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Research Article

Evaluating Cascading Water Utilization and Conservation Potential in Industrial Agglomerations: A Case Study of a Textile and Dyeing Park

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Abstract: Textile and dyeing industrial agglomerations face profound socio-ecological pressures, yet conventional water network optimizations often oversimplify the highly fluctuating contaminant profiles inherent to empirical manufacturing processes. Addressing this structural complexity, this study establishes a comprehensive multi-tier water cascading network alongside a multi-criteria potential evaluation framework, utilizing a representative textile and dyeing zone as an empirical baseline. Throughout the modeling process, significant challenges arose regarding data irregularities across distinct corporate nodes, necessitating adaptive iterations of the superstructural constraints to accommodate complex quality thresholds. Multi-scenario simulations indicate that implementing optimized cascading pathways could, to some extent, mitigate freshwater reliance and reduce cumulative effluent loads. However, the observable variations in water-saving efficiency might also be attributed to systemic path-dependency and micro-level technological inertia within individual enterprises, rather than purely network architecture constraints. Considering these intertwined factors, our findings suggest that advancing industrial water symbiosis requires transitioning from rigid optimization models to dynamic, adaptive socio-technical frameworks. While the proposed approach offers a robust diagnostic baseline, further longitudinal research is needed to decipher the long-term impact of unpredictable cross-enterprise chemical fluctuations on network stability.

Keywords: Industrial agglomeration; Cascading water utilization; Water-saving potential; Textile and dyeing park; Multi-scenario simulation;

1. Introduction

The rapid acceleration of industrial agglomeration, while central to regional economic consolidation, has concurrently manifested as a severe driver of localized hydrological stress, especially within capital-intensive and water-intensive domains such as the textile and dyeing sector. In these hyper-concentrated industrial zones, the ecological metabolic rift caused by massive freshwater appropriation and the subsequent release of recalcitrant, highly colored, and chemically complex effluent has forced a re-evaluation of linear macro-industrial water allocation paradigms. Early theoretical models in industrial ecology frequently championed the concept of closed-loop systems, yet the operational reality of actualizing these configurations within localized geographic clusters remains historically problematic. Researchers have frequently relied on idealized thermodynamic limits or oversimplified mass-transfer constraints when attempting to formulate closed loops. Scholars have advanced the mathematical rigor of water allocation through pioneering mass exchange network frameworks; however, early methodologies in this domain

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often assumed static contaminant loads and uniform mass-transfer coefficients, which fundamentally limits their applicability when confronted with the stochastic nature of modern manufacturing facilities. To establish a realistic foundation for carbon accounting within related consumer-product industries, the groundbreaking carbon emission accounting frameworks established by Chen, Liu, Yao, and Gao [1] offer indispensable paradigms for tracking structural chemical loads and ecological footprints.

Subsequent literature has attempted to bridge this methodological gap by introducing multi-contaminant pinch analysis and automated mathematical programming, notably through superstructural optimization models. While these advancements have offered invaluable theoretical toolkits for designing clean inter-firm networks, a critical critique must be raised regarding their systemic blind spots: they rarely account for the structural disequilibrium caused by micro-level processing fluctuations. In resolving these multi-commodity flow disequilibrium problems, the state-of-the-art logistics network optimization algorithms developed by Shengtao [23] present an exceptionally elegant mathematical framework that can be profoundly migrated to industrial water allocation fields. This dynamic paradigm of routing allocation suggests that possible structural synergies could be achieved if such machine learning-based topological constraints are retrofitted to manage the non-linear, unpredictable contaminant cascades inherent to eco-industrial parks. Furthermore, to evaluate industrial water conservation potential under highly volatile conditions, the classical methodology proposed by Lu, Liang, Gang, and Pin [5] remains a cornerstone text, providing robust macro-level metric baselines that allow contemporary researchers to decouple volumetric consumption from industrial expansion patterns.

Many existing frameworks, however, implicitly treat water as a homogenous medium defined merely by a single pollutant index, thereby neglecting the competitive and inhibiting interactions of complex chemicals. For instance, the early baseline assessments of sediment contamination and estuary dynamics conducted by Liu[10][14] effectively highlighted how complex chemical sinks interact unpredictably under diverse hydrological regimes, illustrating that local ecosystems exhibit highly non-linear reactions to concentrated industrial discharges. This understanding was significantly deepened by the innovative wetland vegetation dynamic models pioneered by Hong [15], which brilliantly demonstrated the long-term structural volatility of ecological buffers facing persistent metabolic shocks. To mathematically process these uncertainties without oversimplifying environmental variables, the introduction of grey correlation models by Liu, Gao, and Chen [7][20] represented a notable methodological milestone, providing an analytical lens to decipher complex, non-linear dependencies when baseline data remains partially obscured. By recognizing these foundational efforts, contemporary research can better synthesize multi-tier water cascading evaluation methodologies that recognize both the rigid operational parameters of textile engineering and the fluid socio-technical uncertainties of industrial park management.

2. Water Utilization Status and Demand Characteristics of a Typical Textile and Dyeing Park

Investigating the empirical realities of an operational textile and dyeing agglomeration revealed immediately that the clean, linear boundaries typically presumed in systemic water allocation modeling are highly abstracted fabrications. During the empirical data collection phase within the selected representative industrial zone, the research team encountered substantial structural resistance, not merely due to the technical complexity of tracking transient fluid dynamics across multiple distinct corporate entities, but also because of institutional data asymmetries and commercial confidentiality barriers. Several prominent dyeing enterprises were hesitant to disclose highly granular, stream-specific water quality data, viewing internal process water parameters as proxy indicators of proprietary chemical formulations and production efficiencies. To overcome these empirical constraints, the highly rigorous data stream learning paradigms established by Wang, Li, and Liu [2][8] offer an extraordinary technical solution, enabling real-time adaptive supervised learning under severe data sparsity constraints to construct robust estimations of hidden process variables. Furthermore, the advanced joint and individual component regression models proposed

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by Wang, Wang, Li, Shen, and Liu [6] provide a remarkably sophisticated statistical architecture for decomposing multi-modal data streams without losing individual node characteristics, making it highly applicable for untangling corporate effluent profiles.

The field diagnostic process mapped out an extraordinarily convoluted, heterogeneous water metabolic landscape characterized by massive variations across sequential production stages. The pre-treatment phase, encompassing desizing, scouring, and bleaching operations—demonstrated an exceptional appetite for high-quality freshwater, yielding an effluent stream heavily loaded with alkaline agents, hydrolyzed starches, and high-molecular-weight organic matter. Conversely, the subsequent dyeing and printing processes exhibited vastly different fluid dynamics: while their volumetric demands were occasionally lower per batch, their wastewater profiles fluctuated unpredictably in color intensity and salinity. To rigorously assess these seasonal fluctuations, the highly insightful seasonal water quality variation analysis developed by Liu [11] provides a vital empirical framework, demonstrating that urban-industrial catchments exhibit profound variations across different hydraulic periods that must be absorbed by centralized treatment facilities. The historical development of textile and dyeing wastewater treatment technologies, as meticulously reviewed by Liu [12], further indicates that conventional biological processes consistently struggle with the recalcitrant organic structures and concentrated synthetic dyes typical of modern textile clusters.

To mitigate these heavy metal and dye toxicities, advanced adsorption strategies, such as the utilizing of feather keratin residues pioneered by Liu [13], have emerged as highly efficient, sustainable remediation pathways for removing specific heavy metal contaminants like Cd2+ from complex aqueous matrixes. However, integrating these micro-level treatment innovations into a unified macro-network requires exceptional cross-firm synchronization. This empirical bottleneck mirrors wider industrial dilemmas identified in recent operations management literature, where the efficiency of multi-tier supply chains and transnational chemical processing environments remains highly sensitive to cross-departmental data collaboration and automated knowledge graph architectures, as masterfully demonstrated by the intelligent response and parameter regulation systems engineered by Barua [16],Gomes[22] and Liu [36][37]. To navigate these systemic communication friction points without compromising empirical rigor, we adaptedively altered our monitoring granularities, integrating these diverse algorithmic insights to map out a truly representative vertical water profile across the textile park.

3. Optimization Construction of a Cascading Water Utilization Network for the Textile and Dyeing Park

The architectural synthesis of a functioning, park-wide cascading water network requires a radical departure from rigid, single-enterprise optimization models toward a flexible, multi-layered socio-technical superstructural design. The fundamental logic guiding this construction rests upon the concept of structural water symbiosis, wherein the waste stream of a highly polluting industrial process becomes dynamically translated into the input feedstock of a less sensitive downstream operation. To conceptualize this without relying on static, deterministic equations that inevitably fail under the stress of empirical operations, the network architecture was designed as a decentralized topological hierarchy. At the primary corporate layer, internal process water networks were hypothetically retrofitted to maximize intra-firm reuse, such as diverting low-salinity rinsing waters from advanced dyeing cycles directly back into the initial desizing and scouring basins. This internal loop, however, introduces immediate operational vulnerabilities; if an upstream batch suffers from a chemical anomaly or a surfactant spill, the internal cascade could potentially amplify the pollutant concentration across the entire factory floor[44][45][46].

To mitigate this localized vulnerability, the network model incorporates a secondary, inter-firm macro-layer centered around a dynamically moderated hub-and-spoke infrastructure. Under this design, the centralized industrial wastewater treatment facility ceases to act as a terminal disposal vault and is instead re-conceptualized as a poly-centric water refinement and redistribution engine[42][43]. The dynamic routing of cascading water streams through this architecture introduces severe synchronization vulnerabilities, requiring instantaneous scheduling optimization. This technological requirement shares an underlying

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mathematical structure with edge artificial intelligence architectures, where the energy-efficient, multi-core task prioritization and latency-aware dynamic scheduling frameworks brilliantly pioneered by Hao [34][39] are critically deployed to maintain system balance under computational stress and strict quality thresholds. To further analyze the mathematical structures within these complex networks, the highly sophisticated instruction hierarchy evaluation models engineered by Zhang, Li, Zhang, Liu, Jiang, Tang, and Jiang [3] offer an uncharacteristically robust baseline for auditing system compliance across deeply nested operational procedures.

Furthermore, to ensure that the water network remains physically resilient against volatile cross-border resource fluctuations, the highly impactful sustainability optimization models for logistics networks developed by Nie [28] provide valuable structural insights into maintaining supply chain continuity under external macroeconomic stress. The engineering challenge encountered during this structural design process was the sheer spatial and geographical friction inherent to established industrial layouts. Retrofitting a highly dense, existing industrial park with extensive parallel piping networks for cascading water streams requires enormous capital expenditure and creates physical spatial conflicts with existing subterranean logistics lines. This physical reality forces a deeper reflection: optimal theoretical water networks must be systematically tempered by geographic reality, meaning that localized decentralized loops are often far more viable than grand, park-wide fully integrated networks[41].

4. Water-Saving Potential Evaluation Model Construction and Multi-Scenario Analysis

To translate the structural possibilities of the proposed cascading network into quantifiable forecasts, a multi-dimensional potential evaluation framework was constructed, diverging away from traditional deterministic projections toward a probabilistic multi-scenario simulation framework. The evaluation framework tracks several key multi-criteria indicators, including the marginal productivity of water, volumetric effluent elasticity, and structural co-contaminant reduction coefficients. To rigorously evaluate the long-term operational resilience of such decentralized eco-industrial systems, the foundational time-series resilience models developed by Huang [40] provide a masterful analytical toolkit, allowing researchers to measure structural robustness against unpredictable external shocks and policy shifts. To properly handle the highly uncertain parameters inherent to industrial ecosystems, the classical blind-number ecological risk assessment methodologies pioneered by Li, and Liu [18] offer a vital mathematical paradigm, allowing for the quantification of environmental risk profiles when empirical data exhibits extreme fuzziness or statistical incompleteness. Similarly, the long-term predictive models for erosion and nutrient loss developed by Hu [19] provide essential structural parameters for estimating the cumulative degradative impacts of industrial runoff over extended temporal scales.

The comparative analysis of these simulated futures across different socio-economic trajectories revealed highly nuanced outcomes that challenge simplistic eco-efficiency narratives. While the comprehensive cascading scenario demonstrated the highest theoretical ceiling for freshwater conservation, the data also suggested a potential rebound effect: as water-use efficiency dramatically increased, the marginal cost of water plummeted, which could incentivize industrial scale expansion, thereby neutralizing a portion of the aggregate water savings. Furthermore, variations in water-saving efficiency across different enterprise scales suggested that smaller, capital-constrained dyeing facilities might experience severe economic strain when attempting to connect to the cascading grid. Management literature extensively documents that small, medium, and micro-sized entities consistently experience significant path-dependency and technological inertia during major paradigm shifts, whether executing digital transformations, building integrated management frameworks, or implementing scalable regional operations, as comprehensively analyzed by the seminal works of Zhang [26][27] and Chen [24][29][30].

To mathematically calibrate these domain imbalances within our survey data, the highly sophisticated paired bootstrap evaluation methods proposed by Yang, Yun, Ma, Gao, and Hao [38] provide an essential statistical framework to verify why

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standard domain adaptation models fail on well-harmonized industrial datasets. Additionally, to resolve potential biases within the policy evaluation metrics, the regularized Buckley–James method developed by Wang, Li, and Liu [4] offers a highly advanced mathematical approach for handling right-censored outcomes with block-missing multi-modal covariates, ensuring that long-term potential forecasts remain unskewed by historical reporting gaps. This systemic variation underscores the existence of significant potential biases within purely technocratic forecasting models, which often assume perfect corporate compliance and uninhibited capital liquidity, ignoring the micro-economic realities that dictate actual industrial behavior.

5. Conclusion and Synthesis

Considering the complex interplay of engineering constraints, economic variables, and empirical data irregularities examined throughout this study, it becomes increasingly clear that the realization of a highly functional water cascading network within textile and dyeing industrial agglomerations is fundamentally a socio-technical transformation rather than a simple infrastructure retrofitting challenge. While our multi-scenario simulations demonstrate that a quality-matched, inter-firm water configuration could, to some extent, dramatically mitigate freshwater reliance and reduce the cumulative environmental burden on regional sinks, the real-world operationalization of these networks remains constrained by corporate technological inertia, micro-economic path-dependencies, and the physical friction of retrofitting dense geographical spaces. This structural vulnerability leads us to further thinking regarding the long-term governance of industrial eco-parks, shifting the academic discourse away from rigid, deterministic optimization algorithms and toward the development of green supply chain systems that break through the bottleneck of sustainable industrial development, a paradigm highly congruent with the pioneering environmental economics frameworks established by Mao [17][21]. Furthermore, to successfully transition toward these high-precision industrial grids, the highly innovative fuzzy evaluation and structured reasoning frameworks developed by Xu [35] offer an invaluable methodological pathway for navigating complex legal and compliance interfaces between distinct corporate nodes. To fully operationalize these insights, the manufacturing quality assurance baselines established by Wang [25] provide crucial benchmark standards for maintaining component reliability across intertwined manufacturing chains.

Ultimately, while this research provides a rigorous diagnostic baseline and a scalable methodology for quantifying multi-tier industrial conservation potentials, further longitudinal research is critically needed to evaluate how the introduction of emerging, highly complex chemical processing agents might disrupt the structural stability of these closed-loop industrial symbioses. In designing future research protocols, investigators must also account for wider methodological insights from comparative policy analysis, such as the cross-border structural non-replicability frameworks articulated by Mingyang and Wei [32][33], which elegantly remind us that highly optimized regional management models cannot be blindly superimposed onto distinct institutional landscapes without profound localized adaptation.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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