

Design–Cost Nexus of Rapid Sand Filter Systems in Water Supply Projects: A Comparative Construction Management Analysis from Nepal

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Abstract

Rapid Sand Filters (RSFs) are the dominant treatment technology in Nepalese water supply projects, yet similar-capacity systems exhibit markedly different construction costs, suggesting inconsistent design practices and poor cost efficiency. Methods: This study employs a mixed-methods approach—combining quantitative analysis of design drawings, hydraulic data, Bills of Quantities (BOQs), and cost estimates with qualitative insights from field observations and expert interviews—across four completed water quality improvement projects in Sindhupalchowk and Kavrepalanchowk districts. Key design parameters (filter bed area, structural depth, RCC volume, reinforcement quantity, filter media, underdrain system) were systematically compared and a simple linear regression was performed to quantify the reinforcement–cost relationship. Results: Total construction costs ranged from NPR 1.91 million to NPR 6.11 million. Civil works constituted 48–58% of cost in three projects; mechanical and electrical works dominated Project D at 77.8%. Reinforcement quantity explained 96.9% of cost variation ($R^2 = 0.969$; $p = 0.016$), with a unit rate of NPR 150 per kg. Conservative structural detailing and absence of standardized design norms are identified as the primary sources of cost disparity. Conclusion: Rationalising structural depth and reinforcement specifications through context-sensitive design guidelines can substantially reduce RSF construction costs without compromising treatment performance.

Keywords: Rapid Sand Filter, Design–Cost Nexus, Construction Management, Cost Optimisation, Water Treatment Nepal

1. Introduction

Rapid Sand Filters (RSFs) are the cornerstone of conventional water treatment in Nepal, widely deployed in both urban plants and rural water supply schemes. Despite treating comparable volumes, RSF units from different projects often differ substantially in construction cost—a disparity attributable to variations in engineering practice, material availability, and financial constraints rather than differences in raw-water characteristics or performance targets [1,2].

Civil works typically represent the largest budget component of an RSF unit. Even modest changes in structural dimensions can trigger disproportionate cost escalations, because excavation volume, reinforced concrete (RCC) quantity, formwork area, and reinforcement weight all scale non-linearly with wall height and plan area [3]. Overdesigned filters—a common outcome of risk-averse local engineering judgement—deliver no additional treatment benefit yet significantly inflate capital expenditure, undermining affordability and long-term sustainability of rural water schemes [4].

Despite the widespread use of RSF technology, systematic empirical research quantifying the influence of specific design parameters on construction cost from a construction management perspective remains scarce in the Nepalese context [5]. The present study addresses this gap by analysing four water quality improvement projects in Bagmati Province. The objectives were to: (i) identify design parameters that influence RSF construction cost; (ii) compare

cost patterns across projects; (iii) quantify design–cost relationships through regression analysis; and (iv) provide actionable construction management insights.

2. Materials and Methods

2.1 Study Sites

Four water quality improvement projects (WQIPs) located in Sindhupalchowk (Projects A, B, C) and Kavrepalanchowk (Project D) districts of Bagmati Province were selected (Table 1). Selection criteria included: availability of RSF units; access to approved design drawings and BOQs; observable variation in key design parameters; and comparable institutional context. Projects were anonymised (A–D) to preserve confidentiality.

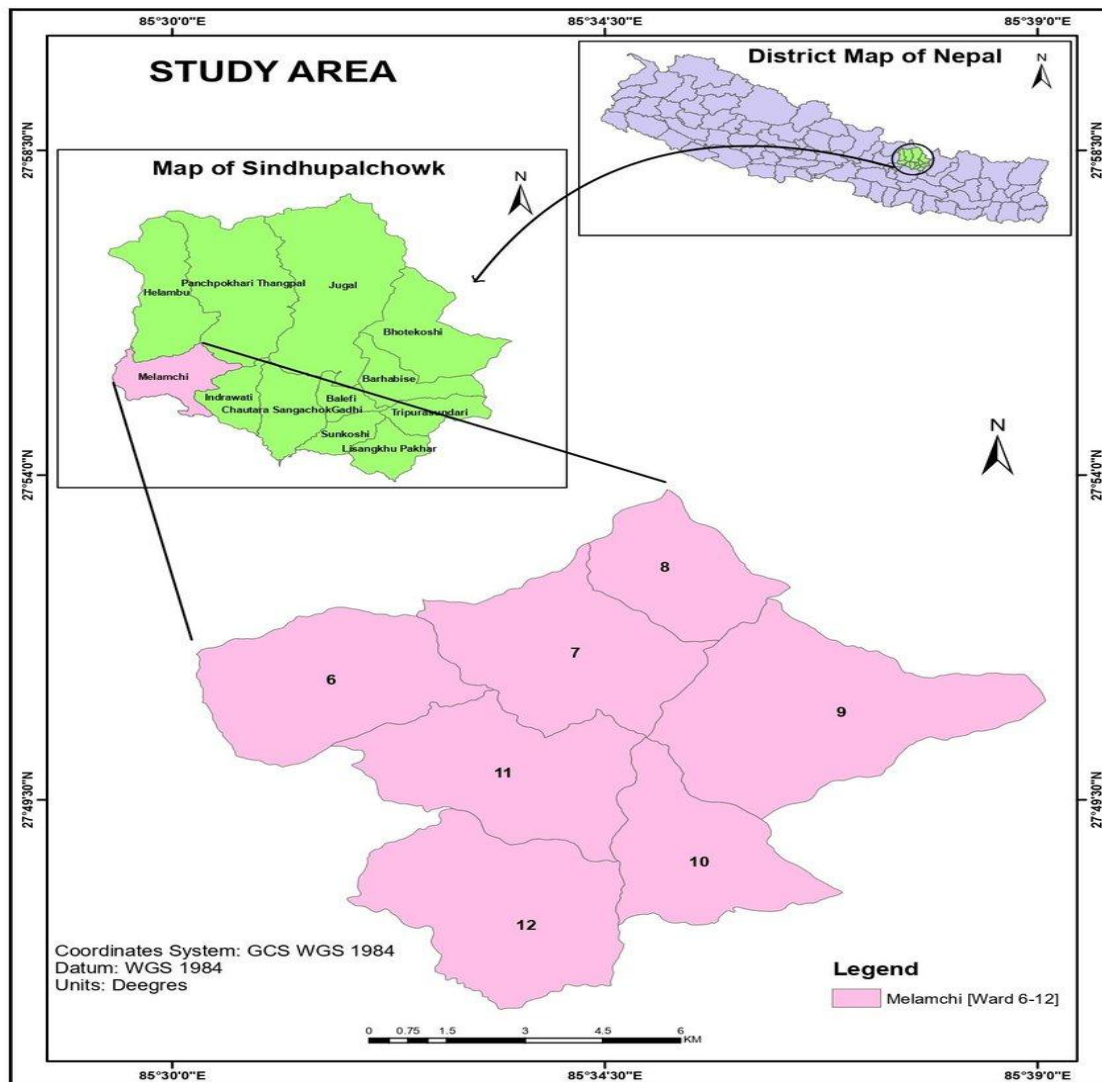


Figure 2.1. Study Area of Project A (Source: GIS)

This study focuses on multiple water supply projects located in different geographic and operational contexts of Nepal. Four projects were selected based on the inclusion of Rapid Sand Filter units, availability of approved design drawings and Bills of Quantities, observable variation in key RSF design parameters and a comparable institutional and

functional context. The selected projects were anonymized and designated as Project A, Project B, Project C and Project D to ensure analytical consistency and maintain confidentiality.

PROJECT A: LABHGAUN KYEURANI WATER QUALITY IMPROVEMENT PROJECT, MELAMCHI-8, SINDHUPALCHOWK

The project is located in Melamchi municipality. It is one of the selected project towns proposed under Labhgaun Kyeurani WQIP. This project has been proposed to cover the selected priority areas of the municipality. This new Labhgaun Kyeurani WQIP has been executed in Ward 8, Kyeurani lies within, what is formerly known as Dubachaur Village Development Committee ward 7,8 and 9 (by virtue of the new constitution of Nepal) situated in Sindhupalchowk District in Bagmati Province of Nepal. The geographical location of the project area lies in the hilly region of Nepal from 27° 49' 30" N to 27° 52' 48" N latitude to 85° 33' 36"E to 85° 37' 12"E longitude with its elevation ranging from 692m to 2156m above mean sea level. This project area originally belongs to former Dubachaur VDC that was surrounded by Indrawati River in the east, Melamchi Municipality ward 7 in the west and south, Helambu and Panchapokhari VDC in the north. Interestingly, the name Kyeurani is said to be originated from the word “Kyeu” meaning water in Tamang Language which is one of the oldest civilizations of this area. The total design population for this project is slightly more than 2000 living in the area of about 7.45 Km².

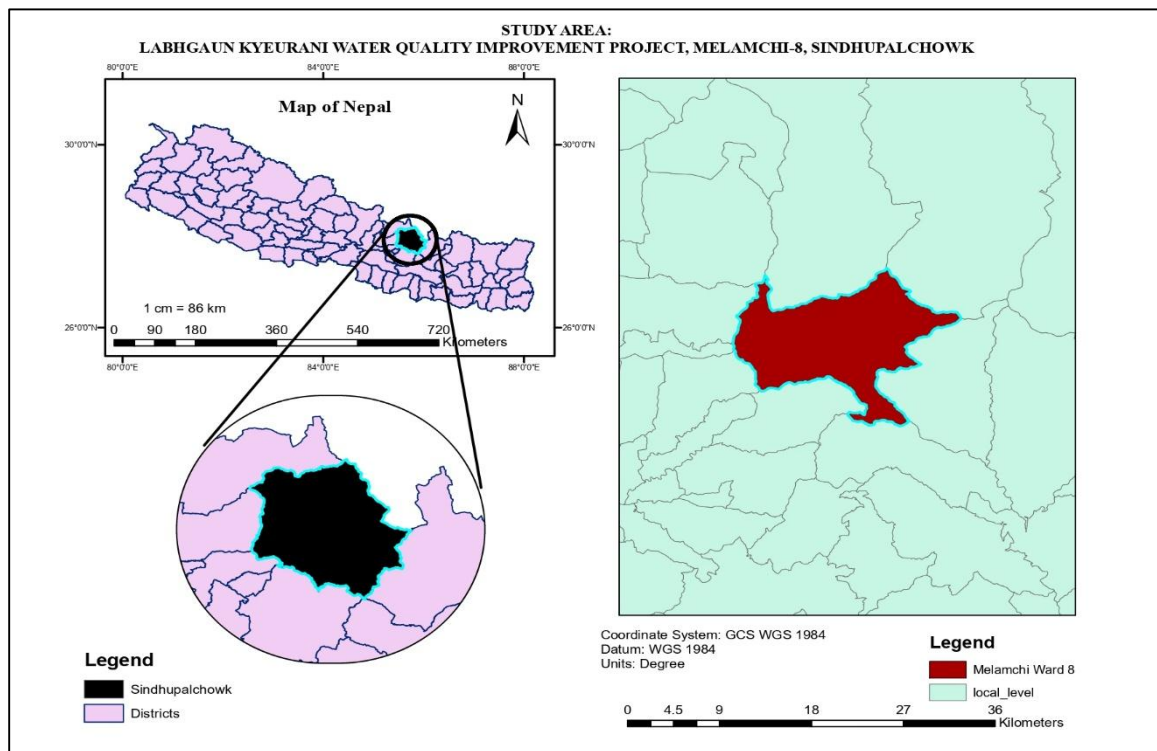


Figure 2.1. Study Area of Project A (Source: GIS)

PROJECT B: LAPSE NIGRE SIKRE WATER QUALITY IMPROVEMENT PROJECT, SUNKOSHI-6, SINDHUPALCHOWK

The Lapse Nigre Sikre WQIP is located in Ward No. 6 of Sunkoshi Rural Municipality, Sindhupalchowk District. The project covers the settlements of Lapse, Nigre, and Sikre and aims to improve access to safe and reliable drinking water in priority settlement clusters. The area lies in the mid-hill region of Nepal between approximately 27°43' N to 27°47' N latitude and 85°47' E to 85°51' E longitude. The elevation of the project area ranges from about 800 m to 2,100 m above mean sea level, with steep hills, narrow valleys, and scattered settlements typical of the region. The project area is bordered by the Sunkoshi River in the south, hilly ridges to the north, and neighboring wards and rural

municipalities on the other sides. The settlements have a mixed population, mainly Tamang and other hill ethnic groups, whose livelihoods depend on farming, livestock rearing, and seasonal labor. The project is designed to serve an estimated population of about 2,000 to 2,500 people.

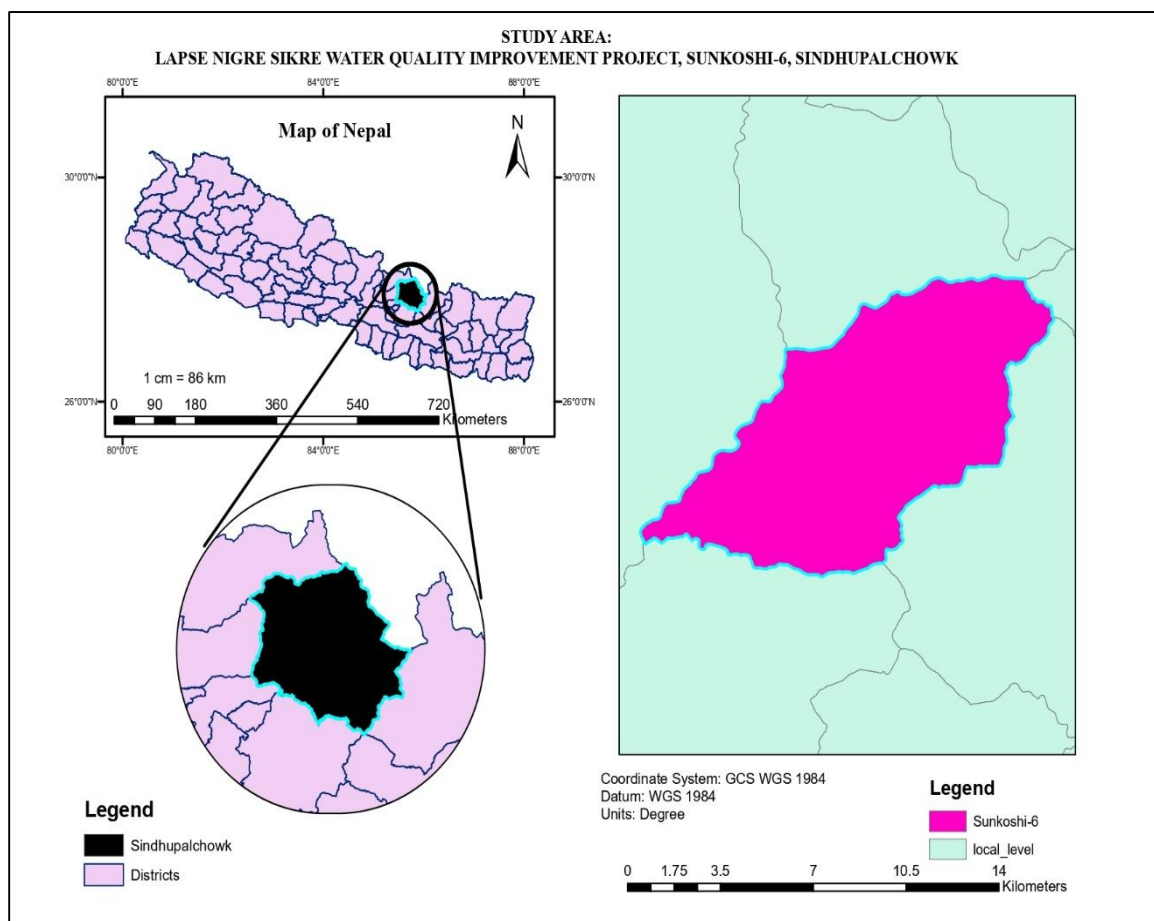


Figure 2.2. Study Area of Project B (Source: GIS)

PROJECT C: CHISO SWASTHYA RAMCHE THULOPATA WATER QUALITY IMPROVEMENT PROJECT, MELAMCHI-1, SINDHUPALCHOWK

The Chiso Swasthya Ramche Thulopata WQIP is located in Ward No. 1 of Melamchi Municipality, Sindhupalchowk District. The project covers the settlements of Chiso Swasthya, Ramche and Thulopata. The project area lies in the mid-hill region of Nepal between about 27°47' N to 27°51' N latitude and 85°34' E to 85°38' E longitude with elevations ranging from approximately 760 m to nearly 2,000 m above mean sea level. The area is bordered by the Melamchi River in the south, adjoining municipal wards to the east and west, and upland settlements extending north toward Helambu. The region is characterized by natural springs, terraced agriculture and scattered settlements with a predominantly Tamang and hill-caste population. The design population for the project is estimated at about 2,100 people living within an area of approximately 7–8 km².

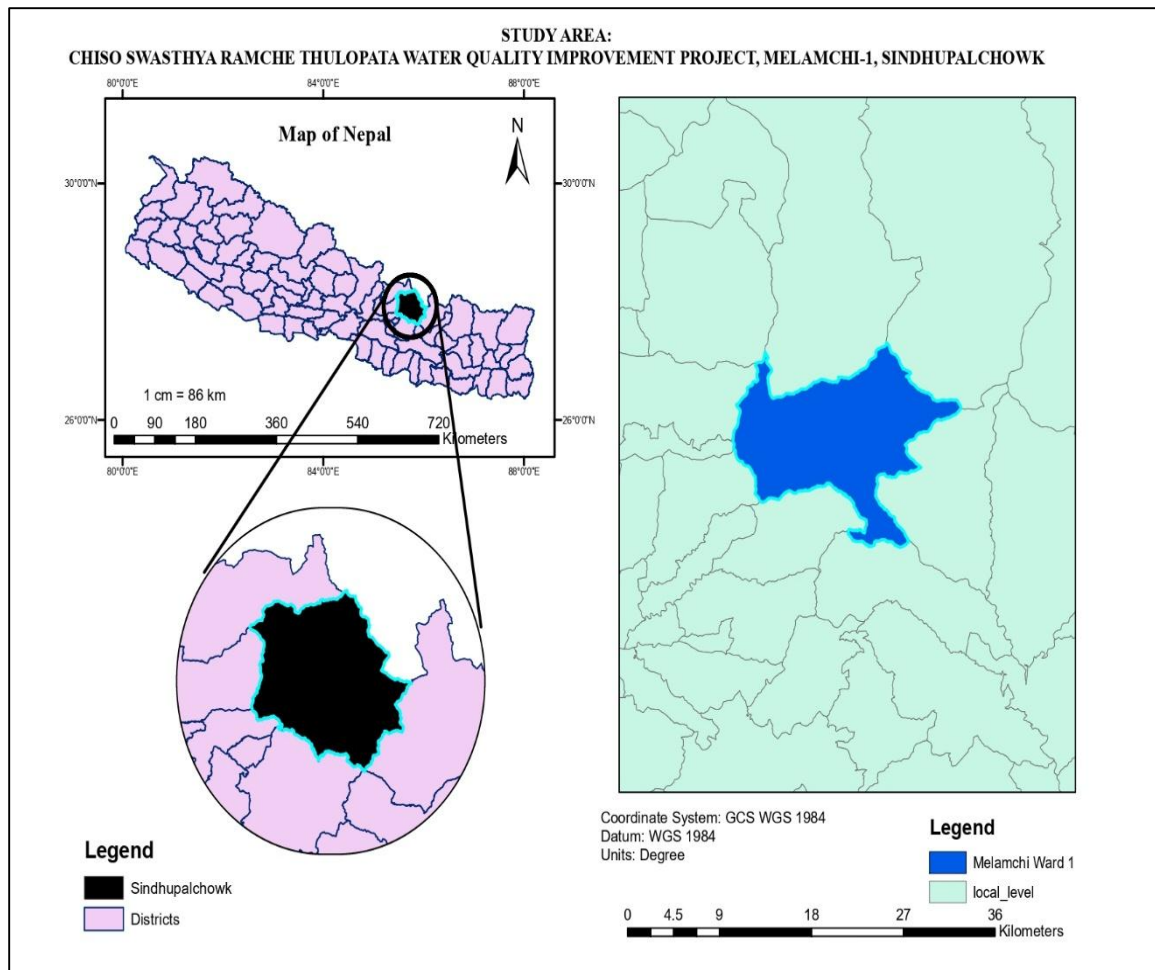


Figure 3.3. Study Area of Project C (Source: GIS)

PROJECT D: RABIGAUN WATER QUALITY IMPROVEMENT PROJECT, PACHKHAL-2, KAVREPALANCHOWK

The Rabigaun Water Quality Improvement Project is located in Ward No. 2 of Panchkhal Municipality, Kavre District, Nepal. The project area lies in a hilly region of Bagmati Province between 27°39'00" north latitude and 85°37'00" east longitude. The project town is situated to the west of the proposed water source, the Sunkoshi River. An all-weather black-topped road passes through the service area, while most internal roads are gravel and earthen. The project area has a humid sub-tropical to temperate climate with dry winters and warm summers. Climatic data used in this study were taken from the nearest station located at Panchkhal. The mean monthly temperature is about 24.9°C and the average annual rainfall is approximately 1,020 mm.

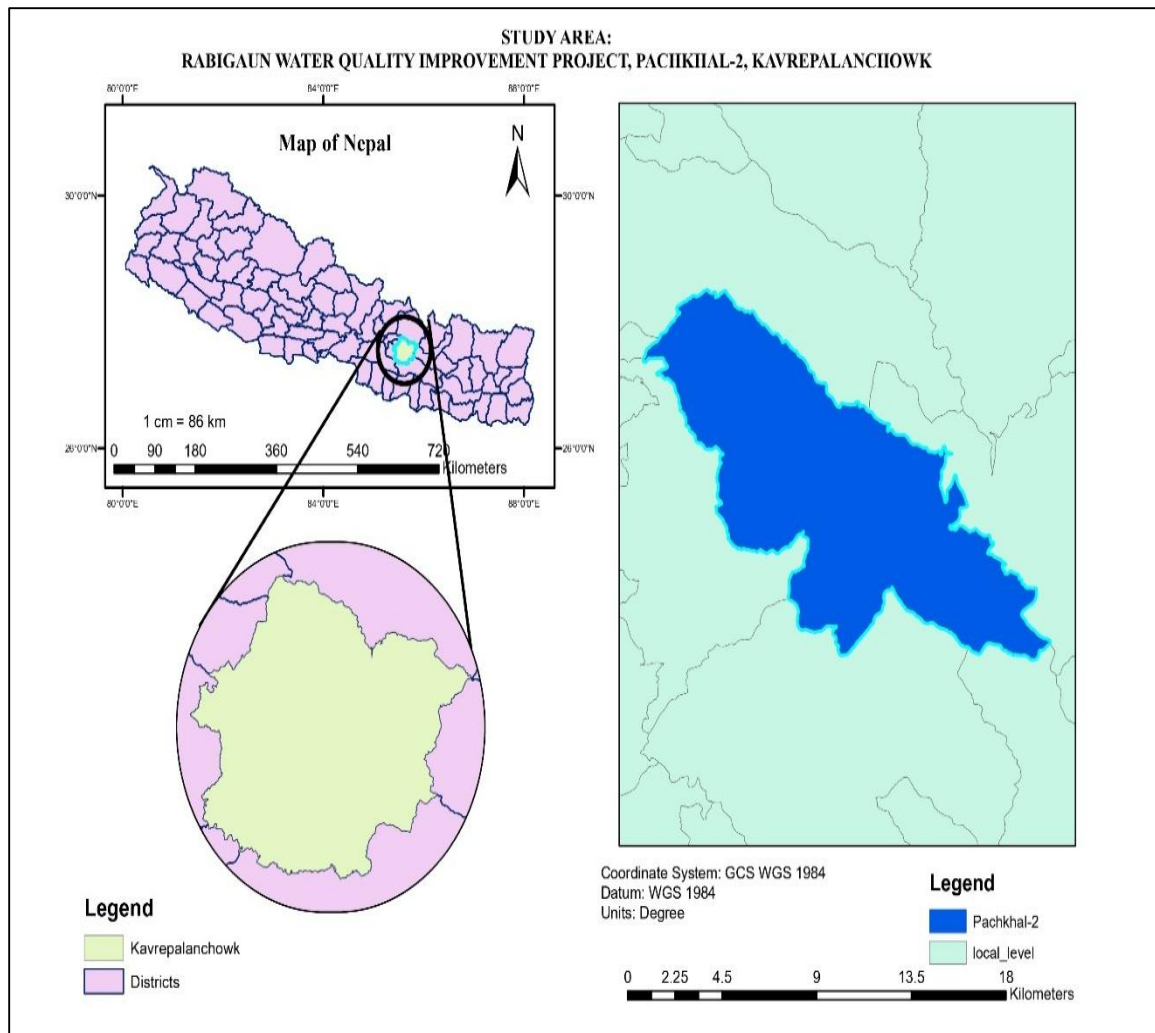


Figure 3.4. Study Area of Project D (Source: GIS)

Table 1. Selected Study Projects

Project	Location	Municipality	Design Pop.
A	Melamchi-8, Sindhupalchowk	Melamchi Municipality	~2,000
B	Sunkoshi-6, Sindhupalchowk	Sunkoshi Rural Mun.	~2,250
C	Melamchi-1, Sindhupalchowk	Melamchi Municipality	~2,100
D	Panchkhal-2, Kavrepalanchowk	Panchkhal Municipality	~1,800

2.2 Data Collection

Primary data were collected through: (a) structured field observations using systematic checklists and photographic records; and (b) semi-structured in-depth interviews (45–60 min) with project engineers, designers, and technical experts.

Secondary data included Detailed Project Reports (DPRs), approved plan and section drawings, hydraulic design sheets, BOQs, and cost estimates. National RSF design guidelines issued by DWSSM and RWSSFDB were consulted

for compliance benchmarking. Cost data from all projects were adjusted to a common price base to eliminate temporal variation.

2.3 Design Parameter Identification

The following parameters were extracted and quantified from approved drawings using standard engineering measurement procedures: filter bed area (m²); structural depth (m); filter media specifications (sand and gravel depth, D₁₀, uniformity coefficient Cu); underdrain pipe diameters; backwash flow rate; RCC volume (walls + slab + partitions); excavation volume; and reinforcement quantity (kg), estimated as:

$$R = \rho \times V_{\text{RCC}} \times 1000 \quad \dots \quad \text{Equation (1)}$$

where R is reinforcement (kg), ρ is the reinforcement ratio (0.01–0.02), and V_{RCC} is total RCC volume (m³).

2.4 Cost Component Analysis

Construction costs were disaggregated into four components: (i) civil works (excavation, backfilling, stone soling, PCC, RCC, formwork, plaster); (ii) mechanical and electrical works (valves, sluice gates, air release valves); (iii) filter media (sand and gravel); and (iv) ancillary items (manhole covers, safety rings, pipe fittings, site preparation, contingencies).

2.5 Regression Analysis

Due to the limited sample size, a simple exploratory linear regression was conducted using Ordinary Least Squares (OLS). The model was:

$$C = \beta_0 + \beta_1 X + \varepsilon \quad \dots \quad \text{Equation (2)}$$

where C is total RSF construction cost (NPR), X is the selected independent design variable, β_0 and β_1 are the intercept and slope, and ε is the error term. Results are interpreted through the sign and magnitude of β_1 and coefficient of determination R². Statistical significance was assessed at the 5% level, but results are treated as indicative given the small sample.

3. RESULTS AND DISCUSSION

3.1 Design Parameters

Table 2 presents the key RSF design parameters. All projects include a minimum of two filter units for continuous operation. Filter bed area ranges from 5.36 m² (Project B) to 10.13 m² (Project A)—a variation of ~47%, which directly scales excavation and RCC quantities. Structural depth varies from 1.50 m (Project C) to 1.90 m (Projects A and B). All projects use identical sand grading (D₁₀ = 0.58 mm, Cu = 1.5) and a uniform gravel layer of 0.60 m. Hydraulic loading rates fall within the recommended 4–6 m/hr range, with a filtration rate around 2.3–2.9 m³/m²/hr across all four projects.

Table 2. RSF Key Design Parameters

Proj.	Bed Area (m ²)	Depth (m)	Sand Dep. (m)	Gravel (m)	HLR (m ³ /m ² /h)
A	10.13	1.90	0.20	0.60	2.882
B	5.36	1.90	0.19	0.60	2.869
C	5.99	1.50	0.16	0.60	2.341
D	8.84	1.63	0.19	0.60	2.843

Under drain analysis showed Project A employing the largest lateral diameter (63 mm) and manifold (500 mm), yielding the lowest backwash velocity (0.105 m/s). Projects B, C, and D use 50 mm laterals with velocities up to

0.125 m/s—approaching limits for uniform flow distribution. Backwash discharge scaled proportionally with filter area, ranging from 191.84 m³/hr (Project B) to 362.53 m³/hr (Project A), all using a wash rate of 35.8 m³/m²/hr.

3.2 Construction Cost Analysis

Total RSF construction costs varied from NPR 1.91 million (Project B) to NPR 6.11 million (Project D). The cost distribution across components is summarised in Table 3.

Table 3. Construction Cost Distribution (%)

Proj.	Civil Works	Mech. & Elec.	Filter Media	Ancillary
A	57.67%	37.86%	3.23%	1.24%
B	48.91%	47.73%	1.79%	1.57%
C	52.54%	43.67%	2.36%	1.43%
D	20.52%	77.83%	1.26%	0.39%

Civil works dominated costs in Projects A, B, and C, confirming that gravity-fed RSF systems are structurally intensive. Within civil works, reinforcement was the single largest sub-item—contributing 35.27% (Project A), 29.95% (B), 32.75% (C), and 11.67% (D) of the respective total project costs. M20 RCC was the second largest sub-item, followed by formwork and stone soling. Filter media (sand and gravel) accounted for only 1.3–3.2% of total cost across all projects, confirming its marginal influence on capital cost compared to structural components.

Project D's cost profile diverged markedly: mechanical and electrical works captured 77.8% of total cost, driven by a large MS trough (61.70% of project total) and more sophisticated backwash equipment. This reflects a design philosophy shift toward greater mechanisation rather than conventional gravity-concrete construction.

3.3 Design–Cost Nexus

Filter bed area showed a strong positive association with total construction cost. The 47% variation in plan area across projects corresponded to an 18–30% variation in total cost, attributable to proportional increases in excavation, PCC, and RCC quantities. Structural depth demonstrated a comparable relationship: the RCC cost share ranged from 4.42% (Project D, depth 1.63 m) to 11.47% (Project A, depth 1.90 m), a seven-percentage-point spread.

The design–cost interaction can be conceptualised as a cascade: design dimensions → quantity estimation → component-wise cost → total construction cost. Empirical evidence confirms that cost variation originates primarily in design scale and layout decisions, not in unit rate fluctuations or material market differences.

3.4 Regression Analysis: Reinforcement vs. Cost

Simple linear regression of reinforcement quantity (kg) on total construction cost (NPR) yielded:

$$\text{Cost (NPR)} = 150.29 \times \text{Reinforcement (kg)} + 15,142 \quad \text{Equation (3)}$$

The model statistics are presented in Table 4. The coefficient of determination $R^2 = 0.969$ indicates that reinforcement quantity alone explains 96.9% of cost variation. The slope coefficient ($\beta_1 = 150.29$ NPR/kg) was statistically significant at the 5% level ($p = 0.0158$), confirming reinforcement as a primary cost driver. Residuals were small relative to total cost (Table 5), indicating good model fit with no extreme outliers.

Table 4. Regression Model Statistics

Statistic	Value
Multiple R	0.984
R ²	0.969
Adjusted R ²	0.953
Standard Error (NPR)	25,562
p-value (slope)	0.0158

Table 5. Residual Analysis

Proj.	Predicted Cost (NPR)	Residual (NPR)
A	844,912	+15,726
B	568,309	+5,436
C	677,382	+9,494
D	743,978	-30,656

3.5 Qualitative Findings

Field observations confirmed that raw-water sources (rivers, streams, shallow groundwater) experience elevated turbidity during the monsoon, yet RSF designs were largely uniform throughout the year. Operator competence varied substantially, with inconsistent backwashing practices reducing effective filter run-times. In-depth interviews with project engineers and municipal officials corroborated that design decisions were predominantly shaped by past project templates and conservative safety margins rather than site-specific hydraulic analysis—supporting the quantitative finding of cost inefficiency.

3.6 Discussion in Relation to Prior Studies

The finding that reinforcement and RCC works dominate RSF capital cost is consistent with IRC Wash [9], who developed an early capacity-based regression cost model for rapid sand filters. The current study refines this by isolating reinforcement quantity as the strongest predictor within the civil works category. Tamakhu and Amatya [1] showed that filter media selection affects both efficiency and cost; the present study extends this by demonstrating that structural specifications exert a far greater influence on capital cost than media choice alone.

Pyakurel et al. [2] emphasised hydraulic interconnection among treatment stages; this study adds that design conservatism at each stage cumulatively inflates structural dimensions and therefore cost. The recommendation by K Consultation [3] to adapt rural water supply designs to local conditions is empirically validated here: standardised design templates applied uniformly across varying site contexts were the proximate cause of cost disparities of up to 220% between the least- and most-expensive projects. Poudel [5] attributed infrastructure cost overruns partly to procurement rigidity; this study shows that technical rigidity in design standards is an equally important lever.

4. CONCLUSION

This study examined the design–cost nexus of Rapid Sand Filter construction across four Nepalese water supply projects. The key conclusions are:

- Civil works—particularly reinforced concrete and structural depth—are the dominant cost drivers, constituting 49–58% of total RSF cost in gravity-fed projects.
- Reinforcement quantity alone explains 96.9% of cost variation ($R^2 = 0.969$; $p = 0.016$), with every additional kilogram adding approximately NPR 150 to the project cost.
- Filter bed area variation of ~47% across projects corresponds to cost differences of 18–30%, confirming a strong design–cost association.
- Filter media costs are marginal (1.3–3.2%) and have limited capital-cost influence compared to structural components.
- Developing context-sensitive, site-adaptive RSF design guidelines and improving coordination between design engineers and construction managers would substantially reduce unnecessary cost escalation without compromising treatment performance.

REFERENCES

- [1] Tamakhu, G. & Amatya, I. M. (2021). Turbidity removal by rapid sand filter using anthracite coal as capping media. *Journal of Innovations in Engineering Education*, 4(1), 69–73.
- [2] Pyakurel, H. R., Khatri, N. R. & Lekhak, B. (2024). Field approach on the effectiveness of hydraulic flocculator followed by sedimentation and rapid sand filter. *Himalayan Journal of Applied Science and Engineering*, 4(2), 54–62.
- [3] K Consultation. (2013). *Methods for rural water supplies*. K Consultation.
- [4] Kruisdijk, C., van Loosdrecht, M. & Pronk, M. (2024). Design optimisation of rapid sand filtration systems. *Water Research*, 240, 120123.
- [5] Poudel, K. (2025). The procurement process of World Bank funded projects and government funded projects in Nepal. *Academia Journal of Humanities & Social Sciences*, 2, 153–164.
- [6] Singh, D. B. & Amatya, I. M. (2021). Treatment efficiency of rapid sand filters on intermittent use. *IJERT*, 10(9).
- [7] UWSSP. (2021). *Urban water supply and sanitation project report*. Asian Development Bank.
- [8] Yadav, R. (2023). Cost analysis of water treatment infrastructure in Nepal. *Journal of Infrastructure Development*, 15(1), 55–70.
- [9] IRC Wash. (1984). *Cost model for rapid sand filters and comparative cost data*. WEDC Report.
- [10] Fajar, M., Sembiring, E. & Handajani, M. (2022). The effect of filter media size and loading rate to filter performance. *Journal of Engineering and Technological Sciences*, 54(5), 220512.