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Effects of Continuous Rainfall on Water Environment and Health in Giant Freshwater Prawn Farming

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Abstract Continuous rainfall is an important environmental disturbance in giant freshwater prawn (*Macrobrachium rosenbergii*) farming, particularly in high-density pond culture systems. Unlike short-term rainfall events, prolonged rainfall can cause repeated and cumulative changes in water temperature, dissolved oxygen, pH, salinity, turbidity, nutrient concentrations, and sediment conditions, thereby reducing the stability of the culture environment. This review summarizes the major effects of continuous rainfall on the water environment and health of giant freshwater prawns, with particular attention to the interactions among physicochemical conditions, nutrients, microbial communities, and host responses. Continuous rainfall can alter nitrogen cycling and organic matter dynamics, resulting in fluctuations or accumulation of ammonia nitrogen and nitrite, while increased runoff and sediment disturbance may further elevate turbidity and suspended solids. At the microbial level, rainfall-induced environmental changes can restructure phytoplankton and bacterial communities, including changes in *Chlorophyta*, *Bacillariophyta*, *Bacteroidetes*, and cyanobacterial populations, which may subsequently influence nutrient transformation and oxygen dynamics. For giant freshwater prawns, these environmental fluctuations may affect feeding activity, osmoregulation, gill function, oxidative balance, immune responses, growth, and disease susceptibility. The combined effects of hypoxia, temperature fluctuations, and nitrogenous compounds may further increase physiological stress during prolonged rainfall. A case study framework is also proposed to integrate changes in water quality, microbial communities, and prawn health before, during, and after continuous rainfall events. Finally, adaptive management strategies involving real-time water-quality monitoring, aeration, nutrient regulation, rainfall forecasting, and early-warning systems are discussed. Understanding the coupled interactions between continuous rainfall, aquatic environmental processes, microbial communities, and host health may provide a scientific basis for improving the resilience and sustainability of giant freshwater prawn farming under increasingly variable weather conditions.

Keywords Continuous rainfall; Giant freshwater prawn; Water quality; Microbial community; Aquaculture health

1 Introduction

Giant freshwater prawn (*Macrobrachium rosenbergii*) farming has become an important component of tropical and subtropical aquaculture because the species is widely cultured, commands strong market demand, and supports both domestic consumption and export trade (Pillai et al., 2022). Over recent decades, this industry has expanded from a relatively small production base into a globally significant freshwater crustacean sector, reflecting its adaptability to diverse farming environments and its value to rural livelihoods and commercial supply chains. Recent estimates further show that global production remains substantial, with output exceeding 300,000 t in 2021 and a market value above USD 2.45 billion, underscoring the species' economic relevance for major producing countries in Asia and beyond. At the same time, the production chain of *M. rosenbergii* is increasingly viewed not only as a food-producing system but also as a development pathway that can generate income, employment, and relatively low environmental burdens when culture is managed responsibly (Haslawati et al., 2022).

Despite this importance, giant freshwater prawn farming remains highly sensitive to environmental variability because pond-based production depends on relatively narrow ranges of water quality, hydrology, and husbandry stability. Across aquaculture systems, rainfall fluctuations can alter key pond conditions such as salinity, dissolved

oxygen, sediment loading, and nutrient transport, while extreme or prolonged rainfall can also trigger flooding, drainage failure, and biosecurity disruption. Studies from pond culture systems show that rainy periods increase water flow and carry suspended particles, organic matter, and dissolved materials between connected ponds, thereby reshaping limnological conditions and sometimes intensifying downstream water-quality deterioration. Seasonal evidence from intensive shrimp ponds likewise indicates that rainy conditions are associated with stronger fluctuations in phosphate, nitrite, and total organic matter than dry-season conditions, reinforcing the view that persistent rainfall acts as a major driver of pond-water instability rather than a simple background weather variable (Ariadi et al., 2023).

For cultured crustaceans, such hydro-environmental instability matters because changes in oxygen, salinity, pH, nitrogenous wastes, and temperature can directly influence stress physiology, immune performance, and disease susceptibility. Environmental stressors in aquatic systems can weaken immune function and increase vulnerability to infection, especially when exposures are chronic or occur in combination with other production stressors. In crustacean aquaculture more broadly, abiotic stress is recognized as a major factor compromising growth, health, and immunity, and disease outbreaks in pond systems are increasingly linked to periods of extreme weather that drive abrupt deterioration in physicochemical conditions. This general concern is especially relevant to *M. rosenbergii*, a species already affected by a growing range of viral and bacterial diseases as production expands, including host-specific and emerging pathogens that threaten survival, profitability, and trade (Zhao et al., 2022). The culture cycle also contains multiple points at which water-quality disturbance can promote pathogen introduction or transmission, which is why disease management has become central to the long-term sustainability of the industry.

Against this background, the present review focuses on the effects of continuous rainfall on the water environment and health status of giant freshwater prawn farming systems. Its first objective is to synthesize how prolonged rainfall modifies pond-water characteristics, including hydrological exchange, suspended solids, nutrient dynamics, oxygen conditions, and related parameters that structure the pond environment. Its second objective is to examine how these rainfall-driven changes can translate into biological stress, impaired health, and greater disease risk in cultured prawns through pathways involving unstable physicochemical conditions and weakened biosecurity. The scope therefore spans environmental disturbance, host health, and farm-level risk, with emphasis on linking water-quality processes to practical concerns in grow-out systems. By bringing these dimensions together, the review aims to clarify why continuous rainfall should be treated as an emerging management issue in freshwater prawn aquaculture and to identify the knowledge base needed for more climate-resilient farming.

2 Characteristics of Continuous Rainfall and Responses of Aquaculture Systems

2.1 Rainfall characteristics and hydrological disturbance

Continuous rainfall in aquaculture is best understood as a sequence of repeated wet-weather inputs that alters pond hydrology through runoff, inflow, drainage pressure, and enhanced exchange between ponds and surrounding landscapes. In pond systems, rainy periods produce more dynamic water-quality behavior than dry periods, and rainfall can drive both nutrient dilution and the transport of suspended particles, sediments, and external materials from pond margins and connected waterways into culture units (Ariadi et al., 2023). Where ponds are shallow or connected in series, this disturbance becomes cumulative because rainfall-induced flow redistributes particles and dissolved materials from one unit to the next, amplifying siltation and uneven loading across the farm.

The hydrological effects of continuous rainfall also depend on pond configuration, connectivity, and rainfall intensity. In high-rainfall settings, heavy runoff produces direct inflow that changes incoming water temperature and promotes mixing between deeper and surface layers, while extreme rainfall and drainage failure can inundate ponds, increase sedimentation, and create escape and biosecurity risks. Hatchery and pond systems are therefore vulnerable not only to water-quality deterioration but also to physical disruption, as erratic rainfall, flash flooding, and heavy storms can wash away broodstock or seed and interrupt normal aquaculture operation.

2.2 Physical changes in pond water

Under continuous rainfall, the most immediate physical changes in pond water are shifts in temperature, salinity, transparency, and vertical structure. Rainy seasons are associated with oscillatory rainfall and temperature variation that make pond conditions more unstable, and in open ponds rainfall inflow can directly disturb water quality through external water entry (Ariadi et al., 2023). In brackish and saline ponds, rainfall can also generate salinity stratification or a halocline, and this density layering can interrupt vertical mixing and alter the distribution of turbidity and dissolved oxygen through the water column.

Rainfall also reduces water clarity by increasing suspended solids and resuspending bottom particles, although the exact mechanism can vary across pond types. In shallow systems, rainfall increases turbidity through sediment resuspension and reduced light penetration, while during rainy seasons pond brightness tends to be lower because suspended mud, floc, lime particles, and plankton-derived materials accumulate in the water column. The resulting physical structure is not always simple dilution: in saline ponds, rainfall-induced heat storage layers have been linked to correlated variation in temperature, turbidity, and dissolved oxygen, indicating that prolonged rainfall can reorganize the pond water column rather than only freshen it.

2.3 Chemical changes induced by rainfall

Continuous rainfall changes pond chemistry by altering pH, dissolved oxygen, nitrogen compounds, organic matter, and nutrient delivery from both sediments and catchment runoff. Rainfall can lower pH through acidic runoff, reduced sunlight, and carbon dioxide accumulation, and rainy-weather observations showed much stronger daily instability of pH and dissolved oxygen than sunny conditions. These shifts matter because pH and ammonia toxicity are tightly linked in aquaculture systems, and even moderate but repeated chemical fluctuations can increase physiological stress and reduce production performance.

Nitrogen and phosphorus dynamics also become less stable during prolonged rainfall because runoff imports pollutants and because mixing can mobilize nutrients already stored within the pond. Excess rainfall has been linked to increased ammoniacal nitrogen after polluted surface runoff enters ponds, while rainy-season pond studies reported phosphate, nitrite, and total organic matter above aquaculture thresholds (Ariadi et al., 2023). Sediments further intensify this process because they can act as a net nutrient source to the overlying water, especially for ammonium, and post-monsoon pond waters have shown elevated ammonia and biochemical oxygen demand beyond standard limits in intensive aquaculture areas.

3 Effects of Continuous Rainfall on Nutrients and Water Quality

3.1 Nitrogen dynamics and accumulation of toxic nitrogen compounds

Continuous rainfall can intensify nitrogen instability in aquaculture ponds by importing nitrogen-rich runoff while simultaneously disrupting in-pond transformation pathways. In pond systems, excess nitrogen beyond assimilatory capacity leads to deterioration of water quality through the accumulation of toxic ammonia and nitrite, and feeding remains the main nitrogen input driving the buildup of ammonia, nitrite, and nitrate in shrimp culture water (Chen et al., 2024). Rainfall then adds an external loading pathway, because high runoff during the rainy season has been shown to increase NH3-N and NO_3-N in reservoir aquaculture waters by transporting agricultural, domestic, and livestock wastes from the watershed (Wiranegara et al., 2023).

Rainfall-associated nitrogen risk is amplified by the role of sediments, which act not only as nutrient stores but also as active internal sources of toxic nitrogen compounds. In intensive shrimp ponds, sediment porewater NH_4^+-N averaged 29.68 times higher than the overlying water, and net sediment-to-water nutrient release was observed, with fluxes dominated by ammonium. This helps explain why rainy-season pond conditions often become chemically unstable: in intensive ponds, nitrite exceeded aquaculture thresholds during the rainy season, while comparative pond studies found ammonium and nitrite reached 4.14 mg/L and 0.29 mg/L, respectively, under nutrient-imbalanced conditions (Bai et al., 2022; Ariadi et al., 2023).

3.2 Phosphorus, organic matter and nutrient availability

Continuous rainfall alters phosphorus and organic matter dynamics through both catchment delivery and internal pond recycling. Monsoon-scale rainfall strongly affected nutrient regimes, and runoff increased total phosphorus inflow and eutrophication tendency in receiving waters, while in aquaculture-influenced reservoirs high rainfall transported agricultural, domestic, and livestock wastes that increased PO_4 and sediment phosphorus (Wiranegara et al., 2023). In pond culture, this pattern appears as rainy-season enrichment and instability rather than simple dilution, because phosphate and total organic matter exceeded aquaculture threshold values during the rainy season.

Rainfall effects on phosphorus availability also depend on sediment processes and organic matter decomposition, which can release previously stored nutrients back into the water column. Converted aquaculture ponds showed markedly enhanced labile phosphorus and soluble reactive phosphorus across sediment-water profiles, with strong internal release and fast kinetic exchange at the sediment-water interface (Hu et al., 2023). At the same time, phosphorus cycling is tightly linked to organic matter: higher total phosphorus accelerated nitrogen regeneration through extracellular enzyme activity in ponds, and redox changes caused by enzyme-mediated decomposition of proteins and lipids were identified as an important mechanism promoting sediment phosphorus release (Bai et al., 2022).

3.3 Turbidity, suspended solids and sediment disturbance

Continuous rainfall rapidly increases turbidity and suspended solids by mobilizing catchment particles and resuspending previously deposited sediments. Storm runoff is typically very turbid and rich in organic matter, and flood-period inflow increased turbidity to 73.75 NTU while generating stratified water-quality structure in the reservoir water column. At finer temporal scales, turbidity peaks closely track rainfall-driven streamflow peaks, and downstream turbidity rises sharply when rainfall intensity is high enough to generate strong surface runoff from farmed land. Ponds can trap suspended solids during moderate flows, but under continuous or intense rainfall they may become sources rather than sinks of sediment and associated pollutants. Connected ponds retained suspended solids and soluble reactive phosphorus during baseflow and some smaller storm events, yet large storm events caused resuspension of deposited sediment and net downstream loss of sediment and phosphorus (Figure 1) (Robotham et al., 2021). This event dependence is important for aquaculture interpretation, because rainfall changes not only suspended sediment load but also how turbidity reflects particle concentration: heavy rainfall triggers major sediment influxes, and the turbidity-suspended sediment relationship shifts with rainfall intensity and particle-size composition.

4 Continuous Rainfall and Aquatic Microbial Community Dynamics

4.1 Changes in phytoplankton and primary producers

Continuous rainfall can reorganize phytoplankton communities in aquaculture waters by simultaneously altering nutrient supply, thermal structure, and mixing intensity. Heavy rainfall has been shown to reset phytoplankton succession through hydrological pulses, and precipitation-driven shifts in nutrient levels and TN:TP ratios can move communities between diatom- and cyanobacteria-dominated states (Li et al., 2025). For giant freshwater prawn ponds, this means that prolonged wet periods are unlikely to cause simple dilution alone; rather, they create repeated disturbance-and-recovery cycles that favor opportunistic taxa able to respond quickly to unstable light and nutrient conditions. The biological response to rainfall is often time-lagged and directionally complex. After heavy rainfall, phytoplankton abundance and biomass can show a V-shaped trajectory, with *Cyanobacteria* and *Chlorophyta* recovering rapidly while *Bacillariophyta* respond later under turbidity-limited light, and rainstorms above 50 mm/d can immediately suppress cyanobacteria before diatoms peak first and cyanobacteria regain dominance about 20 days later (Li et al., 2025). In aquaculture settings, this instability matters because phytoplankton dynamics are linked to animal health, and more stable phytoplankton communities are associated with healthier shrimp culture environments (Lyu et al., 2021).

4.2 Responses of bacterial communities

Bacterial communities in pond water and sediment are highly responsive to rainfall-driven changes in oxygen,

turbidity, nitrogen, and phosphorus. During rainy seasons in eutrophic lakes, bacterial composition varies significantly over time, and the strongest correlates of community structure include pH, dissolved oxygen, turbidity, total nitrogen, ammonium, and nitrate. Flood-season work further shows that water-level fluctuations and frequent resuspension-deposition events redistribute bacteria between water and sediment, a mechanism directly relevant to shallow prawn ponds exposed to repeated runoff and sediment disturbance. Aquaculture studies indicate that these rainfall-sensitive communities are shaped mainly by inorganic nutrients and can shift toward more heterotrophic and potentially pathogenic assemblages under deteriorating water quality. In pond systems, nitrate, nitrite, ammonium, and phosphate are key drivers of bacterial community composition, while heterotrophic taxa such as *Actinobacteria*, *Flavobacteria*, and *Vibrio* become more abundant in culture water than in source water. This has direct health implications because higher NH_4^+-N increases the variety of pathogenic bacteria in pond water, and higher nitrogen levels can increase the relative abundance of genera such as Mycobacterium while culture pattern and species also shape pathogen structure (Niu et al., 2025).

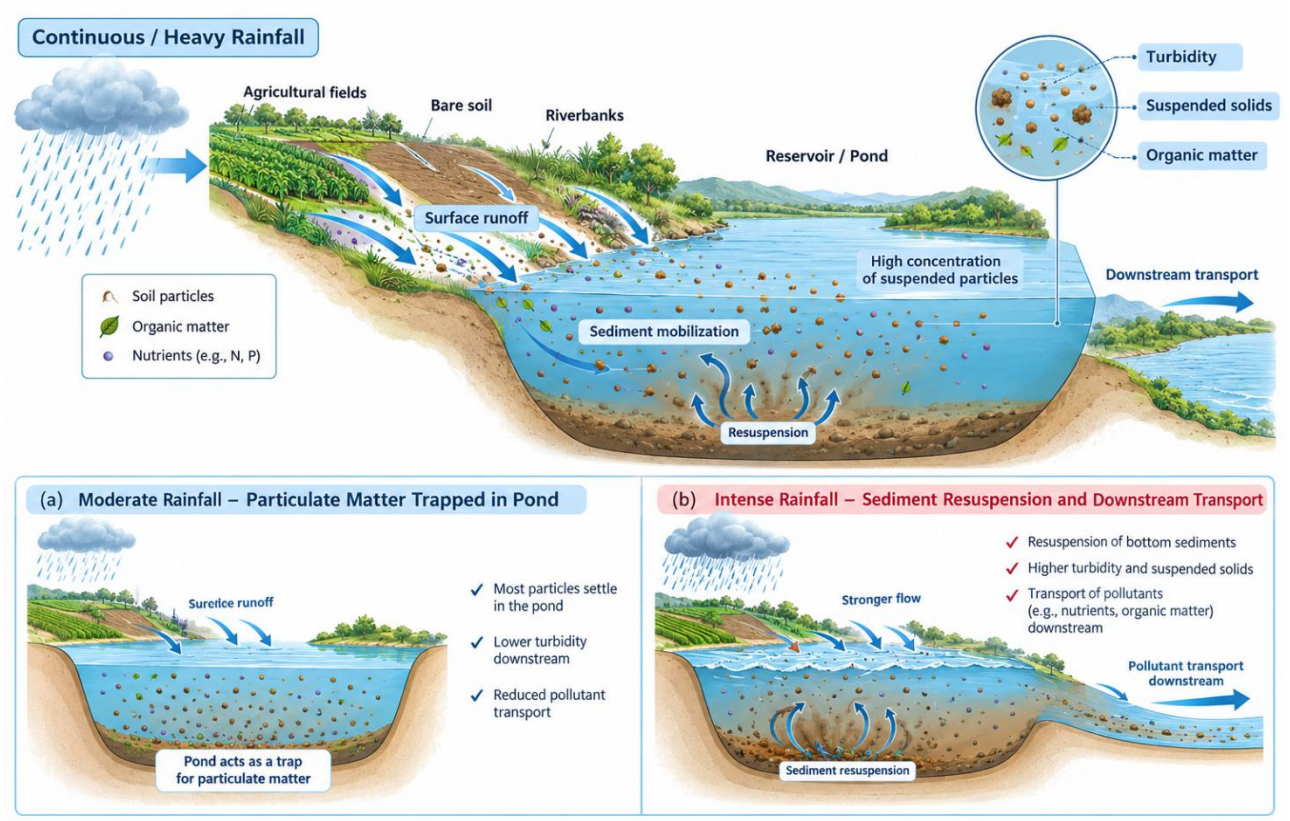


Figure 1 Conceptual pathway linking continuous rainfall, runoff, sediment mobilization, and turbidity increases in aquatic systems.

4.3 Microbial processes and biogeochemical cycling

Continuous rainfall affects not only microbial composition but also the functions microbes perform in nutrient cycling. Rainy-season bacterial communities show month-to-month variation in nitrogen, phosphorus, and sulfur metabolism, and these communities appear especially sensitive to nutrient loads and low dissolved oxygen during wet periods. More broadly, microorganisms regulate organic matter decomposition, primary production, nitrification, and denitrification across aquatic systems, and these functions are shaped by hydrological connectivity, redox gradients, temperature shifts, and nutrient loading-all processes intensified by sustained rainfall.

Evidence from aquaculture ponds shows that nutrient enrichment changes both microbial metabolism and the environmental outcomes of that metabolism. Pond environments increase bacterial functions linked to carbon and nitrogen metabolism, while metagenomic work in shrimp farming systems shows that carbon fixation and nitrogen, sulfur, and phosphorus cycling are all active and correlated with environmental conditions. Under higher nitrogen loading, aquaculture ponds emit more N_2O and shift toward ammonia-oxidizing bacteria-driven

nitrification, whereas alternative culture models such as rice-crayfish co-culture appear to favor nitrogen assimilation and pollutant removal rather than pathways that generate ammonium, nitrite, nitric oxide, and nitrous oxide

5 Physiological Responses and Health Effects in Giant Freshwater Prawn

5.1 Stress responses under rainfall-induced environmental fluctuations

Continuous rainfall exposes *Macrobrachium rosenbergii* to rapid shifts in salinity, temperature, and dissolved oxygen, all of which can trigger acute stress responses. Experimental evidence shows that prawns maintain normal behavior up to 10 ppt and below 30°C, but higher salinity or temperature causes abnormal behavior, sharp mortality, and reduced haemocyte-based immunity, indicating that rainfall-driven fluctuation beyond the normal tolerance window can quickly impair physiological stability (Bir et al., 2024). Oxygen decline is similarly damaging: exposure to 2.75 mg/L dissolved oxygen depressed total haemocyte count, phenoloxidase activity, respiratory burst, phagocytosis, and bacterial clearance, showing that hypoxia associated with prolonged cloudy, rainy conditions can weaken both stress tolerance and host defense (Cheng et al., 2002).

These stressors also alter metabolism and survival before overt mortality becomes widespread. Under moderate hypoxia, aerobic metabolism in muscle and swimming performance declined, and at lower oxygen both aerobic and anaerobic metabolism were suppressed, suggesting that prawns under rainfall-linked oxygen stress conserve energy at the cost of locomotor capacity and normal activity (Wang et al., 2023). Temperature stress produces a comparable oxidative trajectory: cold exposure caused early hepatocyte vacuolation, later structural deterioration and apoptosis, with antioxidant defenses rising initially and then falling as malondialdehyde increased, consistent with a transition from short-term compensation to cellular injury.

5.2 Gill Function, osmoregulation and oxidative stress

Gill tissues are among the first organs affected by rainfall-driven salinity and water-quality disturbance because they mediate both respiration and osmoregulation. Acute salinity stress increased hemolymph osmolality and produced marked gill injury, including reduced gill filament diameter and stronger apoptotic signals under higher salinity, indicating direct structural costs of osmoregulatory adjustment (Wang et al., 2023). Evidence from lower-salinity exposure further shows that osmoregulatory disruption is coordinated across the gills and antennal glands rather than confined to a single organ. Acute low-salinity stress caused thinning of gill filaments and disorganization of pillar cells, while also decreasing hemolymph sodium and potassium; with longer exposure, prawns increased gill Na^+/K^+-ATPase activity and antioxidant capacity, indicating partial acclimation but at physiological cost. Under ammonia exposure, gills also undergo progressive epithelial lifting, lamellar fusion, and hemocytic infiltration, while SOD and CAT rise adaptively under mild stress but are suppressed under severe exposure, showing that prolonged rainfall-related ammonia accumulation can convert compensatory oxidative responses into dysfunction (Liaqat et al., 2026).

Oxidative stress is a central mechanism linking environmental instability to tissue damage. In acute ammonia-N exposure, antioxidant enzymes in haemolymph and gill were significantly altered, and malondialdehyde increased after 72 h, indicating lipid peroxidation and systemic oxidative injury rather than a localized response alone (Dong et al., 2021). Salinity stress shows the same broader pattern: excessive stress promotes reactive oxygen species overproduction, and higher-salinity treatment produced stronger TUNEL-positive apoptosis in gills, tying osmotic disturbance directly to oxidative damage and cell death (Wang et al., 2023). When ammonia and hypoxia occur together, their effects are not simply additive but strongly synergistic. Survival fell to 2.8% in the high-TAN hypoxia group, while antioxidant defenses that rose under moderate stress were sharply suppressed under severe combined exposure and malondialdehyde increased steadily, indicating that rainfall episodes which couple oxygen depletion with nitrogen accumulation can overwhelm prawn defenses very quickly (Liaqat et al., 2026). Transcriptomic evidence supports this interpretation, because TAN-hypoxia co-stress downregulated mitochondrial oxidative phosphorylation and induced apoptotic regulators, linking poor pond conditions to metabolic reprogramming, irreversible oxidative injury, and flesh-quality deterioration.

5.3 Immune responses and disease susceptibility

Immune suppression is one of the clearest health consequences of rainfall-induced water-quality fluctuation in giant freshwater prawn. Salinity and ammonia stress both reduced granulocyte haemocyte counts and phenoloxidase activity during the initial exposure period, while proPO, crustin, and HSP70 expression were significantly downregulated across 3-168 h, showing that common rain-related stressors depress both cellular and molecular immunity (Jariyapong et al., 2020). A broader review of decapod immunity likewise found that low dissolved oxygen, abnormal pH, high temperature, and ammonia-N each decrease phenoloxidase activity in *M. rosenbergii*, thereby increasing susceptibility to bacterial infection. Disease risk rises further when stressed prawns encounter pathogens under suboptimal oxygen conditions. In challenge tests with Enterococcus, onset of mortality occurred within 6 h at 1.75 mg/L dissolved oxygen and within 12 h at 2.75 mg/L, and cumulative mortality was significantly higher at lower oxygen, directly demonstrating that hypoxia increases infection-related death. The range of pathogens relevant to prawn farming is broad, including host-specific agents such as white tail disease and pathogens shared with other crustaceans, so rainfall-driven physiological stress likely acts on an already diverse and expanding disease landscape.

Ammonia appears particularly important because it links deteriorating pond chemistry to both immune weakening and pathogen susceptibility. Experimental and review evidence indicates that ammonia exposure depresses immunity, increases susceptibility to pathogen invasion, and significantly affects osmoregulation, metabolic profiles, and immune function in crustaceans (Dong et al., 2021). At the biochemical level, acute salinity stress also reduced alkaline phosphatase activity and elicited immune stress, while high temperature and salinity reduced total and differential haemocyte counts, reinforcing that rainfall-linked water-quality instability can weaken host resistance through several overlapping pathways (Bir et al., 2024).

6 Interactions among Rainfall, Water Quality and Disease Risk

6.1 Synergistic effects of hypoxia, temperature and nitrogen stress

Under continuous rainfall, oxygen depletion, thermal fluctuation, and nitrogen accumulation are likely to interact synergistically because these stressors frequently co-occur in intensive prawn culture and jointly depress survival more strongly than either stress alone. In *Macrobrachium rosenbergii*, ammonia-hypoxia co-stress reduced survival to 2.8% in the high-TAN hypoxia group and caused progressive myofiber damage, showing that combined rainfall-driven deterioration can rapidly exceed the prawn's compensatory capacity (Liaqat et al., 2026).

The interaction is mechanistically consistent with broader stress physiology in this species. Hypoxia is already a major challenge in high-density prawn culture, with the gills acting as the primary functional organ during hypoxia-reoxygenation, while temperature or salinity beyond the tolerated range causes abnormal behavior, mortality, and declines in haemocyte-based immunity (Bir et al., 2024). At the immune level, ammonia-N at 0.55 mg/L or greater decreases phagocytic activity and clearance efficiency to *Lactococcus garvieae*, and temperatures of 35°C likewise depress immunity and increase mortality after pathogen exposure, indicating that rainfall-linked nitrogen and temperature instability can amplify infection risk through the same host-defense pathway.

6.2 Rainfall-driven pathogen and microbial risks

Rainfall-driven water-quality instability tends to increase microbial risk by raising turbidity, organic load, and nitrogen stress while lowering oxygen stability. Longitudinal pond observations showed that higher BOD/COD and turbidity were associated with elevated bacterial loads, and ammonia/nitrite, dissolved oxygen, turbidity, and organic load were consistent predictors of infection risk (Mutai et al., 2026). Similar pond-scale evidence from shrimp farming found that elevated ammonia and nitrite, low dissolved oxygen, and fluctuating pH were significantly correlated with greater bacterial pathogen loads, with *Vibrio* spp. the most prevalent group.

Rainfall can also intensify pathogen pressure by redistributing pathogens through hatchery-water connections and by favoring pathogen-enriched pond microbiota. Environmental DNA monitoring in Bangladesh detected substantially higher pathogen loads in hatcheries than in linked natural sites, with frequent co-infections and clear evidence of effluent spillover into surrounding waters (Hossain et al., 2026). In pond ecosystems, higher NH4+-N

increased the variety of pathogenic bacteria, while nitrogen and phosphorus concentrations were significantly correlated with genera such as *Aeromonas*, *Serratia*, and *Vibrio*, supporting the view that rainy-season nutrient pulses can restructure microbial communities toward greater disease risk (Figure 2) (Niu et al., 2025).

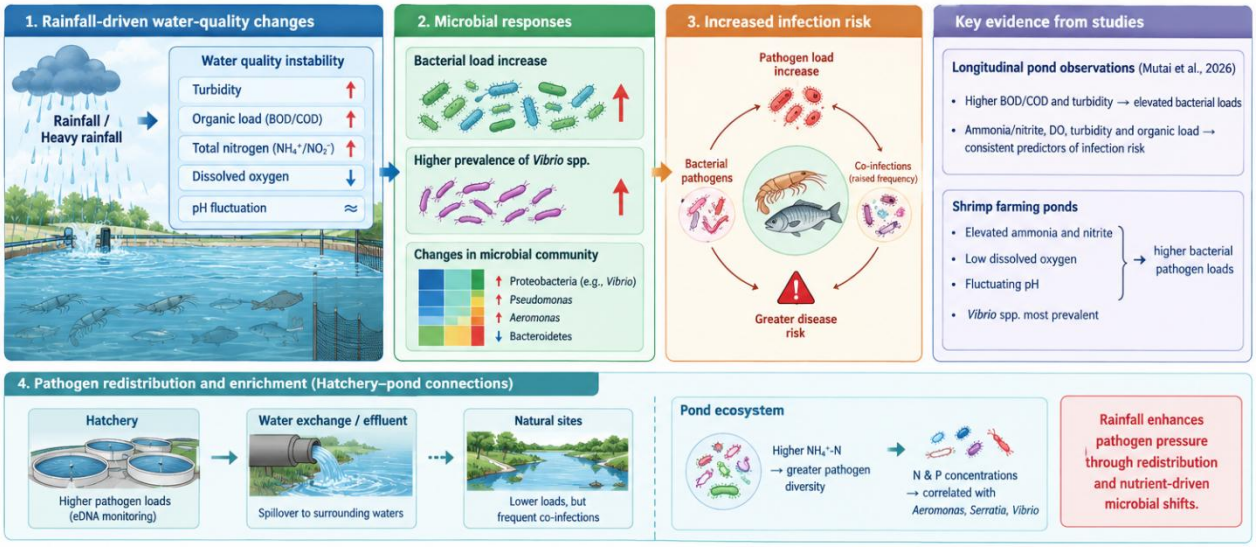


Figure 2 Rainfall-driven water-quality instability and its impact on microbial risk in aquaculture systems

6.3 From environmental instability to production losses

Once rainfall-driven instability weakens host physiology and elevates pathogen pressure, the outcome is often reduced survival, poorer growth, and lower market value rather than disease alone. In giant freshwater prawn farming, disease emergence has been accompanied by losses in yield, profit, and trading potential, and pathogens can reduce value not only through mortality but also by producing smaller or substandard animals. Sector-level assessments likewise identify disease outbreaks and low survival during grow-out as major reasons for declining prawn production and farmer profitability.

Environmental instability also undermines production indirectly by degrading water quality before clinical disease becomes obvious. In traditional *M. rosenbergii* monoculture, deteriorating water quality from effluent discharge is linked to frequent disease outbreaks, whereas integrated systems that improved dissolved oxygen and reduced phosphorus or phytoplankton pressure offered ecological benefits without reducing survival. More generally, chronic exposure to suboptimal water-quality variables stresses cultured animals and increases disease vulnerability, and pond water parameters show measurable associations with both yield and disease incidence, explaining why prolonged rainy periods can translate quickly into production losses even before mass mortality occurs.

7 Case Study: Continuous Rainfall Events in Giant Freshwater Prawn Farming

7.1 Environmental changes before, during and after continuous rainfall

Before prolonged rainfall, pond and intake-water conditions are generally more stable, but this stability erodes quickly once wet-season inputs begin. In shrimp ponds, dry-season water quality remained comparatively stable, whereas rainy-season conditions became dynamically fluctuating and pushed phosphate, nitrite, and total organic matter above aquaculture thresholds; similarly, rainfall events in tropical rivers sharply increased turbidity and nitrite while reducing transparency and pH after rain (Ariadi et al., 2023). For a giant freshwater prawn pond, the likely “during-rainfall” pattern is therefore a rapid transition from relatively predictable chemistry to a more oscillatory state characterized by runoff-driven nutrient pulses, lower clarity, and unstable acid-base conditions.

Storm-affected aquaculture waters show that this disturbance can persist beyond the rainfall itself because salinity, suspended solids, and other variables continue to shift during recovery. In coastal farming areas, Typhoon Yagi caused a marked September salinity drop from freshwater influx, while total suspended solids later rose toward

the end of the season; in smallholder ponds, seasonal water-quality shifts aligned closely with disease patterns, indicating that post-rain conditions remain biologically important rather than returning immediately to baseline (Van et al., 2025; Mutai et al., 2026).

7.2 Responses of microbial communities and giant freshwater prawn health

Once rainfall destabilizes pond chemistry, microbial communities appear to respond faster than the cultured animals themselves. Pond microbiota are strongly structured by NH_4^+-N, total nitrogen, nitrite, nitrate, and phosphorus, and increased NH_4^+-N significantly increases the variety of pathogenic bacteria; more broadly, unstable microbial environments are closely associated with disease occurrence in aquaculture systems (Niu et al., 2025). This implies that the microbial response to continuous rainfall is not only a community shift but also a shift toward higher pathogen opportunity, especially when nitrogen-rich runoff and sediment release coincide. For *Macrobrachium rosenbergii*, the health response is consistent with this microbial risk pattern because rainfall-related hypotonic stress and oxygen decline both weaken defenses. Hypotonic stress below 8‰ impaired immune function in post-larvae and enriched pathogenic bacteria such as *Vibrio* and *Flavobacterium*, while dissolved oxygen as low as 2.75-4.75 mg/L depressed immunity and increased susceptibility to *Enterococcus* infection.

7.3 Integrated Interpretation of Rainfall-Environment-Health Interactions

Taken together, the case-study sequence is best interpreted as a cascading interaction rather than a set of isolated stressors. Continuous rainfall alters hydrology and pollutant delivery, which changes water quality and eutrophication risk, while in ponds the small water volume and limited exchange allow physicochemical and biotic conditions to shift rapidly once disturbance begins (Niu et al., 2025). In this framework, the "before-during-after" pattern is a progression from baseline stability, to acute runoff and mixing disturbance, to a biologically amplified recovery phase in which sediment nutrients, microbial restructuring, and host stress can remain elevated after the rain stops. The health consequence is that environmental instability converts into disease pressure when host stress and pathogen opportunity rise at the same time. Seasonal disease work in aquaculture shows that opportunistic, r-strategist bacteria dominated during high-risk outbreak periods and reduced microbial network complexity, while giant freshwater prawn farming already faces a wide pathogen pool, including both host-specific and cross-species agents that affect yield and profit. The network pattern behind pathogen-prone community simplification is shown in a microbial interaction diagram where opportunistic taxa expand as community structure weakens.

8 Management Strategies and Future Perspectives

During continuous rainfall, water-quality management should prioritize rapid control of dissolved oxygen, turbidity, and nitrogenous wastes, because these variables shift quickly under hydrological disturbance and directly affect prawn stress and disease risk. Aeration remains a core intervention because low dissolved oxygen causes stress and lowers disease resistance in pond culture, while dissolved oxygen setpoint management can maintain production without unnecessary energy costs when control thresholds are chosen carefully. Rainfall management should also include pond-bottom and sediment remediation, because organic-rich, reduced sediments amplify ammonia, sulfide, and turbidity problems after disturbance. Drying pond bottoms, correcting acidic soils with agricultural limestone, and enhancing oxidation of reduced substances are established practices in pond aquaculture, while newer sediment-water interface treatments have maintained dissolved oxygen above about 2 mg/L for 21 days and removed 94% of ammonia, 89% of sulfide, and 93% of turbidity under simulated pond conditions. The treatment logic and target variables are illustrated in a management schematic showing simultaneous oxygenation and contaminant removal at the sediment-water interface

At the farm-system level, rainfall resilience depends on reducing waste accumulation before storm periods rather than reacting only after water quality has already deteriorated. Proper feed management, probiotics, and greater wastewater-treatment capacity have been recommended to reduce ammonia and nitrate loads in shrimp-farming waters, and intensive coastal pond studies show that seasonal water-quality decline can be substantial without

regular temporal and spatial control. For giant freshwater prawn ponds specifically, integrated culture designs can improve environmental buffering capacity while maintaining production. Biofloc and periphyton systems appear promising because they recycle nutrients, produce natural food, and reduce environmental impact, and integrated multitrophic aquaculture can decrease waste release through extractive plants and mollusks that improve water quality and ecosystem function.

During prolonged rainfall, precision monitoring should focus on continuous tracking of dissolved oxygen, temperature, pH, turbidity, and ammonia, because manual observation is too slow to capture rapid pond deterioration. IoT-based systems can collect real-time water-quality data at regular intervals and support anomaly detection using relationships among dissolved oxygen, pH, and temperature, while integrated six-sensor platforms now monitor dissolved oxygen, ammonia, turbidity, pH, temperature, and total dissolved solids in real time at much lower cost than conventional packages. For prawn farming, the practical value of these systems lies in remote visibility and fast intervention. A prototype smart pond system for giant freshwater prawn has already combined water treatment, automated control, and smartphone-based IoT monitoring, producing a 93.3% survival rate and disease-free harvests, while freshwater shrimp monitoring platforms in Bangladesh have shown that real-time alerts can be delivered when parameters move outside optimal ranges. The sensor-to-dashboard workflow is shown in an IoT monitoring architecture that links pond sensors, cloud transfer, and farm-level decision support.

Early-warning systems should move beyond monitoring alone and incorporate prediction, calibration, and threshold-based alerts. Recent frameworks combine floating buoy sensors, automated calibration, and disease-prediction models so that water-quality fluctuations can be linked quantitatively to outbreak risk, and time-series forecasting has reached high accuracy for predicting near-term trends in pH, dissolved oxygen, and ORP before conditions become critical. Long-term field usefulness, however, depends on reliability under rural farm conditions. Low-cost IoT systems have operated continuously for extended periods when supported by regular calibration, and review evidence indicates that sensor automation still faces practical challenges in maintenance, parameter control, and operability in remote aquaculture settings.

Future research should shift from describing rainfall impacts toward building rainfall-resilient prawn farming systems that combine genetics, engineering, and ecology. Climate change is increasing dissolved oxygen depletion and disease pressure in inland aquaculture, and resilience breeding in *Macrobrachium rosenbergii* has been proposed as a priority using reaction norms, genotype-by-environment approaches, and genomic or multi-omics tools. Climate adaptation research should also become more predictive at farm and regional scales. Species-distribution modeling shows that suitable aquaculture areas for *M. rosenbergii* are strongly determined by extreme temperature variation and may decline by about 6.00%-29.11% under future climate scenarios, which supports integrating climate projections into strategic siting, stocking calendars, and rainfall-risk planning.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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