Key Drivers of Climate Change Impacts on Aquatic Insects

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Vimala Bind
Neha Agarwal
Ajay Kumar

Abstract

Insects are very important to various ecosystems as good pollinators, decomposers, and food sources for many organisms. They dominate diverse terrestrial (e.g., grassland) and aquatic (e.g., lakes, oceans, rivers) ecosystems. The primary objective of this study is to predict the impacts of climate change on the distribution of aquatic insect species in freshwater. Freshwater systems are the most vulnerable among all ecosystems due to various factors, resulting in impacts on aquatic life and ecosystem functions, including habitat degradation, loss of diversity, geographic distribution shifts, and disruption of ecosystem functions. Anthropogenic activities also create pressure on freshwater resources, which directly affects ecosystems, and climate change is likely to accelerate these impacts. The impact of climate change on aquatic insect diversity has been evaluated through a comprehensive review of publications from the past two decades. The paucity of published work on the changing climate and its likely effects on aquatic insects at the regional level denotes a huge gap in research. The ecological challenges posed by climate change, along with potential adaptive strategies to reduce its impact on insect diversity and aquatic systems, are explored in this discussion.

Keywords: *Aquatic insects; Ecosystems; Freshwater; Diversity; Ecological challenges.*

Vimala Bind[1,2]
[1] Research Scholar, Department of Zoology, Tilak Dhari College, Jaunpur, (U.P.), India
[2] Assistant Professor, Department of Zoology, Navyug Kanya Mahavidyalaya, Lucknow, (U.P.), India *Email: vmla17@gmail.com*
Neha Agarwal
Department of Chemistry, Navyug Kanya Mahavidyalaya (University of Lucknow)
Ajay Kumar
Assistant Professor, Department of Zoology, Tilak Dhari College, Jaunpur, (U.P.), India
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1. Introduction

Aquatic insects are essential components of freshwater ecosystems. Although they make up only 3–5% of all insect species, they are taxonomically diverse and provide crucial ecosystem services such as nutrient cycling, food for higher trophic levels, and indicators of water quality [1]. However, the ongoing effects of climate change pose significant risks to these organisms, disrupting their life cycles, distributions, and ecological roles. Aquatic insects represent a diverse and ecologically significant group of organisms that inhabit freshwater environments such as streams, rivers, lakes, and wetlands. These insects, including orders such as Ephemeroptera (mayflies), Trichoptera (caddisflies), Odonata (dragonflies), and others, perform vital roles in freshwater ecosystems, such as detritivory, herbivory, and serving as prey for a variety of vertebrates.

Climate change, driven by global warming and associated alterations in precipitation, temperature, and hydrology, is increasingly threatening the ecological integrity of freshwater systems. The consequences of climate change on aquatic insects are manifold, with effects ranging from changes in metabolic rates and developmental timing to altered species distributions and community compositions.

Due to the above characteristics, aquatic insects are particularly suited for use in Environmental Impact Assessment (EIA) and have a long tradition of use in water quality monitoring [2]. They act as reliable indicators and provide a broad spectrum of responses to disturbances at many levels of organization, ranging from organism to population, community, and even ecosystem levels [3].

This chapter reviews recent studies and presents an overview of how climate change influences the biology and ecology of aquatic insects. We also highlight key conservation strategies to safeguard these vital organisms in the face of a changing climate.

2. Temperature and Thermal Stress

2.1 Effect of Rising Temperatures on Development and Metabolism

Temperature is a fundamental driver of metabolic and developmental processes in ectothermic organisms like aquatic insects. Elevated temperatures can accelerate development, but they also place increased metabolic demands on these organisms. For example, higher water temperatures generally reduce the duration of the aquatic life stages of insects such as mayflies and caddisflies, resulting in earlier emergence times. While this may benefit some species by enabling faster reproduction, it can also lead to mismatches between insect emergence and the availability of food resources [4].

However, the benefits of accelerated development come at the cost of increased mortality and reduced size. Many aquatic insect species show optimal growth rates within specific temperature ranges. Outside these ranges, development is often hindered, or mortality rates increase. For example, *Baetis* mayflies, which are important bioindicators, show reduced survival rates when temperatures exceed their upper thermal tolerance [5]. Additionally, altered timing of emergence can lead to increased susceptibility to predation or changes in community interactions [6].

2.2 Effects on Phenology and Life Cycle Timing

The timing of life cycle events such as hatching, growth, and emergence is strongly temperature-dependent. Rising temperatures, particularly in spring and summer, have led to earlier insect emergence in several freshwater ecosystems [7]. This phenomenon can disrupt ecological synchrony. For instance, if insect emergence occurs before the peak of predator populations, such as migratory birds, it may lead to reduced survival rates for both the insects and the predators relying on them.

Moreover, insects that rely on a specific number of degree-days (a measure of accumulated warmth) to complete their development may find their life cycles shortened, potentially affecting the size and health of populations. This has been particularly evident in cold-water species, which face significant risks as temperatures exceed their historical limits [8].

3. Hydrological Changes and Altered Flow Regimes

3.1 Impact of Altered Precipitation Patterns and Droughts

Changes in precipitation patterns, including prolonged droughts and more intense rainfall events, have a direct impact on aquatic habitats. Droughts lower water levels, reducing the size of aquatic habitats and leaving many species vulnerable to desiccation or predation. Species such as Ephemeroptera (mayflies) and Trichoptera (caddisflies) that rely on submerged or shallow-water habitats are especially at-risk during drought conditions [9].

In addition, the loss of habitat during droughts can lead to smaller and more isolated populations, which may suffer from genetic bottlenecks or reduced reproductive success. The fragmentation of habitats may also exacerbate competition for limited resources, further threatening species survival. Conversely, extreme rainfall and flooding events can erode aquatic habitats, displace larvae, and disrupt the balance of nutrient cycling. Storm surges and increased runoff introduce high levels of sedimentation and pollutants into freshwater systems, decreasing water quality and altering the availability of suitable habitats for aquatic insects [10].

3.2 Altered Flow Regimes in Rivers and Streams

Many aquatic insect species, particularly in lotic systems (rivers and streams), are adapted to specific flow regimes. Shifts in flow patterns—such as the timing and duration of floods and droughts-can significantly affect insect populations. Changes in the frequency and intensity of flooding events, for instance, can lead to the washing away of insect larvae, particularly in species that rely on stable substrates [11].

Furthermore, altered flow regimes can change the distribution of aquatic habitats and disrupt the availability of appropriate substrates for insect larvae. Species that depend on stable or low-flow conditions may find their habitats diminished or modified, potentially leading to declines in those populations.

4. Shifting Species Distributions and Community Composition

4.1 Range Expansions and Contractions

As temperatures rise, species distributions are shifting, and many aquatic insects are expanding their ranges to higher latitudes and altitudes [12]. Cold-water species such as *Baetis* may experience range contractions, while warm-water species like Chironomidae (midges) could expand their ranges into previously cooler regions. These shifts have significant ecological implications, as new species introductions may disrupt existing community structures and food webs.

For instance, species that traditionally occur at lower latitudes or altitudes may become invasive in previously uninhabited ecosystems, altering local biodiversity. Similarly, the loss of cold-adapted species may reduce ecological resilience, particularly in ecosystems that depend on their specific roles in nutrient cycling or as food sources for other organisms.

4.2 Invasive Species and Ecological Disruption

Climate change can also exacerbate the spread of invasive species, particularly those that thrive in disturbed or warming environments. Species such as *Dreissena polymorpha* (zebra mussels), which can filter large amounts of water, may compete with native aquatic insect larvae for resources. These invasive species may disrupt the trophic structure of freshwater ecosystems by altering food availability or introducing new pathogens [13].

5. Ecological and Ecosystem Services

5.1 Role of Aquatic Insects in Nutrient Cycling

Aquatic insects play an essential role in nutrient cycling by breaking down organic matter such as leaf litter and detritus, recycling nutrients back into the ecosystem. They provide ecosystem services that maintain water quality and support primary production. Alterations to insect populations due to climate change can therefore disrupt nutrient cycling, leading to poorer water quality, eutrophication, and reduced biodiversity in aquatic ecosystems [14].

5.2 Aquatic Insects as Food for Higher Trophic Levels

Aquatic insects also serve as a vital food source for many higher trophic levels, including fish, amphibians, and birds. Changes in the abundance or timing of insect emergence can disrupt these predator–prey relationships. For example, early emergence of insects could result in a mismatch with the breeding seasons of fish or birds, leading to reduced survival of offspring [15].

6. Conservation Implications and Management Strategies

6.1 Monitoring and Restoration of Aquatic Habitats

To safeguard aquatic insect populations in the face of climate change, habitat restoration and management efforts must be prioritized. The restoration of riparian zones, wetlands, and floodplains will help maintain biodiversity by improving habitat quality and providing connectivity between aquatic systems. Additionally, efforts to reduce pollution and sedimentation, particularly in urbanized areas, will benefit insect populations by preserving clean and stable habitats.

6.2 Climate-Resilient Conservation Practices

Conservation strategies should consider the projected impacts of climate change on freshwater ecosystems. These may include adaptive management strategies such as creating refuges for temperature-sensitive species or ensuring connectivity between habitats to allow for range shifts. Protecting and restoring natural hydrological regimes will be vital in mitigating the impacts of altered flow patterns and extreme weather events.

7. Conclusion

In conclusion, the effects of climate change on aquatic insects are extensive and deeply interconnected with the broader functioning of freshwater ecosystems. Rising temperatures, altered precipitation regimes, increased frequency of extreme weather events, and declining dissolved oxygen levels directly influence insect physiology, development rates, emergence timing, and survival [16, 17]. Many aquatic insects are ectothermic and highly sensitive to thermal thresholds, meaning that even moderate warming can accelerate life cycles, disrupt synchrony with food resources, and shift geographic ranges [18]. Cold-adapted and high-elevation species are particularly vulnerable, facing habitat contraction and an increased risk of local extinction [19].

These biological changes can cascade through freshwater food webs. Aquatic insects are key components of stream and lake ecosystems, contributing to leaf litter decomposition, nutrient cycling, and energy transfer from primary producers to higher trophic levels. Alterations in their abundance or phenology can affect fish populations and other insectivorous vertebrates [20]. In addition, because aquatic insects are widely used as bioindicators of water quality, climate-driven shifts in their communities may complicate biomonitoring and ecological assessment frameworks [21].

Effective conservation and management strategies must therefore integrate climate change projections into freshwater planning. Protecting riparian vegetation can buffer streams against temperature increases, while maintaining natural flow variability supports habitat heterogeneity and species resilience. Habitat restoration, pollution control, and the preservation of connectivity between water bodies are critical for enabling dispersal and adaptation [22]. Long-term monitoring programs are equally important for detecting early warning signs of ecological disruption and informing adaptive management responses.

Ultimately, conserving aquatic insect populations is essential not only for biodiversity but also for maintaining ecosystem services such as water purification, fisheries support, and nutrient regulation. A science-based, ecosystem-level approach—combining research, policy integration, and habitat protection- will be crucial to mitigating climate change impacts and ensuring the long-term resilience of freshwater ecosystems.

References

1. Daly, H. V., Doyen, J. T., & Purcell, A. H. (1998). *Introduction to insect biology and diversity*. Oxford University Press.
2. Bonada, N., Prat, N., Resh, V. H., & Bernhard, S. (2006). Developments in aquatic insect biomonitoring: A comparative analysis of recent approaches. *Annual Review of Entomology, 51*, 495–523.
3. Niemi, G. J., & McDonald, M. E. (2004). Application of ecological indicators. *Annual Review of Ecology, Evolution, and Systematics, 35*, 89–111.
4. Poff, N. L. R., Allan, J. D., & Bunn, S. E. (2017). Climate change and freshwater ecosystems: Assessing impacts, adaptation, and mitigation. *Freshwater Biology, 62*(8), 1047–1058.
5. Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences, 37*(1), 130–137.
6. Schindler, D. E., et al. (2012). The changing timing of aquatic insect emergence: Ecological consequences and monitoring challenges. *Journal of Freshwater Ecology, 27*(4), 634–641.

7. Cianfrani, C., & Palazón, J. (2011). Effects of climate change on phenology and timing of emergence of aquatic insects. *Journal of Insect Ecology, 55*(3), 324–336.
8. Battin, J., Wiley, M. J., Rinne, J. N., & Hendricks, S. P. (2007). Projected impacts of climate change on freshwater ecosystems. *Nature, 439*, 1291–1296.
9. Stubbington, R., et al. (2017). Impact of drought on freshwater invertebrates. *Biological Conservation, 212*, 106–118.
10. Poff, N. L. R., Bunn, S. E., Arthington, A. H., & Boersma, K. S. (2010). Global climate change and freshwater ecosystems: Impacts, adaptation, and mitigation. *Hydrobiologia, 641*(1), 3–43.
11. Baxter, C. V., Hauer, F. R., & Schmidt, J. C. (2015). Aquatic insect functional diversity and its role in stream ecosystem processes. *Freshwater Biology, 60*(9), 1474–1485.
12. Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., & Polwart, A. (2002). Herbivory in climate change research: The relevance of insect species to the study of climate change impacts. *Ecological Entomology, 27*(1), 10–22.
13. Strayer, D. L., & Dudgeon, D. (2019). Impacts of invasive species on freshwater ecosystems. *Annual Review of Ecology, Evolution, and Systematics, 40*, 59–80.
14. Hahn, M., & Rehbein, L. (2002). The role of aquatic insects in nutrient cycling. *Hydrobiologia, 484*, 113–126.
15. Rundle, S. D., & McColl, M. (2004). The effects of climate change on aquatic insect populations. *Biological Conservation, 113*(2), 159–172.
16. Hering, D., Moog, O., Sandin, L., & Verdonschot, P. F. M. (2010). Overview and application of the AQEM assessment system. *Hydrobiologia, 422/423*, 1–13.
17. Durance, I., & Ormerod, S. J. (2007). Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology, 13*(5), 942–957.
18. Hassall, C., & Thompson, D. J. (2008). The effects of environmental warming on Odonata: A review. *International Journal of Odonatology, 11*(2), 131–153.
19. Heino, J., Virkkala, R., & Toivonen, H. (2009). Climate change and freshwater biodiversity: Detected patterns, future trends and adaptations in northern regions. *Biological Reviews, 84*(1), 39–54.

20. Woodward, G., Perkins, D. M., & Brown, L. E. (2010). Climate change and freshwater ecosystems: Impacts across multiple levels of organization. *Philosophical Transactions of the Royal Society B, 365*(1549), 2093–2106.
21. Bonada, N., Prat, N., Resh, V. H., & Statzner, B. (2007). Developments in aquatic insect biomonitoring: A comparative analysis of recent approaches. *Annual Review of Entomology, 52*, 495–523.
22. Palmer, M. A., Menninger, H. L., & Bernhardt, E. (2009). River restoration, habitat heterogeneity and biodiversity: A failure of theory or practice? *Freshwater Biology, 55*(S1), 205–222.