Appendix (Supplementary Materials)

Appendix 1. Analysis of Aquaculture Waste Load Estimates

Analysis of estimates of pollutant load from aquaculture activities was conducted using formulae from Gompi et al. (2023):

- Food conversion rate = 1.8
- Left uneaten food = 15% of the food

$$\text{Food waste} = 15\% * (P/FCR)$$

Where,

FCR = food conversion rate, 1.8

P = aquaculture production, tonnes/year

Appendix 2. Analysis of Riverine Pollution Load Estimates

The analysis of river pollution load estimates use the formulae of (Environmental Ministry Decree Number 28/2009 about Carrying Capacity and Assimilative Capacity):

$$\text{Pollution load}_i = C_i \times Q$$

Where:

- C_i = Concentration of the *i*-pollutant (e.g., in **mg/L**)
- Q = Mean river flow rate or mean discharge (e.g., in **L/s** or **m³/s**)
- Pollution Load$_i$ (e.g., in **mg/s**, **kg/day**, depending on the unit conversion)

Data on annual mean concentration of the I- water quality parameter and mean river discharge were collected from environmental statistics of Indonesia.

Appendix 3. Methods for calculating River Water Quality (WRQI-IKA) (Environment and Forestry Ministerial Regulation No. 27 of 2021)

The IKA is a composite index summarizing key water quality parameters—including pH, BOD, COD, TSS, DO, NO_3-N, total phosphate, and fecal coliform counts—and is calculated using weighted sub-indices on a 0–100 scale. The classification thresholds used above are based on the standard national interpretation:

- Very Good: 90-100
- Good: 70-89
- Moderate: 50-69
- Poor: 25-49
- Very Poor: 10-24

For each water-use category *j* (e.g. domestic use, aquatic life), a Pollution Index (IP_n) is calculated using multiple water quality parameters:

$$IP_j = \sqrt{\frac{\frac{Ci}{Lij}M^2 + \frac{Ci}{Lij}R^2}{2}}$$

- Ci is the measured concentration of parameter *i* (e.g. DO, BOD, COD, pH, TSS, total phosphate, nitrate, fecal coliform).
- Lij is the regulatory standard (limit) for that parameter relative to water use *j* (e.g. Class II river standard per PP 22/2021).

Commonly measured parameters for Indonesian river WQI include:

- pH
- Dissolved Oxygen (DO)
- Biochemical Oxygen Demand (BOD_5)
- Chemical Oxygen Demand (COD)
- Total Suspended Solids (TSS)
- Nitrate (NO_3-N)
- Total Phosphate (T-Phosphate)
- Fecal Coliform (or Total Coliform)

Appendix 4. Methods for calculating Sea Water Quality Index (SWQI-IKAL)

Under Indonesia's Ministerial Regulation No. 27 of 2021, the IKAL is calculated using five key parameters, based on the NSF-WQI model adapted for marine waters:

- Total Suspended Solids (TSS)
- Dissolved Oxygen (DO)
- Oil and Grease
- Total Ammonia (NH_3-N)
- Ortho-Phosphate (PO_4-P)

These parameters were selected for their relevance to marine pollution sources and ecological impact, including turbidity, hypoxia, toxicity, and eutrophication potential.

The Marine Water Quality Index (IKAL) is calculated as the sum of the sub-indices of each seawater parameter, multiplied by the weight of each parameter

$$\text{IKAL} = \sum_{i=1}^{n} (W_i \times Q_i)$$

where mana:

- Q_i= sub-index of i-parameter ke-i
- W_i= weighted score of i-parameter
- n= number of parameter

Appendix 5. Analysis of Risk Assessment

Risk assessment is conducted using a risk analysis approach based on a simple formula that incorporates three key variables: probability, impacts, and adaptive capacity, within the context of a specific pollution scenario (Cornelly et al., 2018; Ortega et al., 2014).

The variables probability and impacts are positively correlated with the level of risk—meaning that as their values increase, the overall risk also increases. Conversely, adaptive capacity is negatively correlated to risk value.

Probability refers to the likelihood or potential for a specific pollution event to occur, which in this context is represented by the magnitude of pollution sources within a given area. Higher probability values indicate a greater risk. The probability is measured on a scale from 1 to 5. The data for this variable represents the likelihood of a specific type of pollution occurring, based on its pollution source. The data was collected through discussions during focus group discussions (FGDs) as well as from available secondary data, such as environmental statistics from a given region. FGD participants were asked to assign a probability score ranging from 1 to 5, where a score of 1 indicates low probability, and a score of 5 indicates high probability.

The next variable, impacts, comprises several sub-variables, including the existing water quality in the relevant coastal or marine waters, the deviation of parameter values from quality standards, social impacts, and ecological impacts. This variable is also positively correlated with the risk value—greater impacts are associated with higher levels of risk. Impacts are also scored on a scale from 1 to 5. Impact data represents the severity of the consequences resulting from a specific pollution contamination event in a given area. The impact data consists of the following variables: (1) sea water quality index (IPAL), (2) water quality status relative to standards, (3) social impacts, and (4) ecological impacts. Each variable is assigned a score ranging from 1 to 5. FGD participants were asked to determine the score, where a score of 1 indicates low impact and a score of 5 indicates high impact.

The final variable, adaptive capacity, represents the ability of a management unit to effectively manage a specific type of pollution within its administrative area. A higher adaptive capacity indicates stronger management capability, and therefore, is negatively correlated with risk. Adaptive capacity is also rated on a scale from 1 to 5. Based on this assessment, adaptive capacity consists of the following variables: (1) the level of existing pollution management, (2) availability of financial allocation, and (3) availability of regulations. The higher the aggregate capacity of a unit to manage pollution, the lower the resulting pollution risk. The formula for risk calculation is as follows:

Risk = (P * I)/AC, where:

- P = probability
- I = Impacts
- AC = Adaptive Capacity

The risk value, ranges from 0.2 to 25, with the following risk classification levels:

- Very low = 0.2 - 1.0
- Low = 1.0 - 3.0
- Moderate = 3.0 - 8.0
- High = 8.0 - 12.5

- Very High = 12.5 - 25

Appendix 6. Results of the risk assessment analysis for each type of pollution and administrative region (source: data analysis 2025)

Administrative Area	Type of pollution	Source of pollution	Probability		Impact					Adaptive Capacity				Risk	Class
			Source of pollutant (1-5)	Average Probability (1-5)	Sea Water Quality Index (1-5)	Status towards Standard (1-5)	Social impact (1-5)	Ecological Impact (1-5)	Average Impact (1-5)	Existing pollution management level (1-5)	Financial allocation availability (1-5)	Regulation availability (1-5)	Average AC	(0.2-25)	
Riau Archipelago Province															
Batam City and Bintan	Oil	seaport, oil facility, shipping activity	5	5	5	5	5	5	5.0	2	3	4	3.0	8.3	H
	Hazardous waste and heavy metals	industry	5	5	4	4	3	4	3.8	3	3	4	3.3	5.6	M
	Plastic-marine debris	Domestics	4	4	3	3	4	4	3.5	3	3	4	3.3	4.2	M
	Organics/nutrients	Domestic, agriculture, aquaculture	5	5	5	5	4	4	4.5	3	3	4	3.3	6.8	M
	E-Coli and bacteria	Domestics	5	5	5	5	4	3	4.3	3	3	4	3.3	6.4	M
	Pesticides	Agriculture	3	3	2	2	2	2	2.0	3	3	3	3.0	2.0	L
	TSS	Mineral Mining and sand mining	5	5	4	5	4	5	4.5	2	3	4	3.0	7.5	M
Bangka Belitung Province															
	Oil	seaport, oil facility, shipping activity	4	4	3	3	3	3	3.0	2	3	4	3.0	4.0	M
	Hazardous waste and heavy metals	industry, mineral mining	3	3	3	3	3	3	3.0	3	3	4	3.3	2.7	L

Administrative Area	Type of pollution	Source of pollution	Probability		Impact					Adaptive Capacity				Risk	Class
			Source of pollutant (1-5)	Average Probability (1-5)	Sea Water Quality Index (1-5)	Status towards Standard (1-5)	Social impact (1-5)	Ecological Impact (1-5)	Average Impact (1-5)	Existing pollution management level (1-5)	Financial allocation availability (1-5)	Regulation availability (1-5)	Average AC	(0.2-25)	
	Plastic-marine debris	Domestics	5	5	4	4	4	3	3.8	3	3	4	3.3	5.6	M
	Organics/nutrients	Domestic, agriculture, aquaculture	5	5	4	4	3	3	3.5	3	3	4	3.3	5.3	M
	E-Coli and bacteria	Domestics	5	5	5	5	4	3	4.3	3	3	4	3.3	6.4	M
	Pesticides	Agriculture	3	3	2	3	2	2	2.3	3	3	4	3.3	2.0	L
	TSS	Mineral Mining and sand mining	5	5	5	5	4	5	4.8	3	3	4	3.3	7.1	H
West Kalimantan															
	Oil	seaport, oil facility, shipping activity	3	3	3	3	3	3	3.0	3	3	4	3.3	2.7	L
	Hazardous waste and heavy metals	industry, mineral mining	4	4	4	3	3	4	3.5	3	3	4	3.3	4.2	M
	Plastic-marine debris	Domestics	4	4	4	4	4	4	4.0	3	3	4	3.3	4.8	M
	Organics/nutrients	Domestic, agriculture, aquaculture	5	5	5	5	3	3	4.0	3	3	4	3.3	6.0	M
	E-Coli and bacteria	Domestics	5	5	5	5	3	3	4.0	3	3	4	3.3	6.0	M
	Pesticides	Agriculture	4	4	3	3	3	3	3.0	3	3	4	3.3	3.6	M
	TSS	Mineral Mining and sand mining	4	4	4	4	3	4	3.8	3	3	4	3.3	4.5	M

Appendix 7. Types of pollution and government actions against marine pollution

No	Type of Pollution	Location	Pollution Status	Mitigation and Prevention Measures/ Efforts
1	Oil Pollution	Riau Islands Province	Moderate (2020) and Good (2021) (source: 2020-2021 Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province) Good (source: Q1 2025 Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province)	1. Environmental Pollution and/or Damage Control Program: Coordination, Synchronization, and Implementation of Greenhouse Gas Emission Control, Climate Change Mitigation and Adaptation 2. Environmental Complaint Handling Program 3. Hazardous and Toxic Materials (B3) and Hazardous Waste (B3 Waste) Control Program (source: 2024 Work Agreement, 2024 Government Agency Performance Report, 2025 Annual Work Plan, 2021-2026 Strategic Plan DLHK/ Environmental and Forestry Agency of Riau Islands Province)
	Oil Pollution	Batam City	Moderate (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)	1. Environmental Planning Program 2. Environmental Pollution and/or Damage Control Program 3. Environmental Education, Training, and Community Outreach Program (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)
	Oil Pollution	Bintan Regency	Black oil waste found along the coast of Bintan Regency. This is not the first occurrence; oil spills happen every year. (source: Agusthin *et al*. 2024)	1. Sent letter to the Ministry of Environment regarding water pollution on Bintan Island by Bintan Environmental Agency Held Oil Spill Coordination 2. Meeting attended by various agencies such as the Coordinating Ministry for Maritime Affairs, BAKAMLA/ Indonesian Maritime Security Agency, and others 3. Collaboration between DLHK/ Environmental and Forestry Agency of Riau Islands Province, Bintan Environmental Agency, and coastal communities

No	Type of Pollution	Location	Pollution Status	Mitigation and Prevention Measures/ Efforts
				for cleaning black oil waste; collected into drums for transport to B3 Waste Management Facility in Batam 4. Issued Decree on Formation of Oil Spill Response Team in Riau Islands Province (Governor Decree No. 742/2018 dated 14 May 2018) (source: Agusthin *et al*. 2024) (source: Agusthin *et al*. 2024)
	Oil Pollution	Nationwide	-	Oil spill pollution mitigation (10 locations): 1. Pulau Bintan 2. Provinsi Aceh 3. Provinsi Banten 4. Provinsi Jawa Barat 5. Provinsi Jawa Tengah 6. Provinsi Nusa Tenggara Barat 7. Provinsi Nusa Tenggara Timur 8. Provinsi Sulawesi Selatan 9. Provinsi Maluku 10. Provinsi Maluku Utara (source: 2024 Action Plan and 2024 Performance Report Directorate of Coastal and Marine Pollution and Damage Control, KLHK/ The Ministry of Environment and Forestry)
2	Marine Debris	Riau Islands Province	Moderate (2020) and Good (2021) (source: 2020-2021 Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province) Good (source: Q1 2025 Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province)	1. Environmental Pollution and/or Damage Control Program: Coordination, Synchronization, and Implementation of Greenhouse Gas Emission Control, Climate Change Mitigation and Adaptation 2. Environmental Planning Program: Preparation and Implementation of SEA for Development Plans with Potential Environmental Impact/Risk 3. Environmental Complaint Handling Program 4. Waste Management Program: Provision of Waste Handling Facilities at Regional Final Disposal Site (TPA)/ Integrated Waste Processing Facility (Integrated Waste Processing Facility) 5. Watershed Management Program: Implementation of Inter-District/City and Intra-Province Watershed Management (source: 2024 Work Agreement, 2024 Government Agency Performance Report, 2025 Annual Work Plan, 2021-2026 Strategic Plan DLHK/ Environmental and Forestry Agency of Riau Islands Province; 2024 Work Agreement and 2024 Government Agency Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province)

No	Type of Pollution	Location	Pollution Status	Mitigation and Prevention Measures/ Efforts
	Marine Debris	Batam City	Moderate (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)	1. Environmental Planning Program 2. Environmental Pollution and/or Damage Control Program 3. Environmental Education, Training, and Community Outreach Program 4. Domestic Waste Management Facility 5. Muka Kuning WTP Construction 6. Development of Sewage System in Batam 7. Wastewater Management and Development 8. Waste Management Program (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)
	Marine Debris	Nationwide	-	1. Marine debris and microplastic monitoring (24 provinces): 1. Aceh 2. Sumatera Utara 3. Kepulauan Riau 4. Sumatera Barat 5. Sumatera Selatan 6. Bangka Belitung 7. Lampung 8. Banten 9. Jawa Barat 10. DKI Jakarta 11. Jawa Tengah 12. Jawa Timur 13. D.I. Yogyakarta 14. Bali 15. Nusa Tenggara Barat 16. Nusa Tenggara Timur 17. Kalimantan Barat 18. Kalimantan Timur 19. Sulawesi Utara 20. Gorontalo 21. Sulawesi Selatan 22. Sulawesi Tengah 23. Maluku 24. Papua Barat 2. Technical approval for wastewater discharge into the sea (50 proposals) (source: 2024 Action Plan and 2024 Performance Report Directorate of Coastal and Marine Pollution and Damage Control, KLHK/ The Ministry of Environment)
3	Hazardous Pollution	Riau Islands Province	Moderate (2020) and Good (2021) (source: 2020-2021 Performance Report DLHK/ Environmental and Forestry Agency of Riau Islands Province) Good (source: Q1 2025 Performance Report	1. Environmental Pollution and/or Damage Control Program: Coordination, Synchronization, and Implementation of Greenhouse Gas Emission Control, Climate Change Mitigation and Adaptation 2. Environmental Complaint Handling Program 3. Hazardous and Toxic Materials (B3) and Hazardous Waste (B3 Waste) Control Program 4. Hazardous and Toxic Materials (B3) and Hazardous Waste (B3 Waste) Control Program

No	Type of Pollution	Location	Pollution Status	Mitigation and Prevention Measures/ Efforts
			DLHK/ Environmental and Forestry Agency of Riau Islands Province)	(source: 2024 Work Agreement, 2024 Government Agency Performance Report, 2025 Annual Work Plan, 2021-2026 Strategic Plan DLHK/ Environmental and Forestry Agency of Riau Islands Province)
	Hazardous Pollution	Batam City	Moderate (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)	1. Environmental Planning Program 2. Environmental Pollution and/or Damage Control Program 3. Environmental Education, Training, and Community Outreach Program 4. Hazardous Waste Management Facility (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)
4	Habitat Degradation	Batam City	Moderate: Illegal Sand Mining (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)	1. Environmental Planning Program 2. Environmental Pollution and/or Damage Control Program 3. Environmental Education, Training, and Community Outreach Program (source: Executive Summary of 2024 Environmental Management Performance Information DLH/ Environmental Agency of Batam City)
	Habitat Degradation	Nationwide	-	1. Marine Water Quality Monitoring (37 provinces) 2. Marine Water Quality Index Formulation (37 provinces) 3. Port performance evaluation (36 ports): 1. PT Pelabuhan Indonesia (Persero) Cabang Lhokseumawe 2. PT Pelabuhan Indonesia (Persero) Cabang Malahayati 3. PT Pelabuhan Indonesia (Persero) Cabang Belawan 4. PT Pelabuhan Indonesia (Persero) Cabang Kuala Tanjung 5. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Balai Karimun 6. Badan Pengelola Pelabuhan Batam- Operasional Pelabuhan Batu Ampar 7. PT Pelabuhan Indonesia (Persero) Cabang Teluk Bayur 8. PT Pelabuhan Indonesia (Persero) Cabang Dumai 9. PT Pelabuhan Indonesia (Persero) Cabang

No	Type of Pollution	Location	Pollution Status	Mitigation and Prevention Measures/ Efforts
				Palembang 10. PT Pelabuhan Indonesia (Persero) Cabang Bengkulu 11. PT Pelabuhan Indonesia (Persero) Cabang Panjang 12. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Pandan 13. PT Pelabuhan Indonesia (Persero) Cabang Pangkal Balam 14. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Priok 15. PT Pelabuhan Indonesia (Persero) Cabang Banten 16. PT Pelabuhan Patimban Internasional 17. PT Pelabuhan Indonesia (Persero) Cabang Cirebon 18. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Emas 19. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Intan 20. PT Pelabuhan Indonesia (Persero) Cabang Tanjung Perak 21. PT Pelabuhan Indonesia (Persero) Cabang Teluk Lamong 22. PT Pelabuhan Indonesia (Persero) Cabang Lembar 23. PT Pelabuhan Indonesia (Persero) Cabang Tenau Kupang 24. PT Pelabuhan Indonesia (Persero) Cabang Labuan Bajo 25. PT Pelabuhan Indonesia (Persero) Cabang Pontianak 26. PT Pelabuhan Indonesia (Persero) Cabang Banjarmasin 27. PT Pelabuhan Indonesia (Persero) Cabang Balikpapan 28. PT Kaltim Kariangau Terminal 29. PT Pelabuhan Indonesia (Persero) Cabang Bitung 30. PT Pelabuhan Indonesia (Persero) Cabang Manado 31. PT Pelabuhan Indonesia (Persero) Cabang Gorontalo 32. PT Pelabuhan Indonesia (Persero) Cabang Makassar 33. PT Pelabuhan Indonesia (Persero) Cabang Ambon 34. PT Pelabuhan Indonesia (Persero) Cabang Manokwari 35. PT Pelabuhan Indonesia (Persero) Cabang Sorong 36. PT Pelabuhan Indonesia (Persero) Cabang Jayapura 4. Seagrass/coral reef ecosystem restoration (11 locations): 1. Gorontalo 2. Maluku 3. Kalimantan Timur 4. DKI Jakarta 5. Sulawesi Selatan 6. Sulawesi Tenggara 7. Sulawesi Tengah 8. Bengkulu 9. Nusa Tenggara Timur 10. Bali 11. Jawa Timur (source: 2024 Action Plan and 2024 Performance Report Directorate of Coastal and Marine Pollution and Damage Control, KLHK/ The Ministry of Environment)