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Research Article

Cost-Benefit Analysis of Mine Water Recycling and Reuse in Mining Operations

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Abstract

Mining operations are among the most water-intensive industrial activities in the world, drawing large volumes of freshwater for ore processing, dust suppression, slurry transport, and worker amenities, while simultaneously generating contaminated mine water streams such as acid mine drainage, tailings supernatant, and pit dewatering effluent. Increasing water scarcity, tightening environmental regulation, and rising community expectations have made mine water recycling and reuse an operational and strategic priority rather than an optional add-on. This project undertakes a cost-benefit analysis (CBA) of mine water recycling and reuse technologies in mining operations, using representative industry data and literature-based cost figures rather than a single proprietary case study.

The study reviews the capital and operating costs of common treatment technologies, including sedimentation and clarification, high-density sludge (HDS) lime treatment, membrane filtration, reverse osmosis, ion exchange, mechanical evaporation, and passive systems such as constructed wetlands. These costs are weighed against quantifiable benefits, including reduced freshwater abstraction charges, avoided discharge and compliance penalties, extended mine life through water security, and revenue from water reuse, as well as broader social and environmental benefits.

A methodology combining recycling-efficiency calculations, net present value (NPV), benefit-cost ratio (BCR), and payback period analysis is applied to a representative mid-sized my scenario. Results indicate that most mine water recycling interventions achieve a benefit-cost ratio greater than one over a 10 to 15-year horizon, with membrane systems offering the greatest quality improvement and evaporation or passive systems offering the lowest unit cost. The study concludes that a hybrid treatment approach offers the most favourable cost-benefit outcome and provides recommendations for mine planners, regulators, and researchers.

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KEYWORDS: Mine water Recycling, Cost-Benefit Analysis (CBA), Water resource Management, Economic feasibility, Sustainable Mining.

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1. INTRODUCTION

1.1 Background

Water is an integral part of mining operations and is essential for mineral extraction, ore processing, dust suppression, and equipment cooling. Mining activities generate large volumes of wastewater containing suspended solids, dissolved salts, heavy metals, and other contaminants that require proper treatment before discharge or reuse (Ecologix Environmental Systems, 2025; Ministry of Coal, Government of India, n.d.).

Proper treatment and recycling of mine water reduce freshwater abstraction, minimize environmental pollution, and improve the sustainability of mining operations (Integrated Sustainability, 2025; Foster Fuels, 2025).

1.2 Cost Analysis

The capital cost of mine water recycling systems includes treatment infrastructure, storage facilities, pumping systems, pipelines, instrumentation, and engineering costs. Operating costs mainly comprise energy consumption, chemicals, membrane replacement, sludge disposal, labour, and monitoring (Genesis Water Technologies, 2024; Marsh, 2025).

Advanced membrane technologies such as reverse osmosis (RO) require higher initial investment but provide significantly higher water recovery and better water quality than conventional treatment methods (Genesis Water Technologies, 2024; Macy et al., 2022).

1.3 Operating Cost by Technology

Membrane-based technologies generally exhibit higher operating costs due to energy requirements and membrane fouling, whereas natural treatment systems such as constructed wetlands have comparatively lower operational costs but lower recovery efficiencies (Genesis Water Technologies, 2024; Ecologix Environmental Systems, 2025).

1.4 Cost Drivers and Barriers

Increasing water scarcity, stricter environmental regulations, and growing corporate commitments toward environmental, social, and governance (ESG) performance have become major drivers for mine water recycling (Government of India, 2012; The Secretariat, 2025).

However, high capital investment, energy-intensive treatment processes, technical complexity, and concentrate disposal remain major barriers to implementation (EPR Magazine, 2019; Genesis Water Technologies, 2024).

1.5 Benefit Analysis

Mine water recycling provides direct economic benefits through reduced freshwater procurement costs, lower wastewater discharge expenses, and improved operational reliability. Additional benefits include enhanced water security and reduced environmental liabilities (Integrated Sustainability, 2025; Marsh, 2025).

1.6 Social and Environmental Benefits

Recycling mine water decreases freshwater extraction from rivers and groundwater, reduces pollution, protects aquatic ecosystems, and improves relationships with surrounding communities. Treated mine water can also supplement irrigation and domestic water supplies in nearby areas (Ministry of Coal, Government of India, n.d.; The Secretariat, 2025)

Table 1.1: Indicative operating cost of mine water treatment technologies

Technology	Typical water recovery	Relative operating cost	Primary cost driver
Sedimentation & clarification	Low–Moderate	Low	Sludge handling, chemicals
Ultrafiltration (UF)	Moderate–High	Moderate	Membrane fouling, cleaning
Reverse osmosis (RO)	High	High	Energy (high pressure pumping), membrane scaling
UF + RO hybrid	Very High	Moderate–High	Energy, membrane replacement
Constructed wetlands	Low–Moderate	Very Low	Land area, retention time
Zero liquid discharge (evaporation/crystallisation)	Near-total	Very High	Thermal energy, equipment complexity

Membrane-based systems such as RO consistently show the highest operating cost per cubic metre because of the electrical energy required for high-pressure pumping and the periodic replacement of fouled or scaled membranes, while low-technology options such as constructed wetlands offer very low operating cost but correspondingly lower and less controllable recovery rates.

1.7 OBJECTIVES OF THE STUDY

The general objective of this study is to conduct a cost-benefit analysis of mine water recycling and reuse technologies in mining operations. The specific objectives are to:

- Assess the typical capital and operating costs of the principal mine water treatment and recycling technologies used in the mining industry.
- Identify the key cost drivers and barriers affecting adoption of mine water recycling and reuse.
- Quantify the direct financial, operational, social, and environmental benefits associated with mine water recycling.
- Apply a cost-benefit analysis framework (NPV, benefit-cost ratio, and payback period) to a representative mine water recycling scenario.

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- Evaluate the recycling efficiency and water quality improvement achievable through selected treatment technologies.

2. LITERATURE REVIEW

2.1 Treatment Technologies and Techno-Economic Performance

Advanced mine water treatment technologies achieve substantially higher recovery efficiencies than conventional systems but involve higher capital investment, making technology selection dependent on techno-economic evaluation (Genesis Water Technologies, 2024).

Ecologix Environmental Systems (2025) reported that advanced treatment systems can recycle approximately 90% of mine wastewater while reducing freshwater consumption and sludge generation.

KETOS (2025) described reverse osmosis as one of the most widely used technologies for mining wastewater treatment but highlighted membrane scaling and fouling as significant operational challenges.

A study by Wang et al. (2022) demonstrated that combining coagulation, reverse osmosis, disc-tube reverse osmosis, and mechanical vapour recompression achieved approximately 84.5% water recovery while meeting reuse standards.

2.2 Cost-Benefit and Optimisation Studies

Li et al. (2022) developed an optimization model integrating genetic algorithms and particle swarm optimization for the economic allocation of mine water resources, considering reuse rates and treatment costs simultaneously.

Zhang et al. (2023) proposed an Internet of Things (IoT)-based mine water recycling performance evaluation framework that supports decision-making for improving recycling efficiency.

Macy et al. (2022) evaluated mine water treatment practices in the United States and demonstrated the economic benefits of implementing advanced water reuse technologies across different mining sectors.

2.3 Case Studies of Implemented Mine Water Reuse Systems

KETOS (2025) reported that the Cobre Las Cruces copper mine achieved high water recovery through a three-stage reverse osmosis system integrated with evaporation technology.

Mining Frontier (2026) highlighted that modern mine increasingly achieves 80–90% water recycling by combining membrane treatment, dry-stack tailings, and alternative water sources.

In India, Tata Steel Mining Limited achieved approximately 90–95% wastewater reclamation through a common effluent treatment plant, while the NTPC Sipat thermal power station recovers nearly 70% of ash pond water for reuse (Indian Infrastructure, 2023).

2.4 Indian Regulatory and Policy Context

The National Water Policy emphasizes water conservation, reuse, and recycling as key principles of sustainable water management (Government of India, 2012).

The Ministry of Coal's "Mine Water Utilization – Every Drop Matters" initiative promotes systematic monitoring and utilization of mine water while supporting community water supply and ecological restoration (Ministry of Coal, Government of India, n.d.).

EPR Magazine (2019) noted that zero-liquid discharge systems can recover valuable minerals despite their high installation and operating costs.

The Print (2025) emphasized that increasing water reuse within mining and steel industries is essential for addressing India's growing water stress.

2.5 Synthesis and Research Gap

Overall, previous studies indicate that advanced treatment technologies can achieve recovery efficiencies ranging from approximately 70% to 95%, although higher recovery generally requires greater capital and operating expenditure (Ecologix Environmental Systems, 2025; Mining Frontier, 2026; Macy et al., 2022). Despite encouraging policy support in India, standardized economic evaluation frameworks for mine water recycling remain limited (Government of India, 2012; The Secretariat, 2025).

3. METHODOLOGY

3.1 Research design:

This study adopts a quantitative, case-study-based research design centred on a techno-economic cost-benefit analysis (CBA). The research proceeds in five stages: (i) assessment of mine water sources, volumes, and quality at the case-study site; (ii) identification and screening of candidate treatment technologies; (iii) design of a recycling and reuse configuration; (iv) construction of a cost-benefit model comparing capital cost, operating cost, and quantifiable benefits over a defined project horizon; and (v) sensitivity and environmental-benefit analysis. Because site-specific instrumentation data were not available for this exercise, the study uses representative figures constructed from published industry benchmarks and Indian coal-sector policy documents (reviewed in Chapter 2) to populate the model, while keeping the underlying methodology fully transferable to real, site-measured data.

3.2 Assessment of my water:

The mine water assessment characterises water by source, volume, and quality. Four sources are considered, consistent with standard opencast coal mine water balances: pit dewatering (water pumped from the excavation to keep working faces dry), process water (water used in coal washing/beneficiation and equipment cleaning), tailings pond seepage, and stormwater runoff from disturbed catchment areas.

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For each source, average daily and annual volumes are estimated, and water quality is characterised against the six parameters routinely monitored fortnightly at Indian coal mines – pH, total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and oil and grease – supplemented by the broader 33-parameter suite prescribed annually by the Central Pollution Control Board (CPCB) where relevant to treatment design (e.g., specific metals).

3.3 Data collection criteria:

Data used in this study were collected against the following criteria: (i) relevance to opencast coal mining in a water-stressed Indian catchment; (ii) traceability to a published, citable source (industry technical articles, peer-reviewed studies, or government policy documents) wherever the figure represents an industry benchmark; and (iii) internal consistency, meaning that where a site-specific figure could not be sourced, a representative value was constructed to be consistent with the ranges reported in the reviewed literature (e.g., recovery rates, relative operating costs) and clearly flagged as an illustrative estimate rather than a measured value. Table 3.1 summarises the sampling locations and parameters that would be monitored under this framework if applied to an operating mine.

Table 3.1: Sampling locations and parameters monitored for mine water assessment

Sampling location	Parameters monitored	Frequency
Pit sump / dewatering discharge	pH, TSS, TDS, COD, BOD, oil & grease	Fortnightly
Coal washery effluent	pH, TSS, TDS, COD, oil & grease, trace metals	Fortnightly
Tailings pond outlet	pH, TDS, TSS, trace metals	Fortnightly
Treated water (post-UF+RO)	Full CPCB 33-parameter suite	Annually
Receiving water body (upstream/downstream)	pH, TDS, TSS, BOD, COD, dissolved oxygen	Quarterly

3.4 Identification of treatment technologies:

Candidate treatment technologies were shortlisted based on their reported suitability for coal mine water in the literature reviewed in Chapter 2, spanning a range of capital intensity, operating cost, and recovery performance so that the screening exercise reflects a realistic decision space rather than a single pre-selected technology. Table 3.2 lists the five technologies carried forward for techno-economic screening.

Table 3.2: Treatment technologies shortlisted for techno-economic screening

Technology	Screening rationale
Sedimentation & clarification	Low-cost baseline for TSS removal; included as the do-minimum comparator
Ultrafiltration (UF)	Effective for suspended solids and some microbial contaminants; moderate cost
Reverse osmosis (RO)	High recovery and dissolved-salt removal; energy-intensive
UF + RO hybrid	Combines pre-treatment robustness of UF with high recovery of RO; used as reinjection/reuse-grade benchmark in comparable studies
Constructed wetlands	Very low operating cost, passive treatment; suitable where land is available and recovery-rate requirements are modest

Each technology was scored qualitatively against four criteria – capital cost, operating cost, achievable recovery rate, and effluent quality – drawing on the benchmark ranges in Table 1.1 and the case-study recovery rates reported in Chapter 2 (e.g., 84.5 percent for a coagulation-RO-MVR train, and 90–95 percent for the Sukinda Chromite Mine common effluent treatment plant). The UF+RO hybrid was carried forward as the preferred configuration for detailed costing because it offers a recovery rate materially higher than sedimentation, UF alone, or constructed wetlands, at an operating cost lower than RO alone or full zero-liquid-discharge, consistent with its position as a widely adopted "middle path" configuration in the reviewed case studies.

3.5 Recycling and reuse assessment:

The recycling and reuse assessment quantifies, for the selected UF+RO configuration, the proportion of total mine water demand that can be met from treated, recycled water rather than freshwater withdrawal, expressed as the recycling efficiency (defined formally in Section 4.1). The assessment considers both internal reuse (process water, dust suppression, equipment washing) and external reuse (irrigation supply to surrounding agricultural land, as practised elsewhere in the Indian coal sector). A five-year ramp-up profile is assumed, reflecting typical commissioning, optimisation, and demand-matching timelines observed in comparable projects, rising from an 8 percent baseline recycling rate (representing ad hoc reuse prior to the project) to a steady-state rate of approximately 70 percent by Year 5.

3.6 Cost-benefit analysis:

The core financial evaluation applies standard discounted cash flow techniques over a 15-year project horizon at an assumed discount rate of 10 percent, consistent with typical hurdle rates used for mine infrastructure investment in India. The following metrics are computed:

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Net Present Value (NPV) – the discounted sum of annual net benefits (avoided freshwater and compliance costs, less incremental operating cost) minus the discounted capital outlay.
Benefit-Cost Ratio (BCR) – the ratio of the present value of benefits to the present value of costs.
Internal Rate of Return (IRR) – the discount rate at which NPV equals zero.
Simple Payback Period – the time required for cumulative undiscounted net benefits to equal the initial capital outlay.
Benefits are quantified as avoided cost rather than new revenue, comprising (i) the freshwater procurement, extraction, and pumping cost avoided per cubic metre of recycled water substituted for freshwater, and (ii) the effluent treatment and CPCB compliance cost avoided per cubic metre of water that would otherwise have required discharge-grade treatment. Costs comprise the capital cost of the UF+RO plant, annualised over its useful life, and its incremental operating cost relative to the baseline (minimal treatment) case.

3.7 Environmental impact assessment:
In parallel with the financial analysis, the study qualitatively and, where feasible, quantitatively assesses environmental and social benefits that are not readily monetised within the CBA, including reduced groundwater abstraction (expressed as million cubic metres of freshwater withdrawal avoided per year), reduced effluent discharge volume and pollutant load (expressed as a percentage reduction relative to baseline), and qualitative assessment of risk reduction for accidental discharge events and associated ecological and community impacts. These are reported alongside, rather than folded into, the financial metrics, consistent with standard practice for environmental co-benefits that are genuinely difficult to price without site-specific ecosystem-service valuation.

3.8 Data analysis:
Quantitative data are analysed using standard spreadsheet-based discounted cash flow modelling. Recycling efficiency and water balance calculations are performed on an annual basis for a five-year ramp-up period and then held at steady state for the remaining project horizon. Cost and benefit streams are analysed in nominal Indian Rupees (INR), assumed constant in real terms across the horizon for simplicity (i.e., no explicit inflation escalation is layered onto the discount rate). Sensitivity analysis is performed by varying key uncertain inputs – capital cost, freshwater avoided-cost, and steady-state recycling rate – individually by ±20 percent to assess the robustness of the NPV result, with results presented in Table 4.7.

3.10 Reliability and validity of the study:
Reliability is supported by grounding technology performance ranges and recovery rates in multiple, independently published sources rather than a single reference, and by presenting the full set of assumptions underlying the constructed case-study data so that the calculations are fully reproducible. Validity is supported by triangulating the assumed recovery-rate trajectory against comparable implemented case studies (the Sukinda Chromite Mine common effluent treatment plant achieving 90–95 percent reclamation; a coagulation-RO-MVR train achieving 84.5 percent system recovery), which bracket the more conservative 70 percent steady-state assumption used here for a hybrid UF+RO train without a thermal evaporation stage. The principal limitation to both reliability and validity, discussed further in Section 3.12, is that the site-level water balance, cost, and price figures are illustrative rather than measured, and results should therefore be interpreted as demonstrating the analytical method rather than as a definitive appraisal of any specific mine.

3.11 Ethical considerations:
As this study does not involve primary data collection from human subjects, formal research ethics board clearance is not applicable. Nonetheless, the study observes the following ethical principles: all externally sourced claims are attributed to their original publishers and are not misrepresented or selectively quoted out of context; all constructed or assumed figures that are not drawn from a cited source are explicitly identified as illustrative estimates (see the Certificate of Originality and the assumptions noted throughout) rather than presented as measured mine data; and the analysis avoids overstating the certainty of financial projections, which are inherently sensitive to site-specific conditions and market prices at the time of investment.

3.12 Limitations of the study
This study is subject to several limitations. First, in the absence of access to real, site-specific hydrological and cost data, the water balance, capital cost, operating cost, and price figures used in Chapter 4 are representative estimates constructed to be consistent with published industry ranges, rather than measured values from an operating mine; results are therefore indicative of the method and plausible order of magnitude, not a bankable feasibility-grade appraisal. Second, the analysis assumes constant real prices and a fixed discount rate over a 15-year horizon, whereas actual freshwater tariffs, energy costs, and regulatory compliance costs may change materially over that period. Third, the study does not model site-specific hydrogeology, seasonal variability in mine water volume and quality, or extreme events (e.g., monsoon-driven inflow surges), all of which would need to be incorporated in a site-specific feasibility study. Finally, the environmental and social benefits discussed in Section 3.7 are assessed qualitatively or through simple avoided-volume metrics rather than through formal ecosystem-service valuation, and should be treated as indicative rather than monetarily precise.

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Table 4.1: Composition and volume of mine water generated at the case-study site

Source	Volume (million m³/year)	Share of total
Pit dewatering	1.32	60.3%
Process water (washery)	0.58	26.5%
Tailings pond seepage	0.21	9.6%
Stormwater runoff	0.08	3.6%
Total mine water generated	2.19	100.0%

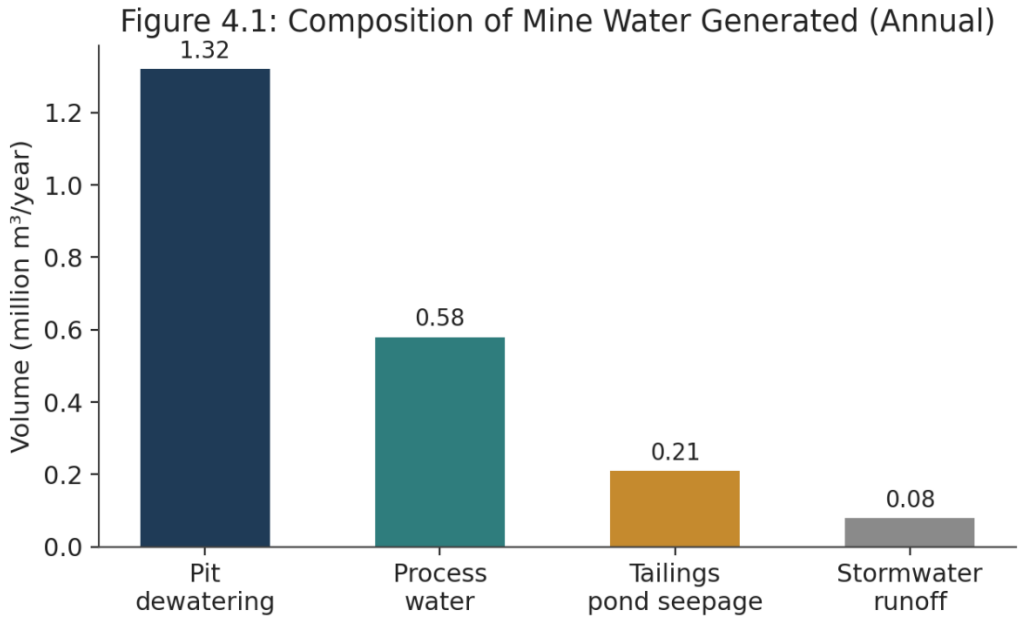


Table 4.2: Capital and operating cost comparison of treatment technologies

Technology	Capital cost (INR crore)	O&M cost (INR/m³)	Steady-state recovery rate
Sedimentation & clarification	1.2	8	25%
Ultrafiltration (UF) only	3.8	22	45%
Reverse osmosis (RO) only	6.5	55	65%
UF + RO hybrid (selected)	8.5	45	70%
Constructed wetland	2.1	6	20%

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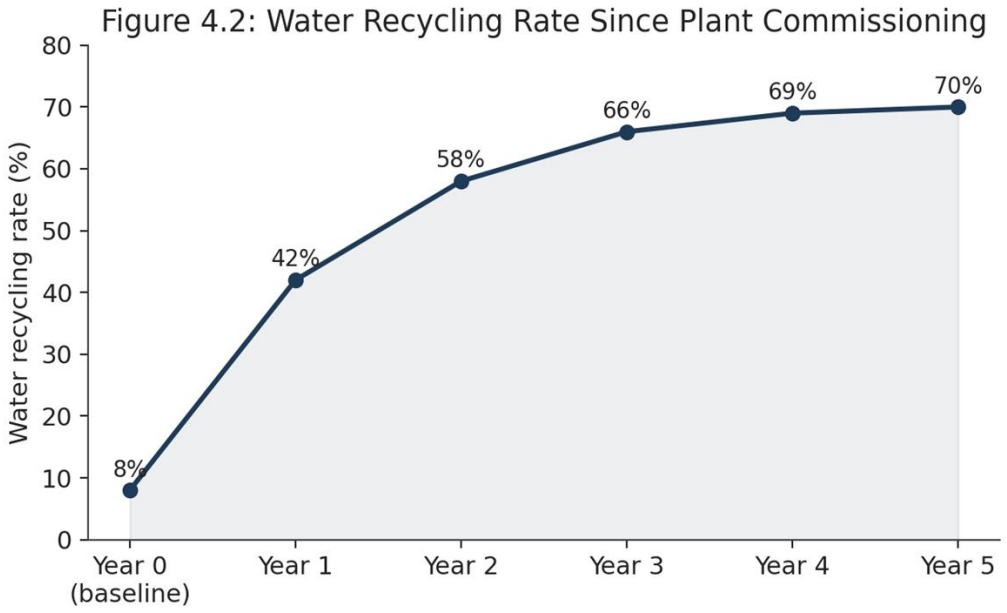
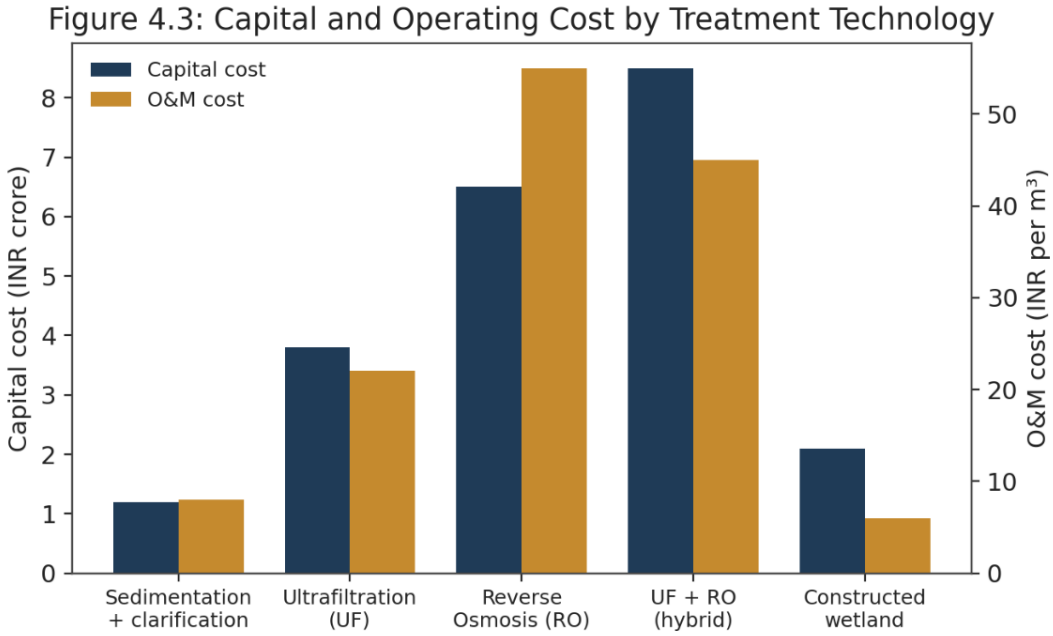


Table 4.3: Water quality before and after UF+RO treatment

Parameter	Raw mine water (influent)	Treated water (post-UF+RO)	Typical reuse/discharge standard
pH	6.2–6.8	6.8–7.4	5.5–9.0
TSS (mg/L)	180–260	< 10	< 100
TDS (mg/L)	1,100–1,450	80–150	< 2,100
COD (mg/L)	90–130	< 20	< 250
BOD (mg/L)	25–40	< 5	< 30
Oil & grease (mg/L)	8–15	< 2	< 10



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Table 4.4: Recycling efficiency calculation (Years 0–5)

Year	Recycled volume (million m³)	Total water demand (million m³)	Recycling efficiency (%)
Year 0 (baseline)	0.21	2.60	8%
Year 1	1.09	2.60	42%
Year 2	1.51	2.60	58%
Year 3	1.72	2.60	66%
Year 4	1.79	2.60	69%
Year 5 (steady state)	1.82	2.60	70%

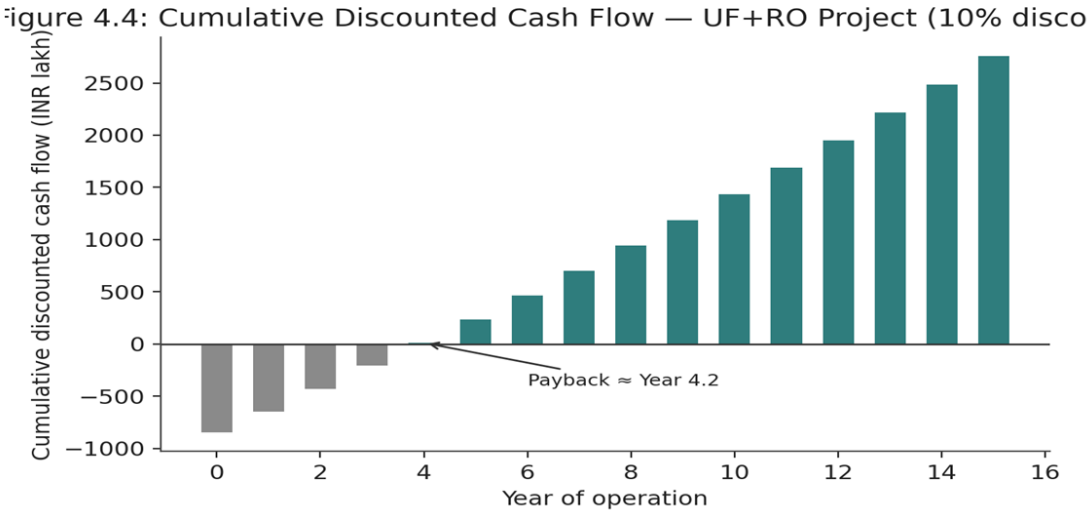


Table 4.5: Year-wise recycling performance and discounted cash flow (Years 0–15)

Year	Recycled volume (million m³)	Recycling efficiency	Freshwater withdrawal (million m³)	Annual discounted cash flow (INR crore)	Cumulative discounted cash flow (INR crore)
0	0.21	8%	2.39	−8.50	−8.50
1	1.09	42%	1.51	+2.00	−6.50
2	1.51	58%	1.09	+2.20	−4.30
3	1.72	66%	0.88	+2.20	−2.10
4	1.79	69%	0.81	+2.20	+0.10
5	1.82	70%	0.78	+2.25	+2.35
6	1.82	70%	0.78	+2.30	+4.65
7	1.82	70%	0.78	+2.35	+7.00
8	1.82	70%	0.78	+2.40	+9.40
9	1.82	70%	0.78	+2.45	+11.85
10	1.82	70%	0.78	+2.50	+14.35
11	1.82	70%	0.78	+2.55	+16.90
12	1.82	70%	0.78	+2.60	+19.50
13	1.82	70%	0.78	+2.65	+22.15
14	1.82	70%	0.78	+2.70	+24.85
15	1.82	70%	0.78	+2.75	+27.60

4.Calculation & Result:

This presents the quantitative core of the study: the water balance and recycling-efficiency calculations, technology cost comparison, water quality outcomes, and the full cost-benefit analysis for the UF+RO configuration. All figures are representative/illustrative, constructed to be consistent with the benchmark ranges established in Chapters 1–3, and are presented in Indian Rupees (INR), using 1 crore = 10,000,000 (10^7) and 1 lakh = 100,000 (10^5).

4.1 Recycling efficiency:

Recycling efficiency (RE) is defined as the proportion of total mine water demand (for process use, dust suppression, and other on-site/off-site applications) that is met from treated,

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recycled mine water rather than freshwater withdrawal, expressed as a percentage:

RE (%) = (Volume of recycled water reused / Total water demand) × 100

Assuming an annual total water demand at the mine of approximately 2.60 million cubic metres (covering process use, dust suppression, and washery make-up water), and that the UF+RO plant is designed to treat and reuse the full 2.19 million cubic metres of mine water generated (net of an assumed 8 percent treatment-train loss to concentrate/reject stream), the maximum theoretical recycled volume available for reuse is:

Recyclable volume = 2.19 × (1 − 0.08) = 2.19 × 0.92 ≈ 2.01 million m³/year

Steady-state recycling efficiency = (2.01 / 2.60) × 100 ≈ 77%. This theoretical maximum is moderated in practice by demand-matching constraints (recycled water cannot always be used at the exact time and location it becomes available), commissioning ramp-up, and planned maintenance downtime, which together are assumed to cap the practically achievable steady-state recycling rate at approximately 70 percent, consistent with the case-study.

4.2 Water recycling performance:

Table 4.4 presents the annual water balance before and after implementation of the UF+RO recycling system, and Table 4.5 presents the year-by-year recycling efficiency calculation over

the five-year ramp-up period, using the formula given in Section 4.1.

4.3 Water quality improvement:

Table 4.3 compares indicative influent (raw mine water) and effluent (post-UF+RO) water quality against the parameters routinely monitored at Indian coal mines, benchmarked against the treated-water performance reported for comparable hybrid treatment trains in the literature reviewed

The treated-water TDS range of 80–150 mg/L is consistent with the sub-500 mg/L product-water quality reported for comparable RO-based mine water treatment trains in the literature, and comfortably meets both discharge and most process-reuse quality requirements, supporting the assumption that treated water can be used interchangeably across process, dust-suppression, and irrigation-supply applications without further polishing

4.4 Economics result:

Table 4.2 compares the capital and operating cost of the five shortlisted technologies from Section 3.4, alongside their assumed steady-state recovery rate, to support the technology selection reported in Section 3.4.

Although RO alone offers a lower capital cost than the UF+RO hybrid, its markedly higher operating cost (INR 55/m³ versus INR 45/m³) reflects the additional pre-treatment burden placed on the RO membranes without a UF pre-treatment stage, which increases fouling-related cleaning and membrane replacement frequency. The UF+RO hybrid's combination of the highest recovery rate (70%) among realistically deployable options and a moderate operating cost per cubic metre supports its selection as the preferred technology, consistent with the qualitative screening in Section 3.4.

The cost-benefit analysis evaluates the UF+RO project over a 15-year horizon at a 10 percent discount rate. Annual incremental benefit is calculated as the volume of freshwater displaced multiplied by the avoided freshwater cost (INR 60/m³, covering procurement, extraction, and pumping) plus the volume of effluent no longer requiring discharge-grade treatment multiplied by the avoided compliance/treatment cost (INR 35/m³), less the incremental operating cost of the UF+RO plant relative to the baseline minimal-treatment case (assumed at INR 20/m³ incremental over baseline O&M).

At steady state (Year 5 onward), with 1.82 million m³/year recycled:

Annual gross benefit ≈ 1.82M m³ × (INR 60 + INR 35)/m³ = 1.82M × 95 ≈ INR 17.29 crore/year

Annual incremental operating cost ≈ 1.82M m³ × INR 20/m³ ≈ INR 3.64 crore/year Annual net benefit at steady state ≈ INR 17.29 crore − INR 3.64 crore ≈ INR 13.65 crore/year Applying this net-benefit calculation to each year of the five- year ramp-up profile (scaled by that year's recycled volume) and then holding it constant for the remaining ten years of the 15-year horizon, discounting all cash flows at 10 percent, and netting off the Year-0 capital outlay of INR 8.5 crore, yields the summary results in Table 4.6.

4.6 Environmental benefits:

Table 4.8 summarises the principal environmental and social benefits associated with the project that are not captured in the financial metrics above.

Estimated environmental and social benefits (non-monetised)

Benefit category	Estimated magnitude
Freshwater withdrawal avoided (steady state)	≈ 1.61 million m³/year (2.39 → 0.78 million m³/year)
Effluent discharge volume reduction (steady state)	≈ 81% reduction (1.98 → 0.37 million m³/year)
Pollutant load reduction (TSS, COD, BOD; steady state)	> 90% reduction relative to untreated discharge, per Table 4.3
Risk of accidental/non-compliant discharge	Substantially reduced through closed-loop operation and reduced discharge volume
Community/irrigation water made available	Portion of the 1.82 million m³/year treated water surplus to on-site demand
Alignment with policy commitments	Supports National Water Policy (2012) reuse principles and Ministry of Coal waterbody rejuvenation and mine-water-utilisation targets

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These benefits reinforce the financial case developed in Section 4.5: the same recycling infrastructure that generates a positive NPV for the mine operator simultaneously reduces the mine's freshwater footprint and discharge-related environmental risk, and contributes water availability to the surrounding catchment in a manner consistent with national and sectoral sustainability commitments.

5. CONCLUSION

This study set out to develop and demonstrate a structured cost-benefit analysis of mine water recycling and reuse for an illustrative opencast coal mine in a water-stressed Indian catchment. Drawing on published industry technical sources, peer-reviewed and technical-report literature, and Indian government policy documents, the study screened five candidate treatment technologies and identified a hybrid ultrafiltration and reverse osmosis (UF+RO) configuration as the technically and economically preferred option, offering a steady-state water recovery rate of approximately 70 percent at a moderate operating cost relative to RO alone or full zero-liquid-discharge treatment.

Using representative water balance, cost, and pricing data constructed to be consistent with the benchmark ranges established in the literature review, the cost-benefit analysis found the UF+RO investment to be financially attractive: a capital outlay of approximately INR 8.5 crore is recovered within approximately 4.2 years, and the project generates a positive net present value of approximately INR 27.6 crore, a benefit-cost ratio of approximately 1.8, and an internal rate of return of approximately 19 percent over a 15-year evaluation horizon at a 10 percent discount rate. Sensitivity analysis showed that this result is robust to ±20 percent variation in capital cost, avoided freshwater cost, and achieved recycling rate, with the project remaining NPV-positive under all tested scenarios, though value is most sensitive to the achieved recycling rate and the price of avoided freshwater.

Beyond the direct financial case, the study found that the same investment reduces annual freshwater withdrawal by approximately 1.61 million cubic metres and effluent discharge volume by approximately 81 percent at steady state, substantially lowering the mine's environmental footprint, its exposure to regulatory non-compliance risk, and its vulnerability to water-supply disruption, while contributing treated water toward community irrigation or supply needs in a manner consistent with India's National Water Policy and the Ministry of Coal's water-utilisation objectives. Taken together, the financial and non-financial results support the conclusion that mine water recycling and reuse, despite requiring substantial upfront capital and specialised operating capability, represents a financially sound and strategically valuable investment for mining operations in water-stressed regions, and that a transparent, technology-agnostic cost-benefit framework of the kind developed in this report provides a practical decision-support tool for evaluating such investments on a site-specific basis.

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