ARTICLE IN PRESS

JGLR-01373; No. of pages: 10; 4C:

Journal of Great Lakes Research xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Evidence of persistent, recurring summertime hypoxia in Green Bay, Lake Michigan

Klump J. Val [a,*], Shelby L. Brunner [a,d], Brice K. Grunert [a,c], Jerry L. Kaster [a], Kim Weckerly [a], Erin M. Houghton [b], John A. Kennedy [b], Tracy J. Valenta [b]

[a] School of Freshwater Sciences, Great Lakes WATER Institute, University of Wisconsin-Milwaukee, 600 E. Greenfield Ave., Milwaukee, WI 53204, United States of America
[b] Green Bay Metropolitan Sewerage District, NEW Water, 2231 N Quincy St, Green Bay, WI 54302, United States of America
[c] Michigan Technological University, Department of Geological and Mining Engineering and Sciences, Houghton, MI 49931, United States of America
[d] NOAA Climate Program Office, 1315 East-West Hwy, Suite 1100, Silver Spring, MD 20910, United States of America

ARTICLE INFO

Article history:
Received 4 November 2017
11 April 2018
Accepted 3 July 2018
Available online xxxx

Guest Editor: John Bratton

Keywords:
Green Bay
Lake Michigan
Hypoxia
Dissolved oxygen
Historical records
Dead zones

ABSTRACT

Six years (2009–2015) of temperature and dissolved oxygen profile data show hypoxic conditions are common in the bottom waters of southern Green Bay, Lake Michigan during the summer. Depleted oxygen concentrations (<5 mg L^{-1}) affect nearly 70% of the 38 stations sampled representing an area of ~500–600 km^2. Stratification typically lasts 2+ months, from late June to early September, and some stations exhibit bottom water hypoxia (<2 mg L^{-1}) at a frequency of nearly 25% when sampled during this period. A monitoring program initiated in 1986 by the Green Bay Metropolitan Sewerage District has provided a 23 year, recreational season record (May–September) of continuous (15 min interval) in situ bottom water oxygen and temperature measurements at the Entrance Light station of the Green Bay navigational channel. The duration of the hypoxic season ranges from 2 weeks to over 3 months at this shallow 7 m offshore site. This variability likely results from a combination of thermal stratification, oxygen consumption in deeper waters of the bay, and physical forcing mechanisms that drive cool, oxygen depleted, bottom waters on a southerly trajectory across this sensor. These data suggest the duration of hypoxic conditions may have increased during the stratified season in recent years. Hypoxia in the bay would also appear to be sensitive to relatively small changes in these forces, particularly changes in organic carbon loading and the duration of stratification.

Background

Worldwide, the number of marine hypoxic zones has approximately doubled each decade since the 1960s, fueled largely by cultural eutrophication, and numbering over 400 today (Altieri and Gedan, 2015; Committee on Environment and Natural Resources, 2010; Diaz and Rosenberg, 2008). Freshwater systems appear to have had an earlier history of developing hypoxia beginning near the turn of the 20th century that is also linked to increased nutrient emissions but this history is limited to systems in which long term monitoring or paleolimnological records are available (Jenny et al., 2014, 2016). In the Great Lakes, the central basin of Lake Erie represents the best known and most intensively studied example of large scale hypoxia going back decades (Charlton, 1980; Rosa and Burns, 1987; Scavia et al., 2014), yet other regions of the Great Lakes are likely susceptible to conditions under which dissolved oxygen concentrations fall below the water quality standard of 5 mg L^{-1} or even to the level generally recognized as defining hypoxia of <2 mg L^{-1} (Biddanda et al., 2018). This susceptibility is exacerbated by warming trends and by increased organic matter loading in the form of nutrient runoff fueled eutrophication (Rabalais et al., 2009; Rigosi et al., 2014). Hypoxia has probably been a feature of the Green Bay system (Fig. 1) since the mid to early part of the last century (Kennedy, 1982, 1989), but the extent, duration and frequency of hypoxic "dead zones" has only recently received significant attention.

Oxygen depletion is not only a water quality standard issue and a recognized Beneficial Use Impairment for the bay, but the occurrence of hypoxia is a broad scale indicator of ecosystem health. Hypoxia integrates a number of key environmental processes and management challenges and co-occurs with a number of environmental stressors (Committee on Environment and Natural Resources, 2010): nutrient loading from point and non-point sources; projected increases in the intensity of extreme precipitation and runoff events which in this system control up to 50–80% of the total load on an annual basis; hyper-eutrophication and excessive algal production; climate warming and extended stratification; increased retention of labile, algal-derived organic matter; and a severely limited benthos in terms of both numbers of organisms and their diversity. Arguably, two of the best indicators for

* Corresponding author.
E-mail address: vklump@uwm.edu (J.V. Klump).

https://doi.org/10.1016/j.jglr.2018.07.012
0380-1330/

Please cite this article as: Klump, J.V., et al., Evidence of persistent, recurring summertime hypoxia in Green Bay, Lake Michigan, J. Great Lakes Res. (2018), https://doi.org/10.1016/j.jglr.2018.07.012

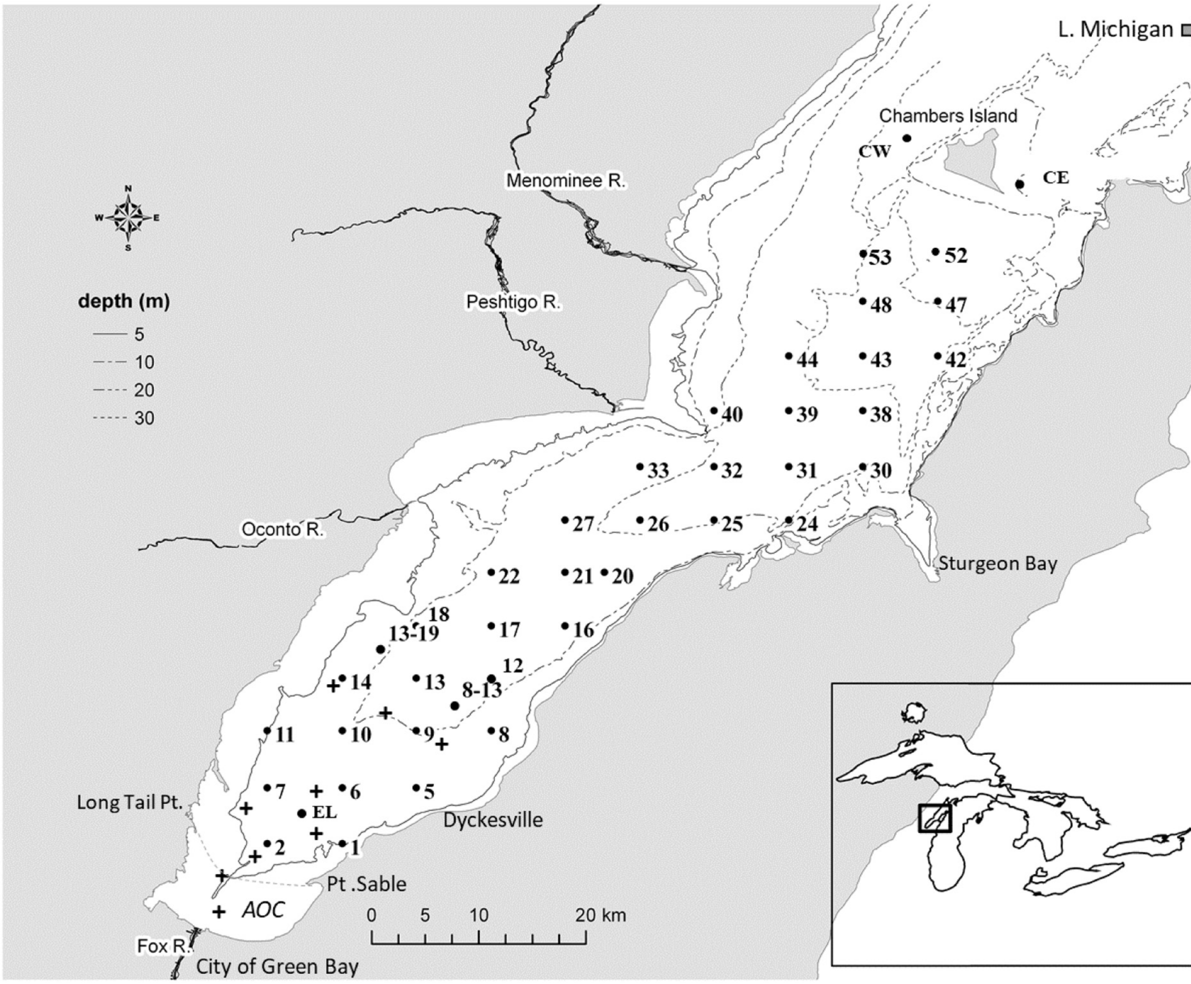

Fig. 1. Sampling stations in Green Bay used in the current study (numbered). EL designates the Entrance Light station maintained by the Green Bay Metropolitan Sewerage District (GBMSD). Stations routinely sampled by GBMSD are designated by a +. The Area of Concern (AOC) is approximately the area of the bay south of a line drawn between Pt. Sable on the east and Long Tail Pt. on the west.

Green Bay that sustained, permanent restoration has occurred will be an improvement in summertime hypoxia and an increase in abundance and diversity of the benthic fauna (Kaster et al., this issue).

Some of the earliest reports of hypoxia in the waters of Green Bay date from observations in the winters of 1939, 1956 and 1966 (Schraufnagel et al., 1968; WSCWP, 1939). Observations taken through the ice in what is now designated an Area of Concern (AOC) at the southern end of the bay (Fig. 1), revealed extensive oxygen depletion. The major culprit at that time was assumed to be industrial waste water discharge loadings, primarily as waste sulphite liquor from paper mills in the Fox River, which resulted in river water that was often devoid of oxygen and which propagated in the river plume outward into the bay. In the late 1930s oxygen sensitive benthic species like the mayfly *Hexagenia limbata* were relatively abundant; however, by 1956 and 1969, benthic fauna surveys throughout the lower bay found *Hexagenia* to be completely absent (Balch et al., 1956; Howmiller, 1971; Howmiller and Beeton, 1971). Their disappearance was assumed to result from consistently low oxygen concentrations during the winter, which occasionally forced commercial fishermen to abandon their nets (Schraufnagel et al., 1968).

Water quality in the Fox River improved dramatically in the 1970s following implementation of the Clean Water Act's waste-water discharge limits (Harris et al., this issue). Winter surveys conducted in 2009 and 2010, as part of a cisco spawning habitat assessment, showed bottom water oxygen concentrations to be consistently near saturation throughout the bay (Madenjian et al., 2011). A revisit of a few nearshore stations by our lab in 2014 in the waters off Dyckesville (eastern shore) and in 2015 inside Long Tail Point (western shore) confirmed dissolved oxygen at or above saturation under the ice (Klump and Kaster, unpubl). Improvements in water quality in the Fox River have apparently ameliorated depressed oxygen conditions of the lower bay in the winter. In summer, the shallow nature of these waters in the AOC (<3 m) generally assures adequate mixing and reaeration. This is not the case, however, for deeper regions of the bay where seasonal thermal stratification isolates bottom waters for extended periods of time (Grunert, 2013; Grunert et al., this issue).

Although infrequently examined, late summer conditions in the bottom waters of the bay at large were historically observed to exhibit highly depleted dissolved oxygen concentrations. Middle Green Bay, defined as the area from the entrance light at kilometer 16 (as measured from the mouth of the Fox River) to kilometer 56 off Sturgeon Bay, was generally seen as outside the influence of the Fox River plume, but cool (12.7 °C), oxygen depleted (<2.5 mg L^{-1}) waters were observed at the 24 and 40 km stations along this transect (Schraufnagel et al., 1968). Several years later during the summer of 1980 under stratified conditions, Kennedy (1982) and Conley (1983) reported nearly anoxic waters in the lower Fox River and, by August, depleted bottom water oxygen levels as far north as Sturgeon Bay. More recently, during the summer of 2005, from June through September, Valenta (2013) reported dissolved oxygen levels in the bottom meter of the water column in lower Green Bay as being below 2 mg L^{-1} for >25% of the time. In an incident reported for August 5th of that summer, persistent winds

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