# *Hexagenia* Mayflies: Biological Monitors of Water Quality in the Upper Mississippi River

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ABSTRACT—Analysis of *Hexagenia* mayfly distribution patterns has proven to be a simple, inexpensive method of monitoring water quality in the Upper Mississippi River. Burrowing *Hexagenia* nymphs live at the mud-water interface intimately associated with organically enriched sediments that have a strong affinity for contaminants. By their presence or absence in silted habitats, they assess the synergistic effects of hypoxia, toxins, and other stresses throughout the year. Adults are large and easily collected, providing inexpensive water quality monitoring on a river so large that comprehensive chemical, physical, and biological analyses are not logistically feasible or affordable. Pollution abatement in metropolitan Minneapolis-St. Paul allowed a recurrence of *Hexagenia* in formerly denuded areas of Pool 2 and Lake Pepin during the early 1980s, but the drought of 1988 caused a population crash in both areas, demonstrating that the environment at the mud-water interface was intolerable to *Hexagenia* during low flow conditions.

## Introduction

*Hexagenia* mayflies (Figure 1) are vital members of many freshwater ecosystems. I became interested in them in 1956 when, as a graduate student at Iowa State University, I was asked to investigate a nuisance "river bug" problem at Keokuk, Iowa, the site of the largest lock and dam on the Mississippi River (MR). The main nuisance insect species were *Hexagenia* mayflies (which dominated the silted river bottom in the impoundment behind the dam) and several species of hydropsychid caddisflies (which thrived in the fast water of the rocky tailwaters). The life histories and ecology of the nuisance species were relatively unstudied and I spent the next three years working with them, subsequently devoting 30 additional years to the study of *Hexagenia* mayflies and MR ecology (1). My research has led me from the source of the MR at Lake Itasca to many lakes and tributaries within the watershed, and downstream to the Gulf of Mexico.

In 1958, ship captains, lock masters, and interested river residents were solicited to collect adult mayflies during mass emergences along the MR and its tributaries (2). This system, used annually through 1969, was reemployed in 1976, 1986 and 1988. The resultant mayfly distribution patterns have been used to monitor habitat quality. Ideally, water quality investigations should include chemical and physical testing of water and sediments at many locations throughout the year, as well as qualitative and quantitative analyses of zoobenthic communities (3). However, such comprehensive studies are usually not logistically feasible or affordable on large river systems. *Hexagenia* mayflies have proven to be good monitors of water quality because of their long nymphal lives and intimate association with organically enriched sediments where toxins accumulate. They are especially vulnerable to hypoxia which may kill them directly or cause them to abandon their burrows, subjecting them to predation by fish (4). While chemical tests provide instantaneous descriptions of water and sediment quality in terms of specific parameters, mayfly distribution assesses the synergistic effects of hypoxia, toxins, and other stresses throughout the year. In addition to being economical in terms of time, money, and resources, the method has been educational for the general public. River residents have come to associate mayflies with water quality, realizing that their presence does not prove the river is clean enough to drink or to swim in, but that it is in good biological condition. *Hexagenia* distribution has been drastically altered by humans in recent years; pollutants have eliminated the insect from portions of Lake Michigan's Green Bay (5), Lake Huron's Saginaw Bay, most of Lake Erie (6, 7, 8), and segments of the Illinois and MR (4,

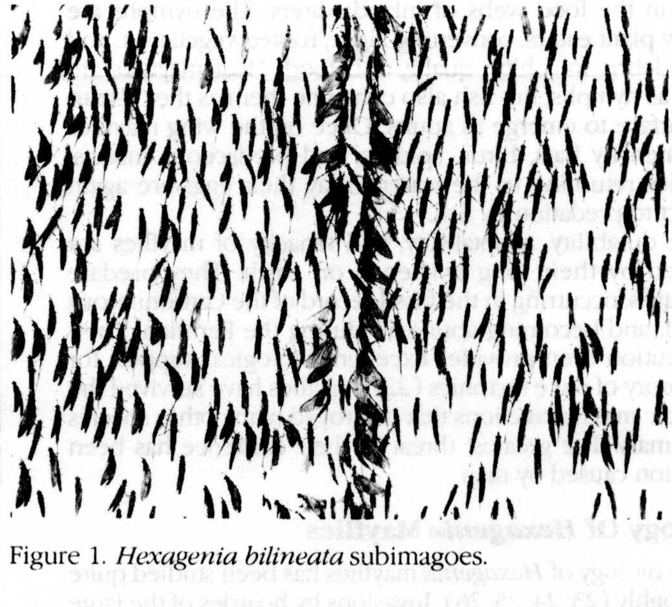

Figure 1. *Hexagenia bilineata* subimagoes.

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9, 10). Pronounced declines in the abundance of *Hexagenia* in lakes are mainly due to eutrophication (11).

*Hexagenia* adults recently have been used to monitor levels of polychlorinated biphenyls (PCBs) along the Upper Mississippi River (UMR) (12, 13). Currently, *Hexagenia* adults and nymphs from the UMR are being tested at several area laboratories for heavy metals and chlorinated hydrocarbons. Nymphs are also used as bioassay organisms in toxicity tests (14, 15). Laboratory culture methods have been developed (16), as well as artificial substrates, testing apparatus, and protocol (17, 18, 19). Nymphs for laboratory study can be purchased by mail, and a film on the ecology of the insect is available (20).

## General Mayfly Life History

Mayflies have fascinated man for centuries because of the brief span of their adult lives. They spend most of their lives as aquatic nymphs or naiads (the British call them larvae) in a wide variety of standing and running freshwater habitats, then develop into winged stages which mate, lay eggs, and soon die. Although a few species survive as adults for a week or more, most have an adult life of only a day or two. This brevity of life is implied in their order name, Ephemeroptera, for the winged stages are indeed ephemeral. When the winged adult emerges from the nymph it is called a subimago which later molts into the final winged stage or imago. Mayflies are the only insects that molt as adults. The mouthparts and digestive tract of the adult are vestigial; all feeding is done in the nymphal stage.

Mayflies are very habitat specific, yet they are almost worldwide in their distribution, being absent only from Antarctica, the extreme Arctic, and small oceanic islands. All but three of the 20 families in the world occur in North or Central America. Taxonomists have listed about 625 species of mayflies from North America north of Mexico. Worldwide, about 1,800 species have been described, and new species are being identified each year (21). Trout fishermen have long been the most avid amateur students of mayflies, skillfully tying artificial flies to "match the hatch" and keeping detailed record of when "hatches" occur on the streams they fish.

The real economic value of mayflies lies in their importance in the food webs of inland waters. The nymphs are mainly plant eaters, converting algae, rooted vegetation, and plant debris into high quality fish food. Most mayflies are eaten as nymphs, but fish also consume them as they rise to the surface to emerge as adults. Once on the wing mayflies are eaten by bats, birds, spiders, and predaceous insects. Females returning to the water to lay their eggs are again subject to predation by fish.

The durability, adaptability, and tenacity of mayflies are attested by their long existence on earth. They predate dinosaurs, occurring in the fossil record of the Carboniferous Period, and becoming abundant during the Permian. Their distribution even provides excellent biological support for the theory of plate tectonics (22). Mayflies have survived the periodic mass extinctions that destroyed many other species of animals. The greatest threat to their existence has been pollution caused by man.

## Ecology Of *Hexagenia* Mayflies

The biology of *Hexagenia* mayflies has been studied quite thoroughly (23, 24, 25, 26). Invasions by hoardes of the large insects are familiar phenomena on warm summer evenings along the UMR (Figure 2). Drifts of the insects form under street lights, often blanketing parked cars. Traffic is impeded, shoppers desert the streets, and in extreme cases, snow plows are called out to reopen highway bridges that have become impassable. Drifts of decaying mayflies smell like rotting fish, hence the common name "fish fly."

Subimagoes usually emerge from the water at night, fly to trees along the shore, and remain motionless during the following day, usually moving only when disturbed or to keep themselves shaded. The adult molt begins in the afternoon, peaking about 4 PM. The resultant imagoes are noticeably more delicate than the subimagoes, but their powers of flight are greater. Mating swarms form along the riverside in the evening and copulation takes place in flight. The males usually remain near the mating area, but the females fly upstream to lay their eggs (27), apparently flying until they have exhausted their energy reserves. They may travel several miles, depending on air temperature and wind, and then land on the water surface. Each female lays two packets of eggs, each containing about 4,000 eggs. The eggs separate from each other, sift slowly to the silted river bed, and hatch in about 12 days, depending on water temperature (28). Most nuisance problems are created by females being diverted to light sources during their oviposition flight. Problems have been lessened in recent years by the use of sodium vapor lights whose longer wavelengths are less attractive to most insects.

*Hexagenia* nymphs are easily recognized by large mandibular tusks, broad forelegs modified for digging, and feathery gills on the dorsum of the abdomen (Figure 3). They dig U-shaped burrows in the silted bottoms of lakes, rivers, and streams. In addition to providing seclusion, the burrows function as respiratory tubes as the nymphs pump water through them with undulatory gill movements. Because nymphs are highly sensitive to hypoxia, they occur below the thermocline only in lakes which have sufficient hypolimnetic dissolved oxygen (DO). Increased input to the sediments of

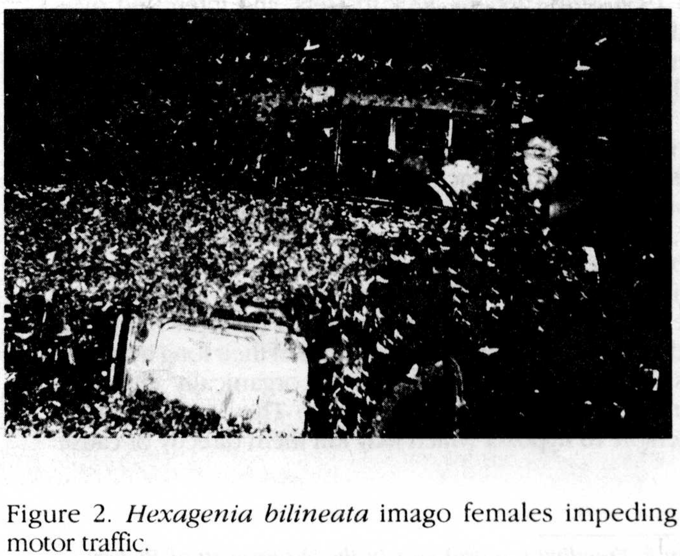

Figure 2. *Hexagenia bilineata* imago females impeding motor traffic.

decomposing organic matter contributes to lower sediment redox potentials and higher concentrations of reducing substances, some of which (e.g. sulfide) may be directly toxic to nymphs (11). As oligotrophic lakes become increasingly eutrophic, *Hexagenia* mayflies disappear and are replaced by chironomids, which are more tolerant of low levels of DO.

Nymphs consume organic detritus, algae, bacteria, protozoans, other small organisms, and large amounts of indigestible inorganic matter. They apparently selectively ingest organic matter of high caloric content (29). Growth rate is a function of temperature; life cycles are completed in as little as 12 weeks under laboratory conditions (16), but require as long as two years in northern lakes (24). The life cycle is completed in one year or less in the MR below the Twin Cities. In prime habitats, last instar nymphs have been found in concentrations of 340/m² (23) and nymphs of various instars at concentrations of 823/m² (4). *Hexagenia* nymphs are important members of aquatic ecosystems, tilling sediments and converting organic detritus into fish food. They are among the largest benthic animals and their long life cycles ensure their availability to fish at all seasons; because nymphs pass through many molts, they are food for a wide variety of fish species of various sizes (11). Vigorous *Hexagenia* populations increase turbidity, and their detritivory may prolong the life of lakes and impoundments by reducing the organic content of sediments.

Two species of *Hexagenia* dominate the UMR watershed. *H. bilineata* inhabits large rivers, the adults seldom straying far from their banks. *H. limbata* inhabits lakes and streams as well as large rivers, its adults often occurring several miles from their nymphal habitat. The two species tend to emerge en masse from the UMR at intervals of 6-11 days, causing nuisance problems from mid-June until mid-August. Lakes within the UMR watershed may also be host to *Ephemera simulans*, a closely related burrowing species (19).

Figure 3. *Hexagenia bilineata* nymph in burrow.

## Water Quality Relationships Downstream from Metropolitan Minneapolis and St. Paul

*Hexagenia* mayfly distribution patterns have dramatically documented water quality changes in Pool 2 (River Mile 815.3-847.7), which lies just downstream from the Twin Cities Metropolitan Area (TCMA), and in Lake Pepin (RM 764-787) (1). Scarpino (32) reviewed the 1890-1950 water quality history of the UMR in the TCMA corridor, where early pollution control was dictated largely by development of the river for navigation. Channelization practices begun in 1878 included dredging and construction of groins that constricted the river, increasing its velocity and ability to transport sewage away from TCMA. In 1917, the U.S. Army Corps of Engineers completed the Twin Cities Lock and Dam (now L&D 1), creating a 5-mile (9.3 km) pool that received most TCMA sewage. In 1930, the Corps finished L&D 2 at Hastings; its 32-mile (51.5 km) pool extended upstream to the foot of the Twin Cities L&D and became a resting place for the remainder of TCMA sewage, including wastes from packing houses and stockyards. During late summer, the river for 45 miles (72.5 km) below St. Paul lacked sufficient oxygen to sustain fish life of any type. Because of intolerable health and aesthetic problems created by the pooled sewage, sewage treatment facilities were constructed in the TCMA (31). In succeeding years, most small treatment plants were consolidated with the Metropolitan Waste Control Commission (MWCC) plant at Pig's Eye (RM 836.3); treatment efficiency was increased, effluent quality was markedly improved, bypasses due to combined sewer overflow were reduced, and water quality improved. For example, annual average effluent biological oxygen demand dropped from almost 190 mg/L in 1967 to less than 20 mg/L in 1986 (1).

Poor water quality downstream from TCMA prior to 1980 was documented by *Hexagenia* distribution. During my studies of 1957-1969 and 1976, 1,164 collections of *H. bilineata* and 209 collections of *H. limbata* were made along the UMR between Cairo, IL and Brainerd, MN. Only 6 *H. bilineata* and 2 *H. limbata* emergences were reported from Pools 1 and 2, even though the broad, silted expanses of Pool 2 were potentially excellent habitat. Both species were abundant in pooled reaches upstream from TCMA. Benthos collections made during 1957-1976 substantiated the lack of *Hexagenia* and the domination of Pool 2 by chironomids and tubificid worms, both pollution-tolerant forms (34).

Water quality improved markedly in Pool 2 during the 1980s, and mayfly response was dramatic. Benthos sampling by MWCC personnel in July 1985 yielded a wide variety of taxa, including *Hexagenia* of various instars at concentrations of 421/m² just above L&D 2. In 1986, 21 *H. bilineata* and one *H. limbata* mass emergences were reported from Pool 2, and the insects caused nuisance problems at harbors and in downtown St. Paul (35). On June 23, 1987, mayflies blocked the Highway 494 bridge in South St. Paul, causing two accidents and forcing the Highway Patrol to close it until it could be plowed and sanded (36).

Lake Pepin serves as a repository for some of the TCMA's pollutants; only eight *H. bilineata* and three *H. limbata* collections were made there during 1957-1976. Low numbers of *Hexagenia* nymphs (frequency of occurrence 1.5%) and domination of Lake Pepin by *Chironomus* midge larvae (frequency of occurrence 88%) were documented (37). Adult midges caused most of the nuisance problems during that period.

Conditions also improved in Lake Pepin after 1980. In 1986, 26 collections of *H. bilineata* and two of *H. limbata* were made during July. Benthos sampling of Lake Pepin in 1986 repeated the study done in 1976; frequency of occurrence of *Hexagenia* nymphs within samples was 84 percent while that of *Chironomus* larvae was 78 percent. Highest concentrations of *Hexagenia* were in the upper third of the lake (T. Claflin, Univ. Wisc., LaCrosse, pers. commun.). These data demonstrated that improved water quality allowed *Hexagenia* to thrive in areas that were previously denuded.

## *Hexagenia* Crash During the 1988 Drought

During the drought of 1988, only two collections of *H. bilineata* were made from Pool 2 and only one collection was made from Lake Pepin. No nuisance problems were reported from either area. In River Lake of Pool 2 (RM 826.2-827.3), *Hexagenia* nymphs numbered about 100/m$^2$ in 1987, but none were found in 1988 (D. Hornbach, Macalester College, pers. commun.). In weekly DO samples taken by the MWCC at eight sites from TCMA to L&D 3 between May 1 and September 30, 1988, 86 percent of values were above 5 mg/L, while 14 were 2.9-5.0 mg/L. At automatic sampling sites at Pig's Eye (RM 837), Newport (RM 831), Grey Cloud Island (RM 827) and L&D 2 (RM 815) during May 1 to September 30, monthly mean DO equalled or exceeded 5 mg/L. However, in neither survey was sampling done at the mud-water interface where DO is usually lowest. Conventional techniques fail to sample this thin stratum upon which *Hexagenia* mayflies and most other benthic invertebrates depend for their respiratory water (38). Because of its low DO and its proximity to sediments that may be laden with heavy metals (39), chlorinated hydrocarbons, and other pollutants, water at the mud-water interface may be lethal when conventional monitoring techniques indicate that conditions are tolerable.

Because of its large size and shallowness, Lake Pepin is windswept and does not usually thermally stratify. Therefore, its broad expanses of organically rich sediments are potentially excellent *Hexagenia* habitat. However, Lake Pepin has a history of poor summer DO and algal problems in low flow years like 1988. At L&D 4, the first dam below Lake Pepin, minimum flows of 5,700 cfs (160 m$^3$/s) occurred during June 29-30 and July 3-7, 1988; average normal summer flow there is about 18,000 cfs (504 m$^3$/s); average normal minimum flow is about 12,000 cfs (336 m$^3$/s).

Low river flows during spring and summer of 1988 increased the average hydraulic residence time of Lake Pepin from about nine days to several weeks, causing increased eutrophic conditions. Anoxic conditions caused by decaying algae were cited as the most likely cause for a July 12-15 fish kill at Maiden Rock, WI (J. Sullivan, Wisc. Dept. Nat. Resour. unpubl. memo, Aug. 22, 1988). At a continuous monitoring site 75 yards (67.5 m) off the Minnesota shore near Lake City (RM 771.4) in 4 ft (1.2 m) of water (sensor mid-depth), there were 15 episodes of 1 to 82 hr duration when DO concentrations fell below 5 mg/L during July 15-September 2. Low DO conditions occurred mainly with a southwest wind, indicating that surface water was pushed toward the Wisconsin shore, causing an undercurrent of low DO bottom water in the opposite direction (G. Rott, Minn. Poll. Control Agency unpubl. memo, Feb. 7, 1989). A similar phenomenon was documented on June 23 at RM 771.4 when transect sampling across the lake showed that a southeast wind caused a countercurrent of low DO (0.8-2.0 mg/L) water to cover a large area on the Wisconsin half of the lake at depths of 21-28 ft (6.3-8.4 m) (Minn. Dept. Nat. Resour. unpubl. lake surv. rept.) The most extensive temperature and DO measurements from Lake Pepin were made by Renny Foster and his father Jerry as part of a science fair project. Using a Yellow Springs Instrument Co. DO-temperature meter, they sampled 36 locations throughout Lake Pepin during the last week in August at surface, mid-depth and just above the bottom. They noted no thermal stratification, but found a distinct pool of water containing less than 1.0 mg/L DO at depths greater than 26 ft (7.8 m) between RM 766 and 770, near the outlet of the lake. Mississippi River backwaters also were impacted by low flow. Goose Lake (RM 788-789) was thermally stratified on June 25 and had less than 0.2 mg/L DO at all depths greater than 6 ft (2 m) (Minn. Dept. Nat. Resour. unpubl. rept.).

These data suggest that *Hexagenia* populations may also have been adversely impacted in other backwaters of the UMR in 1988 when low flow conditions necessitated reduced flow through navigation dams to maintain pool levels as required by the 9-ft channel project. This probably caused hypoxia at the mud-water interface in large areas. The largest *H. bilineata* emergence of the season normally occurs between July 9 and July 12. I have observed it annually in Pool 5A for 31 years. No mass emergence was observed in Pool 5A during that interval in 1989.

## Summary

The results of these studies support the use of *Hexagenia* mayfly distribution as a simple, inexpensive method of assessing water quality in the UMR. The replacement of *Hexagenia* by chironomid midges is an ominous sign whether it occurs in a river or lake. By their presence or absence, *Hexagenia* mayflies monitor DO and many other parameters including synergistic effects that cannot be measured in other ways. The 1988 crash of *Hexagenia* populations in Pool 2 and Lake Pepin demonstrated that potentially rich *Hexagenia* habitat became intolerable during low flow conditions, even though conventional water chemistry sampling indicated that water quality was satisfactory marginal. *Hexagenia* baseline data collected during the past 34 years will be invaluable in judging the effectiveness of future pollution abatement measures. Burrowing mayflies still have not returned to Lake Erie, and only relatively small numbers occur in Green Bay of Lake Michigan. When *Hexagenia* returns in force to these areas we will know that pollution control efforts there are succeeding.

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