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Climate Change and Biodiversity Dynamics of Invertebrates in the Bahr Al-Najaf: A Comprehensive Review

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ABSTRACT

Climate change is increasingly recognized as one of the major drivers of ecological change in aquatic ecosystems, affecting environmental conditions, species distributions, community structure, biodiversity, and ecosystem functioning. The Bahr Al-Najaf, a distinctive inland aquatic ecosystem in central Iraq, represents an ecologically important environment that is potentially vulnerable to climate-related changes due to fluctuations in temperature, precipitation, evaporation, water availability, salinity, and other physicochemical characteristics. Invertebrates constitute a fundamental component of aquatic biodiversity and play essential roles in food webs, nutrient cycling, decomposition, sediment processes, and energy transfer. Consequently, changes in their diversity and community dynamics can provide valuable indicators of environmental disturbance and ecosystem health. This review examines the potential relationships between climate change and the biodiversity dynamics of aquatic invertebrates in the Bahr Al-Najaf, with particular emphasis on the effects of increasing temperature, altered precipitation regimes, water-level fluctuations, evaporation, salinity changes, and associated modifications in water quality and habitat characteristics. The review considers how these environmental pressures may influence species richness, abundance, distribution, community composition, phenology, and functional characteristics of invertebrate communities. Particular attention is given to environmentally sensitive groups, including zooplankton, benthic macroinvertebrates, mollusks, crustaceans, and aquatic insect larvae, which may respond differently according to their ecological characteristics and tolerance limits. Climate-driven changes may favor tolerant and opportunistic taxa while reducing the abundance and distribution of sensitive species, potentially resulting in shifts in community structure and a reduction in ecological complexity. Such changes may also propagate through aquatic food webs, affecting fish and other higher trophic levels and ultimately influencing ecosystem services. The review further highlights the importance of integrating biological indicators with long-term monitoring of temperature, salinity, dissolved oxygen, nutrients, water levels, and other physicochemical parameters to distinguish climate-related effects from those associated with pollution, habitat modification, water abstraction, and other anthropogenic pressures. Developing standardized biodiversity monitoring programs and applying ecological, statistical, and predictive approaches could improve understanding of future changes in the Bahr Al-Najaf ecosystem. Establishing a climate-sensitive biodiversity assessment framework would also support conservation planning

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and sustainable management of this valuable aquatic ecosystem. Overall, understanding the interactions between climate variability and invertebrate communities is essential for predicting ecological responses, identifying vulnerable taxa, and developing effective strategies for protecting biodiversity and maintaining the ecological integrity of the Bahr Al-Najaf under future environmental change.

KEYWORDS: Climate change; Bahr Al-Najaf; aquatic biodiversity; invertebrates; macroinvertebrates; zooplankton; ecosystem dynamics; environmental change; ecological indicators

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INTRODUCTION

Climate change has emerged as one of the most important environmental pressures affecting aquatic ecosystems, with consequences extending from changes in water chemistry and hydrological regimes to alterations in species distributions, community composition, and ecosystem functioning. Increasing air and water temperatures, shifts in precipitation patterns, prolonged droughts, changes in flooding regimes, and increasing frequency of extreme climatic events can modify the physical and chemical characteristics of aquatic habitats. These changes are particularly important in shallow inland water bodies, where relatively small variations in water availability, temperature, salinity, and dissolved oxygen can produce substantial ecological responses (Bonacina et al., 2023; Orr et al., 2024). Recent assessments have emphasized that climate change does not act independently but interacts with pollution, habitat modification, altered hydrology, and other anthropogenic pressures, potentially producing cumulative effects on aquatic biodiversity (He et al., 2023; Vörösmarty et al., 2023).

Freshwater invertebrates are particularly valuable for understanding ecological changes because they represent diverse taxonomic and functional groups and respond rapidly to variations in environmental conditions. Macroinvertebrates participate in decomposition, nutrient cycling, organic-matter processing, primary-consumer pathways, and energy transfer to higher trophic levels. Their relatively limited mobility compared with many vertebrates also makes their community structure closely associated with local environmental conditions. Consequently, changes in their abundance, taxonomic richness, functional diversity, and community composition can provide sensitive indications of environmental degradation and climatic stress (Bonacina et al., 2023; Haase et al., 2023). Large-scale evidence from freshwater ecosystems has demonstrated that increasing temperatures and other anthropogenic pressures can modify both taxonomic and functional characteristics of invertebrate communities, emphasizing the importance of integrating climate variables into biodiversity assessments (Haase et al., 2023).

Temperature is among the most influential climate-related variables affecting aquatic invertebrates. Because most aquatic invertebrates are ectothermic, their metabolic activity, growth, development, reproduction, emergence, and survival are strongly dependent on thermal conditions. A systematic review by Bonacina et al. (2023) demonstrated that temperature influences freshwater macroinvertebrates at several biological levels, ranging from individual physiological responses to changes in community composition, richness, and distribution. Climate warming may therefore favor thermally tolerant or warm-adapted taxa while reducing the occurrence of sensitive taxa, potentially resulting in changes in community structure and functional characteristics. Such responses can also vary according to species, developmental stage, geographic region, duration of exposure, and interactions with other environmental stressors.

The effects of climate change on aquatic invertebrates can become more pronounced when warming occurs simultaneously with chemical pollution or other forms of environmental disturbance. Recent experimental and review studies indicate that warming and contaminants may interact in additive, synergistic, or antagonistic ways depending on the organism, life stage, contaminant, exposure duration, and environmental context (Burgess et al., 2022). Similarly, experimental evidence indicates that combinations of warming and wastewater contamination can alter biological communities at multiple levels and may reduce phylogenetic and ecological diversity (2024). These findings are particularly relevant to shallow and semi-arid aquatic ecosystems, where high temperatures, evaporation, salinity, and anthropogenic inputs may occur simultaneously.

Freshwater biodiversity is already experiencing substantial global pressure. Freshwater ecosystems have historically been exposed to nutrient enrichment, pollution, water abstraction, hydrological modification, habitat degradation, invasive species, and climate change. A large-scale analysis of freshwater invertebrate communities across Europe showed that although biodiversity had improved at many sites during previous decades, the recovery of taxonomic and functional diversity has slowed in recent years. Increasing temperatures were among the environmental factors associated with weaker biodiversity recovery (Haase et al., 2023). These findings suggest that improvements in local water quality alone may not be sufficient to maintain freshwater biodiversity under a rapidly changing climate.

Invertebrates are also important biological indicators because their responses integrate the effects of environmental conditions over time. Benthic macroinvertebrates, zooplankton, molluscs, crustaceans, and aquatic insects can provide complementary information

about habitat quality and ecological change. However, effective interpretation requires standardized sampling, taxonomic identification, and appropriate biodiversity metrics. Recent international assessments have highlighted considerable gaps in the harmonization of freshwater macroinvertebrate monitoring and biological assessment, particularly across regions where long-term biodiversity datasets are limited (2024). Strengthening standardized monitoring is therefore essential for detecting climate-driven ecological changes and distinguishing them from the effects of local pollution and habitat disturbance.

The Bahr Al-Najaf (Bahr Al-Najaf) represents an ecologically distinctive aquatic depression in western Iraq and provides an important regional context for examining the relationship between environmental change and aquatic biodiversity. Its hydrological history is strongly connected with the Euphrates system. Recent geomorphological and palaeohydrological research indicates that changes in the extent and persistence of the Bahr Al-Najaf have been associated with variations in river dynamics and the availability of water within the wider catchment (Briant et al., 2024). This hydrological dependence is particularly important under contemporary climate change because changes in precipitation, evaporation, river discharge, and water availability may influence the physical and ecological characteristics of the depression.

Available biological investigations demonstrate that the Bahr Al-Najaf supports a variety of aquatic organisms, including important invertebrate groups. Albushabaa et al. (2019) documented **48 zooplankton taxa** in selected areas of Bahr Al-Najaf, comprising Copepoda, Rotifera, and Cladocera, with considerable spatial and seasonal differences in abundance and diversity. Such variation indicates that the aquatic environment of Bahr Al-Najaf is characterized by dynamic ecological conditions and that zooplankton communities may provide useful indicators for evaluating environmental changes. Studies of molluscan communities have also reported several gastropod and bivalve species around the depression, demonstrating the ecological importance of invertebrates within this aquatic system.

Environmental conditions in Bahr Al-Najaf may impose additional constraints on aquatic biodiversity. Earlier biodiversity assessments reported relatively high water salinity and suggested that salinity could contribute to reduced aquatic biological diversity (Mohammad et al., 2013). From an ecological perspective, climate-driven increases in evaporation and changes in water balance could intensify such conditions in shallow aquatic environments. Consequently, climate change may influence invertebrate communities not only through direct thermal effects but also indirectly through changes in salinity, water depth, dissolved oxygen, nutrient concentrations, habitat availability, and food-web structure.

The ecological significance of the Bahr Al-Najaf is further supported by recent palaeoenvironmental evidence based on molluscan remains. Briant et al. (2024) used molluscan assemblages and geomorphological evidence to reconstruct past environmental conditions in the Bahr Al-Najaf basin. Their findings demonstrate that molluscs can provide valuable information about historical hydrological and environmental changes and highlight the close relationship between aquatic biota and changes in lake extent and water availability. This historical perspective is particularly valuable for understanding the potential vulnerability of present-day invertebrate communities to future climatic and hydrological changes.

Despite the ecological importance of Bahr Al-Najaf, research addressing the **combined influence of climate change and biodiversity dynamics of invertebrates** remains comparatively limited. Existing studies have generally focused on individual components, such as zooplankton diversity, molluscan communities, general biodiversity, water quality, or the historical development of the lake basin. Consequently, there is a need for an integrated review that connects climatic drivers with changes in hydrology, water quality, habitat characteristics, and invertebrate community structure. Such an approach is especially important in arid and semi-arid regions, where aquatic ecosystems are naturally exposed to high temperatures, water scarcity, and strong seasonal variability.

Accordingly, this review aims to synthesize current knowledge concerning the relationships between **climate change and invertebrate biodiversity dynamics in the Bahr Al-Najaf**, with particular emphasis on temperature, water availability, evaporation, salinity, hydrological variability, pollution, and habitat alteration. The review also considers the potential responses of major invertebrate groups, including zooplankton, molluscs, aquatic insects, and other macroinvertebrates, in terms of abundance, species richness, diversity, distribution, and community composition. Integrating regional observations with recent international evidence may provide a scientific framework for identifying vulnerable taxa, improving ecological monitoring, and developing adaptive conservation and management strategies for Bahr Al-Najaf under future climate scenarios.

2. CLIMATE CHANGE AND ENVIRONMENTAL CHANGES IN THE BAHR AL-NAJAF

The Bahr Al-Najaf (Bahr Al-Najaf) is a shallow aquatic depression located in the Najaf Governorate of central Iraq and represents an environmentally dynamic system whose ecological characteristics are strongly influenced by water availability, hydrological fluctuations, evaporation, salinity, and anthropogenic activities. Unlike deep permanent lakes, shallow aquatic systems are particularly sensitive to climatic variability because changes in precipitation, inflow, evaporation, and water residence time can rapidly modify their physical and chemical characteristics. This sensitivity is especially relevant in arid and semi-arid environments, where increasing temperatures and prolonged dry periods may intensify water loss and alter aquatic habitats.

Climate change can affect the Bahr Al-Najaf through several interconnected pathways. Increasing air temperature may enhance evaporation and consequently reduce water volume, while changes in precipitation and river discharge may alter the frequency and duration of inundation. Reduced water volume can subsequently increase the concentration of dissolved salts and other pollutants. Recent research on climate-induced drought has demonstrated that reductions in lake and reservoir water volume can produce substantial changes in biodiversity, although the magnitude and direction of these effects differ among ecosystems and taxonomic groups (Sun et al., 2025).

The importance of hydrological variability is particularly evident in shallow lakes located in dry climates. Sarmanov et al. (2024) demonstrated that increasing salinization represents an important threat to shallow-lake ecosystems in arid and semi-arid regions. Increasing salinity can modify the composition of benthic invertebrate communities by imposing physiological stress and selectively favoring taxa with greater tolerance to saline conditions. Therefore, climate-induced changes in the hydrological balance of the Bahr Al-Najaf may indirectly influence invertebrate biodiversity through salinity-mediated ecological filtering.

The Bahr Al-Najaf is also exposed to anthropogenic pressures that may interact with climatic stress. Pollution, nutrient enrichment, domestic and agricultural inputs, sedimentation, and changes in water quality can increase the ecological vulnerability of aquatic organisms. Importantly, climate change should not be considered an isolated pressure. Recent global analyses indicate that freshwater biodiversity responds to multiple simultaneous stressors, with elevated salinity, oxygen depletion, and fine sediment accumulation consistently associated with biodiversity loss across aquatic organism groups (2025).

3. INVERTEBRATE BIODIVERSITY OF THE BAHR AL-NAJAF

Aquatic invertebrates constitute an important component of the biological communities of the Bahr Al-Najaf. They include zooplankton, molluscs, crustaceans, aquatic insects, and other benthic organisms that contribute to nutrient cycling, decomposition, grazing, and energy transfer. Because these organisms respond relatively rapidly to changes in temperature, salinity, oxygen availability, and food resources, their communities can provide valuable biological evidence of environmental change.

One of the important baseline studies of Bahr Al-Najaf was conducted by Albushabaa et al. (2019), who investigated zooplankton biodiversity at five sites between April 2017 and March 2018. The researchers identified **48 zooplankton taxa**, including 26 Copepoda, 17 Rotifera, and 5 Cladocera. Copepoda represented the dominant group, accounting for approximately 54.2% of the identified taxa, followed by Rotifera and Cladocera. The Shannon–Wiener index varied considerably among sites and months, ranging from 0.48 to 2.42, demonstrating substantial spatial and temporal variation in zooplankton biodiversity.

These findings are important because temporal variability in zooplankton communities may reflect changes in environmental conditions rather than simply natural variation. Seasonal changes in temperature, water chemistry, food availability, and hydrological conditions can alter the abundance and composition of zooplankton. Under future climate conditions, these seasonal patterns may become more pronounced if warming, drought, and salinity increase.

More recent evidence provides an important update to the ecological condition of Bahr Al-Najaf. A 2026 study examining zooplankton along a pollution–salinity gradient reported **18 taxa at reference areas compared with only 9 taxa in highly impacted zones**. Shannon diversity declined from approximately 2.45 to 1.10, while Simpson diversity decreased substantially under greater environmental stress. The study also reported low dissolved oxygen and elevated total dissolved solids in impacted locations, suggesting that salinity and pollution can jointly influence zooplankton community structure.

The comparison between the earlier survey of Albushabaa et al. (2019) and the more recent investigation provides an important basis for discussing temporal ecological change. However, differences in sampling locations, sampling periods, methodology, and environmental conditions mean that the two studies should **not be interpreted as a direct measurement of biodiversity loss through time**. Instead, they demonstrate that the Bahr Al-Najaf contains considerable spatial and temporal heterogeneity and that current environmental gradients may strongly influence zooplankton communities.

4. EFFECTS OF TEMPERATURE ON INVERTEBRATE BIODIVERSITY

Temperature is one of the principal environmental variables controlling aquatic invertebrate physiology. As ectothermic organisms, invertebrates depend largely on ambient temperature to regulate metabolic processes. Changes in temperature can influence development, feeding, reproduction, growth, emergence, and survival. Consequently, climate warming can alter both the abundance of individual taxa and the overall structure of aquatic communities.

Bonacina et al. (2023) demonstrated through a systematic review that water temperature influences freshwater macroinvertebrates at multiple biological levels, from individual physiological processes to community-level biodiversity. The ecological response depends on species-specific thermal tolerance, developmental stage, geographical distribution, and interactions with other environmental variables. In the Bahr Al-Najaf, increasing temperatures may be particularly important because the system is shallow and situated within a hot, semi-arid region. Higher temperatures combined with reduced water depth can increase thermal stress and decrease dissolved oxygen availability. These processes may disproportionately affect temperature-sensitive taxa while favoring organisms capable of surviving under warmer and more variable conditions.

Recent research also indicates that temperature may interact with salinity and other stressors. A 2025 review of freshwater organisms exposed to multiple stressors concluded that temperature and salinity represent two important climate-related drivers and that increasing temperature can amplify the effects of several additional environmental stressors. Thus, the ecological consequences of warming in Bahr Al-Najaf should be evaluated as part of a **multiple-stressor framework** rather than as an isolated temperature effect.

5. EFFECTS OF SALINITY ON INVERTEBRATE COMMUNITIES

Salinity represents a particularly important environmental factor for the Bahr Al-Najaf. Increased salinity can influence osmoregulation, reproduction, growth, feeding, and survival of aquatic invertebrates. Species differ considerably in their tolerance to salinity, and therefore increasing salinity can act as an ecological filter that changes community composition.

Sarmanov et al. (2024) demonstrated that salinization in shallow lakes within arid and semi-arid climates can significantly influence benthic invertebrate assemblages. The authors emphasized the vulnerability of shallow lakes to climate-related increases in salinity and demonstrated that changes in salinity can restructure benthic communities.

This mechanism is highly relevant to Bahr Al-Najaf. Increased evaporation associated with warming can reduce water volume while concentrating dissolved salts. If reduced inflow occurs simultaneously, the resulting increase in salinity may favor tolerant taxa and reduce the representation of sensitive species. Consequently, climate change may indirectly decrease biodiversity even when temperature itself is not the immediate cause of species loss.

The most recent study of Bahr Al-Najaf also supports the importance of this relationship. The observed association between high total dissolved solids, pollution, and lower zooplankton diversity suggests that salinity-related stress should be considered when interpreting biodiversity patterns in the lake.

6. EFFECTS OF DROUGHT AND HYDROLOGICAL VARIABILITY

Drought is increasingly recognized as a major driver of freshwater biodiversity change. Unlike gradual warming, drought can rapidly alter habitat availability, water depth, connectivity, oxygen conditions, and resource availability. These changes can have cascading effects throughout aquatic food webs.

Machuca-Sepúlveda et al. (2024) reviewed the ecological responses of freshwater macroinvertebrates to intensified drought and reported substantial effects on taxonomic and functional diversity. Importantly, the authors highlighted a major research gap concerning lentic systems and ecosystems in arid and semi-arid regions, which makes studies of systems such as Bahr Al-Najaf particularly valuable.

Drought may influence invertebrate biodiversity through several mechanisms. Reduced water volume can decrease available habitat, increase temperature and salinity, reduce dissolved oxygen, concentrate pollutants, and modify the availability of food resources. These effects may act simultaneously rather than independently. Consequently, drought can transform the entire ecological context in which aquatic invertebrates live.

Sun et al. (2025) similarly concluded that climate-induced drought can substantially affect lake and reservoir biodiversity and ecosystem services, although responses differ among taxonomic groups and ecosystems. For the Bahr Al-Najaf, this suggests that future drought should be regarded as a potential **ecological multiplier**, because its effects may amplify pre-existing problems associated with salinity and pollution.

7. INTERACTION BETWEEN CLIMATE CHANGE AND POLLUTION

An important feature of climate-change impacts is the interaction between climatic and non-climatic stressors. Pollution may become more ecologically significant during periods of low water availability because contaminants can become concentrated when water volume decreases. Similarly, high temperatures can increase physiological stress and potentially reduce organisms' capacity to tolerate contaminants.

The global meta-analysis of freshwater stressors published in 2025 demonstrated that biodiversity responses are strongly associated with several environmental pressures, particularly salinity, oxygen depletion, and fine sediment accumulation. However, responses to warming and nutrient enrichment varied among organism groups, demonstrating the complexity of multiple-stressor interactions.

For Bahr Al-Najaf, this interaction is particularly relevant because the 2026 zooplankton study documented a pollution–salinity gradient accompanied by differences in biodiversity and environmental conditions. This indicates that future research should avoid attributing changes in invertebrate biodiversity exclusively to climate change and should instead distinguish between **climatic drivers, hydrological drivers, pollution effects, and their interactions**.

8. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite increasing knowledge of aquatic biodiversity in the Bahr Al-Najaf, several important research gaps remain. First, there is a shortage of long-term standardized datasets that simultaneously record climatic variables, water chemistry, hydrology, and

invertebrate biodiversity. Second, most available studies focus on particular taxonomic groups or individual environmental variables rather than evaluating the complete ecological response to multiple interacting pressures.

Third, there is a need to expand monitoring beyond zooplankton to include benthic macroinvertebrates, molluscs, aquatic insects, and other functional groups. Recent international work has emphasized that freshwater biodiversity monitoring remains insufficiently standardized, with important gaps in sampling procedures, taxonomic identification, biodiversity metrics, and ecological assessment.

Future investigations of Bahr Al-Najaf should therefore integrate **temperature, precipitation, evaporation, water level, salinity/TDS, dissolved oxygen, pH, nutrients, heavy metals, habitat characteristics, and biological indicators**. Combining these environmental variables with taxonomic and functional biodiversity metrics would provide a stronger basis for determining whether observed ecological changes are primarily associated with climate variability, anthropogenic disturbance, or their interaction.

9. BIODIVERSITY DYNAMICS OF MAJOR INVERTEBRATE GROUPS IN THE BAHR AL-NAJAF

9.1. Zooplankton Communities

Zooplankton represent one of the most important components of aquatic food webs and occupy a central position between primary producers and higher trophic levels. Their short generation times and rapid responses to environmental fluctuations make them particularly useful indicators of ecological change. Changes in temperature, salinity, nutrient availability, dissolved oxygen, and phytoplankton composition can rapidly modify zooplankton abundance and community structure (Bonacina et al., 2023; Haase et al., 2023).

In Bahr Al-Najaf, zooplankton diversity has been documented across different locations and seasons. Albushabaa et al. (2019) recorded 48 zooplankton taxa belonging mainly to Copepoda, Rotifera, and Cladocera. The dominance of copepods and the variation in diversity among sampling sites indicate that environmental heterogeneity plays an important role in determining zooplankton distribution.

Climate change may modify these communities through both direct and indirect pathways. Increasing water temperature can accelerate metabolic rates and shorten generation times in some zooplankton species, while simultaneously exceeding the thermal tolerance of others. Warming may therefore favor thermally tolerant species and alter competitive relationships among taxa. Changes in water level and salinity may further modify habitat suitability, resulting in shifts in community composition.

The ecological importance of these changes extends beyond zooplankton themselves. Because zooplankton constitute a major food source for fish and other aquatic organisms, climate-driven changes in zooplankton abundance and composition can propagate through the aquatic food web. Consequently, monitoring zooplankton biodiversity may provide an early warning of broader ecological changes within Bahr Al-Najaf.

9.2. Molluscan Biodiversity

Molluscs are another important component of aquatic invertebrate communities. Gastropods and bivalves contribute to benthic food webs, organic-matter processing, filtration, nutrient cycling, and sediment–water interactions. Their shells and remains may also provide valuable palaeoenvironmental information.

The importance of molluscs to the ecological history of Bahr Al-Najaf has been highlighted by palaeohydrological research. Briant et al. (2024) demonstrated that molluscan assemblages can provide evidence of past changes in hydrology and environmental conditions within the Bahr Al-Najaf basin. The distribution and preservation of molluscan remains therefore provide a valuable historical perspective for understanding changes in the aquatic environment.Contemporary climate change may influence molluscs through changes in water availability, temperature, salinity, dissolved oxygen, and food resources. Bivalves may be particularly vulnerable to prolonged drought and dewatering because reductions in water depth can restrict suitable habitat and increase thermal and osmotic stress (Cushway et al., 2024).

Increased salinity represents an additional potential pressure. Species with narrow salinity tolerance may decline as evaporation intensifies, whereas euryhaline species may become relatively more abundant. This process can gradually simplify the molluscan community and reduce ecological heterogeneity.

9.3. Crustaceans

Crustaceans, particularly copepods, cladocerans, and other small aquatic forms, represent important components of the Bahr Al-Najaf's aquatic food web. They contribute to the transfer of energy from primary producers to fish and other consumers.

The response of crustaceans to climate change is strongly associated with temperature and water chemistry. Warmer conditions may increase reproductive rates in some taxa but can reduce population persistence when temperatures exceed physiological optima. Similarly, changes in salinity may favor halotolerant taxa while excluding sensitive freshwater species.

Changes in crustacean communities may consequently provide information about the combined effects of warming and salinization. Rather than relying exclusively on total abundance, future assessments should consider species richness, Shannon diversity, dominance, functional diversity, and the relative abundance of tolerant and sensitive taxa.

9.4. Aquatic Insects

Aquatic insects are widely recognized as important biological indicators because many taxa have relatively specific environmental requirements. Groups such as Ephemeroptera, Plecoptera, and Trichoptera are commonly associated with relatively well-oxygenated freshwater environments, whereas other groups can tolerate warmer, more saline, or organically enriched conditions.

Climate change can affect aquatic insects through changes in larval development, emergence timing, thermal tolerance, water availability, and habitat stability. Increasing temperature may accelerate development and shift emergence periods, potentially disrupting synchrony between aquatic insects and their predators or food resources (Bonacina et al., 2023).

In shallow water bodies such as Bahr Al-Najaf, drought can have particularly strong effects because temporary reductions in water depth can eliminate habitats required by sensitive aquatic insect taxa. Therefore, aquatic insects should be incorporated into future biodiversity assessments of the Bahr Al-Najaf rather than relying solely on zooplankton measurements.

9.5. Benthic Macroinvertebrates

Benthic macroinvertebrates are particularly useful for evaluating long-term ecological conditions because they integrate environmental conditions over relatively extended periods. Their community composition reflects multiple environmental variables, including sediment characteristics, dissolved oxygen, organic matter, salinity, nutrients, and contaminants.

Climate change can modify benthic communities through warming, drought, altered hydrological regimes, and changes in sediment conditions. Machuca-Sepúlveda et al. (2024) emphasized that intensified drought can substantially modify freshwater macroinvertebrate communities, although responses differ among taxonomic and functional groups.

Salinity is another important determinant. Sarmanov et al. (2024) demonstrated that salinization can restructure benthic macroinvertebrate communities in shallow lakes located in arid and semi-arid environments. This finding has particular relevance to Bahr Al-Najaf because climatic warming and increased evaporation could intensify salinity stress.

A major advantage of benthic macroinvertebrates is that they can be evaluated using multiple complementary metrics. These include:

- Taxonomic richness
- Shannon–Wiener diversity
- Simpson diversity
- Evenness
- Dominance
- Functional diversity
- Percentage of tolerant taxa
- Percentage of sensitive taxa
- Biological water-quality indices

Using multiple metrics would provide a more comprehensive assessment than relying on species counts alone.

10. CLIMATE CHANGE–DRIVEN SHIFTS IN INVERTEBRATE COMMUNITY STRUCTURE

The effects of climate change on aquatic invertebrates are unlikely to be uniform. Instead, environmental change may result in **species replacement**, whereby sensitive species decline and tolerant species increase. Such replacement can occur without a dramatic reduction in total abundance, meaning that abundance alone may underestimate ecological degradation.

For example, warming and salinization may promote species adapted to higher temperatures and greater ionic concentrations while reducing taxa requiring cooler and less saline conditions. This process can lead to a gradual homogenization of aquatic communities and a reduction in functional diversity.

Haase et al. (2023) demonstrated that freshwater biodiversity responses cannot be fully understood through species richness alone. Functional characteristics and community composition may change even when overall taxonomic richness appears relatively stable. Therefore, climate-change assessments in Bahr Al-Najaf should incorporate both **taxonomic and functional biodiversity**.

11. CONCEPTUAL FRAMEWORK FOR CLIMATE CHANGE EFFECTS ON INVERTEBRATES IN THE BAHR AL-NAJAF

The relationship can be conceptualized as follows:

Climate Change
↓
Increased temperature + altered precipitation + increased evaporation + drought
↓
Reduced water level / altered hydrology
↓
Increased salinity + increased TDS + reduced dissolved oxygen + altered habitat
↓
Physiological stress on invertebrates
↓
Changes in survival, reproduction, growth and distribution
↓
Changes in species richness, abundance and community composition
↓
Changes in food-web structure and ecosystem functioning

This conceptual framework emphasizes that climate change does not necessarily affect invertebrates through a single pathway. Instead, climatic drivers can initiate a sequence of interconnected physical, chemical, biological, and ecological changes.

Table 1. Major Climate and Environmental Stressors Affecting Invertebrate Biodiversity in the Bahr Al-Najaf

Climate / Environmental Stressor	Environmental Response	Affected Invertebrate Groups	Expected Biodiversity Response	Relevance to Bahr Al-Najaf	Key References
Temperature increase	Thermal stress; altered metabolism, growth and reproduction	Zooplankton; aquatic insects; molluscs; benthic macroinvertebrates	Replacement of sensitive taxa by tolerant taxa; changes in richness and community composition	Highly relevant to shallow, warm and semi-arid Bahr Al-Najaf	Bonacina et al. (2023)
Drought / reduced water level	Habitat contraction; increased temperature and concentration of dissolved substances	Benthic macroinvertebrates; molluscs; zooplankton	Reduced habitat availability; possible decline in sensitive taxa	Relevant because hydrological variability can strongly affect the Bahr Al-Najaf	Machuca-Sepúlveda et al. (2024); Sun et al. (2025)
Salinization / increased TDS	Osmotic stress and altered habitat suitability	Zooplankton; molluscs; crustaceans; benthic macroinvertebrates	Decline of freshwater-sensitive taxa and increase in tolerant taxa	Salinity is an important environmental gradient in Bahr Al-Najaf	Sarmanov et al. (2024); Albushabaa et al. (2019)
Low dissolved oxygen	Physiological stress and reduced habitat suitability	Zooplankton; benthic macroinvertebrates; aquatic insects	Reduced abundance and loss of oxygen-sensitive taxa	Potentially intensified by warming, shallow water and organic pollution	Recent multiple-stressor literature (2025)
Pollution	Chemical and physiological stress; interaction	Zooplankton; molluscs; benthic	Reduced diversity and increased dominance of tolerant organisms	Pollution–salinity gradients have been	Albushabaa et al. (2019); recent Bahr

	with climate stressors	macroinvertebrates		reported in Bahr Al-Najaf	Al-Najaf studies (2026)
Altered hydrological regime	Changes in inundation duration, connectivity and water residence time	All major aquatic invertebrate groups	Changes in distribution, seasonal abundance and community composition	Historically important for the Bahr Al-Najaf basin	Briant et al. (2024)
Habitat / sediment alteration	Changes in substrate, organic matter and benthic habitat quality	Benthic macroinvertebrates; molluscs; aquatic insects	Changes in functional and taxonomic diversity	Important consideration for future ecological monitoring	Haase et al. (2023); 2025 multiple-stressor evidence

12. DISCUSSION

The available evidence indicates that climate change may represent an increasingly important driver of invertebrate biodiversity dynamics in the Bahr Al-Najaf. However, its effects should not be considered independently from hydrological alteration, salinization, pollution, and habitat modification. The ecological response of aquatic invertebrates is likely to emerge from the interaction of these pressures, with the magnitude and direction of responses varying among taxonomic and functional groups.

Temperature is expected to be one of the principal direct drivers. Increasing water temperature can modify metabolic activity, growth, reproduction, development, and survival, particularly among taxa with relatively narrow thermal tolerances. Bonacina et al. (2023) demonstrated that temperature can influence freshwater macroinvertebrates from individual physiological processes to community-level characteristics. In the shallow and semi-arid environment of the Bahr Al-Najaf, warming may become particularly important because high temperatures can occur simultaneously with reduced water depth and increased evaporation.

Salinization represents another critical pathway through which climate change may influence biodiversity. Increased evaporation and reduced water availability can concentrate dissolved salts, creating stronger osmotic stress for freshwater organisms. Evidence from shallow lakes in arid and semi-arid environments demonstrates that increasing salinity can substantially restructure benthic macroinvertebrate communities and favor tolerant taxa over sensitive species (Sarmanov et al., 2024). This mechanism is particularly relevant to the Bahr Al-Najaf because salinity and total dissolved solids are important components of its environmental variability.

The available zooplankton evidence provides an important biological perspective. Albushabaa et al. (2019) documented substantial zooplankton diversity in Bahr Al-Najaf, including representatives of Copepoda, Rotifera, and Cladocera, while more recent observations indicate strong differences in diversity along environmental gradients. Nevertheless, differences in sampling periods, locations, and methodologies prevent direct calculation of temporal biodiversity loss from these studies alone. Instead, they should be interpreted as evidence of substantial spatial and temporal heterogeneity and as justification for establishing standardized long-term monitoring.

Drought may represent a particularly important climate-related pressure in the future. Reduced water availability can simultaneously decrease habitat area, increase temperature and salinity, reduce dissolved oxygen, and concentrate contaminants. Machuca-Sepúlveda et al. (2024) highlighted the sensitivity of freshwater macroinvertebrates to intensified drought, while Sun et al. (2025) demonstrated that climate-induced drought can alter biodiversity and ecosystem functioning in lakes and reservoirs. Thus, drought in the Bahr Al-Najaf should be considered an ecological multiplier capable of intensifying the effects of other stressors.

The interaction between climate change and pollution is also important. Low water levels can increase the concentration of pollutants, while warming may increase physiological stress and modify contaminant toxicity. Consequently, an organism already exposed to thermal or osmotic stress may have reduced capacity to tolerate additional chemical stress. The multiple-stressor perspective is therefore more appropriate for understanding future biodiversity dynamics than approaches based on a single environmental variable (He et al., 2023).

An additional consideration is that changes in species richness alone may not adequately describe ecological degradation. Climate change can cause species replacement without necessarily producing an immediate large decline in total abundance. Sensitive taxa may disappear while tolerant organisms increase, maintaining relatively similar total abundance but producing a biologically different community. For this reason, future investigations should combine taxonomic richness with Shannon and Simpson diversity, evenness, dominance, functional diversity, and the relative abundance of sensitive and tolerant taxa.

The Bahr Al-Najaf also provides a valuable opportunity to integrate contemporary biodiversity studies with palaeoenvironmental evidence. Briant et al. (2024) demonstrated that molluscan assemblages and geomorphological evidence can be used to reconstruct

historical hydrological changes in the Bahr Al-Najaf basin. Combining this historical perspective with contemporary biological monitoring could improve understanding of the natural range of environmental variability and help distinguish long-term climatic changes from recent anthropogenic impacts.

Overall, the available evidence suggests that the future biodiversity of invertebrates in the Bahr Al-Najaf will probably depend on the combined effects of **warming, drought, hydrological alteration, salinization, oxygen depletion, pollution, and habitat change**. The relative importance of each factor may vary spatially and seasonally. Therefore, future studies should adopt a multiple-stressor framework and establish long-term standardized monitoring across representative sites within the Bahr Al-Najaf.

13. CONSERVATION AND MANAGEMENT IMPLICATIONS

The conservation of invertebrate biodiversity in the Bahr Al-Najaf requires an integrated management strategy that considers both climatic and anthropogenic pressures. Regular monitoring of temperature, water level, salinity, electrical conductivity, dissolved oxygen, pH, nutrients, and contaminants should be conducted simultaneously with biological sampling.

Zooplankton and benthic macroinvertebrates could serve as complementary biological indicators. Zooplankton can provide rapid information about changes in water-column conditions, whereas benthic organisms can integrate longer-term changes in sediment and water quality. Molluscan communities may provide an additional indicator of hydrological and salinity changes.

Management should also prioritize the maintenance of adequate water availability during periods of severe drought, where feasible, and the reduction of avoidable pollution inputs. Establishing permanent monitoring stations would allow seasonal and interannual changes to be distinguished from long-term climate trends.

The development of a **Bahr Al-Najaf Biodiversity Monitoring Program** would provide an effective framework for integrating climate data, water-quality measurements, biodiversity indicators, and remote-sensing information. Such a program could provide early warnings of biodiversity decline and support evidence-based environmental management.

14. CONCLUSION

The Bahr Al-Najaf represents an ecologically important and environmentally dynamic aquatic system whose invertebrate biodiversity is potentially vulnerable to climate change. The available evidence indicates that increasing temperature, drought, altered hydrology, salinization, oxygen depletion, pollution, and habitat modification can interact to influence the abundance, distribution, diversity, and composition of aquatic invertebrate communities.

Zooplankton, molluscs, crustaceans, aquatic insects, and benthic macroinvertebrates may respond differently to these pressures according to their physiological tolerances and ecological roles. Consequently, climate change is unlikely to produce a single uniform biodiversity response. Instead, it may promote shifts from environmentally sensitive taxa toward more tolerant organisms, alter seasonal patterns, and modify the functional structure of aquatic communities. The review also highlights a significant research gap: there is currently insufficient long-term, standardized information linking climatic variables with invertebrate biodiversity in Bahr Al-Najaf. Future research should therefore establish integrated monitoring programs that simultaneously measure climatic conditions, hydrology, water chemistry, pollution, habitat characteristics, and biological communities. Particular attention should be given to **salinity, water availability, temperature, dissolved oxygen, and pollution**, because these factors may interact and amplify ecological stress. Combining contemporary biodiversity surveys with palaeoenvironmental evidence could further improve understanding of long-term environmental change.

In conclusion, protecting the biodiversity of the Bahr Al-Najaf under future climate scenarios will require a transition from isolated measurements of water quality or individual taxa toward an **integrated ecosystem-based approach**. Long-term biodiversity monitoring, multiple-stressor assessment, climate-informed management, and conservation of critical aquatic habitats are essential for maintaining the ecological integrity and resilience of the Bahr Al-Najaf.

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