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CHAPTER 15

Freshwater ecosystems in Malaysia: Status, pressures and management priorities

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Abstract: Freshwater ecosystems in Malaysia are highly biodiverse and provide critical ecosystem services, yet they are increasingly degraded by interacting land-use and environmental pressures. Evidence on the status, drivers, and ecological consequences of freshwater change across Malaysian river basins show that widespread freshwater ecological degradation is driven by landscape pressures, with impacts evident across biological communities and ecosystem functioning. Deforestation, agricultural plantation expansion, urbanisation, peatland conversion, and industrial water use collectively alter hydrological regimes, water chemistry, sediment dynamics, and organic matter inputs from headwaters to coastal systems. These changes are associated with shifts in ecosystem structure and function, including reductions in biodiversity, losses of sensitive taxa, and a general transition towards simplified, disturbance-tolerant communities across macroinvertebrates, fish, and other aquatic groups. This has functional change implications, affecting ecosystem processes such as nutrient cycling, organic matter processing, and food web structure, which indicate that ecological impacts extend beyond species loss to ecosystem-wide impacts. Forest loss and fragmentation further disrupt catchment linkages, leading to declines in water quality, habitat complexity, and biological integrity, whereas intact and structurally complex forested landscapes consistently buffer against these impacts. Across studies, catchment land-use condition and riparian integrity emerge as key determinants of freshwater ecosystem health, highlighting the importance of maintaining connected forested systems across upland, riparian, and floodplain zones. This underscores the need for more integrated catchment-scale planning and management of freshwater ecosystemsTo effectively safeguard and restore these ecosystems, there is a need for clear, measurable, catchment-context ecological metrics for effective monitoring andmanagement. Overall, the evidence demonstrates that safeguarding Malaysia's freshwater ecosystems depends on shifting from fragmented management approaches towards integrated, metrics-driven catchment governance capable of sustaining biodiversity, ecosystem functioning, and long-term water security.

INTRODUCTION

Freshwater ecosystems in Malaysia are biologically diverse and ecologically significant, shaped by an equatorial climate, extensive hydrological networks, and longstanding interactions between natural processes and human land use (Furtado and Lee 2022). Malaysia experiences high annual rainfall and relatively stable temperatures throughout the year, supporting a dense network of rivers, floodplains, peat swamps, lakes, and reservoirs (Furtado and Lee 2022). These systems comprise both lotic environments (i.e., flowing waters such as rivers and streams) and lentic environments (i.e., standing waters such as lakes, floodplain wetlands, swamps, and reservoirs), which are closely interconnected with their surrounding catchments (Izam *et al*. 2021; Furtado and Lee 2022).

River systems form the backbone of Malaysia's freshwater landscapes with major basins such as the Pahang River and Klang River supporting not only ecological connectivity across terrestrial and aquatic habitats, but also dense human populations and economic activity (Kandari *et al.* 2018; Yusmah *et al.* 2020; Locke *et al.* 2026). Freshwater ecosystems

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also provide critical ecosystem services, including water supply, flood and climate regulation, nutrient cycling, fisheries production, and habitat provision for a wide range of aquatic and semi-aquatic biodiversity (Luke *et al.* 2017; Chellaiah and Yule 2018b; Kandari *et al.* 2018; Philip and Tuen 2023; Locke *et al*. 2026), and are therefore central to both ecological integrity and human well-being.

Despite their ecological and socio-economic importance, freshwater ecosystems in Malaysia face increasing threats from land-use change, pollution, sedimentation, hydrological alteration, and climate variability (Mercer *et al.* 2014; Camara *et al.* 2019; Nafi *et al*. 2021). Rivers that originate in upland forested catchments flow through increasingly modified lowland regions, where agriculture, urbanisation, and industrial development exert strong pressures on water quality and hydrological regimes (Harun *et al.* 2015; Razali *et al.* 2018). As a result, many freshwater systems in Malaysia exhibit agradient of ecological conditions ranging from relatively intact headwaters to heavily impacted downstream reaches (Harun *et al.* 2014; Chellaiah and Yule 2018c).

Malaysia contains approximately 189 major river basins, of which an estimated 30% are considered polluted, reflecting growing pressures from land-use change, pollution, hydrological modification and climate variability (Furtado and Lee 2022). Since 1980, steadily increasing water demand (from 8.9 to 15.5 billion m^3), largely by large-scale rice irrigation and industrial growth, has reduced per capita water availability, eroded access to uncontaminated supplies, and sharpened pressures to meet per capita consumption targets (Ahmed *et al.* 2014). These pressures are further intensified by rapid urban expansion and infrastructure development, particularly in major growth corridors; emerging water-intensive industries such as the expansion of data centres and digital infrastructure are now introducing additional demand on freshwater resources (Deepak *et al.* 2024). Collectively, these trends signal growing risks not only to freshwater biodiversity and ecosystem functioning, but also to long-term water insecurity and socio-economic vulnerability for communities and industries along major river basins (Kandari *et al.* 2018; Yusmah *et al.* 2020).

Freshwater ecosystems remain central to national development, supporting domestic water supply, irrigated agriculture (particularly rice cultivation), fisheries, and industrial activities. As such, understanding their condition is essential for informing sustainable water resource management and biodiversity conservation strategies. This chapter provides an overview of the status of freshwater ecosystems in Malaysia and the main anthropogenic and environmental drivers shaping their condition. It summarises how land-use change and related pressures influence hydrological, physicochemical, and ecological processes, and how these changes are reflected in ecosystem functioning and biological responses to support long-term freshwater ecosystem resilience and water security.

ECOSYSTEM FUNCTIONING AND PROCESS-LEVEL CHANGES

Freshwater systems operate as interconnected networks in which water, energy, nutrients, and organisms are continuously exchanged across spatial and temporal scales (Vannote *et al.* 1980; Graça *et al.* 2005). The hydrological and ecological linkages propagate longitudinally from upland catchments to river mouths, where freshwater inputs interact with estuarine and coastal systems, forming a continuous mountain-to-coast continuum of material and energy transfer (Vannote et al. 1980; Furtado and Lee 2022). These linkages are regulated by catchment characteristics, geomorphology, riparian structure, hydrological connectivity, and biological processes, and are further shaped in tropical regions by high rainfall and seasonal monsoon dynamics (Richardson and Sato 2015; Luke *et al*. 2017; Chellaiah and Yule, 2018b; Taniwaki *et al.* 2019; Furtado and Lee 2022). During wet periods, rivers frequently expand into floodplains and wetlands, linking channels with riparian forest and lentic waters (Furtado and Lee 2022).

Forested catchments act as natural infrastructure, regulating water flow, filtering pollutants, stabilising soils, while also supplying organic matter to aquatic systems, and maintaining water availability during dry periods (Gomi *et al*. 2006; Luke *et al*. 2017; Chellaiah and Yule 2018a). Inputs such as leaf litter and deadwood form the energetic foundation of many freshwater food webs, fuelling decomposition and nutrient cycling in typically nutrient-poor tropical waters (Furtado and Lee 2022). These allochthonous subsidies sustain diverse biological communities (Chellaiah and Yule 2018b), yet their functional importance is often overlooked for aquatic management.

The widespread conversion of forested landscapes to urban spaces, infrastructure, and agriculture (especially oil palm) has altered hydrological regimes, increased sediment and nutrient runoff, and reduced the input of high-quality organic matter to aquatic systems (Chellaiah and Yule 2018a 2018b; Wilkinson *et al.* 2018). At the same time, river regulation through damming and channel modification has disrupted natural flow regimes and connectivity, while urban and industrial discharges continue to degrade water quality (Yule *et al.* 2015; Nafi *et al.* 2021).

These interactions can be conceptualised as a cascading framework linking landscape drivers to ecological outcomes (Figure 1). At the catchment scale, land-use change, hydrological modification, and climate variability act as primary drivers that alter flow regimes, sediment dynamics, and the transport and transformation of nutrients and organic matter (Luke *et al.* 2017; Chellaiah and Yule 2018a; Kandari *et al.* 2018). These physicochemical changes reshape habitat structure and resource availability within freshwater systems, influencing species composition, community structure, and functional diversity (Mercer *et al.* 2014; Chellaiah and Yule 2018a, 2018c; Philip and Tuen 2023; Rojas-Castillo *et al.* 2023a). In turn, these biological responses feed back into ecosystem processes such as primary production, decomposition, and nutrient cycling, ultimately affecting the capacity of freshwater ecosystems to deliver key ecosystem services (Chellaiah and Yule 2019).

When these systems are degraded, these interconnected processes are disrupted throughout the network (upstream to downstream coastal zones), increasing vulnerability to floods, water shortages, declining water quality, and loss of ecological integrity. These pressures are also compounded by climate change, which is projected to intensify rainfall variability, increase temperatures, and amplify the frequency and magnitude of extreme hydrological events (Tan *et al.* 2015; Fulazzaky *et al.* 2023). Collectively, these interacting stressors alter not only species composition but also core ecosystem processes, including metabolism, oxygen dynamics, and nutrient cycling.

LANDSCAPE PRESSURES AND FRESHWATER ECOLOGICAL IMPACTS

Catchment-scale drivers of change

The current status of Malaysia's freshwater ecosystems is shaped by multiple, interacting landscape-scale stressors. Habitat loss and fragmentation are primary drivers of ecological change, with rapid and widespread logging and conversion of forested landscapes to agriculture, oil palm and urban land reducing landscape connectivity and degrading freshwater habitats (Camara *et al.* 2019; Ma *et al.* 2024). In Selangor, forest land decreased between 2000 – 2020 as urbanisation and agriculture expanded, leading to a more fragmented ecological network and weakened habitat connectivity (Ma *et al.* 2024). Similarly, in the Johor river basin, forest land declined while oil palm, other agricultural, and urban land all increased between 2000 – 2015 (Hashim *et al.* 2023).

These land-use changes reduce landscape connectivity thereby disrupting the movement of organic matter, nutrients and sediments that underpin aquatic ecosystem functioning (Zaiha and Ismid 2015; Chellaiah and Yule 2018a, 2018b; Camara *et al.* 2019). Increased anthropogenic impacts in areas of intensive agricultural, industrial, and residential development are often associated with poorer downstream water quality with higher nutrients, suspended solids and organic pollution, while unfragmented tropical forest is consistently linked to better water quality (Chellaiah and Yule 2018a; Nafi *et al.* 2021).

Large scale land-use change also modifies hydrological dynamics with river regulation through damming, channelisation and drainage which alters natural flow regimes, reducing discharge variability and constraining habitat availability for aquatic biota, further compounding impacts on water discharge and quality as well as aquatic biodiversity (Chellaiah and Yule 2018c; Wilkinson *et al.* 2018; Philip and Tuen 2023). For instance, environmental flow assessments in the Kenyir Lake Basin indicate that reduced discharges and altered low-flow periods restrict habitat suitability for larger native fish species (Wahab *et al.* 2025). In wetland and peat swamp systems, drainage and land conversion disrupt seasonal flood pulses and reduce the capacity of these systems to provide key ecosystems such as flood regulation and water storage, and sustain the survival of specialised biodiversity (Sulai *et al.* 2015). Additionally, in the Selangor River, impoundments have reduced natural high flows and increased minimum flows, flattening seasonal variability and altering the timing and magnitude of flood and low-flow pulses that structure aquatic habitats (Hairan *et al.* 2021).

Catchment and land-use change in Malaysian river basins not only alters flow regimes, water quality, and aquatic communities but also reshapes landscape hydrological dynamics and flood vulnerability. Malaysia's flood exposure is closely tied to land-use change and urban growth which alter basic ecological structures such as floodplains, riparian vegetation, wetlands and river morphology, which normally store water, slow runoff and trap sediments (Ahmed *et al.* 2014; Chellaiah and Yule 2018a). When floodplains are infilled and rivers are straightened or confined by embankments, channels become shallower and narrower, so high stream flows more easily overtop banks and inundate low-lying areas (Ahmed *et al.* 2014; Kandari *et al.* 2018; Yusmah *et al.* 2020). Unsustainable development and logging accelerates erosion and sediment delivery further degrading river habitats while simultaneously raising flood levels, directly linking ecological degradation to increased nature-related risk (Ahmed *et al.* 2014). About 35% of the Klang River Basin which drains the highly urbanised Klang Valley is developed for residential, commercial, industrial and institutional uses, leading to shallower and narrower streams that discharges during storms overtop banks and flood surrounding low-lying areas (Kandari *et al.* 2018). In Kuantan, rapid urban expansion into lowland, floodplain and coastal settings has similarly increased flood exposure (Yusmah *et al.* 2020). As flood vulnerabilities increase with intense monsoonal rainfall, logging and climate change, understanding and restoring ecological processes such as sediment transport, floodplain inundation, habitat connectivity is essential for designing effective, long-term resilience strategies.

Beyond these pressures, industrial growth and the growth of water-intensive industries, including digital infrastructure such as data centres, are intensifying water abstraction and contributing to thermal and chemical stress in already degraded catchments (Ruslan *et al.* 2022; Raihan 2023). Together, these interacting drivers create complex and cumulative impacts that extend beyond simple water quality degradation, reshaping flow, habitat structure, landscape connectivity and amplifying flood risk across densely settled Malaysian river basins. As a result, conventional physicochemical indicators alone are insufficient to capture the full extent of ecosystem change, and there is a growing need to incorporate biological and functional metrics that reflect alterations in community structure, ecosystem processes, and overall ecological integrity of freshwater systems (Kuglerová *et al.* 2024).

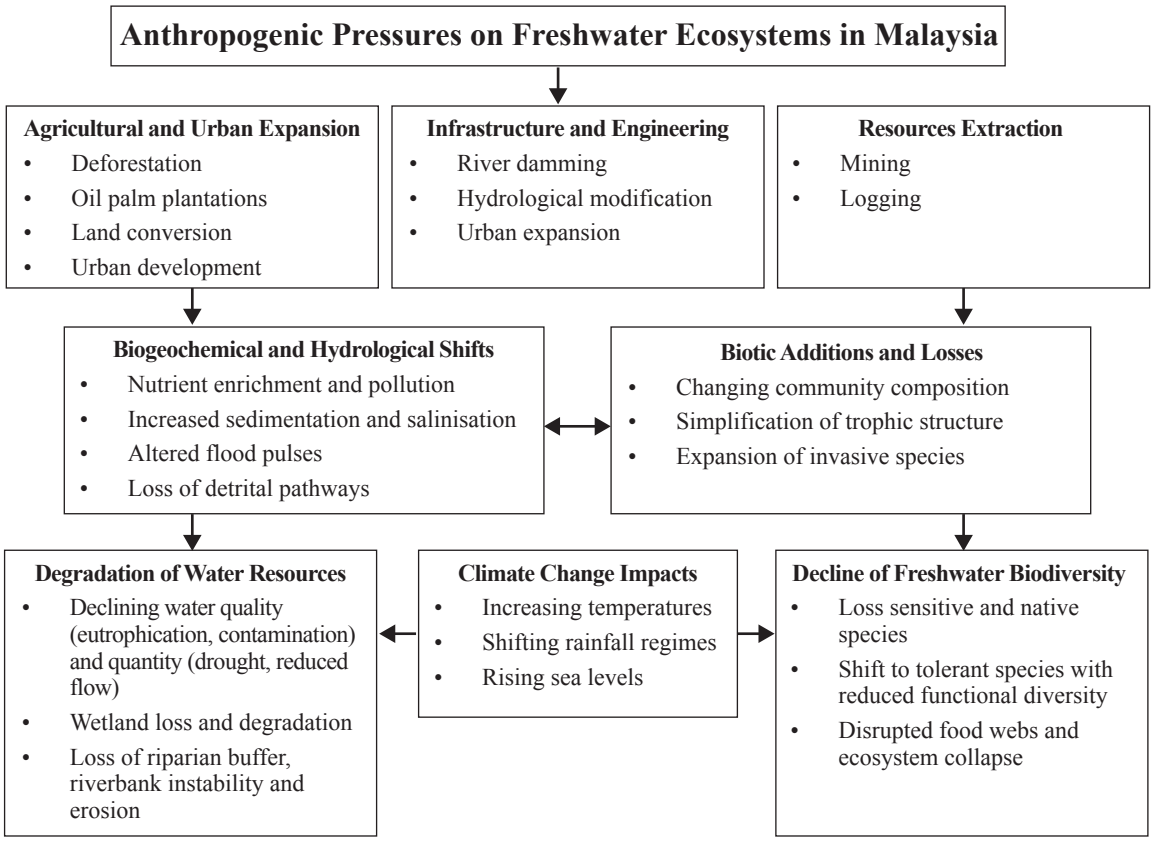

Figure 1. Anthropogenic pressures on Malaysian freshwater systems. Conceptual diagram showing the major human-driven stressors affecting freshwater ecosystems in Malaysia that drive interconnected biophysical response pathways that collectively contribute to ecosystem degradation and biodiversity loss, while interacting with broader climatic drivers that further exacerbate ecosystem-level impacts.

Hydrological and physicochemical responses

Catchment level disturbances typically alter the flow, magnitude, timing and variability of discharge, especially through reduced baseflows and modified storm responses with important consequences for habitat stability, ecological processes and aquatic biota (Hairan *et al.* 2021; Hashim *et al.* 2023). In regulated or heavily modified streams, lower low-flow conditions can constrain habitat availability for flow-specialist native fish and reduce overall habitat stability. At the same time, land-use change often increases surface runoff and shifts streamflow seasonality, with higher wet-season flows and, in some basins, reduced dry-season flows, reflecting combined climate and land-use effects (Aizam and Atkinson 2011; Tan *et al.* 2015)

These hydrological changes are frequently coupled with broader physicochemical responses, particularly increased sediment delivery, nutrient enrichment and altered water quality. Agricultural and oil palm catchments are commonly associated with elevated nutrient and major ions (N, P, Cl-, K+) derived from fertiliser and agrochemical inputs (Harun *et al*. 2014; Chellaiah and Yule 2018a; Itoh *et al*. 2023). In peat swamp systems, drainage and conversion are commonly associated with declines in dissolved oxygen, increased ammonia concentrations, elevated chemical oxygen demand, and more acidic conditions, consistent with organic loading and deteriorated water quality (Gandaseca *et al.* 2015). Constructed drainage systems in plantations on peat may also slightly raise pH relative to natural peat waters while supporting high dissolved organic carbon (DOC) from labile palm litter leachates (Azizan *et al*. 2021).

Altered landscapes further modify organic matter and sediment dynamics. Peat and plantation catchments can export substantial dissolved organic matter (DOM), with major changes in vegetation quantity and quality along major rivers such as the Kinabatangan (Harun *et al.* 2015). This is ecologically important because DOM represents a major basal energy source for aquatic food webs and contributes substantially to ecosystem metabolism. Consequently, land-use change, wetland drainage, channel modification and flow regulation can alter both the quantity and quality of DOM entering freshwater systems, with downstream effects on microbial production, carbon cycling and trophic pathways. Elevated DOC inputs from plantation drains signifies enhanced leaching of labile carbon, which can stimulate microbial respiration and increase oxygen demand, and shift food-web and biogeochemical functioning (Chellaiah and Yule 2018b; Azizan *et al.* 2021). In some cases, conventional metrics like water nutrient levels differ little between forest and plantation streams, implying that shifts in organic matter character and habitat structure may drive much of the ecological response (Luke *et al.* 2017; Chellaiah and Yule 2019).

Salinisation represents an additional physicochemical stressor arising from both natural processes and human activities and is increasingly recognised as a form of land and water degradation (Adnan *et al.* 2021; Izam *et al.* 2021). Salinisation pressures are most pronounced in coastal zones in west Peninsular Malaysia, east Sabah, and the deltas and coasts of Sarawak (Azalina *et al.* 2023; Izam *et al.* 2021) and in intensively farmed uplands such as Cameron Highlands, where high fertilizer and manure inputs, plastic rain-shelter agriculture and intensive land use promote salt accumulation and transport to freshwater bodies (Hashim 2003; Razali *et al.* 2018; Izam *et al.* 2021). Elevated salinity can reduce freshwater species richness and functional diversity, alters trophic pathways by limiting food resources, and promote density stratification, contributing to biodiversity losses in highly saline areas (Mausbach and Dzialowski 2020; Azalina *et al.* 2023). In the Juru River, Penang, a highly degraded system impacted by manufacturing, timber processing, rubber industries, urbanisation, untreated domestic wastewater, and animal waste, the richness and diversity of plankton, fish, and macrobenthos richness and diversity indices were strongly associated with salinity, temperature, total suspended solids (TSS), biochemical oxygen demand (BOD) and pH, underscoring the combined influence of multiple physicochemical stressors on aquatic community structure (Azalina *et al.* 2023).

Hydrological disturbance also enhances erosion, suspended sediment loads and turbidity through deforestation, slope agriculture, and plantation development. In both highland and lowland Malaysian catchments, sediment and chemical oxygen demand (COD) peaks are often associated with wet-season storms, reflecting intensified surface runoff and bank or road erosion (Harun *et al.* 2014; Luke *et al.* 2017; Razali *et al.* 2018). Multi-catchment studies in Sabah further show that logging and oil palm reduce canopy cover, increase sediment benthic cover and simplify channel structure, with hydromorphological impacts persisting more than a decade after logging (Walsh *et al.* 2016; Luke *et al.* 2017). These coupled hydrological and physicochemical changes due to catchment disturbance alter modifying habitat availability, disrupting biogeochemical cycles, and reducing the capacity of aquatic systems to sustain biodiversity and ecosystem services.

Biological responses and community restructuring

Integrated changes in flow regimes, sediment transport, and water and carbon chemistry due to catchment disturbances, constrain habitat suitability and oxygen availability, and nutrient delivery for aquatic organisms, resulting in widespread degradation of biological integrity (Yule *et al.* 2015; Chellaiah and Yule 2018b). In response, aquatic communities typically shift from diverse assemblages dominated by sensitive taxa to simplified systems characterised by smaller numbers of disturbance-tolerant species. Sensitive taxa are frequently lost, while tolerant groups become dominant, reflecting altered habitat structure, sediment regimes, and detrital inputs (Mercer *et al.* 2014; Chellaiah and Yule 2018c; Rojas-Castillo

et al. 2023b). Streams within altered landscapes consistently show reduced abundance, taxonomic richness, and diversity of aquatic biodiversity compared to forested systems, alongside marked shifts in community composition (Chellaiah and Yule 2018c, Ishak *et al.* 2021; Rojas-Castillo *et al.* 2023b). This restructuring reflects loss of sensitive taxa and increased dominance of tolerant groups, driven by altered habitat structure, sediment regimes, and detrital inputs (Mercer *et al*. 2014; Chellaiah and Yule 2018c; Rojas-Castillo *et al.* 2023b).

Macroinvertebrate and semi-aquatic insect communities are particularly responsive to land-use change. In Sabah, Chellaiah and Yule (2018c) reported that overall species richness and diversity of macroinvertebrates were not always significantly reduced in oil palm streams, community composition shifted markedly, suggesting functional changes within these assemblages. In Sarawak, rainforest streams support high macroinvertebrate abundance, richness and diversity, while two entire insect orders (Coleoptera and Hemiptera) were absent from oil palm streams, indicating local taxonomic loss and community reassembly (Mercer *et al.* 2014). Semi-aquatic bugs likewise show 2 to 6-fold declines in abundance and richness from old-growth forest through logged forest to oil palm, with narrow buffer strips providing limited mitigation (Harianja *et al*. 2024a, 2024b).

Along polluted tropical rivers, odonate assemblages become dominated by tolerant damselflies, with adult richness and composition tightly linked to dissolved oxygen, pH, temperature, and riparian vegetation (Abdul *et al.* 2017; Ishak *et al.* 2021). These patterns demonstrate how microhabitat and pollution gradients restructure communities even without large differences in basic water chemistry among reaches, with subsequent implications on secondary production, trophic interactions, and nutrient cycling.

Fish assemblages similarly reflect strong ecological consequences due to anthropogenic stress. Across Sarawak and Sabah, conversion of forest to logged forest and oil palm headwaters reduced fish species richness and functional richness, indicating erosion of ecological roles despite apparently intact fish standing stocks (Wilkinson *et al*. 2018; Philip and Tuen 2023). Any departure from protected forest, regardless of disturbance intensity (including twice-logged and salvage-logged forests), results in persistent impacts on fish communities, with clear losses in native species and functional roles and no evidence of recovery along more intensively modified land-use stages, indicating sustained reductions in fish community diversity following disturbance (Wilkinson *et al.* 2018). Comparable patterns are observed in Peninsular Malaysia, where conversion to mixed-use and oil-palm landscapes substantially reduced native *Macrobrachium* shrimp richness while increasing non-native shrimp abundance, indicating degraded habitat quality and a shift toward less diverse, more invasion-dominated assemblages (Gan *et al*. 2023).

Urbanisation, coastal reclamation, and dredging and associated pollution further intensify these pressures along Malaysia's coasts, modifying habitat structure, reducing fish diversity, and favouring disturbance-tolerant and often non-native species (Hamid *et al.* 2023). In peatland drainage systems converted to oil palm plantations, fish communities are similarly dominated by disturbance-tolerant species, with elevated DOC, temperature and electrical conductivity strongly shaping community composition and growth (Azizan *et al*. 2021).

Additionally, harmful algal blooms represent an emerging and escalating ecological pressure in Malaysia, with blooms becoming more frequent, severe, and including the emergence of previously unrecorded species (Teen *et al*. 2012; Izam *et al*. 2021). Driven by nutrient enrichment from industrialisation, urbanisation, intensive agriculture and domestic effluents, these events are further amplified by climate-driven warming, acidification and deoxygenation of freshwater systems. Algal blooms reduce oxygen and habitat availability

and decrease community evenness, resulting in subsequent declines in aquatic biodiversity (Teen *et al.* 2012). Since 2002, recurrent large blooms have caused recurrent mass fish kills and substantial economic losses, particularly in aquaculture areas such as Penang, highlighting harmful algal blooms as a major and growing threat to freshwater ecosystem health as well as water and food security (Teen *et al.* 2012).

Interacting anthropogenic pressures including deforestation, plantation expansion, urbanisation, industrial water use, and peatland conversion, drive combined hydrological and biogeochemical changes such as changes in runoff, organic matter, nutrients and sediments. These changes propagate from headwaters through river networks to coastal systems, linking upstream land-use change to downstream aquatic degradation. Resulting losses in taxonomic and functional diversity reduce ecosystem functioning across the catchments by disrupting trophic interactions, altering energy transfer pathways, and weakening processes such as nutrient cycling, organic matter breakdown, and secondary production, ultimately reducing ecosystem resilience and stability (Chellaiah and Yule 2019). Collectively, these patterns indicate that biological metrics in terms of composition, functional groups, sensitive-taxa loss can detect and reveal ecosystem degradation even when routine water chemical measurements show minimal differences, emphasising the importance of habitat structure, flow regime, and resource availability in shaping and maintaining healthy freshwater biota.

STATUS AND TRENDS OF FRESHWATER SYSTEMS IN MALAYSIA

Most national and basin-scale assessments rely on Water Quality Index (WQI) and a narrow suite of physicochemical parameters, with limited incorporation of biological or habitat-based indicators (e.g., Malaysian River Integrity Index (MyRII), riparian/large woody debris studies). Overall, Malaysia's freshwater ecosystems exhibit a clear pattern of moderate to degraded condition, with relatively intact water quality in headwater regions but consistent deterioration downstream in intensively developed basins (Goi 2020). Recent trend analyses point to stagnation or worsening in several major systems (Ruhayu *et al.* 2015; Fitri *et al.* 2020). National monitoring data indicate that only around half of rivers can be classified as clean, while the remainder are slightly polluted or polluted, reflecting a long-term decline in overall water quality (Ruhayu *et al.* 2015; Goi 2020; Baharudin *et al.* 2021). Most rivers now fall within intermediate condition ranges, with more severely degraded reaches occurring in urbanised and agricultural lowlands (Fitri *et al.* 2020; Goi 2020).

This upstream-downstream gradient is evident across multiple basins, including the Johor, Langat, and Terengganu rivers, where nutrient loads, suspended sediments, and organic pollution increase downstream (Awal *et al.* 2015; Amir *et al.* 2024; Zaiha *et al.* 2025). Several key basins, such as the Kelantan, Klang, Langat, and Selangor systems, show evidence of worsening trends over time, driven by expanding urbanisation, agriculture, industrial activity, and sewage inputs (Fitri *et al.* 2020; Baharudin *et al.* 2021; Amir *et al.* 2024). Short-term improvements during periods of reduced human activity demonstrate the responsiveness of river systems to reduced pressures (Goi 2020), but overall trajectories suggest stagnation or continued degradation.

Current reporting frameworks therefore primarily capture pollution status rather than broader ecological conditions or resilience. Many rivers classified as "clean" on the basis of chemical thresholds may already exhibit simplified food webs, altered flow-dependent biota, and impaired habitat structure that are invisible to conventional metrics (Chellaiah and Yule 2018c; Azalina *et al.* 2023). Moving beyond pollution control will require routine use of ecosystem-level indicators such as macroinvertebrate indices, fish assemblages, riparian and large woody debris condition, organic matter and flow to safeguard ecological integrity and long-term freshwater ecosystem services. An example is the Malaysian River

Integrity Index (MyRII), an integrated ecological framework combining biological (i.e., Ichthyofaunal Quality Index based on fish and diversity metrics), chemical (Water Quality Index), and physical (River Physical Quality Index including channel and bank stability, riparian condition, canopy cover, pool and riffle availability) indicators to better capture true ecosystem condition beyond conventional water quality assessments, developed for the Malaysian context (Ng *et al.* 2020).

FRESHWATER ECOSYSTEM MANAGEMENT IMPLICATIONS AND WAYS FORWARD

Governance, stakeholders and legal gaps

The effectiveness of freshwater management in Malaysia is constrained by fragmented governance, overlapping federal-state responsibilities, and sectoral approaches that limit integrated river basin management (Rahman and Khalid 2009; Ideres *et al.* 2023). Although legal tools exist such as buffer requirements in drinking-water catchments and state enactments on riparian protection, compliance is often limited (Ligtermoet *et al.* 2009; Chellaiah and Yule 2018a). For example, Sarawak government policy requires buffer widths of 550 m of natural vegetation to be retained along all streams and rivers in drinking water supply catchments, however most of the sites surveyed by Ligtermoet *et al.* (2009) were not meeting guideline widths, especially in logging areas and plantations. While in Sabah, legal requirements for 20 m riparian reserves along larger rivers, and similarly compliance remains uneven (Chellaiah and Yule 2018a; Luke *et al.* 2019).

Certification and sustainability frameworks in the palm oil sector (e.g., RSPO, MSPO)[a] can help embed riparian buffers, reduce agrochemical use and maintain HCV set-asides that provide important ecosystem services, however certification alone, without robust enforcement and complementary national policies, does not fully prevent forest loss or guarantee strong biodiversity and water-quality outcomes (Majid *et al.* 2021; Abidin *et al.* 2024). Strengthening freshwater protection therefore requires not only clearer and better enforced regulations, but also coordinated catchment-scale governance that shifts from reactive and preventative measures to catchment-based conservation and management.

Forest conservation, riparian protection and catchment planning

Effective freshwater protection in Malaysia requires aligning land-use planning, forest conservation, hydrology, and governance with biodiversity and water-quality goals. Catchment-level management is required considering changes to catchment scale forest cover, channel morphology, and flow regimes to re-establish detrital inputs and physical habitat heterogeneity characteristic of forest streams (Luke *et al.* 2017). Maintaining or restoring forested catchments and riparian buffers is therefore a central management strategy (Chellaiah and Yule 2018c). These areas regulate hydrological processes, reduce surface runoff and erosion, filter nutrients and pollutants, and sustain the supply of organic matter that underpins aquatic food webs (Richardson *et al.* 2012; Sweeney and Newbold 2014). They also function as a natural infrastructure by stabilising stream banks, moderating water temperatures through shading, and maintaining connectivity between terrestrial and aquatic ecosystems (Richardson *et al.* 2012).

Empirical evidence from Malaysia and similar tropical systems demonstrates the consequences of riparian and catchment degradation. Conversion to oil palm and logging produces warmer, shallower, more sediment-rich streams with reduced structural complexity and altered nutrient regimes (Mercer *et al.* 2014; Luke *et al.* 2017; Chellaiah and Yule 2018a),

[a] RSPO – Roundtable on Sustainable Palm Oil, an international certification standard for sustainable palm oil production. MSPO – Malaysian Sustainable Palm Oil, Malaysia's national certification standard for sustainable palm oil production.

demonstrating how changes in landscape management can rapidly erode the healthy functioning of freshwater ecosystems on which long-term water security depends. Similarly, in the Bentong River, water quality deteriorated where urban and agricultural patches were fragmented and interspersed, whereas intact forest patches acted as strong buffers, reducing nutrient and organic pollution and serving as indicators of high water quality (Nafi *et al.* 2021).

Recommended measures include establishing and widening riparian buffer zones, sustaining water and riparian connectivity, limiting land-use compactness, and maintaining native, unfragmented forest cover to filter sediments and nutrients and moderate hydrological extremes (Luke *et al.* 2017; Chellaiah and Yule 2018a; Nafi *et al.* 2021; Philip and Tuen 2023). Evidence supports riparian protection as a primary mitigation, but outcomes depend on buffer attributes and broader catchment management. In oil palm plantations in Sabah, streams bordered by intact native-forest buffers had cooler water, lower light levels, more in-stream litter, higher bank stability and better water quality than streams with degraded or no buffers, while channels without any riparian vegetation showed greatly elevated temperatures (up to 4 – 7 °C warmer than forest), higher bank erosion levels and nutrient enrichment (Luke *et al.* 2017; Chellaiah and Yule 2018a). This indicates that relying on narrow, low-quality buffer strips is insufficient and high-quality, forested riparian buffers are needed to restore more natural stream physical and chemical conditions, particularly in agricultural landscapes (Chellaiah and Yule 2018a, 2018c).

Riparian protection must therefore also consider buffer quality, as narrow buffers provide only limited ecological benefit and structurally intact, forested riparian zones are required to deliver effective regulation of stream temperature, sediment inputs, and nutrient loading (Chellaiah and Yule 2018a; Lind *et al.* 2019). Taken together, these findings indicate that catchment and riparian restoration must be embedded within broader catchment-scaleplanning and not treated as a standalone mitigation measure. Maintaining contiguous forest cover including riparian corridors and upland high conservation value (HCV) areas is therefore essential for stabilising hydrological regimes and sustaining long-term freshwater ecosystem function in managed tropical landscapes.

Targeted management metrics

Effective protection and management of freshwater ecosystems require clearly defined, measurable metrics that link environmental change to management action. Given increasing resource vulnerabilities and associated economic risks from freshwater ecosystem degradation, management frameworks must shift towards locally relevant, catchment-specific targets that integrate forest cover, riparian buffer width and condition, water quality thresholds, and flow regime characteristics (Kuglerová *et al*. 2024). Vague or non-operational targets often result in limited implementation, reducing accountability and poor monitoring of ecological recovery. Without such quantifiable targets, it is challenging to credibly demonstrate progress towards resilient freshwater ecosystems and secure water resources.

Relevant biological and functional indicators include ichthyofauna-based indices, fish functional groups, and macroinvertebrate diversity, alongside water-quality metrics such as the Water Quality Index (WQII) and dissolved organic matter character. These are complemented by habitat-based assessments such as the Riparian Quality Index (RPQI) and hydrological metrics including baseflow stability and flow variability, which together provide a more integrated measure of ecosystem condition than nutrient concentrations alone.

However, persistent gaps continue to constrain implementation, including inconsistent designation and protection of water-supply catchments, weak integration between land-use planning and water management, insufficient monitoring and enforcement of buffer and pollution standards, and fragmented institutional responsibilities that slow effective implementation of Integrated Water Resources Management (IWRM) and Integrated River

Basin Management (IRBM) approaches. Moving forward, freshwater management must therefore shift from guideline-based approaches to coordinated, enforceable, and metrics -driven catchment management that links land use, hydrology, riparian and ecological response to safeguard biodiversity and long-term water security in Malaysia.

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