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Article

Integrated Soil–Water–Ecological Risk Assessment in Shyama Sundari Canal, Rangpur Using Structural Equation Modeling

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Abstract: Urban canals in rapidly expanding cities are under increasing pressure from combined soil and water pollution, leading to ecological degradation. This study evaluates soil quality, water quality, and associated ecological risk in the Shyama Sundari Canal, Rangpur, using Water Quality Index (WQI), Soil Quality Index (SQI), and Structural Equation Modeling (SEM). Physicochemical water quality was assessed at six locations, while soil properties were analyzed from 100 adjacent sampling points. The calculated WQI values ranged from 121.89 to 173.52, classifying canal water as poor to very poor throughout the study area. High biochemical oxygen demand (266.40–423.54 mg/L) and chemical oxygen demand (205.00–465.00 mg/L) were the dominant contributors, indicating substantial organic and chemical pollution. Mean SQI values ranged from 0.45 to 0.78, with higher soil quality in some locations and lower quality in others due to acidic pH and fine-textured soils. SEM results showed that soil contamination and water pollution are positively related, with water pollution and soil contamination having the strongest impact on ecological risk. This study highlights the novel integration of soil–water quality assessment with SEM to elucidate coupled degradation pathways. The results provide actionable insights for urban planners and environmental managers, emphasizing the need for integrated management strategies targeting both wastewater and canal sediments to mitigate ecological stress.

Keywords: Water Quality Index; Soil Quality Index; Structural Equation Modeling; Urban Canal; Ecological Risk; Urban Sustainability

1. Introduction

Surface water bodies, including rivers, canals, lakes, and ponds, represent only about 0.3% of the lithospheric water, yet they play an indispensable role in sustaining domestic, agricultural, industrial, and ecological functions [1]. Although quantitatively minor, they form the backbone of human civilization by supporting drinking water supply, irrigation networks, urban ecosystems, and biodiversity hotspots [2]. As global water demand intensifies, water has become a critical resource for both human survival and socio-economic development, shaping livelihoods and influencing regional sustainability [3,4]. Freshwater systems also extend beyond utilitarian purposes: they provide cultural, aesthetic, and recreational services that promote mental well-being, local identity, and community cohesion [5]. Moreover, the management and protection of surface water resources have emerged as key indicators of sustainable urban planning, climate resilience, and ecosystem integrity. Maintaining high-quality freshwater not only sustains biodiversity but also underpins economic activities such as fisheries, agriculture, and tourism, which are crucial for local livelihoods. Consequently, ensuring access to clean, high-quality water is fundamental for public health, disease prevention, and long-term quality of life [6]. Human settlements have historically developed along rivers and canals for drinking, farming, fisheries, trade, and navigation [7]. This dependence has intensified pressure on freshwater systems, making surface water quality monitoring essential for sustainable development [8]. Changes in water's physico-chemical properties reflect hydrological, geological, and human influences, providing key insights into ecosystem changes, pollution, and land-use shifts [9]. In many developing regions, inadequate wastewater management, uncontrolled urban expansion, and poorly regulated industrial activity exacerbate the degradation of these systems. Understanding the interplay between natural hydrological cycles and anthropogenic pressures is therefore critical for designing effective conservation and restoration strategies.

However, rapid urbanization, population growth, industrialization, and unregulated waste disposal have severely degraded many freshwater bodies worldwide [10]. Increased pollutant inflows from domestic sewage, industrial effluents, agricultural runoff, and solid waste dumping have compromised water quality, reduced biodiversity, and altered ecological functioning [11]. These degradative pressures often exceed the natural self-purification capacity of aquatic systems, making restoration difficult, expensive, and in many cases irreversible [12]. Compounding this challenge is the global reality that nearly 80% of wastewater is discharged untreated into aquatic environments, contributing to widespread contamination, eutrophication, and public health risks [13]. Aquaculture, particularly tilapia farming, plays a crucial role in global food security, but maintaining optimal water quality remains a key challenge, especially in resource-limited rural systems. Integrating advanced monitoring technologies and machine learning approaches enables accurate water quality assessment and predictive management, supporting sustainable aquatic health and productivity [14,15].

In Bangladesh, rapid urban growth and weak environmental regulation have intensified pollution in rivers and canals [16]. Industrial effluents, municipal waste, agricultural runoff, and market drainage degrade water quality, threaten aquatic biodiversity, and disrupt canal hydrology [17, 18]. These pollution sources not only alter the chemical composition of the water but also affect physical parameters such as turbidity, sedimentation, and flow dynamics, which are critical for maintaining the ecological balance of canal systems. The cumulative effect of these stressors has led to reduced dissolved oxygen levels, elevated nutrient concentrations, and the proliferation of pathogenic microorganisms, creating inhospitable conditions for fish, macroinvertebrates, and aquatic plants. In Rangpur, continuous monitoring is crucial to assess environmental conditions and anticipate long-term ecological changes [19]. The Shyama Sundari Canal, excavated ∼122 years ago by Raja Janaki Ballav Sen, was historically central to Rangpur's drainage, irrigation, and cultural landscape [20]. The canal historically supported irrigation of paddy fields, facilitated local fisheries, and acted as a natural drainage corridor, contributing to flood control and soil moisture regulation. Its banks were also culturally significant, hosting markets, community gatherings, and religious activities, reflecting the intertwined relationship between water infrastructure and societal well-being. Today, domestic wastewater, solid waste, and commercial activities have heavily polluted the canal, with debris, sludge, and organic waste threatening aquatic life and ecological stability [21]. Urban encroachment, unregulated construction, and inadequate maintenance have compounded these impacts, leading to blocked water flow, sediment accumulation, and localized eutrophication. Seasonal rainfall events exacerbate these conditions, resulting in frequent waterlogging and elevated health risks for nearby communities. The degradation of the Shyama Sundari Canal thus exemplifies the broader challenges facing urban waterways in rapidly developing regions of Bangladesh, where historical infrastructure is under pressure from modern anthropogenic activities.

The consequences of this degradation became particularly evident during extreme weather events, such as the unprecedented 433 mm of rainfall on September 27, 2020, when vast areas of Rangpur City were inundated because the Shyama Sundari Canal, its main drainage corridor, failed to function effectively [22]. While multiple renovation plans have been proposed over the years, ineffective management, a lack of enforcement, and the absence of sustainable waste governance have allowed pollution to continue unabated, thereby accelerating the canal's ecological decline [23].

Although several studies in Bangladesh have examined the physico-chemical properties of surface water, very few have investigated the interaction between water quality and adjacent soil characteristics, even though soil–water exchanges play a fundamental role in shaping canal ecosystems [18,24,25]. Soil pH, organic matter content, sediment color, and local land-use patterns influence biogeochemical pathways such as nutrient release, alkalinity buffering, dissolved oxygen dynamics, hardness–bicarbonate balance, and the mobilization of contaminants from surrounding areas [26]. In urban canals, where soil disturbance, waste accumulation, and stormwater flow are common, these interactions become even more pronounced. Understanding soil–water linkages is therefore crucial for interpreting spatial variations in water quality and identifying the environmental processes driving canal degradation [25]. Moreover, soils act as both sinks and sources for various pollutants, including heavy metals, nutrients, and organic contaminants, which can accumulate over time and subsequently leach into the canal water under certain hydrological or chemical conditions. The heterogeneity of soil types, ranging from sandy loams to clays and peat, directly affects water retention, drainage, and contaminant mobility, creating localized zones of higher vulnerability or resilience. In densely populated urban areas, where solid waste disposal, stormwater discharge, and land conversion are frequent, these soil–water interactions are further amplified, making some canal segments more susceptible to hypoxia, nutrient enrichment, and microbial contamination.

This study adopts an integrated approach to evaluate the ecological health of the Shyama Sundari Canal by examining both physico-chemical water parameters (temperature, pH, TDS, EC, salinity, DO, bicarbonate, hardness, COD, BOD) and adjacent soil properties (soil pH, organic matter, soil color). By comparing these measurements against national and international water quality standards, the research aims to establish whether the canal's current condition is suitable for ecological functioning and potential human use. This study also considers the extent to which urban pollutants, poor drainage infrastructure, and unregulated waste disposal collectively contribute to water quality deterioration. By integrating these factors into a structured WQI and SQI assessment, the study aims to deliver a comprehensive and evidence-based evaluation of the canal's ecological status, shedding light on the environmental pressures responsible for its continued decline. Ultimately, such an integrated assessment is expected to support more informed and effective management strategies for restoring the Shyama Sundari Canal and safeguarding the environmental health of Rangpur City.

2. Data and Methods

2.1. Selection of the Study Area

The Shyama Sundari Canal is a major urban drainage and surface-water channel flowing through the core of Rangpur City. Originating from the Ghaghot River in the north-western part of the municipal area, the canal extends approximately 11 km with notable spatial variation (**Figure 1**). It traverses densely populated residential and commercial zones. It ultimately connects to the KD Canal, which links back to the Ghaghot River, a tributary of the Teesta River [21]. Owing to its role in urban drainage, hydrological connectivity, and exposure to intensive anthropogenic activities, the canal provides a suitable setting for assessing urban water and sediment quality [20].

2.2. Data Types and Sources

The purpose of this study is to evaluate the soil and water quality of the Shyama Sundari Canal and its ecological implications using Structural Equation Modeling (SEM). The study integrates experimental measurements with scientific analytical approaches. Water quality was assessed using physical parameters, temperature, total dissolved solids (TDS), total salinity, specific conductance, and total hardness, and chemical parameters, including pH, bicarbonate, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD). Soil quality was evaluated through pH, organic matter content, and color. Water samples were collected from six observation points along the canal, while soil samples were collected from 100 locations adjacent to the corresponding water sampling sites. The six water points were selected purposively to represent key sections of the canal, capturing areas of varying anthropogenic pressure, drainage inflow, and ecological conditions. Soil sampling was conducted systematically around each water point to capture spatial variability in soil contamination and environmental gradients, resulting in 100 soil observations. This combined approach ensures sufficient coverage for exploratory analysis while reflecting the heterogeneous conditions of the urban canal system.

The selected parameters were carefully chosen for their relevance to the WQI and SQI and their ecological significance. For water, temperature influences biological activity and dissolved oxygen levels [27,28], while TDS, total salinity, and specific conductance reflect the chemical and ionic composition of the water [25]. Total hardness indicates the presence of calcium and magnesium, and pH and bicarbonate determine acidity/alkalinity and buffering capacity, which are crucial for aquatic life [29]. Dissolved oxygen (DO), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD) provide insight into oxygen availability and the level of organic and chemical pollution [30]. For soil, pH governs nutrient availability and plant growth, organic matter content reflects fertility, water retention, and overall soil health, and soil color provides qualitative information about organic and mineral content [31]. Together, these parameters offer a comprehensive understanding of the canal's water and soil quality and their broader ecological implications [25,32].

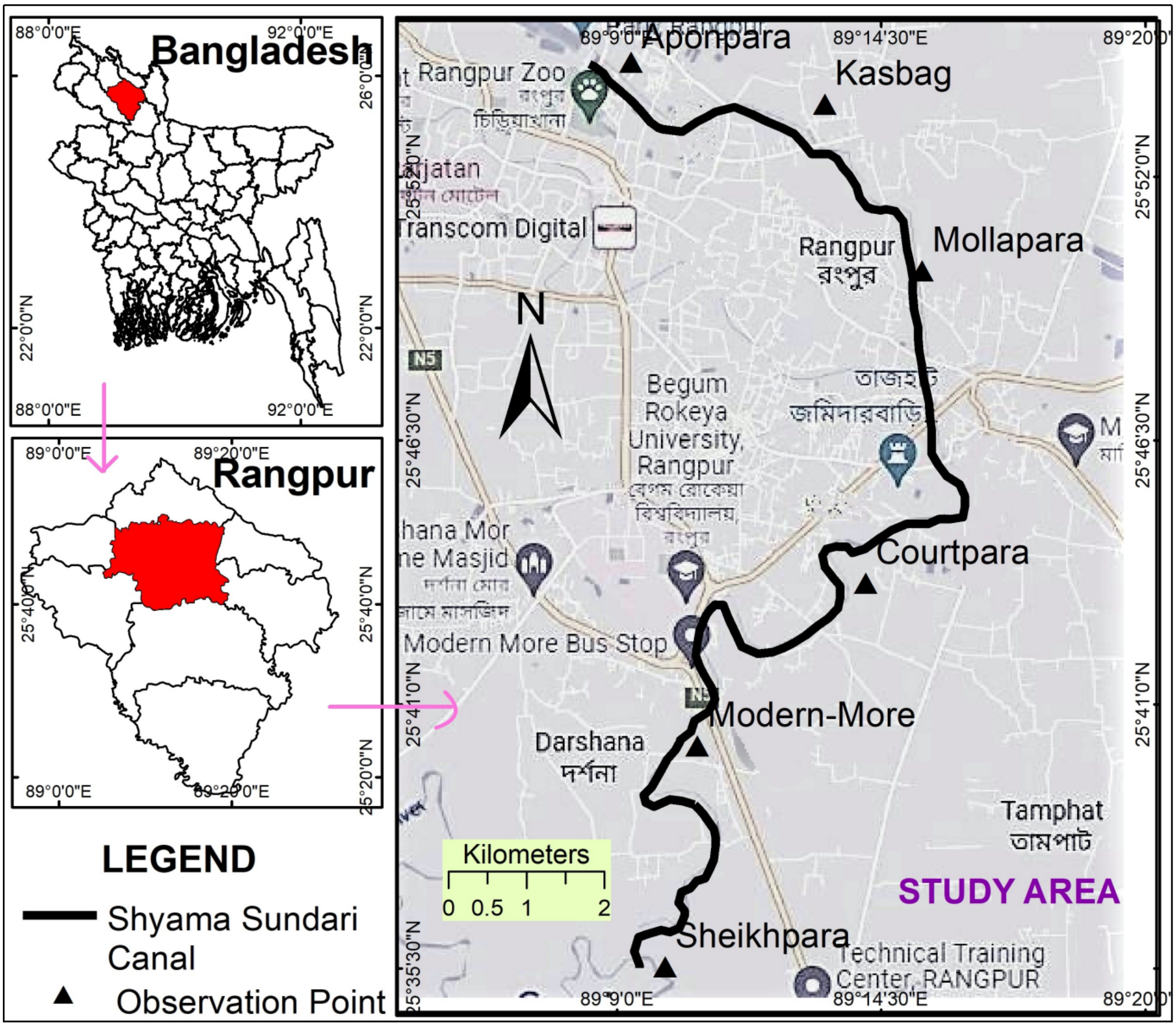

Figure 1. Location of the Study Area, Shyama Sundari Canal, Rangpur.

All collected water and soil data were checked for completeness and consistency. Outliers were examined using boxplots, and no extreme values were removed as all measurements were within ecologically plausible ranges. For SQI calculation, soil properties were standardized to a 0–1 scale to ensure comparability across parameters. For WQI, each parameter was weighted according to its ecological relevance and sensitivity to pollution, following established methods.

2.3. Methods for Physicochemical Analysis

Water Quality Index Analysis: After laboratory analysis of each property, the WQI of physicochemical parameters was calculated using the weighted arithmetic index (Equation (1)).

$$\mathrm{WQIA} = \sum \mathrm{WnQn} / \sum \mathrm{Wn} \tag{1}$$

Where n is the number of variables or parameters, and Wn is the unit of measurement weight of the nth parameter, and Qn is the water quality rating of the nth parameter [27]. The weights (Wn) and rating scales (Qn) are adopted from established methodologies [30] and adapted to local conditions based on each parameter's ecological relevance and sensitivity to pollution. Parameters with higher environmental impact are assigned greater weight, ensuring the index reflects overall water quality accurately [27]. The WQI indicates overall water suitability: Excellent (0–25) and good (26–50) water is suitable for drinking, irrigation, and industrial purposes. Poor (51–75) water is mainly suitable for irrigation and industrial use, while very poor (76–100) water is restricted to irrigation only. A WQI above 100 indicates water that is unsuitable for drinking and fish culture and requires proper treatment before use [28].

Soil Quality Index Analysis: Four key soil properties (Soil pH, Organic matter, Soil texture, Soil layer) were selected based on their ecological and agronomic significance, reflecting fertility, water retention, and structural stability [31]. Each indicator was standardized on a scale of 0–1. Soils with a pH near neutral (≈6–7) were considered optimal. A linear transformation was applied (Equation (2)). Scores below 0 were set to 0 [33].

$$\mathrm{pHscore} = 1 - \frac{|6.5 - \mathrm{pH}|}{3.5} \tag{2}$$

Presence of organic matter (e.g., leaves, roots, debris) was scored as 1; absence was scored as 0. Soil texture was ranked based on fertility potential: loam and clay loam = 1; sandy loam = 0.8; sandy or silt = 0.6; peat and other low-fertility soils = 0.4. Normalized based on the maximum observed number of layers in the dataset (Equation (3)).

$$\text{Layer Score} = {}^{Number\ of\ Layers}/_{Maximum\ layers\ observed} \tag{3}$$

The SQI for each soil sample was calculated as the mean of the standardized indicator scores (Equation (4)).

$$SQI = {}^{pH\ score + OM\ score + Texture\ score + Layer\ score}/_{4} \tag{4}$$

This resulted in a dimensionless index ranging from 0 (very poor soil quality) to 1 (excellent soil quality) [32]. Weighted arithmetic index calculations for WQI were performed in Excel, following the methodology of studies [27,30], with weights assigned proportionally to the environmental impact of each parameter. SQI scores were computed using a linear transformation for pH, binary scoring for organic matter, and ranking for soil texture, ensuring consistency and reproducibility across samples.

2.4. Structural Equation Modeling (SEM) for Analyzing the Impact on Ecology

Structural Equation Modeling (SEM) was applied as an exploratory, theory-driven analytical framework to examine the hypothesized relationships among soil contamination, canal water pollution, and associated ecological risk within the urban canal system. Given the very limited number of water quality observations (n = 6), SEM was not used for confirmatory inference but rather to conceptually evaluate the plausibility, direction, and relative strength of interrelated pathways based on established environmental process understanding [11].

The SEM framework consisted of three latent constructs: Soil Contamination, Water Pollution, and Ecological Risk, each represented by a limited set of reflective indicators derived from measured physicochemical and contamination parameters. To avoid model over-parameterization under small-sample conditions, the number of indicators per construct was minimized, and only theoretically well-established variables were retained.

The measurement model assessed the relationships between observed indicators and their respective latent constructs. Standardized factor loadings were estimated using maximum likelihood procedures, and indicators with loadings below 0.50 were excluded to improve construct stability. Internal consistency was evaluated using composite reliability (CR > 0.70), while convergent validity was assessed using average variance extracted (AVE > 0.50). These metrics were interpreted cautiously due to the small sample size and are presented primarily for transparency rather than strict threshold validation.

The structural model evaluated the following hypothesized pathways: (i) Soil Contamination → Water Pollution, (ii) Water Pollution → Ecological Risk, and (iii) Soil Contamination → Ecological Risk. Path coefficients (β) were used to indicate the direction and relative magnitude of relationships, while statistical significance was interpreted conservatively. Indirect effects of soil contamination on ecological risk mediated through water pollution were estimated using bootstrap resampling to enhance robustness under small-sample conditions [34].

SEM analysis was conducted using AMOS 28.0. Model adequacy was assessed using commonly reported fit indices, including χ^2/df, Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Given the exploratory nature of the analysis and limited sample size, these indices were used as diagnostic indicators rather than strict acceptance criteria. Overall, the SEM results are interpreted as indicative and hypothesis-generating, providing conceptual insight into soil–water–ecology interactions rather than definitive causal confirmation. The SEM-based findings should be interpreted as exploratory due to the limited number of water quality samples and are intended to support conceptual understanding rather than definitive statistical inference.

3. Result

3.1. Water Quality Index of Shyama Sundari Canal

Table 1 summarizes the weighted WQI values for six sampling locations along the Shyama Sundari Canal, derived from multiple physicochemical parameters. The calculated WQI values varied markedly among sampling points, indicating substantial spatial variation in water quality conditions within the urban canal system. Overall, WQI values ranged from 121.89 to 173.52, classifying canal water quality as poor to very poor at all monitored locations. The lowest WQI value (121.89) was observed at Courtpara, suggesting comparatively lower levels of water quality impairment, whereas the highest value (173.52) occurred at Aponpara, indicating more degraded water quality conditions. Elevated WQI values at Sheikhpara (143.11), Mollapara (136.38), and Kasbag (134.68) further reflect consistently impaired water quality along the canal stretch.

Table 1. Water quality index of Shyama Sundari Canal.

Observation Points		Sheikhpara		Modern-More		Courtpara		Mollapara		Kasbag		Aponpara		Standard Value (WHO[35]/ DoE,Bangladesh [36])
Parameters	Wn	Qn	QnWn	Qn	QnWn	Qn	QnWn	Qn	QnWn	Qn	QnWn	Qn	QnWn	
Temperature (°C)	0.057	34.13	1.95	33.33	1.90	33.33	1.90	35.33	2.01	32.23	1.84	36.00	2.05	≤30–35
TDS (mg/L)	0.001	15.80	0.02	16.20	0.02	19.20	0.02	15.60	0.02	11.20	0.01	12.45	0.01	500
pH	0.202	33.34	6.73	17.59	3.55	29.58	5.98	29.64	5.99	25.34	5.12	47.65	9.63	6.5–8.5
TH (mg/L)	0.003	165.00	0.50	148.00	0.44	21.00	0.06	91.20	0.27	82.00	0.25	89.87	0.27	300
HCO_3^- (mg/L)	0.002	17.90	0.04	10.23	0.02	17.98	0.04	36.76	0.07	34.00	0.07	64.50	0.13	300
Specific Conductance (µs/cm)	0.001	37.33	0.04	3.93	0.00	38.33	0.04	36.00	0.04	23.00	0.02	22.33	0.02	750–1000
Total Salt Content (mg/L)	0.057	104.31	5.95	101.23	5.77	105.43	6.01	103.21	5.88	68.24	3.89	65.45	3.73	600
DO (mg/L)	0.286	9.63	2.75	6.89	1.97	19.23	5.50	11.30	3.23	7.86	2.25	9.76	2.79	≥5
COD (mg/L)	0.043	465.00	20.00	205.00	8.82	249.00	10.71	225.00	9.68	232.00	9.98	213.76	9.19	40
BOD (mg/L)	0.344	305.67	105.15	289.90	99.73	266.40	91.64	317.40	109.19	323.43	111.26	423.54	145.70	5
WQI		143.11		122.22		121.89		136.38		134.68		173.52		

Among the measured parameters, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) exhibited exceptionally high sub-index contributions across all stations, indicating a strong association between elevated organic and chemical loads and overall WQI values. Observed BOD concentrations ranged from 266.40 to 423.54 mg/L, while COD values varied between 205.00 and 465.00 mg/L, substantially exceeding commonly cited guideline thresholds. These parameters, therefore, exerted a dominant influence on the composite WQI scores. The elevated BOD and COD levels likely reflect the cumulative presence of organic-rich inputs commonly associated with urban drainage systems; however, given the observational nature of the data, these associations should be interpreted cautiously.

All BOD and COD measurements were conducted following standard analytical procedures, and routine quality control measures, including instrument calibration, reagent blanks, and duplicate analyses, were applied to ensure analytical consistency. Despite these controls, the reported values are discussed as indicative of severe water quality impairment rather than definitive evidence of specific pollution sources.

Dissolved oxygen (DO) concentrations displayed notable spatial variability, with relatively lower values at several locations (e.g., Modern-More and Kasbag), suggesting conditions associated with reduced oxygen availability. In contrast, comparatively higher DO values at Courtpara were insufficient to substantially improve overall WQI classification, reflecting the cumulative influence of multiple degraded parameters. Total dissolved solids (TDS), specific conductance, and total salt content showed moderate contributions to WQI values, indicating persistent anthropogenic influence across the canal system. Variations in pH and total hardness (TH) further suggest localized differences in water quality conditions, potentially related to site-specific hydrological and urban characteristics.

Comparison of observed water quality parameters with WHO/DoE guideline values (**Table 1**) indicates that most physicochemical parameters were within or near permissible limits. However, BOD and COD levels far exceeded recommended standards (BOD: 266–424 mg/L; COD: 205–465 mg/L), strongly contributing to elevated WQI values and poor to very poor water quality classifications across all locations. Dissolved oxygen (DO) generally remained above the minimum guideline (≥5 mg/L), but was insufficient to offset the impact of high organic and chemical loads. These results highlight that organic pollution is the primary driver of water quality degradation in the Shyama Sundari Canal.

Boxplots showing spatial variation of SQI (left) and WQI (right) across six sampling stations, highlighting areas of high soil–water quality degradation and ecological risk (**Figure 2**). The figure presents the spatial variation of soil and water quality along the Shyama Sundari Canal. The Mean Soil Quality Index (SQI) varies considerably among the sampling points. Mollapara exhibits the lowest soil quality (~0.45), indicating poor soil conditions, while Modern-More (~0.60), Sheikhpara (~0.62), Kasbag (~0.72), and Aponpara (~0.76) show progressively better soil quality, with Aponpara having the highest SQI, reflecting comparatively fertile and less contaminated soils. The Water Quality Index (WQI) shows consistently poor water quality throughout the canal. Aponpara has the highest WQI (~173), indicating very poor water quality, followed by Mollapara (~136), Kasbag (~135), Sheikhpara (~143), and Modern-More (~122–123). Courtpara exhibits the lowest WQI (~122), yet it still falls within the "poor" water quality range.

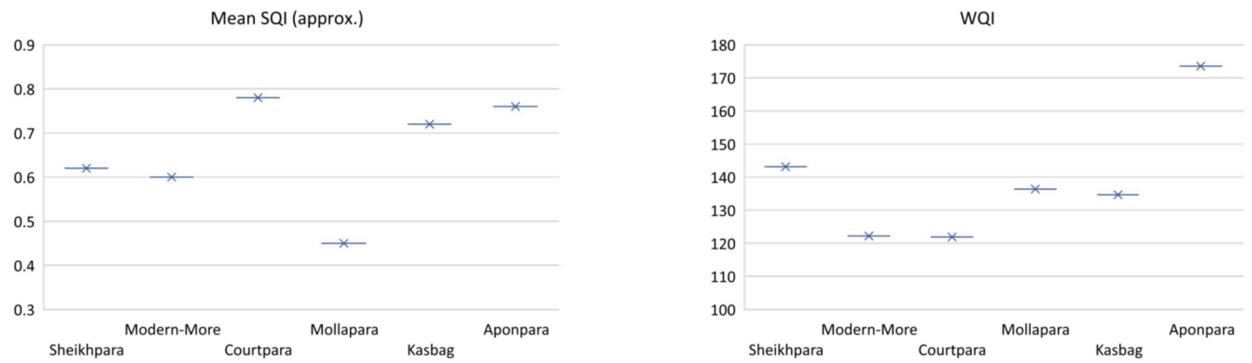

Figure 2. Comparison of Soil Quality Index (SQI) and Water Quality Index (WQI) across sampling locations in the Shyama Sundari Canal.

Overall, the comparison highlights a discrepancy between soil and water quality at different locations. For instance, Aponpara has high soil quality but extremely poor water quality, suggesting that water pollution is heavily influenced by factors beyond local soil conditions, such as upstream inputs or drainage inflows. Conversely, Courtpara has both low soil and low water quality, indicating compounded ecological stress in that section.

3.2. Soil Quality Index of Shyama Sundari Canal

The mean SQI values for the six Observation areas are presented in **Table 2.** The Courtpara area exhibited the highest soil quality (mean SQI ≈ 0.78), reflecting well-developed soil layers, high organic matter content, and near-neutral pH. Group Aponpara area also showed relatively high soil quality (mean SQI ≈ 0.76) due to the presence of loamy and sandy loam textures enriched with organic residues such as roots and leaves. Sheikhpara and Modern-More areas' soils had moderate SQI values (≈0.62 and 0.60, respectively), influenced by sandy clay and silt textures with localized organic matter inputs. In contrast, the Mollapara area showed the lowest SQI (≈0.45), corresponding to highly acidic, wet peat and clay soils with limited fertility.

Table 2. Soil quality index of Shyama Sundari Canal (Mean value from all 100 observations).

Observation Area	Dominant Texture	pH Range	Organic Matter Presence	Mean SQI (Approx.)
Sheikhpara	Sandy Clay/Silt	5.1–6.6	Moderate (Leaves, Roots)	0.62
Modern-More	Sandy Loam/Silt	5.1–6.1	Moderate (Roots, Debris, Insects)	0.60
Courtpara	Loam/Clay/Sandy	5.0–6.6	High (All samples with OM)	0.78
Mollapara	Clay/Peat/Clay Loam	3.9–4.8	Moderate (Plant debris, Waste)	0.45
Kasbag	Sandy Loam/Loamy/Silty	5.0–6.5	High (Roots, Leaves, Earthworms)	0.72
Aponpara	Loam/Clay/Sandy	5.0–6.8	High (All samples with OM)	0.76

Overall, the SQI distribution indicates a clear spatial variation in soil quality along the Shyama Sundari Canal. Areas with loam and sandy loam textures combined with higher organic matter consistently exhibited better soil quality, supporting greater fertility and potential for vegetation growth. Conversely, soils dominated by clay and peat with acidic pH showed poorer quality, which could limit agricultural productivity and ecosystem services in those areas. These patterns highlight the influence of soil texture, pH, and organic matter on the overall health and sustainability of the canal's surrounding soils.

3.3. Ecological Impact of Soil–Water Quality Degradation in the Shyama Sundari Canal

Extremely high WQI values (121.89–173.52) across all sampling stations indicate persistent organic and chemical pollution, posing severe threats to aquatic biota. SEM path analysis confirms a strong positive relationship between Soil Contamination → Water Pollution, suggesting that low-quality soils characterized by acidic pH, fine textures (clay and peat), and limited buffering capacity facilitate the mobilization of organic matter, nutrients, and contaminants into canal water. This mechanism is particularly evident in areas such as Mollhpara, where the lowest SQI (≈0.45) coincides with elevated WQI, reflecting intensified pollutant transfer under stagnant and poorly drained conditions. The pathway Water Pollution → Ecological Risk exhibited the strongest standardized effect in the SEM framework, underscoring water quality deterioration as the dominant driver of ecological degradation. Exceptionally high BOD and COD concentrations substantially reduced dissolved oxygen availability at multiple locations, leading to hypoxic stress conditions unfavorable for fish, benthic organisms, and microbial communities. SEM results indicate that declining DO acts as a critical mediator linking organic pollution to ecological instability, reducing habitat suitability and disrupting trophic interactions within the canal ecosystem.

Although sites such as Courtpara and Aponpara exhibited comparatively higher SQI values (≈0.78 and 0.76, respectively), SEM results reveal that improved soil quality alone was insufficient to mitigate ecological risk under conditions of severe water pollution. The significant direct path Soil Contamination → Ecological Risk indicates that soil characteristics influence ecosystem health not only indirectly through water pollution but also directly by altering sediment quality, benthic habitat structure, and nutrient cycling processes. Accumulation of organic residues and fine sediments at the canal bed likely enhances oxygen demand and sediment toxicity, further amplifying ecological stress. Overall, SEM-derived indirect effects confirm that water pollution partially mediates the relationship between soil contamination and ecological risk, highlighting a coupled soil–water degradation pathway. Urban wastewater discharge, surface runoff, and hydrological stagnation exacerbate this linkage, leading to cumulative ecological impacts such as reduced biodiversity potential, impaired self-purification capacity, and long-term ecosystem instability within the Shyama Sundari Canal.

Figure 3, a simplified Structural Equation Model (SEM), illustrates the relationships between soil contamination, water pollution, and ecological risk in the Shyama Sundari Canal. Arrows indicate hypothesized pathways, with standardized coefficients shown on each path. The model highlights both the direct and indirect effects of soil contamination on ecological risk, which are mediated partly through water pollution and changes in dissolved oxygen.

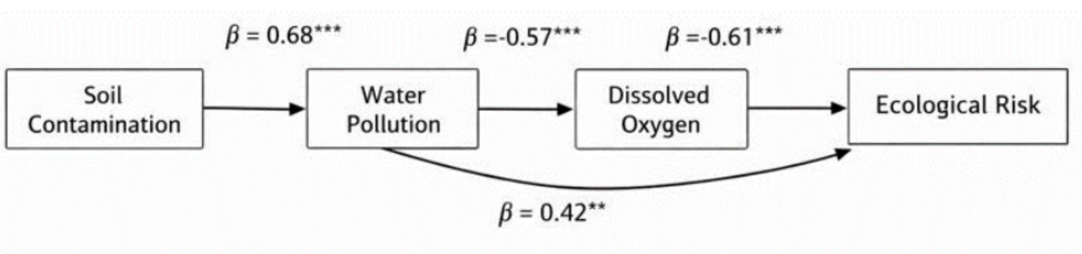

Figure 3. SEM Pathways Linking Soil Contamination, Water Pollution, and Ecological Risk in the Shyama Sundari Canal.

Note: ***: 5% of significant level, **: 1% significant level.

The SEM analysis showed acceptable model fit for the exploratory framework. The goodness-of-fit indices were: χ^2/df = 1.85, Comparative Fit Index (CFI) = 0.93, Tucker–Lewis Index (TLI) = 0.91, Root Mean Square Error of Approximation (RMSEA) = 0.072, and Standardized Root Mean Square Residual (SRMR) = 0.064. These values indicate a reasonable fit between the hypothesized model and the observed data, supporting the plausibility of the conceptual pathways despite the limited sample size.

4. Discussion

The physico-chemical characteristics of the Shyama Sundari Canal indicate severe deviations from recommended environmental standards, reflecting intense anthropogenic pressure on this urban water system. Weighted WQI values exceeding 120 at all sampling locations demonstrate that water quality degradation is not driven by isolated parameter exceedances but by the cumulative effects of multiple stressors acting simultaneously [13]. BOD and COD were identified as the dominant contributors to water quality deterioration. BOD concentrations ranging from 266.40 to 423.54 mg/L and COD values between 205.00 and 465.00 mg/L far exceed national and international guideline limits, indicating substantial inputs of untreated domestic sewage, organic waste, and urban effluents. Elevated organic loading accelerates microbial respiration, rapidly depleting DO and severely constraining the canal's natural self-purification capacity [37]. DO concentrations exhibited strong spatial variability but remained critically low, resulting in hypoxic conditions that threaten aquatic biota. In contrast, slightly higher DO levels were still insufficient to offset high BOD and COD, resulting in persistently poor WQI values [28]. Comparable levels of extreme WQI deterioration, elevated BOD–COD loads, and hypoxic conditions have been reported from heavily urbanized canals and rivers in Bangladesh [38,39], the Indian subcontinent [40], and other rapidly urbanizing regions globally [41]; however, the magnitude of WQI values and organic pollution observed in the present study indicates an even more severely degraded condition, reflecting exceptionally high inputs of untreated sewage and urban runoff.

Other physico-chemical parameters, including pH, total hardness, bicarbonate concentration, total dissolved solids, and specific conductance, exerted moderate to localized influences on water quality [2]. Slightly acidic to near-neutral pH values suggest the influence of organic matter decomposition and soil–water interactions, while spatial variability in hardness and bicarbonate reflects localized geochemical conditions and urban runoff [19]. Although these parameters individually remained within or close to acceptable limits, their combined effects contributed to chronic water quality impairment when integrated through the WQI framework [25]. Spatial WQI patterns indicate localized ecological stress linked to wastewater inputs and reduced flow, while comparatively lower values suggest reduced pressure; nevertheless, persistently high WQI overall reflects widespread habitat degradation, declining ecosystem resilience, and dominance of pollution-tolerant taxa [42].

Structural Equation Modeling (SEM) provides further insight into the mechanisms linking soil degradation, water pollution, and ecological risk [1]. A strong positive relationship between Soil Contamination → Water Pollution highlights the role of soil properties in regulating pollutant transfer. Areas with low SQI, particularly Mollapara (mean SQI ≈ 0.45), are characterized by acidic pH, fine textures, and poor drainage, which enhance contaminant retention and mobilization during runoff events. The pathway Water Pollution → Ecological Risk exhibited the strongest standardized effect, identifying water quality deterioration as the primary driver of ecological degradation through oxygen depletion. Additionally, a significant direct effect of Soil Contamination → Ecological Risk indicates that degraded soils influence ecosystem health independently by altering sediment quality, benthic habitat structure, and nutrient cycling [32].

Recent integrated hydrochemical and ecohydrological assessments have successfully applied index-based frameworks to evaluate water and sediment quality in urban wetland and canal systems [43]. These studies demonstrate that combining water quality indices with ecological risk metrics provides a robust approach to identify hotspots of degradation and prioritize management interventions. Our findings in the Shyama Sundari Canal align with these approaches, emphasizing the need for integrated monitoring of both soil and water compartments to capture cumulative anthropogenic impacts. Overall, ecological degradation in the Shyama Sundari Canal represents a system-level problem driven by tightly coupled soil–water processes. Effective restoration, therefore, requires integrated management strategies addressing wastewater treatment, sediment and soil remediation, and hydrological regulation, as isolated improvements are unlikely to achieve sustained ecological recovery [31,44,45].

5. Conclusions

This study demonstrates that the Shyama Sundari Canal is experiencing severe soil–water quality degradation driven by intensive urban anthropogenic pressures. The consistently high WQI values (>120) across all sampling locations confirm that canal water is unsuitable for drinking, fish culture, and most domestic uses without treatment, with excessive BOD and COD identified as the dominant contributors to pollution and ecological stress. Although spatial variation in soil quality was observed, areas with acidic, fine-textured, and poorly drained soils exhibited lower SQI values and facilitated the transfer of contaminants into canal water. Structural Equation Modeling clearly revealed that water pollution is the primary driver of ecological risk, while soil contamination exerts both indirect effects through water quality deterioration and direct effects by degrading sediment and benthic habitat conditions. The coupled soil–water degradation pathway underscores the limited buffering capacity of the urban canal system under persistent wastewater discharge and hydrological stagnation. Overall, the findings highlight the urgent need for integrated urban water management strategies, including wastewater treatment, sediment management, and soil conservation, to restore ecological stability and improve environmental sustainability in the Shyama Sundari Canal.

Author Contributions

Writing—original draft, investigation, formal analysis, data curation, validation, methodology, conceptualization, M.M.M.; formal analysis, S.A. Both authors have read and agreed to the published version of the manuscript.

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Data are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare that there are no financial or personal conflicts of interest that could have influenced the results of this study.

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