OBSERVATIONS BASED ON MULTI-DECADAL LIMNOLOGICAL MONITORING OF THE FINGER LAKES
Keynote Presentation: 2024 Finger Lakes Institute Research Conference

John Halfman
Professor, Department of Geoscience, Environmental Studies Program
Research Scientist, Finger Lakes Institute
Hobart & William Smith Colleges
Geneva, NY 14456

Introduction:

Since 2005 through 2022, the eight eastern Finger Lakes, Honeoye, Canandaigua, Keuka, Seneca (starting in 1992), Cayuga, Owasco, Skaneateles, and Otisco (starting in 2008) were sampled to investigate the spatial and temporal variability of their open water limnology.

Methods:

A CTD cast, Secchi disk depth (SD), vertical plankton tow (80 µm mesh) and surface & bottom water samples were collected at a minimum of two deepwater sites on a monthly basis during the May – October field-season. Seneca was investigated in more detail, typically weekly samples at 4 sites since 1992. SeaBird CTDs (SBE-19 pre, and SBE-25 since 2007) collected water-column profiles of temperature, specific conductance, pH, dissolved oxygen, light transmission (SBE-19), PAR (SBE-25), total fluorescence (SBE-25), and turbidity (SBE-25). Surface and bottom water samples were analyzed for total phosphorus (TP) and soluble reactive phosphate (SRP), nitrate+nitrite (NO_x), soluble reactive silica (SRSi), chlorophyll-a (Chl-a), total suspended solids (TSS), alkalinity, and major ions (e.g., Cl) using standard limnological techniques in Halfman's research lab. The 2nd largest tributary to Owasco Lake, Dutch Hollow Brook, was sampled near its terminus one to three times a day, from April through November, by an ISCO autosampler to estimate daily and annual nutrient and suspended sediment loads to the lake. Water quality and meteorological monitoring buoys were also deployed mid-lake from April through November at the northern ends of Seneca (since 2006) and Owasco (since 2014) Lakes (YSI/Xylem); and, collected water column profiles of temperature, sp. conductance, dissolved oxygen, turbidity and fluorescence (both total and phycocyanin) every noon and mid-night with an YSI EXO-2 sonde, and 5-min, mean, air temperature, humidity, barometric pressure, wind speed and direction, and light intensity data every 30-min using a standard suite of meteorological instruments. Buoy water column data were calibrated with *in-situ* CTD and laboratory data.

Water Temperature:

CTD: The 2005 – 2022, average, surface water (<2.5m mean) temperatures from each site on each survey date revealed the expected annual-scale variability and, more importantly, multi-decadal warming. All of the lakes, except for the polymictic and shallow Honeoye, revealed summer season thermal stratification. Thermocline depths in 2021 ranged from 5 to 20 m, deeper depths in the largest lakes. Best-fit linear trend lines of the 2005 – 2022 surface-water temperatures revealed warming trends of 0.06 to 0.26 °C/year. Water column heat budgets revealed multi-decadal warming as well.
Thermistor String: A thermistor string deployed year-round from 2015 through 2019 at the deepest location in Seneca Lake in collaboration with colleagues at Great Lakes Environmental Research Laboratory, U Michigan, revealed isothermal profiles through the winter months[1]. Thus, Seneca Lake is warm monoclinic. The findings are consistent with only a few historical reports of ice completely covering the lake for a few days during 1855, 1875, 1885, 1912, 1936, 1962 and 1979[2]. The other lakes typically freeze each winter, but less so in recent years.
Buoy: Long et al. (in press)[3] examined wind induced, internal wave behavior along the thermocline using a new variable-frequency Green's function in Seneca and Owasco Lakes. The analysis reproduced the measured undulations of the thermocline. It also yielded the seiche's seasonal variation of frequency, primarily due to changes in the stratification intensity and thermocline depth. The seiche decay time matched the computed surge-formation time, which limits seiche lifetimes to as little as one seiche period. Finally, the internal seiche exhibits a

[1] Hawley, N. and J.D. Halfman, in prep. Water temperature trends in the Finger Lakes, NY, and the Laurentian Great Lakes. J Great Lakes Research.
[2] Gable, Will, 2009. When Cayuga Lake and Seneca Lake have frozen over. Seneca County Historian.
[3] Long, J.P., J.D. Halfman, N. Hawley, in press. Internal Waves in two long and narrow lakes with different lengths: resonance damping and nonlinear surges. Limnology and Oceanography. https://people.hws.edu/halfman/Data/Internal%20wave%20paper-supplementary%20materials-inpress.pdf

uniquely well-defined resonance with the diel wind pattern in Owasco Lake, and surges propagate bidirectionally, augmenting an often-cited report of surges traveling only in one direction in Seneca Lake.

Phytoplankton:
The 2005 – 2022 phytoplankton communities in the FLs were dominated by diatoms (30 – 70, relative %), followed by dinoflagellates and cyanobacteria (5 to 30% & 2 to 25%), and smaller numbers of green algae (1 to 5%). Seasonal transitions, i.e., diatom to dinoflagellate & greens to cyanobacteria to diatom were observed. Cyanobacteria were always observed in the plankton community, but only recently formed intense surface blooms, and their relative percentages, but not necessarily their concentration, were largest in the oligotrophic, Canandaigua, Keuka & Skaneateles, and eutrophic, Honeoye. The relative percentages of these major groups did not change significantly over time in each lake, except at Keuka and Owasco where cyanobacteria increased in relative abundance by 10 to 20 % since ~2015. The plankton IDs mimicked available bbe Fluoroprobe data.

Surface Water Quality, TP, SRP, NO_x, Si, SD, Chl-a & TSS:
Spatial Variability: The annual mean, 2005-2022, surface water, SD, TP, SRP, Chl-a, and TSS data divide the Finger Lakes into oligotrophic, Skaneateles, Canandaigua, Keuka, boarder-line oligotrophic-mesotrophic, Seneca, Cayuga, Owasco, mesotrophic Otisco, and eutrophic, Honeoye, as defined by Carlson's (1977) Trophic Status Index (SD, TP & Chl-a). Significant year-to-year variability was observed. Honeoye's TP was above the DEC's 20 μg/L TP threshold for impaired water bodies. The trophic status in all but Honeoye correlated to the percentage of agricultural land in the watersheds. Even though Honeoye's watershed is the most forested now, clear-cut logging in the early 1900s facilitated severe soil erosion and delivery of nutrients to the lake. Its polymictic nature and bottom water anoxia during brief periods of stratification induced significant internal loading issues since. Phosphorus is the limiting nutrient based on open water P:N ratios, except for Honeoye and occasionally late in the stratified season at Canandaigua and Keuka.
Temporal Changes: TP, SRP, Chl-a, and TSS concentrations increased from 2005 through 2014/2015 in most of these lakes, and improved since, and inversely paralleled SDs trends. Halfman (2017) suggested that the 2014/2015 peak resulted from intense early spring rainfall and associated runoff in those two years[4]. In support, runoff events delivered 90 to 99% of the annual nutrient and total suspended sediment loads compared to base flow contributions at Dutch Hollow Brook[5] Water quality improvements since 2015 potentially reflected the adoption of best management practices, and/or offshore nutrient sequestration to nearshore locations by macrophyte and/or mussel populations.
Other Observations: SDs in Seneca increased from 2 - 3 m in 1992 to 8 - 9 m in 1997/1998, reflecting the invasion of zebra mussels in ~1993, and their intense filter-feeding pressures. Since 1998, Secchi depths decreased in Seneca Lake, presumably from the first major mussel die off (old age & decreased algal concentrations) since their invasion, recycling of mussel sequestered nutrients, and watershed nutrient loading induced algal growth. Quaggas invaded later (2003?) and within a few years dominated the mussel population. Recent early spring, isothermal, SDs in Seneca Lake were 15 to 22 m, deepest since 2005, and perhaps due to the filter-feeding mussels and lower algal productivity. Annual, mean, NO_x concentrations were largest in Cayuga, Owasco, and Skaneateles, smallest in Honeoye (N-limited), Canandaigua and Keuka, in between at Seneca, and Otisco, and correlated to the percentage of agricultural land. SRSi concentration were inversely proportional to the TP and Chl-a concentrations, and suggests that more productive lakes depleted silica concentrations. A significant spike was observed in the SRSi concentration in Seneca Lake during 1997/1998 mussel induced clear period, and suggests that the invasive zebra mussel population depleted algal communities severely enough to reduce their uptake of Si at that time. Subsurface turbid plumes were observed on a number of surveys after heavy rain events, located just above thermocline and extending from the Owasco Inlet in the south to the northern end of Owasco Lake.

Century-Scale Chloride (Cl^-) Concentrations:
Surface water samples were augmented with published and unpublished decadal, and in some watersheds, century-scale Cl data, and revised previous published Cl source interpretations[6]. Cl concentrations and fluxes

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[4] Halfman, J.D., 2017. Decade-scale water quality variability in the eastern Finger Lakes, New York. Clear Waters. Fall 2017, v. 47, No. 3, pg. 20-32. http://nywea.org/clearwaters/uploads/Decade-ScaleWater7.pdf
[5] Halfman, J.D., M. Horvath, E. Swenson, M. Geiger, I. Dumitriu & L.B. Cleckner, 2023. The 2022 Water Quality Monitoring Report, Owasco Lake, NY. Finger Lakes Institute, Hobart and William Smith Colleges. 47 pg. http://people.hws.edu/halfman/Data/Halfman%202022%20Owasco%20Water%20Quality%20Report.pdf
[6] Halfman, J.D., and M. Horvath, in press. Chloride Ion Hydrogeochemistry in the Finger Lakes: A Revised Story. Anthropocene. https://people.hws.edu/halfman/Data/FL_Cl_Hydrogeochem.pdf

(based on watershed mass-balance models) defined two groups of lakes. Group 1: A mid-1900's peak in Cl concentrations was detected in Seneca and Cayuga Lakes. Models indicated that the peak resulted from a short but significant spike of Cl to the lake, most likely from salt mine wastes before the establishment of the Environmental Protection Agency. Salt mine wastes are now regulated. Group 2: Honeoye, Canandaigua, Keuka, Owasco, Skaneateles and Otisco revealed smaller yet increasing concentrations and fluxes over time, reflecting increased use and subsequent runoff of road deicing salts in their watersheds, and supported by Cl conc. and flux correlations to state and federal road lengths, percentage of impervious surfaces, and water residence times. Estimated Cl inputs from municipal wastewater treatment facilities, individual septic systems (softeners), agricultural land (fertilizers), and the atmosphere (precipitation) exist but were insignificant compared to fluvial inputs in the Finger Lakes region.

Lake Hydrology:
Evaporation & Precipitation: Mean annual evaporation, precipitation, surface inflow and outflow rates, and water residence times for each lake were calculated to use in the chloride mass-balance model used above[7]. Only Seneca and Owasco had sufficient data to calculate all the hydrologic variables. For evaporation, meteorological and water column temperature data from the FLI Buoys estimated an annual linear evaporation rate of 0.77 ± 0.16 m/y for Seneca and 0.81 ± 0.10 m/y for Owasco. An annual linear precipitation rate from the 35 meteorological stations within the Finger Lake watersheds with > 10 years of historical data was 1.01 ± 0.13 m/y.
Surface Outflow: Mean, annual, surface outflow data from Seneca (USGS 04232730, since 2006) and Owasco (USGS 04235440, since 2014) averaged 616 ± 63 km^3/y and 304 ± 186 km^3/y, respectively. Surface runoff (S) to each lake was estimated from the evaporation (E), precipitation (P), and outflow (O), and assumed the lakes were at equilibrium on annual time frames (i.e., $S = O + E - P$). Groundwater flow was assumed negligible compared to the other inputs/outputs.
Other Lakes: For the other lakes, a mean annual evaporation rate was estimated using the average linear E for Seneca and Owasco, 0.79 m/y, and each lake's surface area. A mean annual precipitation rate was estimated using the Finger Lakes linear P average, 1.01 m/y, and each lake's surface area. The mean equilibrium annual outflow (O) and inflow (I) were estimated from each lake's volume, mean published residence time, and evaporation and precipitation rates estimated above (i.e., $O = V/RT - E$, $I = V/RT - P$). These estimated outflows were consistent with USGS mean gauge data when available. Groundwater flow was assumed negligible compared to the other inputs/outputs.
Residence Times: Resultant water residence times (RT) for Seneca and Owasco, based on the published lake volumes, and estimated mean annual evaporation and outflow rates (i.e., $RT = V/[E+O]$), were within their published ranges, and lake volumes matched those estimated from crowd-sourced bathymetric data.

Nearshore HABs Events & Meteorological Linkages:
Meteorological and water quality data were collected in offshore and nearshore settings from 2018 - 2022 in the oligotrophic-mesotrophic Owasco and Seneca Lakes in order to assess cyanobacteria bloom spatial and temporal variability, and precursor meteorological and water quality conditions[8]. Blooms were detected from August through mid-October in both lakes. Blooms were temporally and spatially isolated, i.e., rarely concurrently detected at three (4.2%) or more of the 12 sites, and blooms (75.6%) were more frequently detected at only one of the 12 sites in the 10-minute interval photologs. Both lakes lacked consistent meteorological and water quality precursor conditions. Blooms were detected during the expected calm (< 1 kph), sunny (600 – 900 W/m^2) and warm water (> 23°C) episodes. However, blooms were also detected during overcast/shady (< 250 W/m^2), windier (1 to 20 kph), and/or in cooler water (16 to 21°C). More importantly, the majority of the sunny, calm and/or warm water episodes did not experience a bloom. This paradox suggests that nutrient availability was the essential trigger for blooms in these two, nutrient-poor, lakes. Excess nutrients were speculated to originate from the decomposition of nearshore organic matter, e.g., rotting macrophytes, and runoff from the largest (>5"/24 h) precipitation events. Coincidentally, many of the Finger Lakes observed their first HABs events in 2014 or 2015[9] (just after the 2014/2015 intense spring rains) with earlier, 2012 detections in Honeoye and Owasco, and later, 2017 detections in Skaneateles (after Skaneateles was deluged by a localized but very intense storm in 2017).

[7] Halfman, J.D., and M. Horvath, in press. Chloride Ion Hydrogeochemistry in the Finger Lakes: A Revised Story. Anthropocene.
[8] Halfman, J.D., J. Shaw, I. Dumitriu, L. Cleckner, 2023. Meteorological and Limnological Precursors to Cyanobacteria (HABs) blooms in Seneca and Owasco Lakes, New York, USA. Water, 15, 2363. https://doi.org/10.3390/w15132363
[9] Harmful Algal Blooms (HABs) Archive Page, NYSDEC Website (http://www.dec.ny.gov/chemical/83332.html)

Conclusions:

This multi-decadal limnological dataset has shown that all of the lakes revealed significant year-to-year, lake-to-lake, and multi-decadal variability in surface temperatures, hydrology, Secchi disk depths, and nutrient, total suspended sediment, chlorophyll-a, and chloride concentrations. The stimuli for these changes are numerous, and range from external stressors like global warming and invasive species to local factors like nutrient loading and mine wastes. It indicates that a rigorous monitoring program must be maintained into the future to characterize annual changes in the limnology and water quality of these lakes, and not rely on "once a decade" (or less often) monitoring programs as seen in the past.

Acknowledgements:

This research would not have been possible without the help of numerous colleagues and over 100 undergraduate students. Funding for this long-term investigation was from numerous sources including the National Science Foundation, US Environmental Protection Agency, US Department of HHS, NYS Department of State, NYS Member Item (Senator Nozzolio), Water Resources Research Grants Program (USGS & NYS-DEC), NYSRDA, Andrew W. Mellow Foundation, Fred L. Emerson Foundation, Tripp Foundation, John Ben Snow Foundation, Triad Foundation, Park Foundation, Andrew Patchett Foundation, an Anonymous Foundation, the Nature Conservancy, Keck Consortium, Institute for the Application of Geospatial Technology, Cayuga County Legislation, Cayuga County Soil & Water, Finger Lakes-Lake Ontario Watershed Protection Alliance, Seneca Lake Pure Waters Association, Owasco Watershed Lake Association, Hobart and William Smith Colleges, and various private individuals.

Finger Lake	Conesus	Hemlock	Canadice	Honeoye	Canandaigua	Keuka	Seneca	Cayuga	Owasco	Skaneateles	Otisco
Physiography[1,2,3]											
Maximum Depth (m)	18	29	27	9	84	57	186	132	52	84	20
Length (km)	125.6	10.8	5.1	6.6	24.9	31.6	56.6	61.4	17.9	24.2	8.7
Maximum Width (km)	1.3	0.8	0.6	1.4	2.4	3.3	5.2	5.6	2.1	3.3	1.2
Surface Area (km^2)	13.6	7.2	2.6	7.1	42.3	47	175.4	172.1	26.7	35.9	7.6
Watershed Area (km^2)	180.5	96	32	95	477	405	1,181	1,145	470	154	94
Volume (km^3)	0.157	0.106	0.043	0.035	1.64	1.434	15.54	9.379	0.781	1.563	0.078
Published Residence Time (y)	1.4 - 2.5	2.0 - 2.5	2.0 - 4.5	0.8 - 1.5	7.4 - 10.0	6.0 - 8.0	12.0 – 23.0	8.5 - 10.0	1.5 - 3.1	8.5 - 17.7	1.0 - 1.9
Length Federal & State Rds (km)[3]	111.2	707	0	341.1	1182.9	989.4	976	1175.6	1326.9	1410.8	691.9
Agr, For, Urban Land Use (%)[3]	40,42.9,6.2	21.9,62.8,4.9	9.2,76.7,2.9	11.6,73.4,3.7	34.7,47.1,5.7	31.9,50.5,5.3	40,38.2,6.3	50.3,30.6,6	48.8,35.4,4.5	36.4,36.9,5.6	43.6,40.9,4.5
Impervious Surfaces (%)[3]	0.39	0.53	0.4	0.46	0.64	0.54	1.07	0.98	0.5	0.72	0.54
Hydrology[3]											
Evaporation (10^6 m^3/yr)	10.67	5.33	2.29	5.33	32	35.81	134.76	131.06	20.57	27.43	6.1
Outflow (10^6 m^3/yr)	67.83	47.67	11.15	10.58	156.5	169.04	578.08	856.21	291.83	91.88	45.9
Precipitation (10^6 m^3/yr)	14.14	7.07	3.03	7.07	42.42	47.47	170.22	173.72	27.27	36.36	8.08
Inflow (10^6 m^3/yr)	64.36	45.93	10.41	8.84	146.09	157.39	542.62	813.54	285.13	82.95	43.92
Residence Time (y)	2	2	3.2	2.2	8.7	7	21.8	9.5	2.5	13.1	1.5
Chloride Hydrogeochemistry[3]											
2020 Chloride (µg/L, Cl)		34.8		30.8	53.2	36.6	121.5	49.6	19.9	20.1	40.9
2020 Cl Total Influx (mtons/y)		1660		900	11800	7700	68000	44000	5800	2200	1300
Surface Water Limnology (average of annual means ± 1σ, and maximum - minimum annual averages)[4]											
Secchi Depth (m)				3.0 ± 0.9 4.6 to 1.6	6.1 ± 1.2 10.0 to 4.2	5.8 ± 1.5 10.0 to 3.7	8.3 ± 13.1 8.23 to 3.5	3.7 ± 0.4 4.5 to 3.0	4.0 ± 0.8 5.6 to 2.8	6.9 ± 0.9 9.7 to 3.9	2.8 ± 0.5 3.8 to 2.1
Total Phosphate (µg/L, P)				30 ± 14.0 6.7 to 56.9	9.3 ± 3.3 2.8 to 14.7	8.5 ± 3.4 2.9 to 14.5	13.5 ± 5.9 4.6 to 28.4	12.7 ± 5.2 3.3 to 23.9	11.2 ± 3.8 4.7 to 17.7	11.5 ± 15.6 2.4 to 67.1	17.5 ± 7.9 8.6 tp 36.1
Nitrate+Nitrite (mg/L, N)				0.03 ± 0.04 0.00 to 0.14	0.11 ± 0.05 0.04 to 0.26	0.08 ± 0.04 0.3 to 0.19	0.27 ± 0.08 0.14 to 0.43	0.86 ± 0.19 0.59 to 1.16	0.64 ± 0.12 0.04 to 0.92	0.40 ± 0.10 0.27 to 0.57	0.31 ± 0.13 0.18 to 0.57
SR Phosphate (µg/L, P) SR - Soluable Reactive				4.6 ± 4.5 0.5 to 16.9	0.9 ± 0.7 0.2 to 3.0	1.0 ± 0.9 0.2 to 4.1	1.6 ± 1.1 0.3 to 6.6	1.1 ± 0.9 0.4 to 4.4	1.0 ± 1.3 0.4 to 5.8	1.0 ± 1.2 0.0 to 5.3	2.1 ± 4.4 0.2 to 15.7
SR Silica (µg/L, Si)				1,030 ± 310 590 - 1,780	960 ± 110 790 to 1,090	690 ± 220 420 to 1,080	340 ± 280 100 to 1,430	360 ± 100 150 to 590	790 ± 240 530 to 1,410	440 ± 150 160 to 730	520 ± 220 310 to 1,010
Total Suspended Sediments (mg/L)				4.0 ± 2.0 1.4 to 8.3	1.5 ± 0.8 0.8 to 3.9	1.3 ± 0.9 0.8 to 4.5	1.2 ± 0.4 0.7 to 2.1	1.7 ± 0.4 1.2 to 2.6	1.9 ± 0.5 1.2 to 3.5	0.9 ± 0.4 0.5 to 1.9	3.0 ± 1.3 1.5 to 5.9
Chlorophyll-a (µg/L)				9.8 ± 4.8 1.9 to 19.2	1.8 ± 0.7 1.2 to 4.2	1.6 ± 0.6 0.8 to 2.7	2.5 ± 1.1 0.6 to 4.7	3.3 ± 0.9 2.1 to 5.4	2.9 ± 1.0 0.4 to 4.1	1.0 ± 0.3 0.6 to 1.6	4.0 ± 1.0 2.9 to 5.7
Carlson's (1977) Trophic Index Oligotrophic (< 40) Mesotrophic (> 40 < 50) Eutrophic (> 50)				50.2 ± 2.7 40.9 to 58.2	35.4 ± 1.3 30.4 to 40.6	34.7 ± 1.5 28.0 to 39.7	40.7 ± 1.5 34.9 to 47.5	40.8 ± 1.5 33.2 to 46.1	39.9 ± 1.2 34.7 to 43.3	31. ± 2.4 24.1 to 43.6	44.5 ± 1.4 39.2 to 50.0
Plankton (Relative %, average of annual means ± 1σ)											
Diatoms Dinoflagellates Greens Cyanobacteria				53.4 ± 13.8 12.0 ± 6.1 4.5 ± 5.5 16.0 ± 11.9	44.0 ± 15.5 19.8 ± 11.1 0.7 ± 1.0 16.4 ± 6.9	57. ± 12.7 14.3 ± 8.9 0.6 ± 0.6 12.7 ± 9.5	65.2 ± 7.6 6.1 ± 5.0 0.7 ± 0.7 2.1 ± 1.5	68.5 ± 13.6 5.5 ± 4.9 2.9 ± 3.5 4.1 ± 4.0	57.4 ± 16.7 12.9 ± 11.2 9.0 ± 1.1 7.7 ± 8.9	37.7 ± 12.6 8.7 ± 9.0 4.0 ± 3.7 23.2 ± 7.7	31.7 ± 14.6 29.6 ± 9.9 4.4 ± 2.4 5.3 ± 3.3

[1] Mullins, H.T., et al., 1996. Seismic stratigraphy of the Finger Lakes: A continental record of Heinrich event H-1 and Laurentide ice sheet instability, in Mullins, H.T. and Eyles, N., eds., Subsurface geologic investigations of New York deglaciation and environmental change: Boulder, Colorado, Geological Society of America Special Paper 311, p. 1-35.

[2] Callinan, C.W., 2001. Water quality study of the Finger Lakes. New York State Department of Environmental Conservation, New York. https://nysl.ptfs.com/aw-server/rest/product/purl/NYSL/s/4db31185-781a-497e-a596-948417925a83

[3] Halfman, J.D., and M. Horvath, in press. Chloride Ion Hydrogeochemistry in the Finger Lakes: An Updated Story. Anthropocene.

[4] A 2018 - 2022 Update to: Halfman, J.D., 2017. Decade-scale water quality variability in the eastern Finger Lakes, New York. Clear Waters. Fall 2017, v. 47, No. 3, pg. 20-32. http://nywea.org/clearwaters/uploads/Decade-ScaleWater7.pdf