Feature Article

Ecological Significance of Aquatic Macroinvertebrates in Headwater Streams

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Abstract

Headwater streams are the starting points of river ecosystems, that consist of an array of unique microhabitats. Most of these stream segments are first-order streams and these aquatic ecosystems provide habitats for many macroinvertebrates including arthropods, mollusks, annelids, nematodes, and turbellarians. These species play a significant role in maintaining the ecological integrity of the river ecosystem. Specifically, their feeding habits of scraping, collecting, shuddering, and predating make a significant contribution to maintaining stable food webs within the stream ecosystems. These macroinvertebrates are highly sensitive to environmental changes and consequently, they have been used as indicators of environmental quality. Although the aquatic macroinvertebrates play a crucial role in headwater streams, they face stresses caused either by nature itself or man leading to their extinction on certain occasions. Global warming, acidification, deforestation, forest fires, industrialization, intensive agriculture, and livestock farming practices have been identified as potential stresses behind the extinction and biodiversity losses of macroinvertebrates in headwater streams. Therefore, the abundance and distribution of macroinvertebrates in headwater streams need to be critically considered in developing criteria for development projects, agricultural practices, and other environmental management strategies to protect and conserve these unique environmental creatures.

Key Words: Indicator organisms, caddisfly, water quality, biodiversity, functional feeding groups.

1. Introduction

Headwater streams are the starting point of stream ecosystems that extend from catchments to the river mouth. These ecosystems consist of an array of unique ecological and environmental characteristics, together with their diverse organisms, while most of these streams are first-order streams. Richardson (2019) defined headwaters as the first perennially flowing streams in a river network, and those streams can originate with the presence of surfacing of groundwater (e.g., springs, swales, etc.) which supports the creation of fluvial characteristics of both intermittent and ephemeral streams. Catchment of the headwaters includes forest, alpine or subalpine areas, grasslands, and savannahs. Headwaters are particularly important to maintain the ecological integrity of the entire river network, as these unique habitats provide an array of ecosystem functions that directly and indirectly influence the downstream (Freeman *et al,* 2007, Xenopoulos *et al,* 2017). For example, the provisioning service of water, sediment, and organic matter is largely important for the downstream(Wipfli *et al,* 2007).

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ISSN 2235-9362 Online

Further, headwaters are important for organic matter processing and nutrient cycling (Clarke *et al,* 2008), while the interaction between surrounding terrestrial habitats links both aquatic and terrestrial components. Thus, the overall functions of the headwaters may be vital for maintaining the ecological balance of the entire ecosystem. The headwaters consist of various microhabitats that harbor an array of both fauna and flora (Meyer *et al,* 2007), while many of these organisms are bioindicators of those unique habitats (Jandry *et al,* 2014, Pond *et al,* 2014, Machado *et al,* 2021). Among these fauna, macroinvertebrates play a crucial ecological role in keeping the ecological balance not only in the headwaters themselves but also in the entire river network (Heino 2005, Oester *et al,* 2023). Aquatic macroinvertebrates are animals without a backbone that are living in aquatic habitats and visible under the naked eye. They include arthropods (insects, mites, scuds, and crayfish), mollusks (snails, limpets, mussels, and clams), annelids (segmented worms and leeches), nematodes (roundworms), and turbellarians (flatworms) (Hauer and Resh 2017). Macroinvertebrates involved in transferring organic matter from various sources inside or outside of the stream through the stream food web (Hauer and Resh 2017) while facing huge anthropogenic pressure (Mangadze *et al,* 2019, Strungaru *et al,* 2021). Therefore, the objective of this article is to explore the diversity, ecology, and drivers behind the pressure on aquatic macroinvertebrates in headwaters.

2. Methodology

This feature article was drafted after a comprehensive literature review using published literature available from different academic sources. Information was collected by searching the websites of Web of Science, Scopus, and Google Scholar with the aid of different keywords. Some of the major keywords were, "headwater streams", "macroinvertebrates", "indicator species", "keystone species", "biodiversity", "functional feeding groups" and "aquatic ecosystems". At the same time, information available in conference proceedings not available in online sources was also used. After careful selection, information on macroinvertebrates in headwater streams, their functional feeding habits, adaptations, ecological role, and the threats to those species were extracted, and this article was drafted according to the author's guidelines of the journal.

3. Results and discussion

3.1 Diversity of macroinvertebrates

According to Meyer *et al,* (2007), there are five different types of macroinvertebrates in headwaters, (i) species that are unique to headwaters, (ii) species that are found in both headwaters se and larger streams; (iii) species that migrate into headwaters seasonally due to unfavorable environmental conditions in downstream; (iv) species that spend most of their lives in downstream ecosystems, but require headwaters at particular lifehistory stages (e.g., for spawning or nursery areas); and (iv) species that live around but not in headwater streams. Some of the common aquatic macroinvertebrates are riffle beetle, caddisfly larva, mayfly larva, gilled snail, stonefly larva, water penney, blackfly larvae, and damselfly larva. Most of these aquatic macroinvertebrates are larval stages of terrestrial insects (Fig. 1).

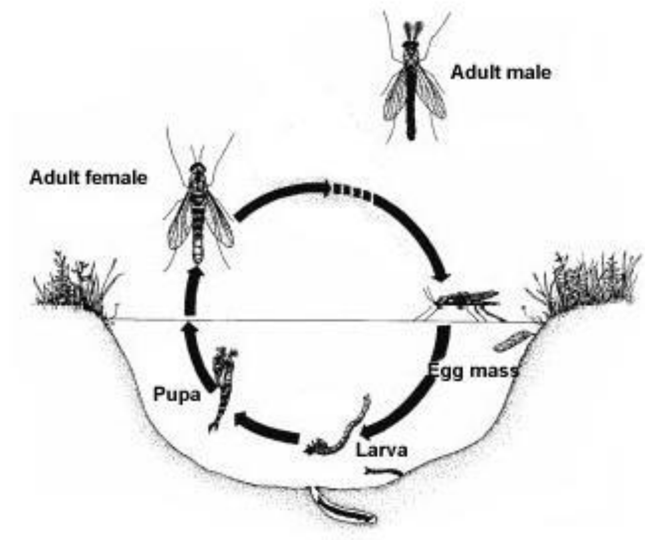

Figure 1: The life cycle of an aquatic insect. source:(https://content.ces.ncsu.edu)

The biodiversity of headwater streams is comparatively higher in almost all geographical regions in the world as these unique habitats consist of an array of different macroinvertebrates (Table 1).

Table 1: Shannon diversity index and taxonomic richness of macroinvertebrates in headwater streams

Region	River and the region	Shanon-Weiner Diversity Index	Taxonomic Richness	Reference
Tropical	Waturawa Stream, Sri Lanka	2.91-3.54	12-20	Sanjaya *et al,* (2015)
	Sapugahadola, Sri Lanka	1.7-1.8	NA	Priyadarshani *et al,* (2019)
	Gurugoda Oya, Kegalle, Sri Lanka	1.03-1.86	7-13	Munasinghe *et al,* (2021)
	Napo River, Ecuador	1.16-1.82	9-29	Espinosa *et al,* (2020)
	Upper São Francisco and Upper Araguari River Basins, Brazil	NA	10-30	Ferreira *et al,* (2014)
	Sapa Highland, northern Vietnam	1.6-3.15	21-33	Jung *et al,* (2008)
Temperate	Bigelow, Brook in north central Massachusetts, USA	0.60-1.9	6-12	Collins *et al,* (2007)
	Selenga-Baikal river Mongolia	0.39 – 2.67	2-23	Pfeiffer *et al,* (2021)
	Pearl, China	NA	45-51	Wang *et al,* (2022)
	Massachusetts (Perennial)	0.78-0.98	15-25	Santos and Stevenson (2011)
	Massachusetts (Intermitant)	0.98 – 1.16	15-27	
	Elklick Run Virginia	NA	10-25	Angradi *et al,* (2001)
	he Chesapeake Bay drainage, USA	NA	40-55	Moore and Palmer (2005)
	Finland	NA	15-28	Astorga *et al,* (2011)
	Korea	0.28 – 2.48	9-50	Bae *et al,* (2016)
	Upper Araguari Basin and Upper São Francisco Basin.	NA	16 - 30	Astorga *et al,* (2011b)

The diversity of macroinvertebrates in aquatic ecosystems can also be classified according to their feeding habits. Accordingly, there are five different functional feeding groups (Table 2).

Table 2. Different functional feeding groups of macroinvertebrates

Functional Feeding Group	Feeding habit	Examples
Scrapers (grazers)	consume algae and associated material	Caddisfly (*Helicopsyche Borealis*) and the beetle (*Optioservus quadrimaculatus*)
Shredders	consume leaf litter or other CPOM, including wood	Caddisfly (*Heteroplectron californicum*) and the stonefly (*Zapada cintipes*)
Collectors (gatherers)	collect FPOM from the stream bottom	Beetle (*Zaitzevia parvula*) and the Dipteran (true flies) (*Antocha monticola*), Mayfly nymph (*Offadens confleens*)
Filterers	collect FPOM from the water column using a variety of filters	Caddishfly larva (Hydropsychidae)
Predators	feed on other consumers	Dragonflies, Caddishfly larva (Polycentopodidae)

3.2 Adaptations of aquatic macroinvertebrates for the aquatic environment

Aquatic macroinvertebrates exhibit various adaptations which support them to live in many different microhabitats in aquatic ecosystems. Caddishly larvae live living flowing waters using a case made by themselves, while water pennies adapted to live in fast-flowing waters by evolving a flat body that supports them to stay attached to rocks with their legs. Further, most of the aquatic insects have developed drfting behavior through their evaluation (Mazzucco *et al,* 2015), while certain mayfly nymphs such as *Psammophilous* nymphs can live either in partial or complete burial in the sand (Dodds 2002).

The presence of very long claws in burrowing mayfly species is the key adaptation that facilitates them for burrowing in bottom sediments of aquatic habitats. Further, gills attached to the swimming legs of mayfly nymphs facilitate their oxygen uptake. Macroinvertebrates live in fast-flowing water, including stoneflies and mayflies, and often use either claws or hooks as adaptations for holding onto rocky surfaces. Certain species are living in slow-moving waters and thus, they need legs for swimming rather than adaptations for attaching to substrates (Alba-Tercedor 2008). Water boatmen an aquatic insects commonly found in both lentic and lotic environments, and they live in slow-moving water. Therefore, legs are designed for swimming rather than holding on. The spiny-gilled mayfly has hairy legs to trap drifting food particles. Although most macroinvertebrates breathe through their gills, other species such as diving beetles trap air bubbles under their exoskeletons for breathing.

3.3 Ecological Role of macroinvertebrates in headwater streams

The feeding behavior of macroinvertebrates plays a crucial role in maintaining the ecological balance of aquatic ecosystems. Scrapers have well-adapted mouthparts with special adaptations for grazing from rocks. Their scraper blade is flat and located at the edge of the mouthparts to graze or scrape materials on surfaces, and consequently important as primary consumers feed on attached algae. This interaction ensures the energy transfer from the primary producer to the next level of the food chain. Caddishly larvae, snails, certain mayflies, and water pennies are some examples of scrapers (Watson-Ferguson 2006, Thorp and Rogers 2010, Cummins 2019). Not only attached algae, scrapers graze minerals, and other substances on different substrates in the stream. This behavior is important to maintain biogeochemical cycles.

Macroinvertebrates adapted to feed primarily on large pieces of decomposing vascular plant tissue (>1 mm diameter) along with the associated microflora and fauna, living vascular macrophytes, or gouge decomposing wood are referred to as shedders. Their feeding habit augments the decomposition process of the stream ecosystem.

Collectors remove fine particulate organic matter (FPOM: <1 mm diameter), in water columns and benthic sediments. These FPOMs accumulate in aquatic ecosystems due to shredders as they largely consume Course Particulate Organic Matters (CPOM) such as leaves, and twigs. Some of the common collector species are the beetle (*Zaitzevia parvula*) and the Dipteran (true flies) (*Antocha monticola*). Collectors remove FPOMs such as fecal pellets and plant fragments available in streams through their feeding mechanism. This mechanism extends their support to maintain biogeochemical cycles and decomposition of organic matter. Similarly, filterers/collectors remove particulate matter from the suspension through their feeding. They have either specialized anatomical structure (setae, mouth brushes, fans, etc) or silk and silk-like secretions to trap these particles (Wallace and Webster 1996). Certain caddish flies back flies, brush-legged mayflies, and mussels are common collectors in stream ecosystems. Predators are commonly found in all microhabitats of river ecosystems, and they feed on other living animals. In addition, macroinvertebrates are important for the translocation of materials in streams. For instance, Previšić *et al,* (2020) detected bioaccumulation of emerging contaminants in *Hydropsyche* larvae under experimental conditions. On the other hand, aquatic macroinvertebrates are good indicators of environmental quality, and thus, they are used as bioindicators. Further, certain macroinvertebrates in headwater streams also play a significant role in keeping the ecological balance and the flow of energy and nutrients through the community. Such taxa are referred to as either keystone species or ecological engineers. Several taxa appear to function as keystone species in headwaters such as crayfish, stoneflies, large shrimps, and tadpoles (Flecker 1996, Zanetell and Peckarsky 1996, Usio 2000).

3.4 Macroinvertebrates as an indicator of water quality

Aquatic macroinvertebrates have been classified into three different groups based on their tolerance limit against the pollution level of the stream, and thus, they are being widely used as indicators in the quality assessments of aquatic ecosystems. Species that are intolerant of pollutants and unable to withstand polluted aquatic environments are known as pollution-sensitive species, while species that are capable of living in moderately polluted, and highly polluted aquatic habitats are referred to as semi-tolerance and pollution-tolerant species respectively (Figure 2).

Macroinvertebrates are highly sensitive to environmental changes, and their abundance has been severely impacted by both natural and anthropogenic influences including acidification, forest fire, hydrological controls, and groundwater abstraction and salinization (Guerold *et al,* 2000, Mellon *et al,* 2008, Timpano *et al,* 2018, White *et al,* 2018). According to Guerold *et al,* (2000), acidification drastically affected all taxonomic groups, and Molluscans, Crustaceans, and Ephemeroptera disappeared totally from strongly acidified streams. Macroinvertebrate diversity was comparatively low, and their communities were dominated by chironomid midges in the burned catchments compared to unburned catchments (Mellon *et al,* 2008). Specifically, forest fire largely influences prey flow to adjacent terrestrial and downstream aquatic habitats. A rapid decline in the richness and abundance of the genera of the order Ephemeroptera has been observed in parallel to the salinization of headwater streams (Timpano *et al,* 2018). Furthermore, agricultural runoff, industrial effluents, acid mine drainages, livestock farming, and deforestations also influence the diversity of macroinvertebrates in headwaters (Hooda *et al,* 2000, Moore and Palmer 2005, Ross *et al,* 2008, Al-Shami *et al,* 2017, Mereta *et al,* 2020). For example, runoff from intensive dairy farming significantly increases physicochemical properties including biochemical oxygen demand (BOD), ammonium-nitrogen (m-N), and molybdate reactive phosphorus (MRP) concentrations in headwater streams making those habitats unsuitable for macroinvertebrates (Hooda *et al,* 2000). A similar trend was reported in response to industrial effluents by Mereta *et al,* (2020). Although conventional agricultural activities made a significant negative impact on macroinvertebrates in headwater streams, Magbanua *et al,*

(2010) observed the benefits of an integrated management system on these organisms. Many development projects including mini hydropower generation, irrigation, agriculture, and tourism also put pressure on these sensitive elements. For example, Munasinghe *et al,* (2021), observed diversity reduction in benthic macroinvertebrate communities due to water diversion for a mini hydropower plant in Gurugoda Oya, Sri Lanka. The stream corridor encroachment of the Pinga Oya catchment located within the upper Mahaweli stream has changed turbidity, biological oxygen demand (BOD), and nitrate concentrations of stream water beyond the tolerance limits (Dissanayake 2021), and consequently, all sensitive biological elements will be affected. Sanjaya *et al,* (2015) observed a significant negative impact of agricultural runoff on macrobenthos diversity in the headwater stream, Waturawa in Deniyaya, Sri Lanka.

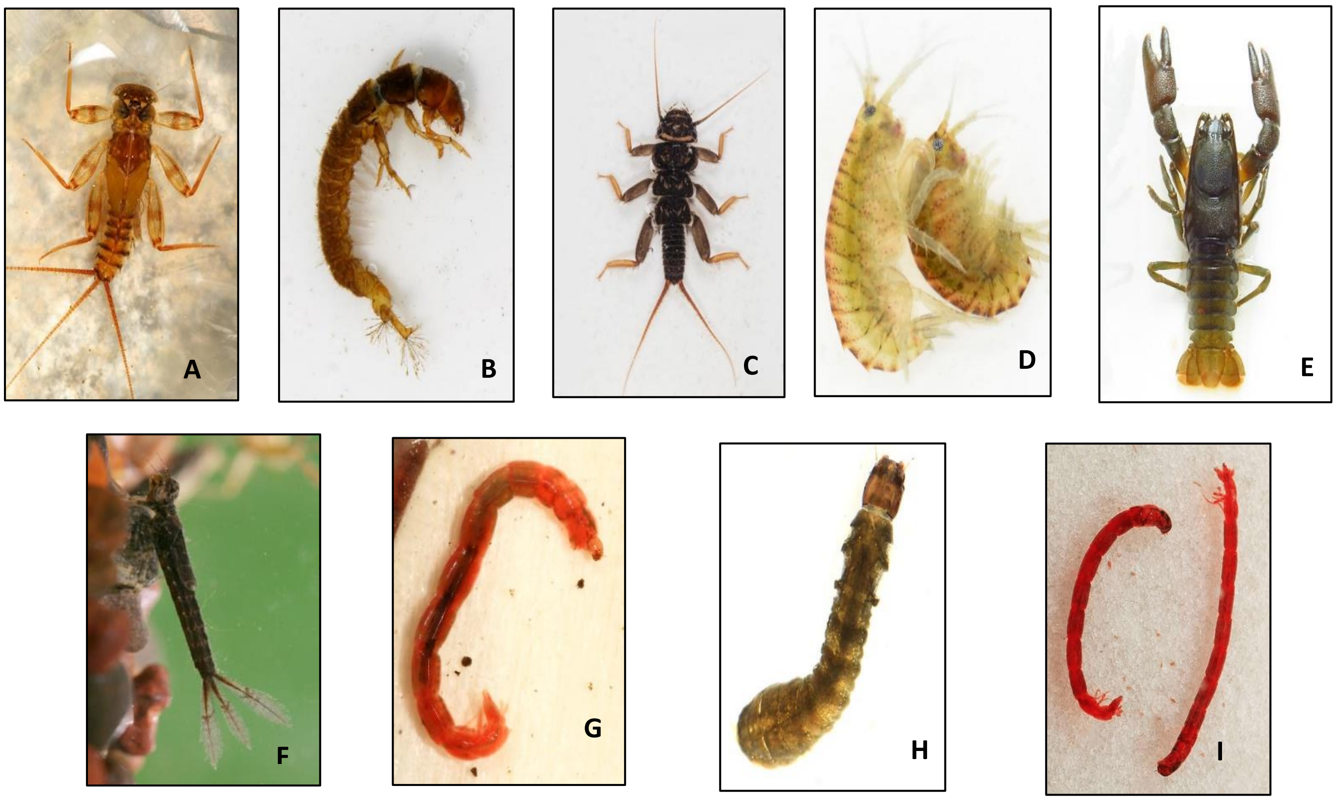

Figure 2: Common aquatic macroinvertebrates found in stream ecosystems. Pollution-sensitive species (A: Mayfly larva, B: Caddisfly larva, and C: stonefly larva), semi-tolerance species (D: Scud, E: Crayfish, and F: damselfly larva), Pollutant tolerant species (G: Midge larva, H: Blackfly larva, and I: *Chironomus* larva). Source of pictures: (https://bugguide.net)

4. Conclusion and Recommendations

Certain macroinvertebrate species are keystone species of those microhabitats and their abundance is essential to keep the ecological balance of the system. Further, aquatic macroinvertebrates play a significant role in maintaining the ecological integrity of aquatic ecosystems, their abundance and distribution need to be critically considered in developing criteria for sustainable development plans.

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