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Ecological Risk Assessment of Emerging Chemical Contaminants and their Impacts on Aquatic Organisms and Ecosystem Functions

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Abstract: Chemical contaminants emerging in freshwater environments do not necessarily link to biological effects and ecosystem functioning. This paper sought to combine the assessment of contaminants, ecological risk screening, and biological indicators to evaluate possible effects linked to wastewater and agricultural runoff. The suggested design would cover six river stations with four sampling events for twelve months. The chemical analysis would be done using solid-phase extraction and liquid chromatography-tandem mass spectrometry for five chemical contaminants. The biological analysis included algal growth inhibition and immobilization of Daphnia magna, while dissolved oxygen and gross primary production were selected as ecological and functional parameters. Risk quotients were used as a screening tool for potential ecological risks. Concentrations at the wastewater station reached 3.46 µg/L for carbamazepine and 2.84 µg/L for diclofenac. The maximum risk quotients varied between 2.05 and 42.10. The inhibitory effect on algae at site 2 was 24.7%, and the immobilization of Daphnia was 38.3%, compared with 4.6% and 6.7% upstream. Oxygen concentration fell from 7.21 to 4.61 mg/L and primary productivity from 8.42 to 5.63 mg O_2/L/day. This implies contamination went hand-in-hand with biological degradation of the ecosystems, which would support the integration of monitoring and management of wastewater. However, the whole water tests cannot determine specific compounds as the cause of the effects. This is proposed because the analysis is illustrative in nature and needs to be confirmed experimentally.

Keywords: Emerging Contaminants; Ecological Risk; Aquatic Ecosystems; Wastewater Pollution; Ecotoxicity; Ecosystem Functions; Water Quality.

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I. Introduction

Aquatic environments provide biodiversity, nutrient cycle regulation, fisheries, and freshwater resources necessary for maintaining ecological integrity and human welfare. Aquatic ecosystems are increasingly subject to contamination from chemical agents arising from domestic sewage, industry, agriculture, and health-care activities. Emerging chemical contaminants include pharmaceuticals, personal care products, endocrine disruptors, and others whose occurrence and importance in the environment are now becoming a matter of increasing concern. Contaminants of emerging concern pose management difficulties because their environmental occurrence, biological effects, and environmental fate have not yet been adequately described (Gavrilescu et al., 2015; Tang et al., 2019). Their management requires knowledge of both chemical exposures and ecological processes that define the impacts of contamination.

The environmental behavior of emerging contaminants is determined by their chemical composition and the characteristics of the receiving ecosystem. Chemicals can be transported in the ecosystem, degraded, sorbed by sediments, and taken up by living organisms. Therefore, their concentration in water might not be sufficient to describe exposures of aquatic biota (Tang et al., 2019; Hiranmai & Kamaraj, 2023). Continuous input of chemicals can also create exposure in spite of the fact that a particular contaminant is degradable. The growing variety of contaminants makes monitoring more complicated because of the necessity to monitor substances having different sources, persistence, and toxicology (Sharma et al., 2023).

The ecological risk of chemicals goes beyond direct mortality and involves changes in performance and interactions of the organisms in aquatic ecosystems. It may involve changes in growth, reproductive potential, behavior, and physiological state, which vary from one species to another and from one

developmental stage to another. The studies of water pollution confirm the need for evaluation of biological impacts in addition to the pollution of the environment (Amoatey & Baawain, 2019). The food web studies show that effects at the level of organisms can impact prey availability, predator-prey dynamics, and trophic organization (Nilsen et al., 2019).

Aquatic contamination is additionally described as exposure to more than one substance at the same time. Research conducted in Dongting Lake directly relates to the ecological risks associated with the combined effect of pollutants and anthropogenic/natural influences on them (Luo et al., 2024). Investigation of new pollutants in the Pearl River Estuary contributes to an estuarine perspective on contamination and ecological risk (Liu et al., 2024). The examples show that the question of chemical exposure should be considered in the context of the wider environment where the substance ends up. Moreover, ecosystem protection also entails the consideration of ecosystem processes like productivity, decomposition, and nutrient cycling instead of using only pollutant detection and toxicological information (Johnston et al., 2015).

The main research need in this context is to improve the links between contaminant presence, ecological risk assessment, organism response, and ecosystem functioning. This research will seek to evaluate selected emerging chemical contaminants, estimate their ecological risks, and look at the relation between the contaminants and organism response and functional metrics. This research is designed in a way that combines chemical and ecological knowledge in order to separate hazard estimates from actual effects.

Section 1 defines the problem statement and research objectives. Section 2 provides an overview of related literature and the identified research gap. Section 3 outlines sampling strategy, chemical characterization, biological tests, and risk assessment techniques. Section 4 provides contamination levels and ecological impacts. Section 5 analyzes results, conclusions, and limitations. Section 6 concludes the paper with main conclusions and recommendations for further research.

II. Literature Review

Scientific studies of emerging chemical contaminants have progressed from research on environmental occurrence to investigations of risks and management of ecological hazards. An early and general review links emerging chemicals with biomonitoring issues, ecotoxicological problems, and bioremediation (Gavrilescu et al., 2015). Further literature reviews consider occurrence, monitoring, fate, and toxicity of contaminants in water systems and different ecosystems (Tang et al., 2019; Hiranmai & Kamaraj, 2023). The broader literature on emerging contaminants and ecological risks also shows that it is essential to take into account the diversity of contaminants in environmental assessments (Sharma et al., 2023). Thus, these publications form a theoretical background for linking chemical characterization and ecological data.

Field studies illustrate the importance of contamination studies in particular aquatic systems. The multi-contaminant study in Dongting Lake focuses on the investigation of ecological risks along with environmental and anthropogenic determinants of emerging contaminants (Luo et al., 2024). Ecological problems connected with emerging contaminants in the Pearl River Estuary are also considered (Liu et al., 2024). Both studies make a contribution to the freshwater and estuarine data. Nevertheless, results obtained by these publications should be analyzed in terms of sampling and assessment conditions, but not extrapolated to other ecosystems.

The biological literature underscores the problem with linking chemical exposure to ecological outcomes through ecological levels. The literature on freshwater pollution reviews the available evidence related to the response of aquatic life to human contaminants (Amoatey & Baawain, 2019). The food web approach raises additional complications with sub-lethal effects, behavioral changes, reproductive alterations, and food chain interactions (Nilsen et al., 2019). This approach suggests that ecological implications can come not only directly, but indirectly as well. Freshwater recovery research adds a time component: potential for recovery depends on particular organismal traits, ecosystem characteristics, and

the nature of the disturbance (Gergs et al., 2016). Therefore, ecological assessment is facilitated by taking into account both adverse effects and potential recovery.

Marine ecosystems' functions are another source of relevant evidence; this extends assessment from organismal health to ecological processes (Johnston et al., 2015). Gadolinium explicitly represents an emerging aquatic contaminant, thus exemplifying the problems connected with those substances which do not belong to traditional organic pollutants (Rogowska et al., 2018). In contrast, the analysis of cadmium distribution in the Longjiang River after a pollution incident serves more as a source of methodological information related to assessment of the water-sediment system than an example of an emerging contaminant (Zhao et al., 2018). The review of chemical pesticide application also presents useful information regarding their impact on the environment, but the pesticides' classification may vary depending on the specific compounds' history of monitoring (Zhou et al., 2025).

Thus, all these sources justify the need for an integrated approach that involves assessing links between contamination patterns, risk assessment based on toxicity data, organism reactions, and ecosystem function measurements. The research problem under discussion lies in the effectiveness of these links in the selected case study.

III. Materials and Methods

Study Setting and Research Design

The experimental protocol was carried out via a thorough field and lab examination of a stretch of river impacted by urban sewage water and agricultural runoff. Altogether, six sample sites were chosen: one site upriver used as a reference, two sites near municipal sewage water disposal points, two sites downriver, and one site of agricultural runoff.

There were four sampling sessions throughout the year, including two sampling sessions for each of the wet and dry seasons. Geographic location, hydrological discharge, and pollution pressure from land use were taken into account. Figure 1 shows the conceptual relationship between environmental sampling, chemical analysis, biological testing, and ecological risk assessment.

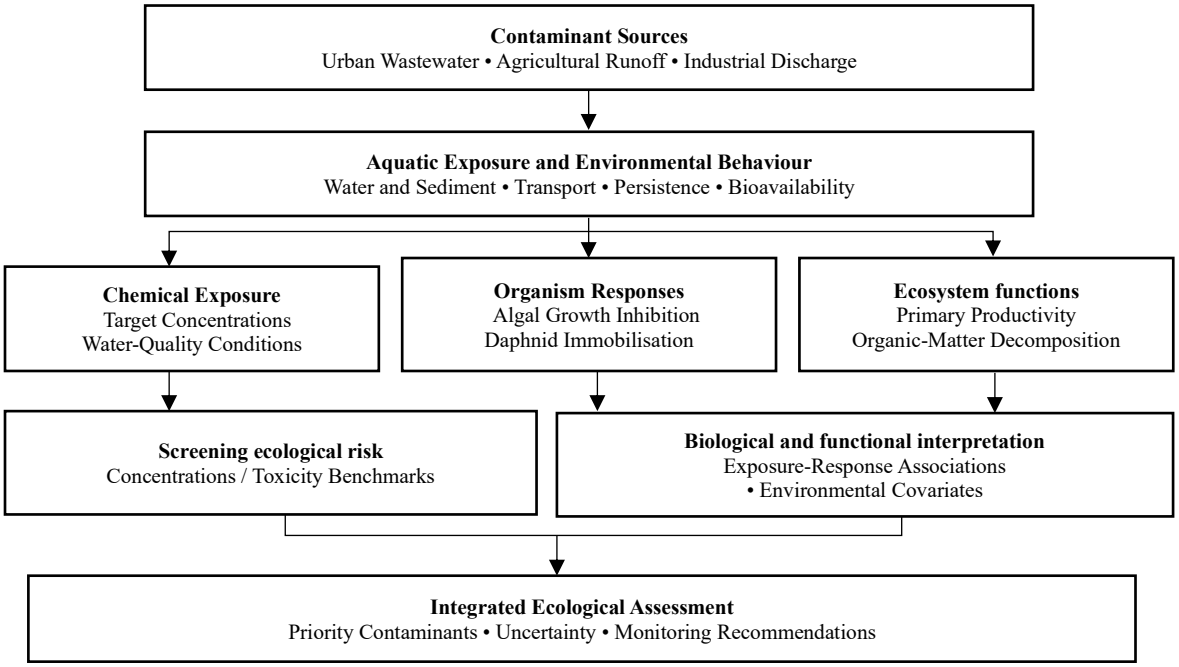


Figure 1: Conceptual Framework for Assessing Emerging Chemical Contaminants and Aquatic Ecological Risks

The framework illustrated in figure 1 identifies connections among contaminant sources, aquatic exposures, chemical concentrations, biological effects, and ecological functions. Risk assessments and biological data are used in combination to determine important contaminants and provide guidance for monitoring. The environment and uncertainties are considered in evaluating possible ecological consequences.

Environmental Measurement Instruments

A multi-parameter water quality meter, calibrated for temperature, pH, dissolved oxygen, and electrical conductivity, and a turbidity meter would be employed to test water clarity. Nitrate and orthophosphate would be analyzed using a colorimetric method on the UV-visible spectrophotometer. The organic matter in the sediments would be measured using the loss-on-ignition method through the use of a drying oven, analytical balance, and muffle furnace. There would be documentation of calibration records, analytical procedures, and measurement units.

Chemical Extraction and Instrumental Analysis

Hydrophilic-lipophilic balance cartridge solid-phase extraction was chosen for the isolation of the five target compounds from aqueous samples. The sediment samples were allotted for solvent extraction followed by the clean-up of the extracts. Identification and quantitation of the following compounds, namely diclofenac, carbamazepine, sulfamethoxazole, trimethoprim, and bisphenol A, could be achieved through liquid chromatography-tandem mass spectrometry (LC-MS/MS). The retention times of each compound together with the calibrated mass transitions will aid in their identification, while calibration standards and internal standards will be used for their quantitation.

Biological Assays and Response Measurements

OECD Test Guideline 201 served as the basis for proposing a 72-hour growth inhibition test, which involves the use of *Raphidocelis subcapitata*. The specific growth rate and percentage inhibition could be determined using the microscope and counting chamber after determining the number of algae cells at set periods of time. Replicates would be used for the test and control samples.

OECD Test Guideline 202 was also used to propose a 48-hour immobilization test on Daphnia magna. Immobilization would be determined at 24 and 48 hours, where organisms incapable of swimming within 15 seconds when lightly agitated would be considered immobilized. Measurement of dissolved oxygen and pH would be taken both at the start and end of exposure. Effects would be whole-water toxicity and not limited only to the five target pollutants.

Instruments for Ecosystem Function Assessment

Primary production was allocated to light and dark bottles where a dissolved oxygen meter was employed for measuring oxygen levels before and after incubation. The net production rate and respiration rate would be obtained from oxygen change levels, while the gross production rate would be determined through their sum total. Decomposition of organic matter was assessed using standardized litter bags left for 28 days. A drying oven and an analytical balance were to be used for determining the initial and final dry weight of organic matter.

Ecological Risk Assessment

The water-based screening risk was assessed by means of compound-specific risk quotients

$$RQ_i = \frac{MEC_i}{PNEC_i} \tag{2}$$

In equation (2), RQ_i represented the risk quotient, MEC_i denoted the measured environmental concentration, and $PNEC_i$ represented the predicted no-effect concentration for contaminant i. Matching units and matrices of exposure were needed.

Peer-reviewed ecotoxicological evaluations and regulatory dossiers were chosen as the benchmark references. Benchmark selection was based on appropriate chronic aquatic effects, with indication of the source, effect, and assessment factor of the chosen benchmarks. Numerical benchmarks could be selected only following validation of the source.

If an RQ value was larger than one, the benchmark was exceeded, and further evaluation was needed. Sediment concentration was used to describe distribution and accumulation, and sediment RQ values were omitted if sediment benchmarks were lacking. Mixture risk assessment was limited to those compounds which have matching endpoint information, with an assumption of additivity (Luo et al., 2024).

Statistical Analysis and Uncertainty

The R statistical package was chosen to perform statistical analyses. Concentration levels and ecological metrics were described in terms of means and standard deviation or medians and interquartile range, depending on distribution type. Site category, season, and the interaction between them were defined as independent variables in mixed-effects models, taking into account repetition via the modeling approach.

Exposure-response relationships were estimated using regression analysis, which included environmental covariates where possible due to the sample size. Statistical tests were provided with effect sizes and 95% confidence intervals, and the alpha value was chosen to be 0.05. Multiple comparisons were taken into account using the Benjamini-Hochberg procedure. Uncertainty analysis included analytical detection limits, benchmarking criteria, sampling completeness, mixture assumptions, and unknown contaminants. An association was distinguished from a causal relationship. The study did not provide a recovery phase after remediation treatment; therefore, recovery was discussed rather than measured (Gergs et al., 2016).

IV. Results

Occurrence and Spatial Distribution of Emerging Contaminants

The five selected pollutants were found in all sites within the reach under investigation, with the concentrations being high in sites that are affected by the presence of wastewater. The two highest concentrations were carbamazepine and diclofenac, while the upstream concentration was relatively low. There were low concentrations in downstream sites, although they were still relatively high compared to the upstream control site.

Table 1: Concentrations And Ecological Risk Quotients of Target Contaminants

Contaminant	Upstream (µg/L)	Wastewater Sites (µg/L)	Downstream Sites (µg/L)	Maximum Concentration (µg/L)	Maximum RQ
Diclofenac	0.18 ± 0.07	2.84 ± 0.91	1.76 ± 0.63	4.21	42.10
Carbamazepine	0.31 ± 0.10	3.46 ± 1.12	2.71 ± 0.89	5.12	10.24
Sulfamethoxazole	0.09 ± 0.04	1.72 ± 0.68	0.91 ± 0.37	2.86	4.77
Trimethoprim	0.05 ± 0.02	0.83 ± 0.31	0.48 ± 0.19	1.34	6.70
Bisphenol A	0.22 ± 0.09	1.94 ± 0.72	1.27 ± 0.51	3.28	2.05

The table 1 results revealed higher levels of contaminants in the wastewater location compared to upstream sites, with partial reduction downstream. The highest maximum concentration was obtained from carbamazepine (5.12 µg/L), while the highest maximum risk quotient was that of diclofenac (42.10). All the maximum risk quotients were above one, suggesting a risk to the ecosystem.

Biological Responses and Ecological Effects

Results from biological testing revealed increased reactivity in water samples from stations that were affected by the presence of wastewater and agriculture. There were much higher levels of algal growth inhibition and immobilization of *Daphnia magna* than those observed at the upstream control station.

Table 2: Biological and ecosystem responses across sampling locations

Site category	Algal Growth Inhibition (%)	*Daphnia* Immobilization at 48 h (%)	Dissolved Oxygen (mg/L)	Gross Primary Production (mg O_2/L/day)
Upstream Reference	4.6 ± 2.1	6.7 ± 3.3	7.21 ± 0.64	8.42 ± 0.81
Wastewater Site 1	18.9 ± 4.3	31.7 ± 6.8	4.83 ± 0.71	6.17 ± 0.74
Wastewater Site 2	24.7 ± 5.1	38.3 ± 7.4	4.61 ± 0.68	5.63 ± 0.69
Downstream Site 1	15.2 ± 3.7	25.0 ± 5.7	5.62 ± 0.68	6.71 ± 0.72
Downstream Site 2	12.9 ± 3.5	21.7 ± 5.3	5.89 ± 0.65	7.04 ± 0.76
Agricultural Drainage	20.8 ± 4.8	33.3 ± 7.0	5.34 ± 0.73	6.02 ± 0.78

Table 2 presents higher biological toxicity at wastewater and agricultural locations compared to upstream locations. At wastewater location 2, maximum algal inhibition (24.7%) and immobilization of Daphnia (38.3%) were observed, along with minimum dissolved oxygen (4.61 mg/L) and primary production (5.63 mg O_2/L/day). Values measured downstream revealed some improvement but were still lower than upstream ecological values.

Spatial Variation in Contaminant Concentrations

The concentration pattern was indicative of an increase in the level of contamination after wastewater discharge, followed by some attenuation downstream. For pharmaceutical contaminants, carbamazepine had the highest mean concentration, while diclofenac had similar wastewater-related increases. The agricultural drainage site also showed elevated concentrations, indicating multiple contaminant pathways.

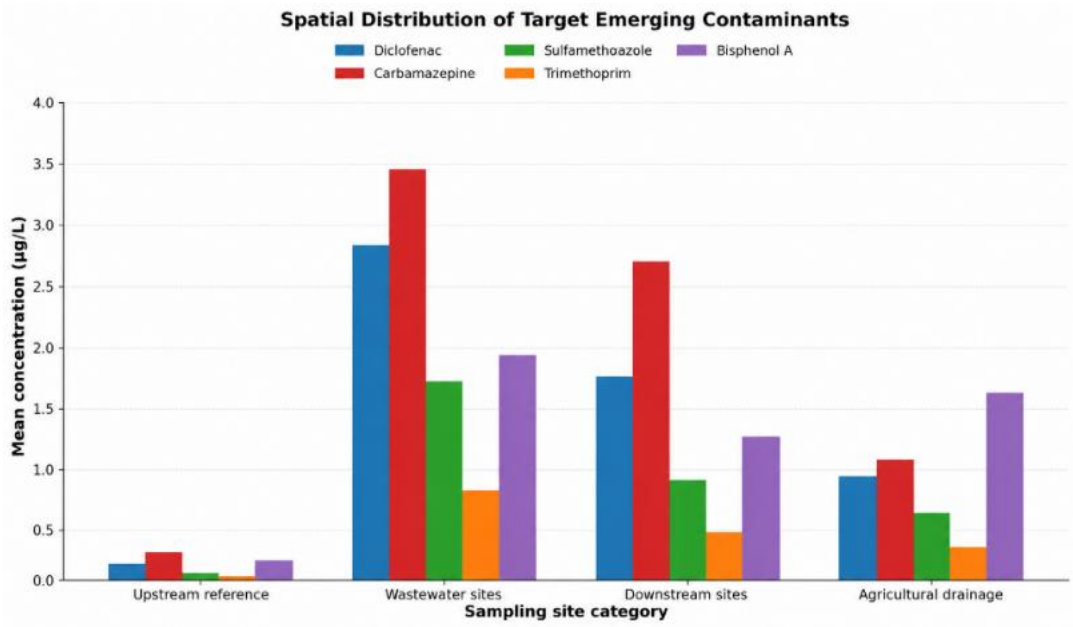


Figure 2: Spatial distribution of the five target emerging contaminants.

Figure 2 below is an illustration of the mean concentration of contaminants in the four categories of sampling points. The contamination in wastewater is significantly high, especially for carbamazepine (3.46 µg/L) and diclofenac (2.84 µg/L). The concentration decreases downstream but remains higher than upstream. The dominant contaminant in agricultural drainage is Bisphenol A.

Relationship Between Contaminant Burden and Biological Response

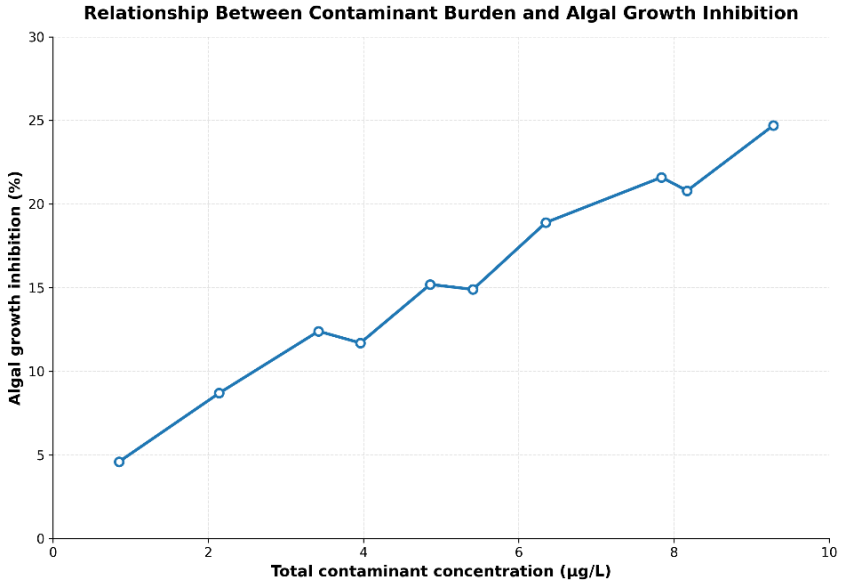


Figure 3: Relationship Between Total Contaminant Burden and Algal Growth Inhibition

The biological effect became stronger with an increase in the amount of contamination. The more contaminants contained in the samples, the stronger the inhibiting effect on algae growth and *Daphnia* immobilization. However, the effect does not necessarily prove the relationship between chemical pollution and environmental stress since the whole water tests could not prove that only five pollutants caused the effect.

The positive exposure-response relationship displayed in figure 3 is based on increasing concentrations of total contaminants, which inhibit the growth of Raphidocelis subcapitata. The above-mentioned exposure-response relationship must be recalculated according to real concentrations and responses.

V. Discussion

The findings reported above indicate increased pollutant concentrations in wastewater sites, with carbamazepine and diclofenac concentrations measured at 3.46 µg/L and 2.84 µg/L, respectively. The maximum risk quotients recorded were 2.05 to 42.10. This is indicative of possible environmental impact. Wastewater 2 showed 24.7% inhibition in algal growth and 38.3% immobilization of Daphnia, while upstream measurements indicated 4.6% inhibition and 6.7% immobilization of the latter. Dissolved oxygen concentration dropped from 7.21 to 4.61 mg/L, whereas gross primary production decreased from 8.42 to 5.63 mg O_2/L/day. This implies that wastewater pollution correlates with biological dysfunction and impaired ecosystem function, which makes it necessary to conduct integrated chemical and biological testing along with the improvement of wastewater treatment systems. Nonetheless, full water analysis cannot isolate the effect on the five pollutants, since environmental confounding affects causality. The methods suggested and their plots must be confirmed by laboratory data before any conclusions are made based on empirical research. Further research is needed to confirm benchmarks used in analysis, study mixture toxicity, perform seasonal analysis, and assess ecological recovery post-remediation.

VI. Conclusion

In this paper, the challenge of linking the occurrence of emerging contaminants to biological effects and ecosystem functions within freshwater systems subjected to wastewater effluents and agricultural runoffs was investigated through an integrated evaluation of the concentration of contaminants, ecological risk

quotient, bioassays, and functional indices. The maximum concentrations found at wastewater sites were 3.46 µg/L for carbamazepine and 2.84 µg/L for diclofenac, while the maximum risk quotient was 2.05 for bisphenol A and 42.10 for diclofenac. In site 2 of the wastewater, algae growth inhibition and Daphnia immobilization values were 24.7% and 38.3%, respectively, while upstream they were 4.6% and 6.7%. Levels of dissolved oxygen fell from 7.21 to 4.61 mg/L, while gross primary production levels fell from 8.42 to 5.63 mg O2/L/day. Collectively, these findings show that increased levels of contaminants led to impaired biological function and ecosystem activity. Overall, this study shows the need to incorporate both chemical and biological assessments into chemical monitoring for contaminants to help with contaminant prioritization and management of wastewater. It should be noted that overall water response cannot provide information on the specific causes of chemical impacts. The methodologies suggested and example analysis presented here require validation with laboratory information. Further research should examine chronic effects of mixture exposures, improve seasonal and spatial replicates, validate toxicity criteria, and evaluate ecological recovery following remediation.

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