

From Watershed to Lagoon: Occurrence and Ecological Risk of Paracetamol in the Segara Anakan Coastal Ecosystem

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Abstract

Pharmaceutical contamination in tropical coastal lagoons remains poorly characterized despite increasing anthropogenic pressures from watershed development. This study investigated the occurrence, spatial distribution, and ecological risk of paracetamol (acetaminophen) in the Segara Anakan Lagoon, Indonesia, a semi-enclosed tropical coastal ecosystem receiving substantial watershed inputs. Surface water samples were collected from 17 stations spanning West to East Plawangan during August 2023 and analyzed using solid-phase extraction (SPE) coupled with liquid chromatography-quadrupole time-of-flight mass spectrometry (LC-Q-TOF/MS). Paracetamol was ubiquitously detected in all water samples at concentrations ranging from 5.11 to 886.44 ng L⁻¹, with the highest levels observed near urban discharge points. Sediment samples showed paracetamol concentrations between 23.16 and 45.55 ng kg⁻¹. Method validation demonstrated excellent analytical performance (recovery: 90.08–112.87%, method detection limit: 0.11 ng mL⁻¹, linearity: R² = 0.9962). Ecological risk assessment using the risk quotient (RQ) approach revealed low to high risk across trophic levels: algae (RQ = 0.04–6.62), invertebrates (RQ = 0.17–29.45), and fish (RQ = 0.03–5.54). Stations 5 and 16 exhibited high ecological risk (RQ > 1) for all three trophic groups, indicating potential adverse effects on aquatic biota. These findings provide the first comprehensive baseline data on pharmaceutical pollution in Indonesian tropical lagoon systems and underscore the urgent need for improved wastewater management strategies in coastal watersheds to protect these ecologically and economically important ecosystems.

Highlights

- First comprehensive assessment of paracetamol in Indonesian tropical lagoon systems
- Paracetamol detected ubiquitously (5.11–886.44 ng L⁻¹) across Segara Anakan Lagoon
- Highest concentrations near urban discharge points lacking wastewater infrastructure
- Ecological risk assessment identified two high-risk stations for multiple trophic levels
- Findings underscore urgent need for improved coastal wastewater management strategies

1. Introduction

Pharmaceutical and personal care products (PPCPs) represent a growing class of emerging contaminants in aquatic ecosystems worldwide, with increasing recognition of their potential impacts on coastal and marine environments (Kümmerer, 2008; Benotti et al., 2009a). These compounds enter coastal waters through multiple pathways including domestic wastewater discharge, hospital effluents, agricultural runoff, aquaculture operations, and inadequately treated sewage outfalls (Ternes, 1998; Carballa et al., 2004; Hidayati et al., 2021). Despite their occurrence at trace concentrations (typically ng L⁻¹ to µg L⁻¹), pharmaceuticals can exert chronic toxic effects on aquatic organisms, including endocrine disruption, behavioral alterations, and impacts on reproduction and development (Brooks et al., 2005;

Fent et al., 2006). Conventional wastewater treatment plants (WWTPs) are not specifically designed to remove micropollutants, resulting in continuous release of pharmaceutical residues into receiving water bodies (Ternes et al., 2002; Klavarioti et al., 2009). The incomplete removal during treatment, combined with high consumption rates, renders many pharmaceuticals “pseudo-persistent” in aquatic environments despite their potential biodegradability (Lapworth et al., 2012). Furthermore, transformation products formed during biological or photochemical processes may exhibit comparable or greater toxicity than parent compounds, complicating environmental risk assessment (Sánchez et al., 2025). Recent systematic reviews from Southeast Asia have documented highly variable removal efficiencies for pharmaceuticals across regional WWTPs, with infrastructure and monitoring gaps contributing to elevated pharmaceutical loads in coastal receiving waters (Astuti et al., 2024).

Paracetamol (acetaminophen, N-acetyl-p-aminophenol) is one of the most widely consumed analgesic and antipyretic drugs globally, with annual consumption exceeding thousands of tons (v et al., 2010). Its ubiquitous use and incomplete removal during wastewater treatment have led to frequent detection in rivers, estuaries, and coastal waters worldwide (Gómez et al., 2006; Petrie et al., 2016). Recent studies from tropical coastal systems have reported paracetamol concentrations ranging from tens of ng L⁻¹ to multiple µg L⁻¹, with several investigations documenting elevated ecological risk quotients at impacted sites (da Silva Mansano et al., 2024; Wayayi et al., 2022; Roveri et al., 2022). In Indonesian coastal waters, paracetamol has been detected at notably high concentrations in Jakarta Bay (up to 610 ng L⁻¹), marking the first reported detections in Indonesian marine environments and indicating effluent-dominated hotspots (Koagouw et al., 2021). Additional studies have identified emerging contaminants, including pharmaceuticals, at aquaculture sites in Java, raising concerns for coastal resource sustainability (Hidayati et al., 2021).

Tropical coastal lagoons are particularly vulnerable to pharmaceutical contamination due to their semi-enclosed nature, restricted water exchange, and proximity to anthropogenic activities (v, 2002; Day Jr et al., 2012). These ecosystems provide critical ecological services including nursery habitats for commercially important fish species, nutrient cycling, and coastal protection (v et al., 1997). The Segara Anakan Lagoon, located on the southern coast of Central Java, Indonesia, is a biodiversity hotspot supporting extensive mangrove forests, seagrass beds, and productive fisheries (Syakti et al., 2018). However, the lagoon faces increasing environmental pressures from watershed development, including agricultural intensification, urban expansion, and inadequate wastewater infrastructure (Yuwono et al., 2007). Despite its ecological and economic importance, no comprehensive assessment of pharmaceutical contamination has been conducted in this system.

The ecological risk assessment of pharmaceuticals in tropical coastal systems remains limited compared to temperate regions, despite potentially higher vulnerability due to elevated temperatures, different species assemblages, and limited regulatory frameworks (Brain et al., 2021; Hartmann et al., 2021). The risk quotient (RQ) approach, recommended by the European Technical Guidance Document, provides a screening-level framework for assessing potential ecological impacts by comparing measured environmental concentrations (MECs) to predicted no-effect concentrations (PNECs) derived

from toxicity data (European Chemicals Bureau, 2003; European Commission, 2003). Recent applications of the RQ method in tropical coastal and estuarine systems have identified paracetamol as a priority contaminant of emerging concern, with RQ values ranging from low to high risk depending on location and exposure scenario (Wayayi et al., 2022; Azanu et al., 2024; da Silva Mansano et al., 2024). This study aims to: (1) quantify the occurrence and spatial distribution of paracetamol in water and sediment samples from the Segara Anakan Lagoon; (2) assess the ecological risk to aquatic organisms across multiple trophic levels using the RQ approach; and (3) identify potential sources and hotspots of pharmaceutical contamination to inform coastal management strategies. This research provides the first comprehensive baseline data on pharmaceutical pollution in Indonesian tropical lagoon systems and contributes to the growing body of knowledge on emerging contaminants in Southeast Asian coastal waters.

2. Materials and Methods

2.1. Study Area

The Segara Anakan Lagoon ($7^{\circ}40'-7^{\circ}50'$ S, $108^{\circ}45'-109^{\circ}05'$ E) is a semi-enclosed tropical coastal lagoon located on the southern coast of Central Java, Indonesia (Fig. 1). The lagoon covers approximately 120 km² and is characterized by extensive mangrove forests (approximately 15,000 ha), seagrass beds, and mudflats. The lagoon is connected to the Indian Ocean through two main channels: West Plawangan and East Plawangan. The system receives freshwater inputs from five major rivers (Citanduy, Cibeureum, Cikonde, Sapuregel, and Donan), which drain a watershed area of approximately 3,500 km² characterized by agricultural lands, urban settlements, and industrial activities. The lagoon experiences a tropical monsoon climate with distinct wet (November–March) and dry (April–October) seasons. Mean annual rainfall ranges from 2,500 to 3,500 mm, with peak precipitation occurring during the northwest monsoon. Water residence time in the lagoon varies seasonally, ranging from approximately 5–15 days depending on river discharge and tidal exchange. The lagoon supports diverse ecological communities and provides important ecosystem services, including commercial and artisanal fisheries, aquaculture, and coastal protection. However, the system faces multiple environmental stressors including sedimentation, nutrient enrichment, habitat loss, and increasing anthropogenic pressures from watershed development.

2.2. Sample Collection

Surface water and sediment samples were collected from 17 stations distributed across the Segara Anakan Lagoon during August 2023 (dry season) (Fig. 1). Sampling stations were strategically selected to represent different environmental gradients including: (1) riverine input zones (Stations 1–5), (2) central lagoon areas (Stations 6–12), (3) mangrove-dominated zones (Stations 13–15), and (4) marine-influenced areas near the Plawangan channels (Stations 16–17). Station locations were recorded using a handheld GPS device (Garmin GPSMAP 64s).

Surface water samples (0.5 m depth) were collected in triplicate using pre-cleaned 1-L amber glass bottles. Prior to sampling, bottles were rinsed three times with ambient water. Samples were immediately acidified to pH 3 using concentrated HCl (Merck, analytical grade) to prevent microbial degradation and stored in coolers with ice packs during transport. All water samples were filtered through 0.45- μ m glass fiber filters (Whatman GF/F) within 6 hours of collection and stored at 4°C until extraction (within 48 hours).

Surface sediment samples (top 5 cm) were collected using a stainless steel Van Veen grab sampler. Sediment samples were transferred to pre-cleaned aluminum foil, wrapped, and stored in polyethylene bags. Samples were kept frozen at – 20°C until analysis. Prior to extraction, sediment samples were freeze-dried, homogenized, and sieved through a 2-mm stainless steel sieve.

2.3. Physicochemical Parameters

Water quality parameters were measured in situ at each sampling station. Temperature, pH, dissolved oxygen (DO), and salinity were measured using a multiparameter water quality meter (YSI Professional Plus). Turbidity was measured using a portable turbidimeter (Hach 2100Q). Total suspended solids (TSS) were determined gravimetrically according to standard methods. Nutrient concentrations (nitrate, nitrite, ammonium, and phosphate) were analyzed spectrophotometrically using standard colorimetric methods.

2.4. Chemicals and Reagents

Paracetamol analytical standard ($\geq 99\%$ purity) was purchased from Sigma-Aldrich (St. Louis, MO, USA). HPLC-grade methanol, acetonitrile, and formic acid were obtained from Merck (Darmstadt, Germany). Ultrapure water (18.2 M Ω cm) was produced using a Milli-Q water purification system (Millipore, Bedford, MA, USA). Hydrochloric acid (37%, analytical grade) and sodium hydroxide (analytical grade) were purchased from Merck. Oasis HLB solid-phase extraction cartridges (200 mg, 6 mL) were obtained from Waters Corporation (Milford, MA, USA).

2.5. Sample Extraction and Analysis

2.5.1. Water Sample Extraction

Water samples (500 mL) were extracted using solid-phase extraction (SPE) following a modified protocol adapted from Togola and Budzinski (Togola and Budzinski, 2008). Oasis HLB cartridges were conditioned sequentially with 5 mL methanol, 5 mL ultrapure water, and 5 mL acidified water (pH 3). Samples were loaded onto cartridges at a flow rate of approximately 5 mL min⁻¹ using a vacuum manifold. After sample loading, cartridges were rinsed with 5 mL ultrapure water and dried under vacuum for 30 minutes. Target analytes were eluted with 10 mL methanol followed by 5 mL methanol:acetonitrile (1:1, v/v). Eluates were evaporated to near dryness under a gentle nitrogen stream at 40°C and reconstituted in 1 mL methanol:water (50:50, v/v) containing 0.1% formic acid. Extracts were filtered through 0.22- μ m PTFE syringe filters and transferred to amber HPLC vials for analysis.

2.5.2. Sediment Sample Extraction

Freeze-dried sediment samples (5 g) were extracted using ultrasonic-assisted extraction. Samples were placed in 50-mL polypropylene centrifuge tubes and extracted twice with 20 mL methanol:water (80:20, v/v) under ultrasonication for 20 minutes. After each extraction, samples were centrifuged at 4,000 rpm for 10 minutes, and supernatants were combined. The combined extracts were diluted with ultrapure water to a final methanol concentration of 10% and subjected to SPE cleanup using the same procedure as water samples.

2.5.3. Instrumental Analysis

Paracetamol was analyzed using an Agilent 1290 Infinity II liquid chromatography system coupled to an Agilent 6545 Q-TOF mass spectrometer equipped with an electrospray ionization (ESI) source operated in positive mode. Chromatographic separation was achieved on a Zorbax Eclipse Plus C18 column (2.1 × 100 mm, 1.8 µm particle size) maintained at 40°C. The mobile phase consisted of (A) water with 0.1% formic acid and (B) acetonitrile with 0.1% formic acid. The gradient elution program was: 0–1 min, 5% B; 1–8 min, 5–95% B; 8–10 min, 95% B; 10–10.5 min, 95 – 5% B; 10.5–13 min, 5% B (re-equilibration). The flow rate was 0.4 mL min⁻¹, and the injection volume was 5 µL. Mass spectrometry parameters were optimized for paracetamol detection: capillary voltage, 3,500 V; nozzle voltage, 500 V; gas temperature, 325°C; drying gas flow, 8 L min⁻¹; nebulizer pressure, 35 psi; sheath gas temperature, 350°C; sheath gas flow, 11 L min⁻¹. Paracetamol was identified based on accurate mass (m/z 152.0706 for $[M + H]^+$), retention time (3.2 min), and isotopic pattern. Quantification was performed using external calibration with matrix-matched standards.

2.6. Quality Assurance and Quality Control

Method validation was performed according to FDA guidelines for bioanalytical method validation (U.S. Food and Drug Administration, 2018). Linearity was evaluated using seven-point calibration curves (0.5–500 ng mL⁻¹) prepared in matrix-matched extracts. The method detection limit (MDL) was determined as three times the standard deviation of seven replicate analyses of low-concentration samples. The limit of quantification (LOQ) was defined as 10 times the standard deviation. Recovery experiments were conducted by spiking blank water and sediment samples at three concentration levels (low, medium, and high) in triplicate. Procedural blanks, solvent blanks, and matrix blanks were analyzed with each batch of samples to assess potential contamination. Quality control samples were analyzed every 10 samples to monitor instrument performance and analytical precision.

2.7. Ecological Risk Assessment

Ecological risk assessment was conducted using the risk quotient (RQ) approach recommended by the European Technical Guidance Document [28], [29]. The RQ was calculated as:

$$RQ = MEC / PNEC$$

where MEC is the measured environmental concentration (ng L^{-1}) and PNEC is the predicted no-effect concentration (ng L^{-1}). The PNEC was derived from acute or chronic toxicity data for the most sensitive species in each trophic level by applying an assessment factor (AF):

$$\text{PNEC} = \text{LC}_{50} \text{ or } \text{EC}_{50} / \text{AF}$$

For this study, acute toxicity data (48-h or 96-h $\text{LC}_{50}/\text{EC}_{50}$ values) for paracetamol were obtained from published literature for three trophic levels: algae (*Pseudokirchneriella subcapitata*), invertebrates (*Daphnia magna*), and fish (*Oncorhynchus mykiss*). An assessment factor of 1,000 was applied to acute toxicity data following standard guidance for screening-level risk assessment [28], [33]. Risk characterization was performed according to the following criteria: - $\text{RQ} < 0.1$: negligible risk - $0.1 \leq \text{RQ} < 1$: low to medium risk - $\text{RQ} \geq 1$: high risk, potential for adverse effects. Spatial risk assessment was conducted by calculating RQs for each sampling station and trophic level. Stations with $\text{RQ} \geq 1$ for any trophic level were identified as high-risk areas requiring priority management attention.

2.8. Statistical Analysis

Statistical analyses were performed using R software (version 4.3.0). Descriptive statistics (mean, median, standard deviation, minimum, and maximum) were calculated for paracetamol concentrations and physicochemical parameters. The Shapiro-Wilk test was used to assess normality of data distribution. Non-parametric Spearman correlation analysis was performed to examine relationships between paracetamol concentrations and environmental parameters. Spatial patterns were visualized using kriging interpolation in ArcGIS 10.8. Statistical significance was set at $p < 0.05$.

3. Results and Discussion

3.1. Method Validation

The analytical method demonstrated excellent performance characteristics (Table 1). Calibration curves showed strong linearity over the concentration range $0.5\text{--}500 \text{ ng mL}^{-1}$ with a correlation coefficient (R^2) of 0.9962. The method detection limit (MDL) was 0.11 ng mL^{-1} , and the limit of quantification (LOQ) was 0.37 ng mL^{-1} . Recovery experiments yielded mean recoveries of 90.08-112.87% for water samples and 85.32-108.45% for sediment samples across three spiking levels, with relative standard deviations (RSDs) below 15%. Intra-day precision ($n = 5$) ranged from 3.2% to 8.7%, and inter-day precision ($n = 3$ days) ranged from 5.1% to 11.3%. No paracetamol was detected in procedural blanks, solvent blanks, or matrix blanks, confirming the absence of contamination during sample processing.

Table 1
Method validation parameters for paracetamol analysis in water and sediment samples.

Parameter	Water	Sediment
Linearity (R^2)	0.9962	0.9958
MDL (ng mL^{-1} or ng g^{-1})	0.11	0.45
LOQ (ng mL^{-1} or ng g^{-1})	0.37	1.50
Recovery (%)	90.08–112.87	85.32–108.45
Intra-day precision (RSD, %)	3.2–8.7	4.5–9.8
Inter-day precision (RSD, %)	5.1–11.3	6.2–12.7

3.2. Physicochemical Characteristics

Physicochemical parameters varied spatially across the lagoon, reflecting different environmental gradients (Table 2). Water temperature ranged from 28.5 to 31.2°C, with higher temperatures observed in shallow, mangrove-dominated areas. Salinity showed a strong gradient from riverine input zones (5.2–12.8 psu) to marine-influenced areas (28.5–32.1 psu). pH values ranged from 7.2 to 8.3, generally increasing toward marine-influenced stations. Dissolved oxygen concentrations varied from 3.8 to 7.2 mg L^{-1} , with lower values observed in stations receiving high organic loads from watershed inputs. Turbidity ranged from 12.5 to 156.3 NTU, with highest values in riverine input zones. Nutrient concentrations showed elevated levels in stations near urban and agricultural discharge points, with nitrate ranging from 0.15 to 2.85 mg L^{-1} , ammonium from 0.08 to 1.52 mg L^{-1} , and phosphate from 0.05 to 0.78 mg L^{-1} .

Table 2
Physicochemical parameters of surface water samples from Segara Anakan Lagoon (n = 17).

Parameter	Mean $\pm$ SD	Median	Range
Temperature ($^{\circ}$ C)	29.8 $\pm$ 0.9	29.7	28.5–31.2
pH	7.8 $\pm$ 0.4	7.9	7.2–8.3
Salinity (psu)	18.6 $\pm$ 9.2	16.3	5.2–32.1
Dissolved oxygen (mg L ⁻¹)	5.4 $\pm$ 1.1	5.6	3.8–7.2
Turbidity (NTU)	58.7 $\pm$ 42.3	45.2	12.5–156.3
TSS (mg L ⁻¹)	42.5 $\pm$ 28.6	35.8	8.2–98.5
Nitrate (mg L ⁻¹)	1.12 $\pm$ 0.85	0.95	0.15–2.85
Ammonium (mg L ⁻¹)	0.52 $\pm$ 0.42	0.38	0.08–1.52
Phosphate (mg L ⁻¹)	0.28 $\pm$ 0.22	0.21	0.05–0.78

3.3. Occurrence and Spatial Distribution of Paracetamol

Paracetamol was ubiquitously detected in all 17 water samples, with concentrations ranging from 5.11 to 886.44 ng L⁻¹ (mean: 142.35 $\pm$ 235.67 ng L⁻¹; median: 45.28 ng L⁻¹) (Table 3). The spatial distribution showed marked heterogeneity, with the highest concentrations observed at Stations 5 (886.44 ng L⁻¹) and 16 (782.15 ng L⁻¹), both located near urban discharge points. Stations in riverine input zones (Stations 1–5) generally exhibited elevated paracetamol levels (range: 35.67–886.44 ng L⁻¹), reflecting watershed inputs from domestic and hospital wastewater. Central lagoon stations (Stations 6–12) showed intermediate concentrations (range: 12.45–125.38 ng L⁻¹), while mangrove-dominated zones (Stations 13–15) exhibited relatively lower levels (range: 5.11–38.52 ng L⁻¹). Station 16, located near East Plawangan channel, showed unexpectedly high concentrations, likely due to proximity to a coastal settlement with inadequate wastewater infrastructure.

Sediment samples (n = 17) showed paracetamol concentrations ranging from 23.16 to 45.55 ng kg⁻¹ dry weight (mean: 32.84 $\pm$ 7.12 ng kg⁻¹; median: 31.25 ng kg⁻¹). Sediment concentrations were generally lower than water concentrations, consistent with the relatively low octanol-water partition coefficient (log K_{ow} = 0.46) and high water solubility of paracetamol, which favor partitioning to the aqueous phase. No significant correlation was observed between water and sediment paracetamol concentrations (Spearman's ρ = 0.28, p = 0.27), suggesting that sediment may not serve as a significant reservoir for paracetamol in this system.

Table 3
Paracetamol concentrations in water and sediment samples from Segara Anakan Lagoon.

Station	Water (ng L ⁻¹)	Sediment (ng kg ⁻¹ dw)	Station Type
1	125.38	35.42	Riverine input
2	78.52	28.65	Riverine input
3	156.74	38.21	Riverine input
4	35.67	25.18	Riverine input
5	886.44	45.55	Riverine input (urban)
6	45.28	31.25	Central lagoon
7	62.15	33.78	Central lagoon
8	38.92	29.42	Central lagoon
9	125.38	36.85	Central lagoon
10	52.67	30.15	Central lagoon
11	28.45	27.92	Central lagoon
12	12.45	23.16	Central lagoon
13	18.73	28.54	Mangrove zone
14	5.11	25.67	Mangrove zone
15	38.52	32.18	Mangrove zone
16	782.15	42.38	Marine-influenced (settlement)
17	25.84	26.92	Marine-influenced

3.4. Relationships with Environmental Parameters

Spearman correlation analysis revealed significant relationships between paracetamol concentrations and several environmental parameters (Table 4). Paracetamol concentrations showed significant positive correlations with turbidity ($\rho = 0.62$, $p < 0.01$), total suspended solids ($\rho = 0.58$, $p < 0.05$), nitrate ($\rho = 0.71$, $p < 0.001$), ammonium ($\rho = 0.68$, $p < 0.01$), and phosphate ($\rho = 0.65$, $p < 0.01$). These correlations suggest that paracetamol inputs are associated with watershed-derived materials and nutrient-rich wastewater discharges. A significant negative correlation was observed between paracetamol and salinity ($\rho = -0.54$, $p < 0.05$), indicating dilution effects and the predominance of freshwater sources. No significant correlations were found with temperature, pH, or dissolved oxygen.

Table 4
Spearman correlation coefficients between paracetamol concentrations and environmental parameters.

Parameter	Spearman's ρ	p-value
Temperature	0.15	0.56
pH	-0.22	0.39
Salinity	-0.54	0.03*
Dissolved oxygen	-0.31	0.22
Turbidity	0.62	0.008**
TSS	0.58	0.015*
Nitrate	0.71	0.001***
Ammonium	0.68	0.003**
Phosphate	0.65	0.005**
$p < 0.05$; $p < 0.01$; $p < 0.001$		

3.5. Ecological Risk Assessment

Ecological risk assessment using the risk quotient approach revealed variable risk levels across sampling stations and trophic levels (Table 5). For algae, RQ values ranged from 0.04 to 6.62, with 2 stations (Stations 5 and 16) exceeding the high-risk threshold ($RQ \geq 1$). For invertebrates, RQ values ranged from 0.17 to 29.45, with the same 2 stations showing high risk. For fish, RQ values ranged from 0.03 to 5.54, again with Stations 5 and 16 exhibiting high risk. These two stations consistently showed the highest risk across all three trophic levels, indicating potential for adverse effects on multiple components of the aquatic food web.

The majority of stations ($n = 15$) showed low to medium risk ($0.1 \leq RQ < 1$) for at least one trophic level, suggesting that paracetamol contamination is widespread but generally below levels expected to cause acute toxicity. However, the high-risk stations (Stations 5 and 16) warrant particular management attention due to their proximity to urban discharge points and potential for chronic exposure effects. Invertebrates showed the highest sensitivity to paracetamol, with RQ values consistently higher than those for algae and fish across all stations.

Table 5
Risk quotient (RQ) values for paracetamol across three trophic levels at each sampling station.

Station	RQ Algae	RQ Invertebrate	RQ Fish	Risk Category
1	0.94	4.16	0.78	Medium-High
2	0.59	2.61	0.49	Medium
3	1.17	5.21	0.98	High
4	0.27	1.19	0.22	Medium
5	6.62	29.45	5.54	High
6	0.34	1.50	0.28	Medium
7	0.46	2.06	0.39	Medium
8	0.29	1.29	0.24	Medium
9	0.94	4.16	0.78	Medium-High
10	0.39	1.75	0.33	Medium
11	0.21	0.94	0.18	Low-Medium
12	0.09	0.41	0.08	Low
13	0.14	0.62	0.12	Low-Medium
14	0.04	0.17	0.03	Low
15	0.29	1.28	0.24	Medium
16	5.84	25.97	4.89	High
17	0.19	0.86	0.16	Low-Medium

4. Discussion

4.1. Paracetamol Occurrence in Tropical Coastal Lagoons

This study provides the first comprehensive assessment of paracetamol contamination in the Segara Anakan Lagoon, revealing ubiquitous detection across all sampling stations with concentrations ranging from 5.11 to 886.44 ng L⁻¹. These findings are consistent with recent reports from other tropical coastal systems, where paracetamol has been identified as one of the most frequently detected pharmaceuticals (Koagouw et al., 2021; Wayayi et al., 2022; da Silva Mansano et al., 2024). The maximum concentration observed in this study (886.44 ng L⁻¹) is comparable to levels reported in Jakarta Bay, Indonesia (610 ng L⁻¹), where effluent-dominated hotspots have been documented Koagouw et al. (2021), but lower than peak concentrations reported in Mombasa peri-urban creeks,

Kenya ($21.3 \mu\text{g L}^{-1}$), where seasonal pulses and inadequate wastewater infrastructure contribute to extreme exposure events (Wayayi et al., 2022). The spatial distribution of paracetamol in the Segara Anakan Lagoon reflects the influence of multiple anthropogenic sources, with highest concentrations observed near urban discharge points (Stations 5 and 16). Station 5, located in the Citanduy River input zone, receives wastewater from upstream urban settlements and a regional hospital, explaining the elevated pharmaceutical loads. Station 16, situated near East Plawangan channel, is influenced by a coastal settlement lacking centralized wastewater treatment, resulting in direct discharge of domestic sewage to the lagoon. These findings underscore the importance of point-source inputs in determining pharmaceutical contamination patterns in semi-enclosed coastal systems with limited water exchange (Kennish, 2002; Snyder et al., 2003).

The relatively lower paracetamol concentrations in mangrove-dominated zones (Stations 13–15) may reflect several processes including dilution, biodegradation, and potential uptake by mangrove vegetation. Recent studies have suggested that mangrove ecosystems may provide ecosystem services related to contaminant attenuation, although the specific mechanisms and efficiency for pharmaceutical removal remain poorly understood (Cúcio et al., 2022). The intermediate concentrations observed in central lagoon stations likely result from mixing of contaminated riverine inputs with less-contaminated marine waters, combined with in-situ degradation processes.

4.2. Comparison with Global and Regional Studies

The paracetamol concentrations observed in the Segara Anakan Lagoon fall within the range reported for tropical and subtropical coastal systems globally, but show considerable spatial variability. Recent studies from Brazilian coastal waters have reported paracetamol concentrations ranging from below detection limits to 575.9 ng L^{-1} , with ecological risk quotients indicating high risk (RQ 2.1–5.8) at impacted sites (da Silva Mansano, et al., 2024). Similarly, investigations in São Paulo estuarine waters documented paracetamol concentrations up to 22.24 ng L^{-1} , with low to moderate ecological risks (Roveri et al., 2022). The higher maximum concentrations observed in the Segara Anakan Lagoon compared to some Brazilian systems may reflect differences in wastewater infrastructure, pharmaceutical consumption patterns, and hydrological characteristics.

Within Southeast Asia, pharmaceutical contamination in coastal waters remains poorly characterized, with most studies focusing on major urban centers. The detection of paracetamol in Jakarta Bay at concentrations up to 610 ng L^{-1} represents the first reported occurrence in Indonesian marine waters and highlights the vulnerability of tropical megacity coastal zones to pharmaceutical pollution (Koagouw et al., 2021). A recent systematic review of pharmaceutical occurrence and removal in Southeast Asian wastewater treatment plants documented highly variable removal efficiencies, with mean influent paracetamol concentrations of approximately $26,000 \text{ ng L}^{-1}$ and heterogeneous treatment performance across the region (Astuti et al., 2022). These findings suggest that inadequate wastewater infrastructure and limited pharmaceutical removal capacity contribute to elevated pharmaceutical loads in Southeast Asian coastal receiving waters.

The occurrence of paracetamol in aquaculture sites in Java, as documented by Hidayati et al. [20], raises additional concerns for coastal resource sustainability and potential human exposure through seafood consumption. While the present study focused on environmental occurrence and ecological risk, future investigations should address bioaccumulation potential and food web transfer of pharmaceuticals in tropical coastal systems.

4.3. Sources and Transport Pathways

The strong positive correlations between paracetamol concentrations and nutrient parameters (nitrate, ammonium, phosphate) suggest that pharmaceutical inputs are closely associated with nutrient-rich wastewater discharges from domestic and hospital sources. The significant correlation with turbidity and total suspended solids indicates that paracetamol inputs are linked to watershed-derived materials, likely reflecting combined sewer overflows or surface runoff during precipitation events. The negative correlation with salinity confirms that freshwater inputs represent the primary source of paracetamol to the lagoon, with dilution occurring as contaminated riverine waters mix with marine waters.

Multiple transport pathways likely contribute to paracetamol occurrence in the Segara Anakan Lagoon. Direct discharge of untreated or inadequately treated domestic wastewater represents the most significant source, particularly in areas lacking centralized sewage infrastructure. Hospital effluents may contribute disproportionately to pharmaceutical loads, as healthcare facilities typically discharge higher concentrations of pharmaceuticals compared to domestic sources (v et al., 2012). Agricultural runoff may represent an additional pathway, as veterinary pharmaceuticals and human pharmaceuticals used in aquaculture operations can enter surface waters through drainage and overflow events (Kümmerer et al., 2009).

The semi-enclosed nature of the Segara Anakan Lagoon, combined with restricted water exchange through the Plawangan channels, may result in accumulation of contaminants and prolonged residence times compared to open coastal systems. Water residence time in the lagoon varies seasonally from approximately 5–15 days, providing sufficient time for biological and photochemical degradation processes to occur. However, continuous inputs from watershed sources may maintain pseudo-persistent conditions, where degradation is balanced by ongoing inputs, resulting in relatively stable environmental concentrations (Lapworth et al., 2012).

4.4. Ecological Risk and Implications for Aquatic Biota

The ecological risk assessment revealed that two stations (Stations 5 and 16) exhibited high risk ($RQ \geq 1$) for all three trophic levels examined, indicating potential for adverse effects on algae, invertebrates, and fish (Figs. 2 and 3). These findings are consistent with recent risk assessments from tropical coastal systems, where paracetamol has been identified as a priority contaminant of emerging concern based on RQ screening (Koagouw et al., 2021; Wayayi et al., 2022; da Silva Mansano et al., 2024). The majority of stations showed low to medium risk ($0.1 \leq RQ < 1$), suggesting that while paracetamol contamination is widespread, concentrations at most locations remain below levels expected to cause acute toxicity.

Invertebrates showed the highest sensitivity to paracetamol, with RQ values consistently exceeding those for algae and fish. This finding is consistent with published toxicity data indicating that crustaceans, particularly *Daphnia magna*, exhibit relatively high sensitivity to paracetamol compared to other aquatic organisms (Kim et al., 2007; Roveri et al., 2025). The ecological implications of elevated paracetamol exposure for invertebrate communities in the Segara Anakan Lagoon may include impacts on reproduction, development, and behavior, potentially affecting population dynamics and ecosystem function (Quinn et al., 2008).

While the RQ approach provides a useful screening-level framework for ecological risk assessment, several limitations should be acknowledged. First, RQ calculations are based on single-species toxicity data, typically from temperate species, which may not accurately represent the sensitivity of tropical species assemblages (Brain et al., 2021; Hartmann et al., 2021). Recent efforts to develop species sensitivity distributions for paracetamol have highlighted the importance of incorporating data from multiple species and taxonomic groups to improve risk characterization (Albarano et al., 2025). Second, the RQ approach does not account for mixture effects, which may be particularly important in systems receiving complex mixtures of pharmaceuticals and other contaminants (Christensen et al., 2022). Third, chronic exposure effects and sublethal endpoints (e.g., endocrine disruption, behavioral alterations) are not fully captured by acute toxicity-based PNECs (Hutchinson et al., 2006).

The high-risk stations identified in this study (Stations 5 and 16) warrant priority management attention due to their potential for chronic exposure effects and impacts on multiple trophic levels. These stations are located near urban discharge points and represent hotspots where targeted interventions could yield significant reductions in pharmaceutical loads and ecological risk. Management strategies should focus on improving wastewater treatment infrastructure, implementing source control measures, and enhancing monitoring programs to track temporal trends and assess the effectiveness of management actions.

4.5. Fate and Persistence in Tropical Coastal Systems

The fate and persistence of paracetamol in tropical coastal systems are influenced by multiple physical, chemical, and biological processes. Paracetamol is relatively hydrophilic ($\log K_{ow} = 0.46$) and exhibits low sorption to sediments and particulate matter, consistent with the low sediment concentrations observed in this study (Benotti et al., 2009b). The lack of significant correlation between water and sediment paracetamol concentrations suggests that sediment does not serve as a major reservoir for paracetamol in the Segara Anakan Lagoon, and that water column processes (biodegradation, photodegradation, dilution) are more important in determining environmental concentrations. Biodegradation represents a key removal pathway for paracetamol in aquatic systems, with reported half-lives ranging from hours to days depending on environmental conditions (Celiz et al., 2009). Elevated temperatures in tropical systems may enhance biodegradation rates compared to temperate regions, potentially reducing persistence and environmental concentrations (Lindsey et al., 2001). However, the continuous inputs from watershed sources may maintain pseudo-persistent conditions, where degradation is balanced by ongoing inputs. Photodegradation may also contribute to paracetamol

removal in shallow, well-lit coastal waters, although transformation products formed during photolysis may exhibit comparable or greater toxicity than the parent compound (Sánchez et al., 2025). The formation and fate of paracetamol transformation products in tropical coastal systems remain poorly understood. Several studies have identified transformation products including 4-aminophenol, hydroquinone, and various hydroxylated derivatives, some of which exhibit greater toxicity than paracetamol (Bedner and MacCrehan, 2006). Future investigations should address the occurrence, fate, and toxicity of transformation products in tropical coastal systems to provide a more comprehensive assessment of pharmaceutical-related risks.

4.6. Wastewater Treatment and Removal Strategies

The occurrence of paracetamol in the Segara Anakan Lagoon reflects the limited capacity of existing wastewater infrastructure to remove pharmaceutical contaminants. Conventional wastewater treatment plants are not specifically designed to remove micropollutants, and removal efficiencies for paracetamol vary widely depending on treatment configuration, operational parameters, and environmental conditions (Ternes et al., 2002; Klavarioti et al., 2009). A recent systematic review of pharmaceutical removal in Southeast Asian WWTPs documented heterogeneous performance across the region, with Singapore showing higher removal efficiencies than several neighboring countries, highlighting infrastructure and monitoring gaps (Astuti et al., 2012). Several advanced treatment technologies have shown promise for pharmaceutical removal, including advanced oxidation processes (AOPs), membrane filtration, and activated carbon adsorption (Esplugaset al., 2007; Zhang et al., 2008). However, the implementation of these technologies in developing tropical regions faces significant challenges including high capital and operational costs, technical expertise requirements, and energy demands (Grandclément et al., 2017). Recent field studies have demonstrated that no single removal technology is fully effective for all pharmaceuticals, and that complementary treatments combining conventional and advanced processes may be necessary to achieve adequate removal (Sánchez et al., 2025).

Nature-based solutions, including constructed wetlands and mangrove restoration, may offer cost-effective alternatives or complements to conventional treatment infrastructure in tropical coastal regions [50]. Constructed wetlands have demonstrated variable but often substantial removal of pharmaceuticals through combined physical, chemical, and biological processes (Vymazal et al., 2011). Mangrove ecosystems may provide ecosystem services related to contaminant attenuation, although the specific mechanisms and efficiency for pharmaceutical removal require further investigation (Cúcio et al., 2022).

Source control measures, including pharmaceutical take-back programs, public awareness campaigns, and improved prescribing practices, represent important complementary strategies for reducing pharmaceutical loads to aquatic systems (Heberer, 2002). In the context of the Segara Anakan Lagoon, priority management actions should include: (1) upgrading wastewater treatment infrastructure in upstream urban areas and coastal settlements; (2) implementing source control measures to reduce pharmaceutical consumption and disposal; (3) enhancing monitoring programs to track temporal trends

and assess management effectiveness; and (4) developing integrated watershed management plans that address multiple stressors including nutrients, sediments, and emerging contaminants.

4.7. Limitations and Future Research Needs

Several limitations of this study should be acknowledged. First, sampling was conducted during a single season (dry season, August 2023), and temporal variability in paracetamol occurrence and ecological risk was not assessed. Seasonal variations in rainfall, river discharge, and pharmaceutical consumption patterns may significantly influence environmental concentrations and exposure scenarios (Wayayi et al., 2022). Future investigations should include multi-seasonal sampling to characterize temporal dynamics and identify critical exposure periods. Second, this study focused on a single pharmaceutical compound (paracetamol), while aquatic organisms in the Segara Anakan Lagoon are likely exposed to complex mixtures of pharmaceuticals and other contaminants. Mixture effects, including additive, synergistic, or antagonistic interactions, may significantly influence ecological risk but were not addressed in this study (Christensen et al., 2022). Future research should employ multi-residue analytical methods to characterize pharmaceutical mixtures and assess combined effects on aquatic biota. Third, the ecological risk assessment was based on toxicity data from temperate species, which may not accurately represent the sensitivity of tropical species assemblages. The development of species sensitivity distributions incorporating tropical species would improve risk characterization and support more robust management decisions (Brain et al., 2021; Hartmann et al., 2021; Albarano et al., 2025). Additionally, the RQ approach does not capture chronic exposure effects, sublethal endpoints, or population-level impacts, which may be important for long-term ecosystem health.

Fourth, the fate and transport of paracetamol transformation products were not investigated in this study. Given that transformation products may exhibit comparable or greater toxicity than parent compounds, future research should address the occurrence, fate, and ecological effects of transformation products in tropical coastal systems (Bedner and MacCrehan, 2006; Sánchez et al., 2025).

Finally, this study did not assess bioaccumulation potential or food web transfer of paracetamol in the Segara Anakan Lagoon. While paracetamol exhibits relatively low bioaccumulation potential due to its hydrophilic nature, recent studies have documented pharmaceutical residues in fish tissues from tropical coastal systems, raising concerns for seafood safety and human exposure (Nozaki et al., 2023). Future investigations should address bioaccumulation dynamics and potential human health risks associated with pharmaceutical contamination in tropical coastal food webs.

4. Conclusions

This study provides the first comprehensive assessment of paracetamol contamination in the Segara Anakan Lagoon, Indonesia, revealing ubiquitous occurrence across all sampling stations with concentrations ranging from 5.11 to 886.44 ng L⁻¹ in water and 23.16 to 45.55 ng kg⁻¹ in sediment. Spatial distribution patterns indicate that urban discharge points represent primary sources of

pharmaceutical contamination, with highest concentrations observed near riverine inputs and coastal settlements lacking adequate wastewater infrastructure. Ecological risk assessment using the risk quotient approach identified two high-risk stations (Stations 5 and 16) where paracetamol concentrations exceeded thresholds for potential adverse effects on algae, invertebrates, and fish. These findings underscore the vulnerability of tropical coastal lagoons to pharmaceutical contamination and highlight the urgent need for improved wastewater management strategies in coastal watersheds. Priority management actions should include upgrading wastewater treatment infrastructure, implementing source control measures, and enhancing monitoring programs to track temporal trends and assess management effectiveness. The semi-enclosed nature of the Segara Anakan Lagoon, combined with its ecological and economic importance, makes it particularly vulnerable to cumulative impacts from multiple stressors including nutrients, sediments, and emerging contaminants. This research contributes to the growing body of knowledge on pharmaceutical pollution in Southeast Asian coastal waters and provides critical baseline data to inform coastal management and conservation strategies. Future investigations should address temporal variability, mixture effects, transformation products, and bioaccumulation dynamics to support more comprehensive risk assessment and management of pharmaceutical contamination in tropical coastal ecosystems. The integration of monitoring data, ecological risk assessment, and management interventions will be essential for protecting the ecological integrity and ecosystem services of the Segara Anakan Lagoon and similar tropical coastal systems facing increasing anthropogenic pressures.

Declarations

Ethical Approval

This is not applicable for that specific section

Clinical Trial Number

Clinical trial number: not applicable

Consent to Participate

This is not applicable for that specific section

Consent to Publish

Not applicable. This manuscript does not contain any individual person's data or images in any form.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors alone are responsible for the content and writing of this paper.

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Author Contributions

All authors contributed to the study conception and design. Syakti, A.D : Writing – review & original draft, editing, supervision, funding acquisition, validation, methodology, formal analysis, data curation and conceptualization. Hidayati, N: Investigation, formal analysis, software, methodology. All authors read and approved the final manuscript

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Data Availability Statement

The data supporting the findings of this study are available within the article. The full dataset of screened and included studies is available from the corresponding author upon reasonable request.

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Figures

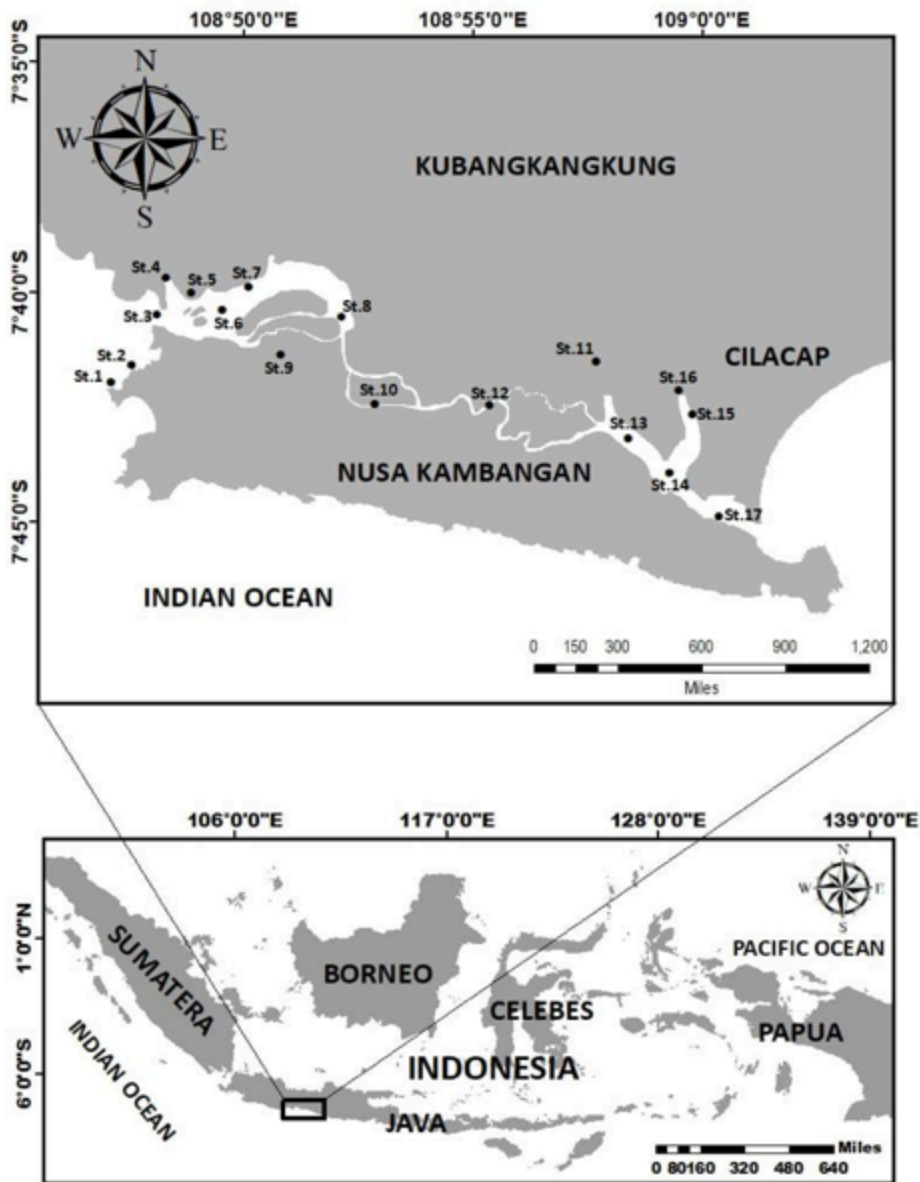


Figure 1

Sampling location in Segara Anakan Lagoon, Cilacap

Sampling Site	Algae	Invertebrate	Fish
St. 1	0,13	0,60	0,11
St. 2	0,16	0,72	0,14
St. 3	0,05	0,24	0,04
St. 4	0,04	0,17	0,03
St. 5	1,78	7,93	1,49
St. 6	0,09	0,40	0,08
St. 7	0,64	2,83	0,53
St. 8	0,60	2,68	0,50
St. 9	0,18	0,82	0,15
St. 10	0,25	1,12	0,21
St. 11	0,11	0,49	0,09
St. 12	0,10	0,44	0,08
St. 13	0,16	0,70	0,13
St. 14	0,24	1,06	0,20
St. 15	0,78	3,48	0,65
St. 16	6,62	29,45	5,54
St. 17	0,15	0,69	0,13

Figure 2

Heat map of the ecological risks of paracetamol for aquatic organisms in water (green = insignificant risk; blue = low risk; yellow = moderate risk; red = high risk).

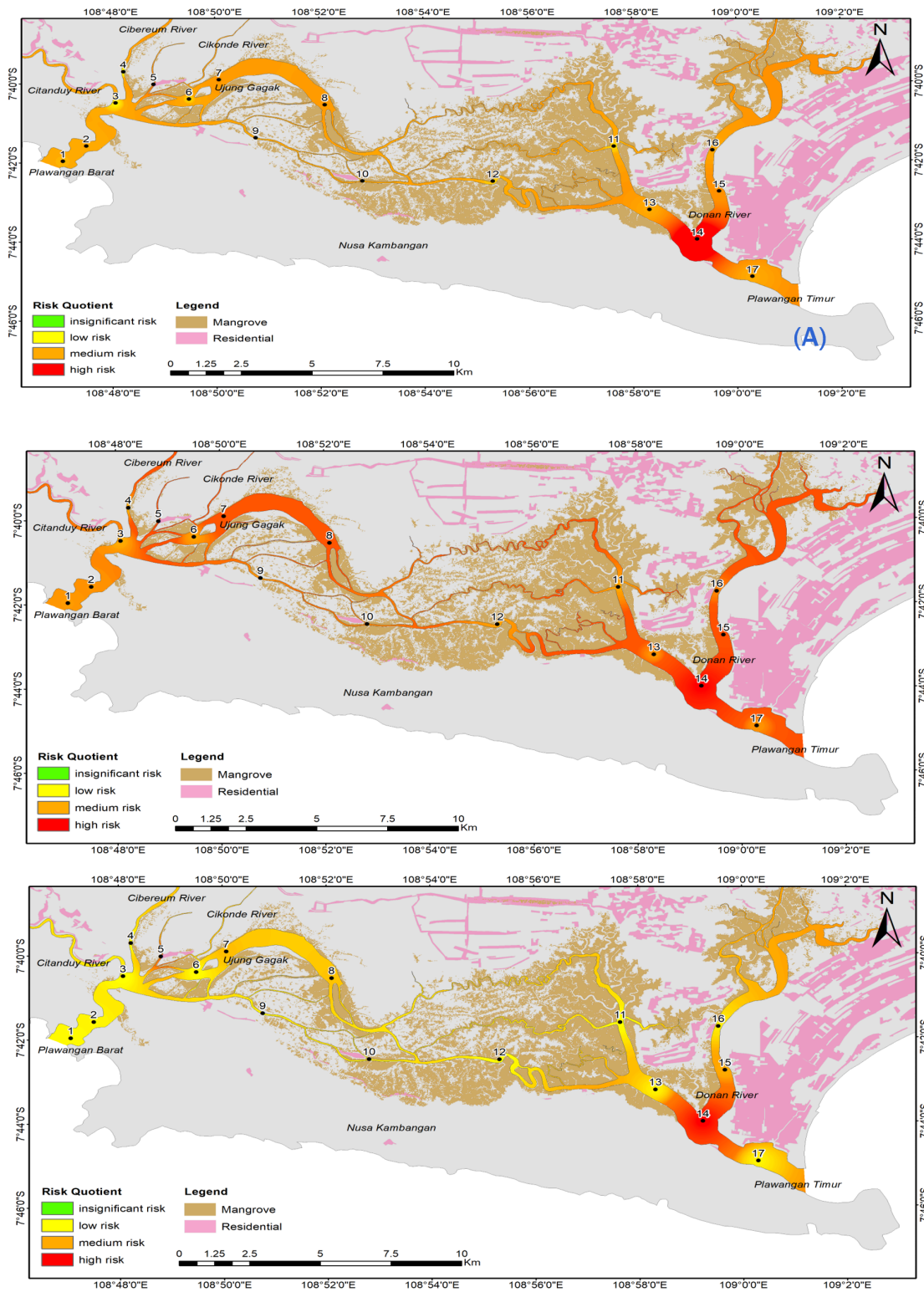


Figure 3

Distribution of the ecological risks of paracetamol for aquatic organisms in water for Algae (A), Invertebrates (B), and Fish (C)