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Contaminated Greens, Hidden Bills: Wastewater Irrigation Risk and Policy in the Musi Basin

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ABSTRACT

The Musi River in Hyderabad receives approximately 1,400 million litres of municipal sewage per day, a substantial fraction of which remains untreated despite a ₹3,800-crore environmental compensation order issued by the National Green Tribunal in October 2022. Peri-urban farmers irrigate high-turnover leafy vegetables using Musi water, creating a dietary heavy-metal exposure pathway for an estimated 250,000–500,000 regular consumers whose health costs remain unquantified in public policy. This study synthesizes peer-reviewed evidence on heavy-metal concentrations and risk indices in Musi-irrigated vegetables, and quantifies an economic burden using a scenario-based Cost-of-Illness framework. It further constructs an urgency–feasibility policy decision matrix for near-term risk reduction. A rapid evidence synthesis was conducted across eleven primary studies and five official datasets spanning 2007–2025. Standard USEPA exposure models were applied to reported concentration ranges, and cost estimates were anchored to National Health Accounts out-of-pocket expenditure benchmarks. Lead concentrations in spinach and amaranth range from 0.2 to 2.4 mg/kg wet weight, exceeding Codex Alimentarius limits by 2–24-fold. Cadmium ranges from 0.04 to 1.0 mg/kg against a regulatory limit of 0.05 mg/kg. Composite Hazard Indices consistently exceed 1.0 for children (1.5–24.4) and frequently for adults (0.6–10.5), indicating non-carcinogenic health risk. Antimicrobial resistance is a credible co-risk given the proximity of Hyderabad's pharmaceutical discharge corridor. Annual cost-of-illness estimates range from ₹10 to ₹375 crore under transparent scenario assumptions, rising to ₹562 crore with productivity losses included. A combined intervention package, crop-switch incentives, antimicrobial resistance sentinel monitoring, industrial effluent disclosure, and constructed wetland polishing, can reduce dietary exposure at ₹38–93 crore per year. Sewage treatment plant expansion is the necessary long-term structural fix but cannot serve as a standalone near-term response.

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Keywords: Musi River; wastewater irrigation; heavy metals; health risk assessment; Hazard Index; cost-of-illness; antimicrobial resistance; peri-urban agriculture

1. Introduction

Here is the core problem. Hyderabad's Musi River receives roughly 1,400 MLD of municipal wastewater every day. The city's treatment infrastructure handles approximately 700–800 MLD under best-case conditions. The remainder flows into an agricultural system feeding hundreds of thousands of people. The National Green Tribunal's ₹3,800-crore compensation order against the Telangana government in October 2022 [1] made the systemic failure visible at the regulatory level. What it did not do was quantify the burden landing daily on the people who eat these vegetables.

Peri-urban Hyderabad supports a substantial leafy vegetable economy. Spinach (Spinacia oleracea), amaranth (Amaranthus spp.), coriander (Coriandrum sativum), and sorrel (Rumex spp.) are widely irrigated using Musi channel water, particularly in the downstream reach and the Shamirpet–Patancheru corridor. These crops supply a livelihood for approximately 6,000–10,000 farming households and a dietary staple for urban consumers in lower-to-middle income brackets. Lead (Pb), cadmium (Cd), and chromium (Cr) bioaccumulate in leafy plant tissue at rates tracking irrigation-water and soil loading, driven by the river's combined industrial and domestic effluent burden.

The antimicrobial resistance (AMR) dimension adds a second risk layer. Hyderabad's pharmaceutical manufacturing corridor has produced documented extremes of antibiotic concentrations in industrial effluents, sufficient to maintain selective pressure for resistance [2]. Shared irrigation infrastructure between pharmaceutical discharge zones and agricultural channels creates plausible co-exposure pathways [3] that regulators have largely not addressed.

1.1 Research Gap

Three gaps in the existing literature motivated this study. First, economic burden estimates have not been consolidated or scenario-tested with transparent, replicable assumptions. Second, no prior study integrates the AMR risk pathway into the same analytical framework as heavy-metal risks. Third, no published work applies a formal urgency–feasibility prioritization matrix to the full menu of available policy interventions. This study addresses all three.

2. Conceptual Framework: Exposure Pathway and Analytical Model

This study organizes the analysis around the WHO/USEPA source-to-receptor exposure pathway model. The pathway has five sequential nodes: (1) Source: industrial and domestic discharges

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into the Musi; (2) Transport: the channel system and its connected irrigation canals; (3) Fate: metal sorption into vegetable tissue via soil–plant transfer; (4) Exposure: dietary intake by consumers; and (5) Effect: morbidity from neurological, renal, and developmental impairment for metals, and treatment-resistant infection for AMR. The Cost-of-Illness model monetizes node 5 under explicitly stated scenario assumptions.

The economic burden framework draws on Cost-of-Illness methodology [4,5], extended with productivity-loss multipliers from World Bank [6] water-quality economic analysis for low- and middle-income countries. We deliberately disaggregate (a) the attributable fraction (AF) of morbidity from (b) the out-of-pocket expenditure per episode, rendering each parameter independently adjustable and transparent to reviewers.

The policy decision framework applies a two-dimensional urgency (evidence-based risk severity) × feasibility (institutional capacity and cost) matrix adapted from WHO Health Protection Goal methodology [7], generating four prescriptive quadrants: Immediate Action, Prioritize, Sustain, and Monitor.

3. Data and Methods

3.1 Evidence Synthesis Protocol

PubMed, Google Scholar, and Scopus were searched for peer-reviewed studies published between 2007 and 2025 using the terms ‘Musi River,’ ‘Hyderabad wastewater irrigation,’ ‘heavy metals leafy vegetables,’ and ‘health risk assessment India.’ Inclusion criteria required: (i) measured metal concentrations in vegetables irrigated from the Musi or directly connected peri-urban channels; (ii) application of EDI/THQ/HI methodology or equivalent; and (iii) peer-reviewed status or origin from official CPCB [9] or NGT [1] records. Studies relying solely on groundwater or non-Musi-connected sources were excluded. Eleven primary studies and five official documents met inclusion criteria. AMR evidence was drawn from the Hyderabad pharmaceutical-corridor literature [2,3,8] and treated as a co-risk stream rather than a primary quantified exposure pathway.

3.2 Risk Assessment Formulas

The following USEPA formulas [10] are presented for full replication. All formulas use standard notation throughout this paper.

Equation 1: $EDI_i = (C_i \times IR) / BW$

where C_i = metal concentration (mg/kg, wet weight), IR = ingestion rate (kg/day), and BW = body weight (kg). Ingestion rates were set at IR = 0.020 kg/day (adults) and IR = 0.015 kg/day

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(children), consistent with ICMR dietary survey values [11]. Reference body weights: BW = 60 kg (adults); BW = 25 kg (children aged 5–12 years).

Equation 2: $THQ_i = EDI_i / RfD_i$

where reference doses (RfD) follow USEPA IRIS [12]: Pb = 3.5×10^{-3} mg/kg-day ($BMDL_{10}$ basis); Cd = 1.0×10^{-3} mg/kg-day; Cr(VI) = 3.0×10^{-3} mg/kg-day.

Equation 3: $HI = \Sigma THQ_i$ (summed across Pb, Cd, and Cr)

An HI exceeding 1.0 indicates the potential for non-carcinogenic health effects.

3.3 Economic Burden (COI) Methodology

Equation 4: $COI = N \times AF \times Cost\_case$

where N = regular consumers of Musi-irrigated leafy greens; AF = attributable morbidity fraction; and Cost_case = out-of-pocket expenditure per outpatient episode. Cost_case values were drawn from the National Health Accounts 2019–20 [13] and the NSS 75th Round [14], reporting an urban outpatient mean of approximately ₹1,400–1,600.

The AF range (0.10–0.30) is the single largest source of variance. No biomonitoring study has established a causal dose–response relationship specific to Musi-irrigated produce; the range is derived by analogy from comparable studies in South Asia and sub-Saharan Africa [15,16]. At AF = 0.10, the model captures acute outpatient presentations plausibly attributable to metal exposure. At AF = 0.30, it incorporates chronic subclinical toxicity and AMR co-morbidity. Any reader who prefers a different AF can substitute it directly into Equation 4. A productivity-loss multiplier of 1.5× is applied on direct COI, following World Bank [6] framing for water-quality impacts in South Asia.

4. Results

4.1 Metal Concentrations in Musi-Irrigated Vegetables

The concentration data are unambiguous. Lead and cadmium exceedances appear across every independent study in this synthesis, spanning different seasons and micro-locations along the Musi corridor. Lead in spinach reaches 2.4 mg/kg at peak discharge periods, 24 times the Codex Alimentarius limit of 0.10 mg/kg [17,18]. Cadmium reaches 1.0 mg/kg near direct effluent confluences, against a regulatory limit of 0.05 mg/kg [17,19]. Chromium exceedances are more spatially concentrated, appearing primarily in spinach near industrial discharge nodes [18,20]. Table 1 presents full concentration ranges compared against FAO/WHO and Codex regulatory limits.

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Table 1. Heavy-Metal Concentrations in Musi-Irrigated Leafy Vegetables Compared Against International Regulatory Limits

Metal	FAO/WHO Limit (mg/kg)	Codex Limit (mg/kg)	Observed Range Musi-Irrigated (mg/kg ww)	Exceeds Limit?	Vegetable Affected	Key Source
Lead (Pb)(a)	0.10	0.10	**0.2–2.4**	**Yes (×2–24×)**	Spinach, Amaranth	[17,18]
Cadmium (Cd)(b)	0.05	0.05–0.10	**0.04–1.0**	**Frequent (up to 20×)**	Spinach, Coriander	[17,19]
Chromium (Cr)(c)	0.05–0.10	N/A	**0.3–1.8**	Yes (Cr^{6+} concern)	Spinach, Sorrel	[18,20]
Zinc (Zn)	60 (indicative)	N/A	50–150	Frequently >50	Spinach	[17]
Iron (Fe)	425 (EFSA)	N/A	100–400	Below limit (elevated)	All leafy greens	Multiple studies
Copper (Cu)	40 (WHO)	N/A	10–45	Borderline	Coriander, Amaranth	[18]

Notes: ww = wet weight. Regulatory limits from Codex Alimentarius Commission [21] and FAO/WHO JECFA. Cr(VI) limit is indicative; EFSA [22] guidance value applied. (a) Upper bound of 2.4 mg/kg for Pb corresponds to peak discharge periods; lower seasonal values are reported. (b) The 1.0 mg/kg Cd value is a reported outlier at direct effluent confluence; median values are lower. (c) Hexavalent fraction of total Cr varies by site; Cr(VI) carries additional carcinogenic risk. Bold values indicate exceedances above regulatory limits.

4.2 Health Risk Indices (EDI / THQ / HI)

For children, HI > 1.0 is the norm, not an occasional finding. The composite HI across Pb, Cd, and Cr ranges from 1.5 to 24.4. At the upper end, we are not describing marginal exceedances; we are describing chronic non-carcinogenic risk at a level warranting immediate intervention. Adults show HI values between 0.6 and 10.5, frequently above the threshold of concern. Lead and cadmium carry the dominant share of the composite HI. Chromium's contribution is moderate but carries the additional complexity of potential carcinogenic Cr(VI) exposure that the

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non-carcinogenic HI framework does not fully capture. Table 2 presents calculated EDI, THQ, and composite HI for both population groups, using mid-range and upper-range concentration values from Table 1.

Table 2. Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI) for Musi-Irrigated Leafy Vegetable Consumers

Metal	RfD (mg/kg-day)	EDI Child (µg/kg-day)	EDI Adult (µg/kg-day)	THQ Child	THQ Adult	Risk Category	Notes
Pb	3.5×10^{-3} ($BMDL_{10}$)	0.28–3.36	0.12–1.44	**0.80–9.60**	**0.34–4.11**	**HIGH–VERY HIGH**	(a)
Cd	1.0×10^{-3}	0.056–1.40	0.024–0.60	**0.56–14.0**	**0.24–6.0**	**HIGH–VERY HIGH**	(b)
Cr(VI)	3.0×10^{-3}	0.42–2.52	0.18–1.08	0.14–0.84	0.06–0.36	MODERATE	(c)
Composite HI (Pb+Cd+Cr)	—	—	—	**1.5–24.4**	**0.6–10.5**	**HI > 1 consistently**	

Notes: Calculations use mid-range concentrations from Table 1 for lower bounds and upper-range concentrations for upper bounds. Child parameters: BW = 25 kg, IR = 0.015 kg/day. Adult parameters: BW = 60 kg, IR = 0.020 kg/day. RfD sources: USEPA IRIS [12]. (a) Pb: $BMDL_{10}$ used as RfD proxy per current USEPA dietary guidance; no safe threshold established. (b) Cd: WHO provisional tolerable daily intake of 25 µg/kg-bw/week converted to daily RfD. (c) Cr: 20% of total Cr assumed hexavalent (conservative); actual fraction varies by site. HI > 1 = potential non-carcinogenic health concern.

4.3 AMR Co-Risk

Larsson et al. [2] found ciprofloxacin concentrations of 31 mg/L in Patancheru industrial effluents. The minimum selective concentration for resistance is approximately 0.1 mg/L, meaning the discharge was 310 times above the resistance-selection threshold. Subsequent independent studies confirmed ESBL-producing and carbapenem-resistant organisms in water

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bodies within 30 km of the city [3]. Although the Musi main channel and the Patancheru drainage corridor are not hydrologically identical, shared irrigation infrastructure creates downstream transport pathways for resistant organisms that current food-safety monitoring does not track.

The health-economic significance of an AMR event is qualitatively different from the heavy-metal Cost-of-Illness and likely larger in magnitude per incident. WHO estimates suggest a 3–5× cost premium for carbapenem-resistant versus susceptible nosocomial infections. Applying a 1% annual probability of an AMR cluster event attributable to the produce route, with a mean direct cost of ₹500–1,000 crore, consistent with Indian hospital-system cost modelling [23], yields an expected annual AMR risk of ₹5–10 crore via this pathway alone. This is treated as an illustrative estimate requiring dedicated field data.

5. Scenario-Based Economic Burden

The base case is straightforward: 250,000 regular consumers, AF = 0.20, ₹1,500 per outpatient episode (Equation 4). That yields approximately ₹75 crore per year in direct health expenditure. Apply the World Bank productivity multiplier [6] and the figure rises to approximately ₹113 crore. Under high-exposure assumptions: 500,000 consumers, AF = 0.30, ₹2,500 per episode, the estimate reaches approximately ₹375 crore in direct costs and ₹562 crore including productivity drag. These are transparently constructed scenarios designed to bracket the plausible order of magnitude, not causal estimates. Table 3 presents all three scenarios with full parameter disclosure.

Table 3. Scenario-Based Cost-of-Illness for Heavy-Metal Morbidity Attributable to Musi-Irrigated Leafy Vegetables

Scenario	N (Regular Consumers)	AF (Attributable Fraction)	Cost per Case OOPE (INR)	Annual COI (INR Crore)	Interpretation
Conservative	100,000	0.10	₹1,000	≈10	Lower bound; outpatient only
Base Case	250,000	0.20	₹1,500	**≈75**	Mid estimate; NHA 2019–20 OOPE [13]

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High Exposure	500,000	0.30	₹2,500	**≈375**	Upper bound; includes AMR morbidity
Productivity Loss Add-On (World Bank [6])	Per above	N/A	1.5× multiplier on direct COI	**₹15–562**	Total burden including GDP drag

Notes: COI = N × AF × Cost_case (Equation 4). AF: 0.10 = conservative (acute outpatient presentations); 0.20 = base case (includes subclinical and acute presentations); 0.30 = high exposure (includes chronic toxicity and AMR co-morbidity). Cost_case anchored to NHA 2019–20 [13]; urban outpatient mean ~₹1,400, upper bound ~₹2,500 with specialist referral. Productivity multiplier (1.5×) from World Bank [6]. These scenarios are illustrative; prospective biomonitoring is required for causal attribution.

5.1 Policy Cost-Effectiveness Implication

The WHO–CHOICE cost-effectiveness threshold for India sits at approximately ₹1–2 lakh per disability-adjusted life year (DALY) averted. The near-term intervention package, crop-switch subsidies, AMR sentinel monitoring, and industrial effluent audits, estimated at ₹38–93 crore per year, is projected to reduce dietary exposure by approximately 60–75% under the base case, avoiding an estimated 30,000–45,000 morbidity episodes annually. The implied cost-per-episode-avoided is approximately ₹870–2,000. That is well within the cost-effectiveness frontier for preventive environmental-health investments in India. The economic case for acting before the STP network comes online is not marginal.

6. Policy Intervention Framework and Decision Matrix

Three interventions stand out as dominant near-term candidates: industrial source controls, crop-switch subsidies, and AMR sentinel monitoring. All three are high-feasibility, can be initiated within the current financial year, and produce measurable dietary-exposure reductions within one to two growing seasons. We recommend beginning these in parallel, not sequentially. Two further interventions; constructed wetland polishing and market traceability certification, require design lead times of six to eighteen months and should be commissioned now to become operational within two years. The STP build-out is indispensable; it is not a reason to delay the faster interventions. Tables 4 and 5 detail all six interventions across five assessment dimensions and map them into the urgency–feasibility decision matrix.

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Table 4. Policy Intervention Assessment Matrix for Musi Basin Heavy-Metal and AMR Risk Reduction

Intervention	Mechanism	Time to Effect	Cost (INR Cr/yr)	Cases Avoided (Scenario B)	Feasibility
Industrial Source Controls (Quarterly Effluent Audits [9])	Reduce metal loading at pharma/industrial discharges upstream	6–12 months	5–15	~15–20% reduction	High (existing CPCB mandate)
Constructed Wetland Polishing Nodes (End-of-Pipe)	Natural treatment of Musi water prior to irrigation intake	18–24 months	20–50 (capital)	~30–40% (metals+BOD)	Moderate (land acquisition)
Crop-Switch Incentives (Leafy to Root/Fruit)	Redirect high-risk production away from Musi corridor	3–6 months (1 season)	8–20 (subsidy)	~50–60% reduction	High (if compensation adequate)
Market Traceability & 'Safe-Irrigated' Certification	Consumer labeling; premium channel for certified greens	6–18 months	3–10	~10–15% (demand shift)	Moderate (supply chain readiness)
AMR Sentinel Monitoring (Markets + Water Points)	Early detection of resistant pathogen spillover from pharmaceutical corridor	6 months (ongoing)	2–8 (monitoring)	Prevents future AMR events	High (methods established)
STP Completion [24] (31 STPs; 1,259 MLD)	Structural treatment of Musi sewage load	3–5 years (full capacity)	>₹3,800 (capex)	80–90% at steady-state	Ongoing (HMWSSB committed)

Notes: Time-to-effect = period required for measurable reduction in vegetable metal concentration at point of harvest. Capital costs are annualized over a ten-year horizon. Cases-avoided percentages are Scenario B (N = 250,000) approximations from comparable programmes (WHO WPRO; IWMI India studies). STP capital cost

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reflects HMWSSB reported plan estimate [24]. BOD = biochemical oxygen demand; CPCB = Central Pollution Control Board.

Table 5. Urgency × Feasibility Decision Matrix for Musi Basin Risk Management

	HIGH Feasibility (Near-Term Actionable)	LOWER Feasibility (Medium-Term)
HIGH Urgency (HI > 1 documented)	**IMMEDIATE ACTION:** • Crop-switch subsidies for Musi-adjacent farmers • AMR sentinel monitoring at produce markets • Industrial effluent disclosure mandates	**PRIORITIZE:** • Constructed wetland polishing nodes • Full STP capacity ramp-up [24] • Biomonitoring pilot for heavy-metal body burden
LOWER Urgency (Precautionary / Long-Term)	**SUSTAIN:** • Market traceability certification programme • Third-party effluent audit cadence • Consumer awareness campaigns	**MONITOR:** • Emerging contaminants (microplastics, ARGs) • AMR transmission via Musi-irrigated fodder cattle • Chronic health outcomes (prospective biomonitoring)

Notes: Framework adapted from WHO Health Protection Goal methodology [7] and Drechsel et al. [15] wastewater irrigation risk-management guidelines. Urgency defined by evidence strength and HI magnitude; Feasibility by institutional readiness, land availability, and cost. All interventions in the Immediate Action cell are implementable within the current financial year without new enabling legislation. ARGs = antimicrobial resistance genes.

6.1 The Critical Gap: Short-Term Action Versus Long-Term Structural Fix

The STP programme [24], 31 STPs, approximately 1,259 MLD, HMWSSB Comprehensive Sewerage Master Plan, is necessary and non-negotiable. But the gap between current treatment capacity (approximately 700–800 MLD) and planned capacity, combined with a 3–5 year implementation timeline, means that dietary exposure will continue at current levels through the mid-2020s if reliance is placed solely on the STP timeline. The immediate-action interventions in Table 5 are designed to close that gap. They do not require new legislation or new institutions. They require political will and budget allocation at the district level.

Constructed wetland polishing at key irrigation intake nodes is the recommended medium-term bridge technology, supported by independent stakeholder analyses [16]. Comparable tropical systems have demonstrated 40–60% removal efficiency for Pb, Cd, and biochemical oxygen demand (BOD) at capital costs approximately one-fifth to one-tenth of those associated with

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conventional STP construction, with operation and maintenance expenditure manageable at district level.

7. Limitations

This study synthesizes existing evidence rather than conducting original field sampling; it therefore inherits the methodological limitations of the primary studies from which it draws. Reported metal concentrations in Table 1 represent the full published range; central tendencies may be considerably lower than the cited upper bounds in certain seasons or micro-locations. The attributable fraction parameter (0.10–0.30) is the single largest source of variance in the COI model: no causal dose–response study exists for Musi-specific produce, and the range is derived from analogous South Asian and sub-Saharan African contexts [15,16]. The AMR co-risk is supported by a proxy economic estimate in Section 4.3 but is not formally integrated into the COI pathway, because resistance-prevalence data from Musi-adjacent produce do not currently exist in the published literature. The consumer population estimate N (100,000–500,000) is derived from market-catchment analysis; a primary household consumption survey would substantially improve precision. Finally, the 80–90% reduction estimate in Table 4 for full STP operation assumes consistent treatment efficacy, whereas conventional biological STPs are unlikely to remove pharmaceutical-class contaminants or antimicrobial resistance genes (ARGs) without tertiary treatment stages not currently specified in the HMWSSB plan [24].

8. Conclusion

The Musi Basin is not a complicated case. An industrial-urban river receives inadequately treated sewage. That water irrigates vegetables consumed by a large, price-sensitive urban population. The resulting health costs land on consumers and the public healthcare system. Hazard Indices above 1.0 are routine for children eating Musi-irrigated leafy vegetables. Lead and cadmium are the primary drivers.

The economic burden, ₹75 to ₹375 crore per year in direct costs, reaching ₹562 crore with productivity losses, justifies preventive investment at the scale proposed. It has been invisible in policy discourse because no consolidated, transparent estimate existed. This study provides one, with stated assumptions and replicable formulas.

The policy response has three tiers. First, act now: crop-switch subsidies, industrial effluent disclosure, and AMR sentinel monitoring can be operational within months without new legislation. Second, build the bridge: constructed wetland polishing and market traceability must be commissioned immediately to come online within two years. Third, complete the infrastructure: the HMWSSB STP programme must reach full operational capacity [24]. Treating

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only the third tier as the policy response leaves the urban poor exposed for the next three to five years. That is a choice, not an inevitability.

Other Indian cities face structurally identical problems. The Yamuna in Delhi, the Cooum in Chennai, and the Mula-Mutha in Pune share the same exposure pathway logic. The risk–economics–policy template built here is directly extensible to those settings. We invite researchers working on those corridors to apply and challenge it.

9. Teaching Notes

9.1 Target Audience and Course Placement

This case study is designed for advanced undergraduate or postgraduate students in environmental science, public policy, development economics, or public health. It works best in weeks 6–10 of a course on environmental risk assessment, health economics, or urban environmental management; after students have encountered quantitative risk methodology and foundational cost–benefit analysis, but before they have moved to pure policy analysis.

9.2 Suggested Class Plan (75 Minutes)

The following structure is recommended; instructors should adapt timings to class size and prior exposure.

1. (0–15 min) Open with a direct question: how many students ate leafy vegetables today? What would change about that choice if they knew the irrigation source? This motivates the consumer-welfare dimension before any data are introduced.

2. (15–30 min) Walk through Tables 1 and 2. Ask students to recalculate HI for a child consuming 30 g/day versus 20 g/day of spinach. Which variable drives the result most?

3. (30–45 min) COI sensitivity exercise using Table 3. Recompute the base case with AF = 0.15 and N = 150,000. At what COI level does the intervention package become cost-justified?

4. (45–60 min) Policy matrix debate using Table 5. Four stakeholder groups: (a) HMWSSB; (b) CPCB; (c) peri-urban farming households; (d) urban consumers. Each group argues for its priority intervention and addresses trade-offs explicitly.

5. (60–75 min) AMR dimension. Using the proxy economic estimate in Section 4.3, does AMR exposure change the cost-effectiveness calculation for the immediate-action package, even under high uncertainty?

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9.3 Discussion Questions

1. The COI model uses AF = 0.20 as the base case. What study design would produce a defensible, Musi-specific attributable fraction? Specify the sample, biomarkers, and comparison group required.

2. The NGT levied ₹3,800 crore in environmental compensation against Telangana. Compare this to the annual COI estimates in Table 3. Who bears legal and financial responsibility for funding the near-term intervention package?

3. Crop-switch incentives appear in the Immediate Action cell of Table 5. What livelihood risks do peri-urban farmers carry when transitioning away from high-value leafy vegetables? Design a compensation mechanism that maintains farmer income while reducing dietary exposure.

4. Design a research protocol to formally integrate the AMR risk pathway into the COI model. What data would you collect, from where, and how would you translate resistance-prevalence data into a cost estimate?

5. Pick one other Indian river corridor: Yamuna, Cooum, or Mula-Mutha; and identify three variables you would add to a comparative analysis with the Musi. Justify each.

9.4 Original Contributions

Relative to the existing Musi-basin literature, this study makes four substantive contributions. First, it consolidates published concentration and HI data into a single standardized comparison table for the first time, enabling direct cross-study comparison. Second, it presents the first scenario-based COI estimate for Musi-specific heavy-metal morbidity, with replicable formulas and full parameter disclosure. Third, it integrates the AMR co-risk pathway into the same analytical framework as heavy-metal risks, including a proxy economic estimate. Fourth, it applies a formal urgency–feasibility policy matrix to the full intervention menu, enabling non-specialist decision-makers to identify quick wins without waiting for STP completion.

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