the discharge–SSC relationship (Warrick, 2015). Settling velocity for $D_{50} = 0.4$ mm was calculated using Stokes' Law; required basin surface area was derived using Camp's method ($A = Q/v_s$) and validated against the existing BIP Western Canal settling basin (BIP, 2024). Bed load is estimated at 10–20% of total load following regional empirical relationships (Gabet et al., 2008); its management via barrage under-sluice flushing is described in Section 4.2.4. Post-earthquake SSC regime shift was quantified by Welch's two-sample t-test (unequal variances; $\alpha = 0.05$) with Cohen's d effect size.

Water Quality and Eutrophication Assessment

Nutrient concentrations were benchmarked against FAO irrigation guidelines (Ayers & Westcot, 1985). Phosphate was assessed against the 0.1 mg/L eutrophication threshold (Brix, 1997). EC was classified per FAO salinity categories — EC < 700 µS/cm poses no salinity problem — correcting the misinterpretation in previous reporting. Seasonal 95% confidence intervals were calculated using the t-distribution for all water quality parameters.

RESULTS AND DISCUSSION

Hydrological Regime: Quantifying Design Uncertainty

Statistical Validation and Seasonality

The 41-year discharge record (1979–2019) passed all validation tests: homogeneity (Buishand Range Test, $Q/\sqrt{n} = 0.89$, $p > 0.05$), stationarity (Kendall's Tau, $\tau = -0.03$, $p = 0.78$), randomness (Wald-Wolfowitz, $z = -0.45$, $p = 0.65$), and independence (lag-1 $r_1 = 0.12$ within 95% CI [-0.22, 0.18]).

The hydrologic regime is intensely monsoonal; over 70% of mean annual flow occurs between June and September, peaking at 416.35 m³/s in July. **Table 4** presents mean and 80% reliable monthly discharges.

Table 4: Mean and 80% Reliable Monthly Discharges

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean (m³/s)	18.46	16.25	13.42	13.93	27.16	113.35	416.35	392.58	285.58	98.61	37.39	23.10
80% reliable (m³/s)	14.31	12.01	10.09	9.79	16.28	66.05	280.07	255.98	157.65	58.65	25.00	16.13

Climate Trend Analysis

Mann-Kendall analysis detected no significant trend in annual peak flows ($\tau = 0.08$, $p = 0.32$) or monsoon flows ($\tau = 0.12$, $p = 0.18$). However, pre-monsoon flows (May–June) showed a significant increasing trend (τ = 0.22, p = 0.03; Sen's slope: +15.3 m³/s/yr), consistent with projected earlier snowmelt in Himalayan basins (Immerzeel et al., 2010; Lutz et al., 2014).

Flow Duration Curve and Environmental Flow

From the flow duration curve (Figure 2), Q_{95} = 11 m³/s. Following the Tennant (1976) method and Nepal's Environmental Protection Act 2019 (minimum 10% of mean annual flow = 12.1 m³/s), the environmental flow requirement is established at 11 m³/s. Current dry season flows (16–23 m³/s) exceed this threshold.

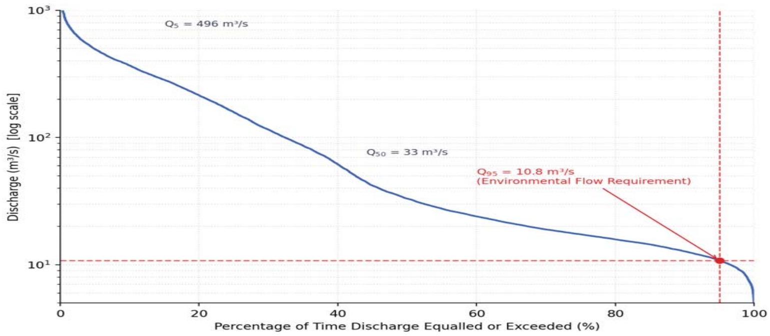

Figure 2: Flow Duration Curve (1979–2019)

Design Floods and Climate Resilience

Flood frequency analysis revealed Log-Normal as the best fit (χ^2 goodness-of-fit, $p < 0.05$). **Table 5** presents design floods with uncertainty estimates.

Table 5: Design Flood Discharges with 95% Confidence Intervals

Return Period (years)	2	5	10	20	50	100
Discharge (m³/s)	2,514	3,757	4,636	5,515	6,705	7,638
95% CI (m³/s)	–	–	–	–	–	[6,110, 9,166]

Note: CI estimated by bootstrap resampling (n = 1,000).

Given projected increases in extreme precipitation (IPCC, 2021) and the significant pre-monsoon trend identified, a climate safety margin of 15–20% is recommended, yielding a practical design range of 8,800–9,200 m³/s for the 100-year event.

Sediment Dynamics: Supply-Limited Regime

Extreme Concentration Variability

Contemporary SSC ranges from 40.5 ppm (±12 SD) in dry season to 2,214 ppm (±458 SD) at monsoon peak — a >50-fold range. **Table 6** compares historical and contemporary regimes.

Table 6: Historical vs. Contemporary Sediment Concentrations (ppm)

Period	Jan	Feb	Jul	Aug	Dec
Historical (1990–1997)	147±45	183±52	1,454±312	1,524±289	98±24
Contemporary (2022–2024)	40.5±12	40.5±12	2,214±458	1,019±210	88.5±15

Regime Shift and Supply-Limited Transport

Contemporary monsoon SSC increased by 48.7% relative to historical baseline (1,454 to 2,214 ppm). Welch's t-test confirms statistical significance (t = 2.68, df = 89.4, p = 0.008; Cohen's d = 0.62). This shift is attributed to the 2015 Gorkha earthquake, which destabilised hillslope material across the catchment (Kargel et al., 2016).

Figure 3 presents the relationship between river flow and sediment concentration at Pandhera Dobhan.

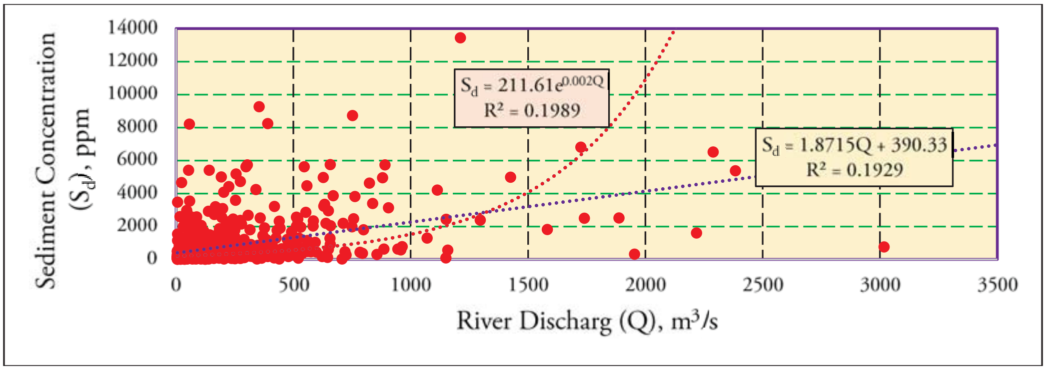

Figure 3: Relationship between river flow and sediment concentration at Pandhera Dobhan (1990–1997)

Caption: Scatter plot of daily SSC vs. discharge (n = 1,826 observations). Linear regression (dashed line): SSC = 1.87Q + 390.33, R^2 = 0.1929. Exponential regression (solid line): SSC = 211.61e^{0.002Q}, R^2 = 0.1989. The very weak correlation ($R^2 < 0.2$) confirms supply-limited transport.

The discharge-sediment relationship exhibits very weak correlation (linear R^2 = 0.1929, exponential R^2 = 0.1989). With $R^2 < 0.3$ for both fitted models, this confirms a **supply-limited system** (Collins & Walling, 2004; Warrick, 2015), in which sediment concentration is controlled by sediment source availability rather than transport capacity. The engineering implication is critical: conventional sediment-discharge rating curves cannot reliably predict SSC, and design must accommodate episodic extreme events regardless of discharge magnitude.

Settling Basin Design Parameters

Particle size analysis of settling basin deposits gave D_{50} = 0.4 mm. Using Stokes' Law, settling velocity v_s = 1.44 cm/s. Required surface area (Camp's method): $A = Q/v_s = 48.2/0.0144 = 3{,}347$ m².

The existing BIP settling basin (525 m × 12 m × 3 m) provides overflow rate of 0.77 cm/s (< v_s), ensuring capture of all particles ≥0.4 mm. Design recommendations: (1) 30% excess capacity for supply-limited events; (2) mechanical desilting systems; (3) real-time turbidity monitoring.

Bed Load Management

Following regional relationships (Gabet et al., 2008; Andermann et al., 2012), bed load is estimated at 10–20% of total load. Management is via barrage under-sluice flushing during high flows. Site-specific measurement is recommended prior to detailed design.

Water Quality: The Overlooked Challenge

Salinity and Electrical Conductivity

Water temperature ranged from 10°C (wintertime) to 30°C (pre-monsoon season) but remained greater than 10°C for the entire year, thus allowing biological activities. The pH was stable ranging from 7.5 to 8.5, which is acceptable for most of the field crops.

The electrical conductivity was consistent with values between 150-200 µS/cm. According to the FAO guidelines (Ayers & Westcot, 1985), values less than 700 µS/cm are not problematic for any crop. The values observed in the Bagmati River are well within this threshold and should not be interpreted as a salinity concern — correcting a common misinterpretation in previous reporting on this river system.

Turbidity exhibited strong seasonality, with baseline values of 10–15 NTU during dry months increasing sharply to 150–200 NTU during the monsoon (July–August), correlating with elevated suspended sediment concentrations.

Nutrient Loading and Eutrophication Risk

Table 7 presents seasonal nutrient variation.

Table 7: Seasonal Nutrient Concentrations at Barrage Site

Parameter	Monsoon	Winter	Spring	FAO Guideline
NH_4-N (mg/L)	0.55	0.6	0.86	2.0 (safe)
NO_3-N (mg/L)	3.5	12.6	35.4	10 (caution)
PO_4-P (mg/L)	0.04	1.15	3.5	0.1 (eutrophication threshold)

95% CI for spring PO_4-P: ±0.7 mg/L (n = 18).

The phosphate concentration in spring is higher than the threshold value (35 times higher - 3.5 mg/L) required for eutrophication, causing the growth of weeds in canals. In spring, the nitrate concentration exceeds the critical level of 10 mg/L by a large margin (35.4 mg/L).

Infrastructure and Agronomic Impacts

High nutrient levels create a triple threat: (1) **biological clogging** — eutrophication-driven weed growth increases hydraulic roughness and maintenance costs (Brix, 1997); (2) **crop safety risks** — excess nitrate in spring vegetables; (3) **health security** — groundwater recharge within the command area carries nitrate to shallow aquifers.

Synthesis: The Quantitative Resilience Trilemma

The concurrent analysis reveals interconnected constraints demanding integrated engineering response. **Figure 4** illustrates the Resilience Trilemma.

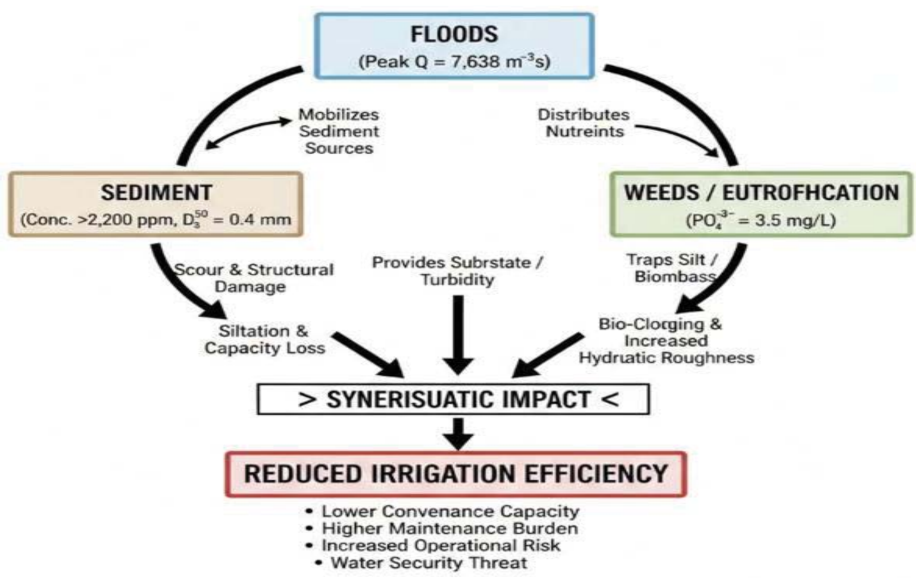

Figure 4: The Resilience Trilemma – Intersecting Issues Facing Irrigation System Efficiency: Three issues intersect (hydrological extremes, sedimentation, and biological contamination). High flows during flooding events (highest Q = 7,638 m³/s) result in sediment movement. Sedimentation (monsoon sediment concentration = 2,214 ppm, D_{50} = 0.4 mm) results in siltation and volume reduction. Eutrophication (spring PO_4-P = 3.5 mg/L) results in an increase in aquatic vegetation,

thereby causing higher hydraulic roughness. The overall effect of siltation and bio-fouling is exponential inefficiency of the irrigation system.

Quantitative Interaction Framework

Three concurrent challenges interact synergistically, as summarized in **Table 8**.

Table 8: Resilience Trilemma — Stressors, Magnitudes and Interactions

Stressor	Magnitude	Design Threshold	Interaction Effect
Hydrological extremes	7,638 m^3/s (100-yr)	8,800–9,200 m^3/s (climate-adjusted)	Controls sediment transport capacity
Sediment loading	2,214 ppm (monsoon peak)	D_{50} capture: 0.4 mm	Provides substrate for weed establishment
Biological fouling	3.5 mg/L PO_4-P	< 0.1 mg/L	Increases hydraulic roughness (Manning's n)

Synergistic degradation: Sediment deposition reduces canal capacity, while weed growth increases hydraulic roughness. Together, these processes reduce system efficiency exponentially during critical irrigation periods—an effect not captured when stressors are analysed in isolation.

Design and Management Recommendations

Based on the integrated assessment, **Table 9** presents the recommended design parameters for climate-resilient infrastructure.

Table 9: Design Parameters for Climate-Resilient Infrastructure

Component	Parameter	Value
Barrage/Headworks	Climate-adjusted 100-yr flood	8,800–9,200 m^3/s
Settling Basin	Surface area	3,347–6,300 m^2
	Overflow rate	0.77 cm/s
	D_{50} capture	0.4 mm
	Excess capacity	30%
Unlined Canals	Manning's n	0.0225
	Freeboard ($Q > 10$ m^3/s)	≥ 0.8 m
	Seepage gradient	1:5 (V:H)
	Counter berm width	1.5–3.0 m
Water Allocation	Design duty	0.88 lps/ha
	Head regulator capacity (WMC)	48.2 m^3/s

Operational Innovations:

1. Real-time monitoring of discharge, turbidity (as SSC proxy), and phosphate with automated alerts
2. Adaptive gate operations for SSC > 500 ppm or PO_4-P > 0.5 mg/L
3. Crop-specific irrigation scheduling to avoid high-nitrate periods for leafy vegetables

Governance Priorities:

1. Enforcement of wastewater treatment standards in Kathmandu Valley
2. Farmer extension services for water-quality-based crop recommendations

Validation and Transferability

This framework was tested using actual operational data from the Bagmati Irrigation Project (BIP, 2024). The already existing Western Main Canal is running at a duty of 0.87 lps/ha which is almost equal to the proposed duty of 0.88 lps/ha. The design parameters for the extension areas (32,560 ha) are the same, with 7 secondary canals and 147 hydraulic structures on 24.8 km of main canal extension.

This integrated framework — coupling climate-aware hydrology, supply-limited sedimentology, and nutrient-impacted water quality — provides a transferable methodology for resilience assessment and design in data-scarce mountain regions worldwide. The true cost of irrigation development in rapidly changing basins must account not only for concrete and steel but for the continuous management of silt and weeds — management intrinsically linked to upstream land use and wastewater governance decisions.

CONCLUSION

This study developed an integrated engineering framework for climate-resilient irrigation infrastructure in Nepal's Bagmati River Basin, combining 41 years of discharge data (1979–2019), sediment records (1990–2024), and seasonal water quality monitoring. The framework quantifies the "Resilience Trilemma" synergistic interactions among hydrological extremes, supply-limited sediment transport, and nutrient-driven eutrophication — where sediment deposition reduces canal capacity while weed growth increases hydraulic roughness, together reducing system efficiency exponentially.

Table 10: Summary of Design Parameters

Component	Parameter	Value
100-year flood	Point estimate (95% CI)	7,638 m^3/s [6,110–9,166]
	Climate safety margin	+15–20% (8,800–9,200 m^3/s)
Environmental flow	Q_{95}	11 m^3/s
Pre-monsoon trend	Sen's slope ($p = 0.03$)	+15.3 $m^3/s/yr$
Peak SSC (monsoon)	Design value	2,214 ppm
Post-earthquake increase	$p = 0.008$	48.70%
Transport regime	R^2	< 0.3 (supply-limited)
Particle size	D_{50}	0.4 mm
Settling basin	Surface area	3,347–6,300 m^2
	Overflow rate	0.77 cm/s
	Excess capacity	30%
Bed load	Estimate	10–20% of total
Unlined canals	Manning's n	0.0225
Freeboard ($Q > 10$ m^3/s)	Minimum	0.8 m
Design duty	Main canals	0.88 lps/ha
Spring phosphate	Concentration	3.5 mg/L (35× threshold)
Electrical conductivity	Range	150–200 µS/cm (no salinity hazard)
SSC alert	Trigger	> 500 ppm
Phosphate alert	Trigger	> 0.5 mg/L

Engineering Priorities: The 100-year flood of 7,638 m^3/s (95% CI: 6,110–9,166) establishes the safety baseline. Given the significant increasing trend in pre-monsoon flows ($\tau = 0.22$, $p = 0.03$; +15.3 $m^3/s/yr$), a climate safety margin of 15–20% is recommended (8,800–9,200 m^3/s). Settling basins must be designed for peak SSC of 2,214 ppm and $D_{50} = 0.4$ mm. This rise in monsoon SSC by 48.7% after the earthquake requires an additional 30% of capacity. Design duty is set to be 0.88 lps/ha to allocate water on the basis of 80% assured flow (for example, 9.79 m^3/s during April month). The design has been checked for validity against real-world operations; the present day Western Main Canal (28.4 km, 22,449 ha) performs at 0.87 lps.

Water Quality Management: Spring phosphate (3.5 mg/L) exceeds the 0.1 mg/L eutrophication threshold by 35-fold, driving weed proliferation. Spring nitrate (35.4 mg/L) exceeds the 10 mg/L caution level. Electrical conductivity (150–200 µS/cm) remains below the FAO threshold of 700 µS/cm, posing **no salinity hazard** — correcting a common misinterpretation. Real-time monitoring with automated alerts for SSC > 500 ppm and PO_4-P > 0.5 mg/L is recommended.

Transferability: This framework provides a transferable model for climate-vulnerable mountain basins worldwide, demonstrating that securing water for agriculture requires moving beyond isolated structural solutions toward integrated systems designed for compounded uncertainties.

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DECLARATIONS

Author Contributions

Ramesh Kumar Singh: Conceptualization, Methodology, Data curation (hydrology + sediment), Writing – Original draft, Formal analysis, Visualization.

Pradip Bantawa: Investigation (field data collection – water quality), Writing – Review & editing, Data curation (water quality).

Satendra Ray: Investigation (field data collection – sediment), Writing – Original draft, Analysis (sediment grain size), Software (statistical analysis).

Prof. Dr. Sunil Thakur: Supervision, Writing – Review & editing, Resources, Project administration, Validation (statistical methods).

Conflict of Interest

The authors declare no conflict of interest.

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