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[Amir Gholipour](#)*

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Article

From Wastewater Reuse to Natural Wetland Degradation Under Regulatory Mirage

Amir Gholipour

Department of Environmental Science, Aarhus University, Frederiksborgvej 399, 4000 Roskilde, Denmark; amir@envs.au.dk

Abstract

Water scarcity compels wastewater reuse, but lax discharge standards generate a regulatory mirage, misleading the public about safety. Despite formal compliance, treated effluent severely harms Iran's effluent-dependent Kashaf River, driving eutrophication, salinization, and the downstream transport of unregulated contaminants of emerging concern, including PFAS and pharmaceuticals. These pressures extend beyond the river channel to adjacent natural wetlands, which act as de facto nature-based treatment systems yet are progressively transformed into sacrificial sinks for excess nutrients, salts, heavy metals, and micropollutants. By benchmarking the Iranian Wastewater Discharge Standards (IWDS) against international guidelines (WHO, EU, FAO), this study quantifies a "Permissibility Gap" frequently greater than 10 for key parameters such as BOD₅, nutrients, and trace metals, revealing how concentration-based limits ignore cumulative mass load and mixture toxicity at the basin scale. The Kashaf River case demonstrates that current end-of-pipe regulation undermines both natural wetlands and planned nature-based solutions, including constructed wetlands, in arid regions where effluent reuse is unavoidable. The study argues that aligning discharge standards with global benchmarks, adopting mass-based permits, and explicitly regulating contaminants of emerging concern are prerequisites for truly safe wastewater reuse and for protecting wetland ecosystems in effluent-dependent basins

Keywords: wastewater reuse; regulatory failure; emerging contaminants; river pollution

1. Introduction

Global water scarcity, affecting 2.4 billion people and projected to impact 5 billion by 2050, drives a shift from wastewater management to reuse (He et al., 2021). Reclaimed water reuse with market value surging from ~USD 18B in 2025 to USD 30-45B by 2030-2034 (compound annual growth rate = 9.73%) triples capacity over 20 years amid water scarcity (Precedence Research, 2025). This intense focus on volume has fostered a policy-science gap where water quality oversight lags. This occurs despite 70% of global wastewater remaining untreated (Xu et al., 2025).

Is the treatment of polluted waters a simple guarantee of safety? The current regulatory frameworks could be a regulatory mirage, where 1) legal compliance is not environmental safety, and 2) focus on quantity over quality. Wastewater treatment plants (WWTPs) meet all local discharge regulations, although this results in the discharge of suboptimal treated wastewater into vulnerable ecosystems (Büttner et al., 2022). Treatment systems are technically effective in removing a wide range of pollutants (e.g., 90% of BOD₅: biological oxygen demand), but the core regulatory failure lies in neglecting the cumulative load, which, when aggregated from multiple sources (Wear et al., 2021). These outdated standards are structurally blind to emerging risks, such as contaminants of emerging concern (CECs), which are often persistent and unregulated (Gholipour et al., 2025).

In the Kashaf River in Mashhad, Iran, the effluent from WWTPs becomes the only consistent flow, transforming the river from a natural ecosystem into a conveyance channel for agricultural supply (Gholipour et al., 2024). Once, the paleochannel of the river was fed by seasonal precipitation. This regulatory disconnect is particularly pronounced in regions like Iran, a country characterized by

an arid climate and intense water stress (Braithwaite et al., 2021). The Kashaf River serves as the archetype for this systemic failure. It flows directly past residential and high-value agricultural zones, where it is abstracted legally and illegally for irrigation. In the Kashaf River basin, this regulatory mirage extends beyond the river channel itself to the natural wetlands that fringe and intercept its flow (Ranjbar et al., 2024a). These valley-bottom marshes and floodplain wetland patches act as unplanned nature-based treatment systems, buffering nutrient pulses, attenuating contaminants, and sustaining biodiversity in an otherwise arid landscape. However, permissive concentration-based limits for BOD₅, nutrients, salinity, heavy metals, and unregulated CECs effectively license a chronic pollutant load that exceeds the assimilative capacity of these wetlands, accelerating eutrophication, sediment contamination, vegetation shifts, and loss of ecological function (Ranjbar et al., 2024a). In effluent-dependent reaches of the Kashaf River, natural wetlands thus become sacrificial sinks for regulatory failure; rather than being protected as priority receptors, they are progressively transformed into extensions of the wastewater infrastructure. This study, therefore, presents the Kashaf River as an early warning case, showing how structural deficiencies in the Iranian Wastewater Discharge Standards (IWDS) create a crisis in both the river ecosystem and its associated wetlands (Akbarzadeh et al., 2023). Similar challenges of river and wetland degradation are evident globally, such as in India, China, Pakistan, Bangladesh, Brazil, South Africa, Mexico, Oman, and Indonesia (Fluet-Chouinard et al., 2023). Do current end-of-pipe discharge regulations ensure that water is safe for reuse and ecosystem health, or do these regulations come into force too late to prevent ecological damage? The findings serve as an urgent call for regulatory reform, not only to secure river health and safe reuse but also to safeguard the remaining natural wetlands in arid basins, where they represent critical nodes of resilience under climate change and escalating water scarcity.

2. Materials and Methods

2.1. Study Area: Kashaf River and WWTP Infrastructure

The study focuses on the effluent-dependent Kashaf River in Mashhad, north-eastern Iran, and the network of municipal wastewater treatment plants that discharge into it, defining the main hydrological and infrastructural context for the subsequent regulatory analysis. Ecosystem collapse is clearly demonstrated in the Kashaf River in Figure 1.



Figure 1. Geographic overview map of Mashhad and the river.

The wastewater treatment infrastructure of Mashhad comprises several primary facilities with a combined design capacity equivalent to a population of 3,268,800 PE (Table S1). Assuming an average wastewater generation of 150 liters per person per day, the total treatment capacity amounts

to approximately 490,000 m³/day. The systemic failure caused by suboptimal standards, especially in arid regions where water reuse is essential, is illustrated in the conceptual model (Figure 2).

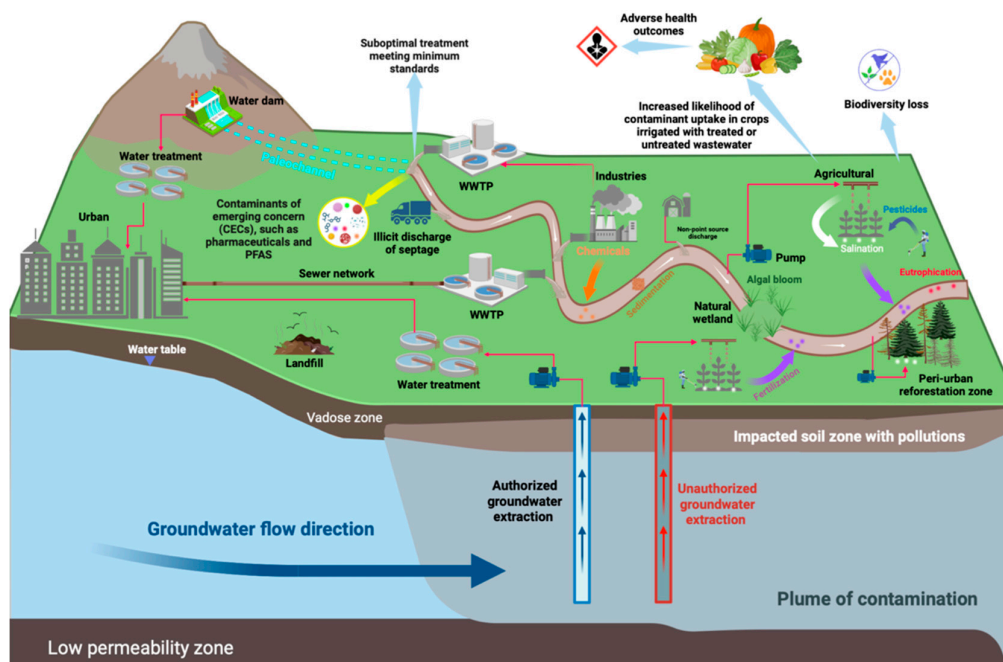


Figure 2. Integrated conceptual framework of systemic treated wastewater failure and reuse in Mashhad .

The non-exhaustive conceptual model illustrated the sources, pathways, and environmental/health impacts of CECs within the integrated urban-agricultural water cycle. The policy-science disconnect is encapsulated at the WWTPs, where suboptimal treatment meeting minimum standards allows a significant pollutant load to enter the river. While the plant may achieve the high concentration limits set by the IWDS for discharge to surface waters (e.g., 50 mg/L BOD₅), this compliance is ecologically devastating in a low-flow environment (Table S4). The effluent, along with risks from illicit discharge and untreated industries, feeds the river. The IWDS's failure to account for the cumulative mass load from multiple sources immediately drives pollutant concentrations far above international safety thresholds in the river. The high allowable limits for phosphate (6 mg/L) and nitrate (50 mg/L) in the IWDS promote eutrophication and algal bloom in the river. The absence of a fixed standard for total dissolved solids, relying instead on a relative 10% increase rule, ensures long-term salinization of the irrigated agricultural soils. The resulting high toxicity, low dissolved oxygen, and altered salinity stress lead directly to biodiversity loss in the river and natural wetland zones. Its blindness to CECs such as pharmaceuticals and PFAS is fundamentally destructive. These pollutants move via the vadose zone (from the contaminated river and potentially landfill leakage), contributing to the plume of contamination in the groundwater. The ultimate consequence is the increased likelihood of contaminant uptake in crops irrigated with unsafe water, leading to adverse health outcomes and compromising the long-term sustainability of the soil itself. The Kashaf River is thus not merely a polluted stream, but a tangible representation of this entire conceptual model as an archetype to quantitatively present how a flawed regulatory policy provides a false license to systematically degrade a vital water resource.

2.2. Regulatory Data Collection

A comparative regulatory analysis framework was applied to quantify the status of IWDS for surface water, particularly in the context of reuse in arid basins (Boyle et al., 2014). Data for the IWDS limits for surface water discharge were compiled from the latest available official documentation

published by the Iranian Department of Environment (Gholipour et al., 2024). To establish relevant safety benchmarks, a comprehensive search of international water quality guidelines and environmental quality standards (EQS) was conducted. These standards represent scientifically derived thresholds for safe water reuse or environmental protection and serve as the safety threshold for comparison. Key sources included 1) World Health Organization (WHO): Guidelines for drinking water quality and wastewater use in agriculture 2) European Union (EU): Water Framework Directive (WFD) EQS for chronic aquatic protection and ecological good status, as well as relevant groundwater and priority substance directives, and 3) Food and Agriculture Organization (FAO): Guidelines for water quality in irrigation (Preisner et al., 2020).

2.3. Permissibility Gap Calculation

The core quantitative assessment centers on comparing the limit (L_{IWDS}) for each pollutant parameter against its corresponding internationally recognized safe environmental threshold (L_{safe}). This comparison, called the permissibility gap (P-Gap), assumes that all Iranian WWTP successfully comply with the L_{IWDS} limits upon discharge into the receiving water body (Brunel & Levinson, 2016). However, several studies in Mashhad have shown that the effluent quality surpassed IWDS in Table S2 (Daei et al., 2019; Gholipour & Stefanakis, 2021). This hypothesis is also considered for other national regulations for the sake of simplicity and robustness.

$$P_Gap = \frac{L_{IWDS}}{L_{safe}} \quad (\text{Eq.1})$$

A P-Gap value of 1.0 indicates that the L_{IWDS} is equivalent to the international safety threshold. Values greater than 1.0 signify a high permissibility risk, demonstrating that the regulatory limit guarantees concentrations that are unsafe for the environment. Values less than 1.0 suggest a more stringent local standard. All P-Gap values are compiled in Table S3. All data treatment, P-Gap calculation, and graphical outputs were performed using Python with standard numerical and plotting libraries.

2.4. Data Analysis and Visualization

All data processing and visualization were performed in Python (version 3.9.6) using the pandas, numpy, seaborn, and scikit-learn libraries. National discharge limits were first compiled in a country-by-parameter matrix (e.g., BOD₅, COD, TSS, TDS, ammonium, nitrate, total phosphorus, fecal coliforms), with countries in rows (Iran, EU, United States, India, China, Pakistan, Bangladesh, Brazil, South Africa, Mexico, Indonesia, Oman) and regulatory limit values in columns. Non-numeric entries (e.g., “no fixed limit”, “managed via total nitrogen”, or “managed via fertilizer needs”) were treated as missing values and set to NaN to avoid biasing summary statistics.

To compare overall regulatory stringency across heterogeneous parameters and units, all concentration-based limits were min–max normalized between 0 and 1 using the MinMaxScaler function from scikit-learn, applied column-wise (Sahoo et al., 2019). Because lower numerical limits indicate stricter regulation, the scaled values were inverted ($1 - \text{normalized value}$) so that higher scores correspond to more stringent standards for visual interpretation. For each country, an aggregate stringency score was then calculated as the mean of the inverted, normalized values across all available parameters, using pairwise deletion for missing data. Countries were ranked from highest to lowest stringency according to this composite score.

Heatmaps were generated with seaborn’s clustermap function to visualize the relative position of each country across parameters and to display the resulting hierarchy of stringency. The columns (parameters) were kept in a fixed order reflecting standard wastewater quality metrics, while rows (countries) were ordered by descending stringency score to emphasize the contrast between more and less restrictive regimes. Colour scales (YlGnBu) were chosen so that darker colours represent stricter limits. All figures (e.g., Figure 3) were exported at publication resolution from Python and annotated in the manuscript to highlight groups of countries with particularly permissive versus stringent wastewater reuse policies.

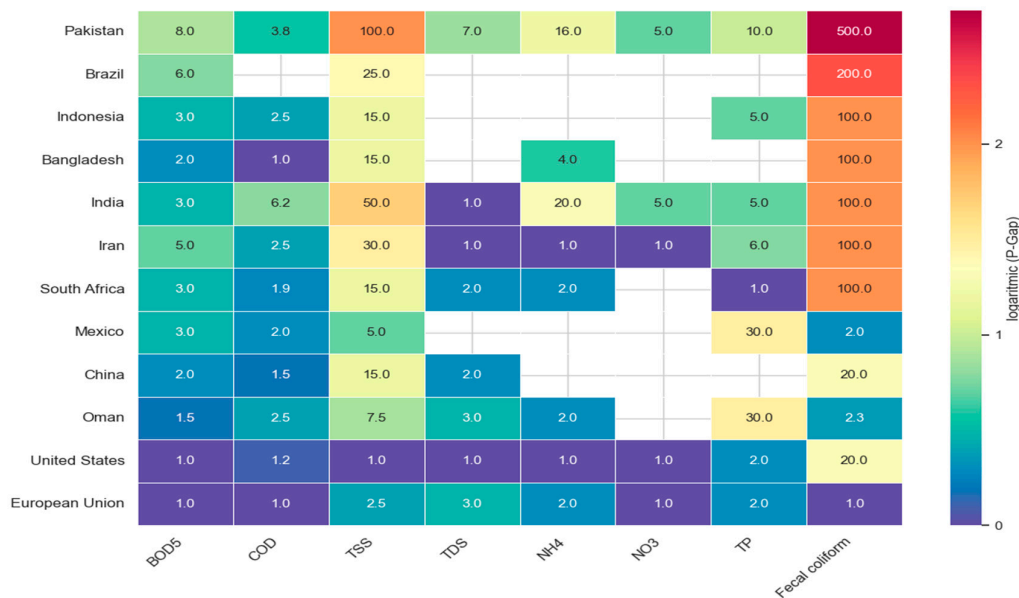


Figure 3. P-Gap Index for key pollutants across selected global regulations.

3. Results and Discussion

3.1. Benchmarking the Failure

The global P-Gap clearly highlights the stringent nature of some regulatory policies like the EU and the US, compared to the high-risk gaps present in Iran and several other developing nations (Figure 3). The lenient regulatory system is structurally wide for Pakistan, Brazil, and Indonesia, requiring special attention to avoid late warnings.

IWDS consistently permits pollutant concentrations far exceeding established safe international environmental limits. It is the primary driver of the ecological damage observed in wastewater reuse scenarios. A P-Gap index of IWDS highlights the parameters exhibiting the most deviations from safe benchmarks (Figure 4).

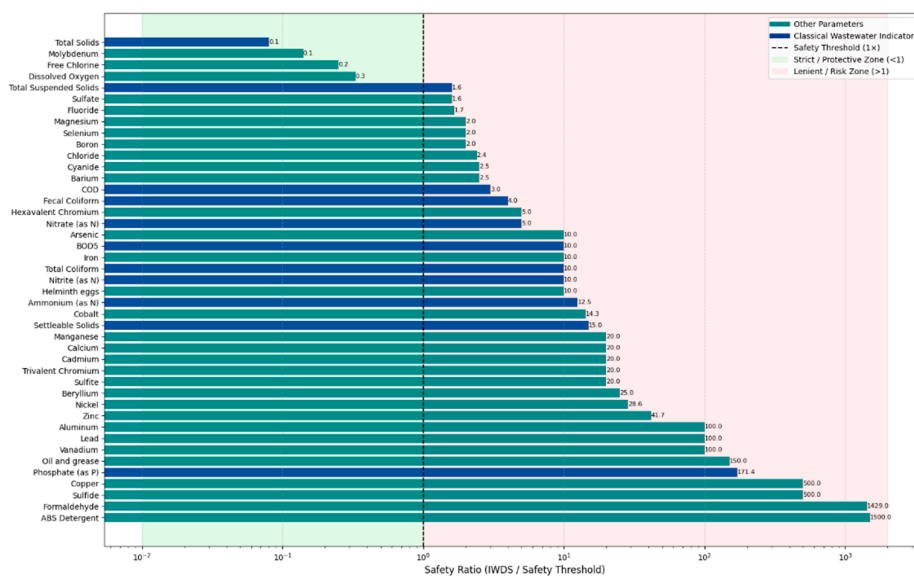


Figure 4. A P-Gap index: IWDS compliance vs. ecological and healthy safety limits.

Based on Figure 4, several heavy metals and persistent organic compounds (e.g., phenol, ABS detergents) exhibit P-Gap ratios spanning multiple orders of magnitude. This underscores a profound failure to harmonize national policy with established ecotoxicological thresholds. Even foundational wastewater parameters, including essential nutrients, oxygen demand indicators, and microbial proxies, prove substantially elevated P-Gap ratios, signaling a systemic vulnerability. From a policy perspective, such limits incentivize the regulatory system, effectively suppressing the mandate for technological upgrades in wastewater treatment, and could diminish the efficacy of national environmental protection legislation. Figure 5 categorizes parameters based on the magnitude of the P-Gap versus the frequency of environmental concern.

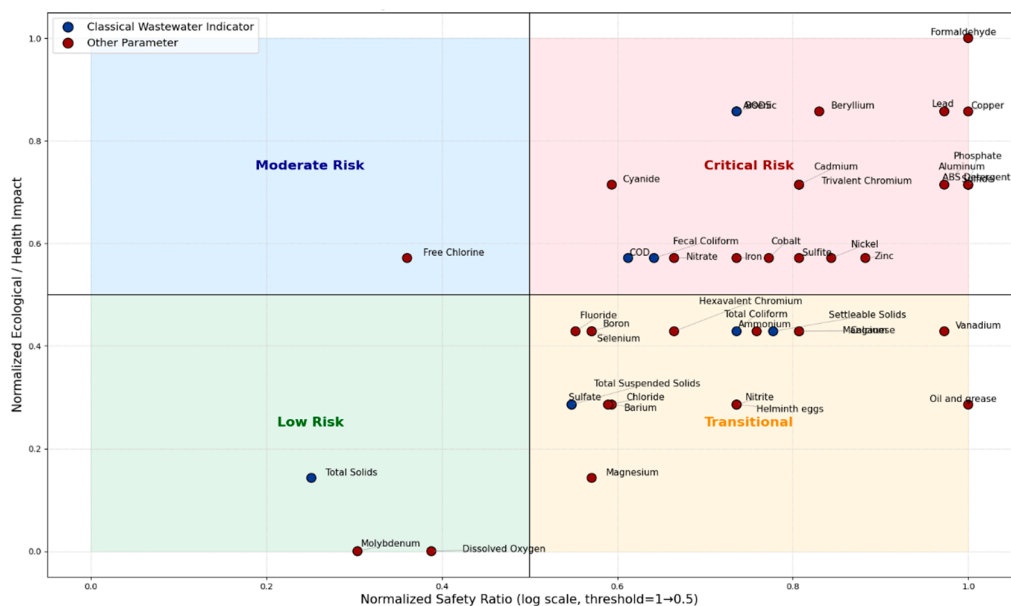


Figure 5. Risk quadrant of IWDS parameters.

Heavy metals and priority organic pollutants cluster, necessitating immediate prioritization for regulatory revision and treatment intervention due to their documented ecotoxicity and human health risks. High consequence/lower P-Gap pollutants (e.g., fecal coliforms, nutrients) require continuous, close attention despite having relatively closer regulatory limits.

3.2. The Unregulated Frontier: The Cocktail Effect

The reliance of IWDS on single-parameter, concentration-based limits creates an unregulated frontier where systemic risks, namely mixture toxicity and cumulative load (Cocktail Effect), are entirely disregarded (the total quantity of a pollutant discharged over time: kg/day). This regulation is fundamentally incapable of addressing the complexities of modern urban effluent. This is particularly critical for the compounds identified in the P-Gap index, which, when combined, can still trigger severe ecotoxicological stress.

The concentration-based IWDS limits fail to protect multi-source rivers with low dilution capacity, such as the Kashaf River, where pollutant masses from multiple dischargers accumulate in a single low-flow channel. This cumulative load drives eutrophication (from phosphate) and oxygen depletion (from BOD₅), revealing a design that ignores both mixture toxicity (“cocktail effect”) and total mass release, twin failures at the core of the regulatory mirage sustaining environmental degradation.

3.3. The Blind Spot: Emerging Contaminant

The IWDS and many other international regulations ignore the chemical landscape. The standard remains blind to the vast and dynamic landscape of CECs; for instance, pharmaceuticals, endocrine-disrupting chemicals (EDCs), and PFAS have been found in many environmental matrices. These unregulated pollutants that pass through WWTPs are persistent, mobile, and bio-accumulative CECs. For organic micropollutants (OMPs), WWTPs are not removal barriers but rather conveyance points into the environment. Studies in the Netherlands, for example, estimate that a substantial fraction of PFAS influent, potentially between 65 and 180 kg annually across the country, is discharged directly into surface waters via WWTP effluent (STOWA, 2021). Many CEC compounds are categorized as very persistent and very mobile (vPvM), meaning they are not only environmentally recalcitrant but also pose a significant threat to groundwater. The potential for these vPvM CECs to leach deep into the subsurface is alarming, with detection reported at depths of 15m below ground (Dauchy et al., 2019), thereby contaminating underlying aquifers.

CECs carried in the effluent affect soil, with PFAS shown to disturb soil enzyme activity, alter microbial availability, and damage cellular structures (Cai et al., 2020). Most critically, the process facilitates the soil-to-crop transfer of these CECs. Bioaccumulation of long-chain PFAS (PFOA and PFOS) has been noted in potato peels and cereal seeds, while highly mobile short-chain compounds readily accumulate in the stems, leaves, and fruits of crops, including leafy vegetables (Stahl et al., 2009). This transfer from biosolids-improved soil to the terrestrial food chain represents a high-risk exposure pathway (Schoeters et al., 2025). The IWDS's silence on CECs amplifies the health danger of the regulatory mirage. Based on the previous studies, the absence of limits for pharmaceuticals could directly contribute to the spread of antibiotic resistance genes (ARGs) in the aquatic environment, a global public health crisis (Gholipour et al., 2025). Likewise, unregulated EDCs might pose chronic threats through endocrine disruption and reproductive harm (Schoeters et al., 2025).

3.4. Natural Wetland Degradation in the Kashaf River Basin

The conceptual framework of systemic failure in the Kashaf River explicitly includes downstream natural wetlands as receptors of treated effluent, agricultural return flows, and diffuse pollution. In the effluent-dependent reaches of the basin, these wetlands are no longer buffered by natural hydrological variability; instead, their hydrology and water quality are largely controlled by wastewater-dominated baseflow and episodic storm events. These valley-bottom marshes and floodplain wetland patches historically provided nutrient retention, sediment trapping, and habitat functions, effectively acting as unplanned nature-based treatment systems within an otherwise arid landscape. Previous studies already documented substantial pollutant loads and ecological stress along the Kashaf River corridor and comparable Iranian rivers (Table 1).

Table 1. Wetland stressors documented for the Kashaf River and similar Iranian rivers.

Reference	Parameter	Reported Range / Value	Relevant Guideline	Implication for Wetlands
(Ranjbar et al., 2024b; Zolfaghari et al., 2018)	Heavy metals in soil and crops (Zn, Pb, Cd; mg/kg)	Average soil concentrations up to ~294 mg/kg Zn, 153 mg/kg Pb and 5.6 mg/kg Cd; plant concentrations up to ~131 mg/kg Zn, 113 mg/kg Pb and 2.5 mg/kg Cd. Cd classified as causing serious ecological risk agricultural soils (Ranjbar et al., 2024b)	Typical agricultural soil guidelines: Cd ≈ 1–3 mg/kg; Pb ≈ 50–100 mg/kg (higher levels indicate elevated risk).	Indicates substantial accumulation of metals in the riverine–wetland corridor and irrigated fields, with ecological risk and bioaccumulation in vegetation, suggesting long-term contaminant storage in adjacent wetlands.

(Gholipour et al., 2024)	Mixed wastewater inputs and ecological condition (qualitative)	River documented as receiving municipal, industrial and agricultural wastewater; described as experiencing “various types of wastewaters” and facing significant ecosystem threats.	Ramsar and national wetland conservation objectives require maintaining ecological character and limiting pollutant inputs.	Confirms the river–wetland corridor is functioning as a sink for multiple wastewater source sand is officially recognized as under environmental stress.
(Kolahi et al., 2024)	General water quality and pollution sources (qualitative)	Identifies discharge of industrial wastewater and agricultural return flows as major drivers of surface-water and groundwater quality deterioration.	National standards for drinking water and irrigation water quality.	Indicates basin-wide pollutant pressure affecting aquatic systems, including riverine wetlands and connected groundwater systems.
(Alizadeh et al., 2020)	Nitrate (mg/L) and phosphate (mg/L) in downstream reaches	Nitrate up to ~20–25 mg/L; phosphate up to ~6–7 mg/L in polluted river reaches.	Typical eutrophication thresholds: nitrate \approx 10 mg/L; phosphate-P \approx 0.1–0.2 mg/L.	Values far above thresholds indicate conditions favorable for eutrophication, algal blooms and hypoxia, threatening ecological function in receiving wetlands.

The high permissibility gaps quantified for key IWDS parameters make long-term degradation of these wetlands structurally unavoidable. Elevated BOD₅ and nutrient limits sanction chronic organic and nutrient loading, promoting eutrophication, algal blooms, and hypoxic conditions in wetland pools, which favor a few opportunistic macrophytes over diverse native plant communities. Likewise, the reliance on a relative 10% rule for total dissolved solids, rather than a fixed salinity cap, drives progressive salinization of wetland soils and pore water, reducing plant species richness and shifting vegetation towards halotolerant assemblages. Lenient or absent limits for heavy metals, phenolic compounds, surfactants, and other priority organics further enable the accumulation of contaminants in wetland sediments and biota, with cascading impacts on invertebrates, fish, and waterbirds that depend on these habitats.

Because of this regulatory context, natural wetlands along the Kashaf River effectively function as sacrificial sinks for excess pollutant loads that remain legally permissible at the WWTP outlet. They buffer short-term peaks in concentration but at the cost of declining ecological function, diminished capacity to absorb future disturbances, and the risk that legacy contaminants will be remobilized during floods or management interventions. Rather than being designated as priority receptors that constrain upstream discharge limits, these wetlands are implicitly treated as extensions of the wastewater infrastructure.

This trajectory is consistent with broader trends of wetland loss and degradation reported across Iran’s arid and semi-arid regions, where climate-driven aridification, upstream abstraction, and pollutant inputs act synergistically. In effluent-dependent basins such as the Kashaf, permissive discharge standards accelerate this decline by locking natural wetlands into a role for which they were neither designed nor institutionally protected. From a management perspective, the results indicate that implementing constructed wetlands or other nature-based solutions upstream, without simultaneously tightening IWDS limits and adopting mass-based, mixture-aware regulation, would mainly redistribute rather than reduce risk. Only by explicitly recognizing natural wetlands as critical

receptors—and setting discharge limits and treatment wetland designs accordingly—can planned green–grey infrastructures help to restore, rather than replace, the ecological functions of the remaining wetland ecosystems in the Kashaf River basin.

3.5. Forging a New Path and Global Implications

Transitioning from legal compliance to environmental and health safety requires an integrated, three-pronged regulatory overhaul.

Pillar I – De-concentrate the risk: Mass-based discharge permits (kg/day) should be replaced by obsolete concentration limits (mg/L). Effluent should target safe thresholds for high-P-Gap contaminants, ensuring suitability for designated reuses such as irrigation.

Pillar II – Close the regulatory loophole: Discharge standards could align with international guidelines like FAO and WHO. The relative rule is replaced with a fixed limit to protect soil health and prevent salinization.

Pillar III – Police the unregulated frontier: Replacement of indicator screen for CECs like PFAS and pharmaceuticals, and stakeholder engagement ensuring implementable, sustainable monitoring and policy resilience.

The analysis of the Kashaf River demonstrates that the regional environmental crisis is not the result of incompetent wastewater treatment but a systemic regulatory failure. The findings from the Kashaf River are not unique to Iran. The archetype of the effluent-dependent river exists across the developing world. In these regions, legacy environmental regulations, often inherited from the mid-20th century, are being outpaced by climate change, population growth, and the proliferation of CECs.

4. Conclusions

IWDS creates a regulatory mirage, where legal compliance leads to multiple environmental degradation pathways rather than genuine protection of water resources. Its structural failure to account for cumulative mass load, mixture toxicity, and unregulated contaminants of emerging concern means that even compliant effluent can drive eutrophication, salinization, heavy-metal accumulation, and PFAS and pharmaceutical pollution in effluent-dependent rivers and their associated wetlands. In the Kashaf River basin, this failure is manifested not only in the main channel but also in the natural wetlands that fringe and intercept the flow, which are progressively transformed from biodiversity refugia and nature-based treatment buffers into sacrificial sinks for excess pollutant loads. The Kashaf River thus serves as an archetype for arid and semi-arid basins globally, demonstrating that the environmental crisis in wastewater-fed rivers and wetlands is, to a large extent, a policy failure rather than a technical limitation of treatment technologies. Addressing this regulatory mirage will require shifting from permissive concentration-based limits to mass-based and mixture-aware standards aligned with international benchmarks, explicitly recognizing natural and constructed wetlands as priority receptors, and integrating nature-based solutions into broader circular water-management strategies.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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