

6.2 Meteorological influences

Meteorological forcing alters stratification, circulation, and external inputs, thereby reshaping water quality around cage farms. Remote-sensing analysis of Typhoon In-fa in the Zhoushan fishery showed that strong vertical mixing from the typhoon led to a marked decrease in sea surface temperature, with more intense cooling on the right side of the track due to asymmetric wind stress and pre-existing temperature structure (Tang et al., 2023). Despite mixing and inflow of hypersaline water, intense rainfall and diluted water input caused an overall post-typhoon decrease in sea surface salinity, illustrating how wind and rain jointly modify the hydrographic context in which cages operate.

Typhoons also directly affect wave and current regimes, with implications for cage integrity and water exchange. Simulation of typhoon Rammasun in Maniao Bay predicted that during the storm, significant wave height in the cage area exceeded 5.5 m and maximum flow velocity reached about $1.5 \text{ m} \cdot \text{s}^{-1}$, surpassing the design carrying capacity of deep-water cages and leading to potential deformation or damage (Zhang et al., 2024). Broader reviews of mariculture net-cage disasters in China emphasize that strong winds and waves associated with typhoons can cause overtopping, frame collapse, and structural instability, producing abrupt changes in the rearing environment that depress growth and increase disease and escape risk.

6.3 Pollution inputs from surrounding marine areas

External pollution inputs from the wider marine environment interact with farm-derived wastes to shape water quality in cage-culture zones. An evaluation of marine aquaculture areas using principal component analysis showed that in cage regions, chlorophyll a, salinity, and dissolved oxygen were dominant factors, while antibiotic resistance genes (ARGs) appeared more diverse and frequent in cages than ponds, suggesting terrestrial inputs contribute to pollution signatures beyond farm discharges alone. In Lake Victoria, comparisons along a strong background eutrophication gradient indicated that terrestrial and other non-cage sources were the major drivers of gulf-wide nutrient enrichment, with cage farms showing no significantly higher nutrient enrichment or turbidity than ambient conditions at paired control sites (Okechi et al., 2022).

At the same time, cumulative nutrient outputs from multiple farms can contribute substantially to regional nutrient budgets and interact with external sources. A global synthesis estimated that each ton of fish produced in marine cages releases on the order of $132.5 \text{ kg} \cdot \text{Nitrogen}$ and $25 \text{ kg} \cdot \text{Phosphorus}$, raising concern that additive discharges from many farms, together with other coastal inputs, may enhance primary production and eutrophication in intensively farmed regions. Long-term analysis in Sansha Bay quantified large percentage increases in sediment heavy metals and substantial enhancements of dissolved inorganic nitrogen and phosphorus attributable to cage culture compared with conservative mixing, demonstrating how aquaculture activities amplify contamination on top of natural and external background processes in semi-enclosed coastal systems (Song et al., 2023).

7 Case Study: Water Quality Dynamics in a Typical Grouper Cage Aquaculture Area

7.1 Study area description and monitoring design

A representative example of grouper cage aquaculture is found in Xincun Port, Lingshui County (Hainan, China), where fixed marine cages dominate the sheltered inner bay. All sampling sites in the aquaculture area are fixed cages with the net body extending 0.7-1.0 m above the surface and 1.5-2.5 m below, stocked exclusively with giant grouper (*Epinephelus lanceolatus*). The farming zone is embedded within a semi-enclosed port that also contains nearby non-aquaculture waters, providing a natural reference for assessing aquaculture impacts under similar hydrological conditions (Liu et al., 2024).

Water quality monitoring in this case followed an integrated design combining in situ profiling and laboratory analyses. Surface water (~1 m depth) was sampled once in May from three aquaculture cages and three non-aquaculture sites, with temperature, dissolved oxygen, conductivity, salinity, redox potential and pH measured immediately using a handheld multiparameter meter. Bulk water was then filtered for colorimetric determination of ammonium, nitrite, nitrate and soluble reactive phosphorus, allowing calculation of dissolved inorganic nitrogen and construction of a multi-indicator dataset linking physicochemical conditions to microbial communities.