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Research Article

Comparing different methods of calculating volume-weighted hypolimnetic oxygen (VWHO) in lakes

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Abstract. In the limnological literature there is no standard method for calculating hypolimnetic volumes using temperature profile data. Consequently, calculations of hypolimnetic dissolved oxygen concentrations differ based on the method chosen. This study examined the differences in calculations of volume-weighted hypolimnetic oxygen (VWHO) concentrations based on different methodologies and profile sampling resolution. Comparisons of VWHO values indicated that differences among methods were greatest in smaller lakes with less hypolimnetic volume. VWHO calculation methodology based on 1 m resolution for profile sampling, where the hypolimnion is defined as the strata below the lower limit of the thermocline (temperature change < 1 °C m^{-1}), produced lower VWHO values compared to other methodologies using coarser (2m) sample resolution and hypolimnetic volume determination based on visually inspecting inflection points of a temperature profile. Differences in calculated VWHO were surprisingly large, highlighting the need for researchers to standardize methodology and sampling resolution used in VWHO calculations. VWHO calculation using a 1 m sampling resolution that defines the hypolimnion as the lower limit of the thermocline is the preferred methodology when VWHO is used as a water quality parameter in assessing the habitat of lake biota sensitive to low VWHO.

Key words. Hypolimnion; dissolved oxygen; sampling protocol; monitoring; assessment; lakes.

Introduction

Hypolimnetic dissolved oxygen (DO) concentrations are commonly used in lake water quality evaluations. Low DO concentrations can enhance internal phosphorus loading or the release of toxic chemicals from sediments under anoxic conditions. Reduced DO levels can negatively influence lake biota, particularly cold-stenothermic species, such as lake trout (*Salvelinus namaycush* Walbaum) (Sellers et al., 1998), which is a keystone species in many Canadian shield aquatic ecosystems. Consequently, collection of hypolimnetic oxygen data is an important component of aquatic ecosystem monitoring and assessment.

Oxygen measurements are typically collected as profile data. However, in multi-lake empirical studies that relate DO levels to other limnological parameters (e.g. total phosphorus (TP), dissolved organic carbon (DOC), lake morphometry), analyses usually require a single numerical value per lake, such as areal or volumetric hypolimnetic oxygen deficit (AHOD or VHOD) (Cornett and

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Rigler, 1979; Cornett, 1989), or the Anoxic Factor (AF) (Nürnberg, 1995). Oxygen deficit values are derived from oxygen mass estimates such as volume-weighted hypolimnetic oxygen (VWHO) concentrations (Wetzel and Likens, 2000). These are also useful in between-lake analyses, as DO water quality criteria for lake biota are typically defined in terms of DO concentrations rather than deficit values.

Calculation of VWHO values requires temperature profile data be collected concurrently with oxygen data to determine characteristics such as depth of the thermocline and hypolimnetic volume. However, several different approaches have been used for determining hypolimnetic volume. These approaches include visually examining temperature profile data to define the top of the hypolimnion (Fig. 6-3 in Wetzel, 1983), or determining the lower limit of the thermocline using a rate-of-change cutoff (first stratum with temperature change < 1°C m^{-1}; Hutchinson, 1957). Additionally, several empirical models to predict hypolimnetic oxygen concentrations use 2 m strata resolution based on long-term monitoring programs that used 2 m resolution in profile sampling (Molot et al., 1992; Clark et al., 2002; Dillon et al., 2003).

Using different criteria and profile resolution to define hypolimnetic volumes will affect resultant calculations on hypolimnetic oxygen concentrations. The purpose of this study was to examine the effect of these different methods and profile sampling resolution on calculated values of volume-weighted hypolimnetic oxygen concentrations (VWHO) in south-central Ontario, Canada, shield lakes. Additionally, this study examined how different calculation methods affected interpretation of long-term patterns (~20 years) in lakes with continuous end-of-summer hypolimnetic oxygen monitoring.

Materials and methods

Volume-weighted hypolimnetic oxygen (VWHO) concentrations were calculated from end-of-summer (typically near 01 September, range 15 August – 15 September) temperature and oxygen data collected from 80 thermally-stratified lakes in south-central Ontario. End-of-summer values were used as these represent 'worst-case' conditions for cold-stenothermic biota such as lake trout (Evans et al., 1996). Although bottom oxygen conditions may continue to deteriorate beyond this cutoff date, lake cooling and erosion of the thermocline later in September tends to provide additional, shallower habitat capable of supporting cold-stenothermic biota (Dillon et al., 2003). Temperature and oxygen data were from the Ontario Ministry of Environment (MOE) and Ministry of Natural Resources (MNR) limnological databases. The study lakes generally had circumneutral pH, and covered a broad range of limnological gradients in trophic status (total phosphorus), water clarity (DOC), lake depth and surface area (Table 1).

Table 1. Range of limnological variables for the 80 thermally-stratified study lakes. Dissolved organic carbon (DOC), total phosphorus (TP) and pH values are 1991–1992, 1996 or 1998 spring overturn or ice-free season averages (collected during same time period as oxygen and temperature data).

Variable	Mean	Minimum	Maximum	Std. Dev
pH	6.70	5.61	7.98	0.54
TP (µg L^{-1})	9.1	2.7	44.7	7.4
DOC (mg L^{-1})	3.50	1.69	6.37	0.99
Maximum depth (m)	32.2	10.4	93.0	17.9
Surface area (ha)	248.5	5.4	1675	313.6

Volume-weighted hypolimnetic oxygen (VWHO) concentrations were calculated using 4 different methods:

(1) '2-m' – used temperature profile data at 2 m resolution to determine the top of the hypolimnion. The first stratum with a temperature change of < 2 °C between adjacent 2-m strata was considered the shallowest hypolimnetic stratum. VWHO calculations were based on 2 m-thick strata, with oxygen measurements at the mid-point of the stratum (e.g. at 13 m for the 12–14 m stratum, etc.; A in Fig. 1).

(2) '1-m T' – similar to (1), but using data at 1 m resolution. The first stratum with a temperature change of less < 1 °C between adjacent 1-m thick strata was considered the shallowest hypolimnetic stratum. VWHO calculations were based on oxygen measurements at the top of the 1-m stratum (e.g. at 12 m for the 12–13 m stratum; B in Fig. 1).

(3) '1-m B' – similar to (2), but with VWHO calculations based on oxygen measurements at the bottom of the 1-m stratum (e.g. at 13 m for the 12–13 m stratum; C in Fig. 1).

(4) 'Inflection' – used raw temperature profile data (no interpolated values) to determine the lower inflection point in the temperature-depth curve by drawing one line through the thermocline and one through the bottom of the profile, and noting the point of intersection (Lasenby, 1975; Lind, 1978). The inflection method also used 1 m resolution data, and calculations were based on oxygen measurements at the top of the 1-m stratum (top of hypolimnion 'D' at 10 m depth in Fig. 1).

Volume-weighted hypolimnetic oxygen values were calculated using a standard method. The VWHO value represented the sum, for all hypolimnetic strata, of the product of stratum oxygen concentration multiplied by stratum volume, divided by total hypolimnetic volume. Temperature and oxygen profile data were linearly interpolated where necessary to achieve 1 m or 2 m resolution. Regardless of the data source, temperature and oxygen data were always collected at depths such as 0 m, 1 m, 2 m, etc., rather than 0.5 m, 1.5 m, 2.5 m, etc. As a result,

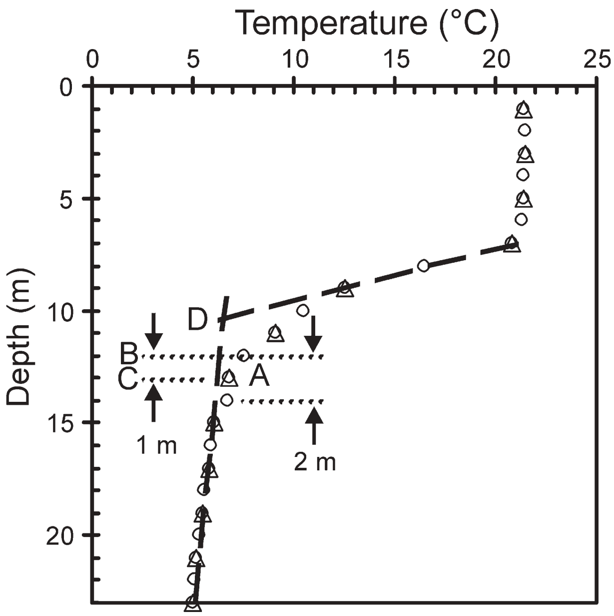

Figure 1. Calculation of hypolimnetic volume and volume-weighted hypolimnetic oxygen concentration (VWHO) from a representative temperature profile (Blue Chalk Lake, 09 Sept 1991). Horizontal dotted lines represent stratum thickness for the 2 m resolution (open diamonds) and 1m resolution (open circles) temperature profiles. 'A' represents the location of the mid-stratum hypolimnetic oxygen measurement for the 2 m resolution profile, 'B' for the 1 m resolution profile (oxygen measurement from top of 1 m stratum), 'C' for the 1 m resolution profile (measurement from bottom of 1 m stratum), 'D' represents the depth of the top of the hypolimnion determined using the Inflection method.

oxygen measurements at the top or bottom of the 1 m-thick strata (1-m T and 1-m B methods) were used rather than mid-stratum estimates of oxygen to avoid conducting analyses of 1 m resolution data based entirely on interpolated values. Stratum volumes were determined using the formula from Hutchinson (1957). Bathymetric data were from MOE and MNR databases. In several sites, bathymetries with 2 m resolution were interpolated to 1 m resolution.

Results and discussion

VWHO calculations were made on 387 profiles from 80 lakes, encompassing the time period 1983–1998, but ranging from 1989–1992 for most lakes. The Inflection and 2-m methods generally resulted in higher calculated VWHO values than the 1-m T and 1-m B methods (Fig. 2). The Inflection method produced the most profiles with high VWHO values (> 7 mg O_2 L^{-1}), while the 1-m B method produced the most profiles with anoxic VWHO values (< 1 mg O_2 L^{-1}) (Fig. 2).

The Inflection method generally produced hypolimnia with greater volumes where the top of the hypolimnion was at a shallower depth. Consequently, the Inflection method had a greater tendency to include strata that were saturated or super-saturated in dissolved oxygen, and many of these lakes displayed positive heterograde oxygen curves in end-of-summer data. As a result, VWHO values from the Inflection method were significantly higher than the other methods (Table 2). There were several profiles where the Inflection method produced lower VWHO than the other methods, being a consequence of the profiles displaying a negative heterograde oxygen curve.

The 2-m method produced significantly higher VWHO values than the 1-m T method. However, these differences were smaller than the Inflection results (Table 2). The 2-m method produced greater hypolimnetic volumes, but to a much lesser extent, than the Inflection method. In many cases (246 of 387 profiles), the 1-m resolution method either had the same hypolimnetic volume as the 2-m method or the top 1-m T oxygen measurement corresponded with the top mid-strata measurement of the 2-m method, with the result that differences were generally small between the 2-m and 1-m T methods.

The 1-m B method produced the lowest VWHO values compared to the other three methods (Figs. 2 and 3). Even though the 1-m T and 1-m B methods used the same total hypolimnetic volume value in the VWHO calculation, the 1-m B method produced lower values (Table 2) since a typical oxygen profile shows steadily decreasing oxygen concentrations through depth. These differences in VWHO values using different calculation methods were not a result of using interpolated temperature and oxygen measurements. If analyses were restricted only to profiles originally with 1 m resolution (n = 234), patterns of differences were nearly identical (data not shown). These slight differences between interpolated and non-interpolated profiles at 1 m resolution should not be interpreted as an indication that 2 m resolution data, which is subse-

Table 2. Average and maximum differences in values in VWHO calculations (mg O_2 L^{-1}) from the 2-m resolution, 1-m T and 1-m B resolution, and Inflection methods (n = 387).

	Average	Maximum	*t* value
Inflection vs. 2-m	+ 0.4	+ 5.1 – 1.7	9.4*
Inflection vs. 1-m T	+ 0.5	+ 5.9 – 1.2	11.6*
Inflection vs. 1-m B	+ 0.9	+ 6.7 – 1.6	14.9*
2-m vs. 1-m T	+ 0.1	+ 2.9 – 3.0	5.0*
2-m vs 1-m B	+ 0.5	+ 5.0 – 1.8	13.0*
1-m T vs. 1-m B	+ 0.3	+ 2.9 – 1.7	14.5*

* all Bonferroni-adjusted *p*-values < 0.001, two-tailed paired *t*-test.

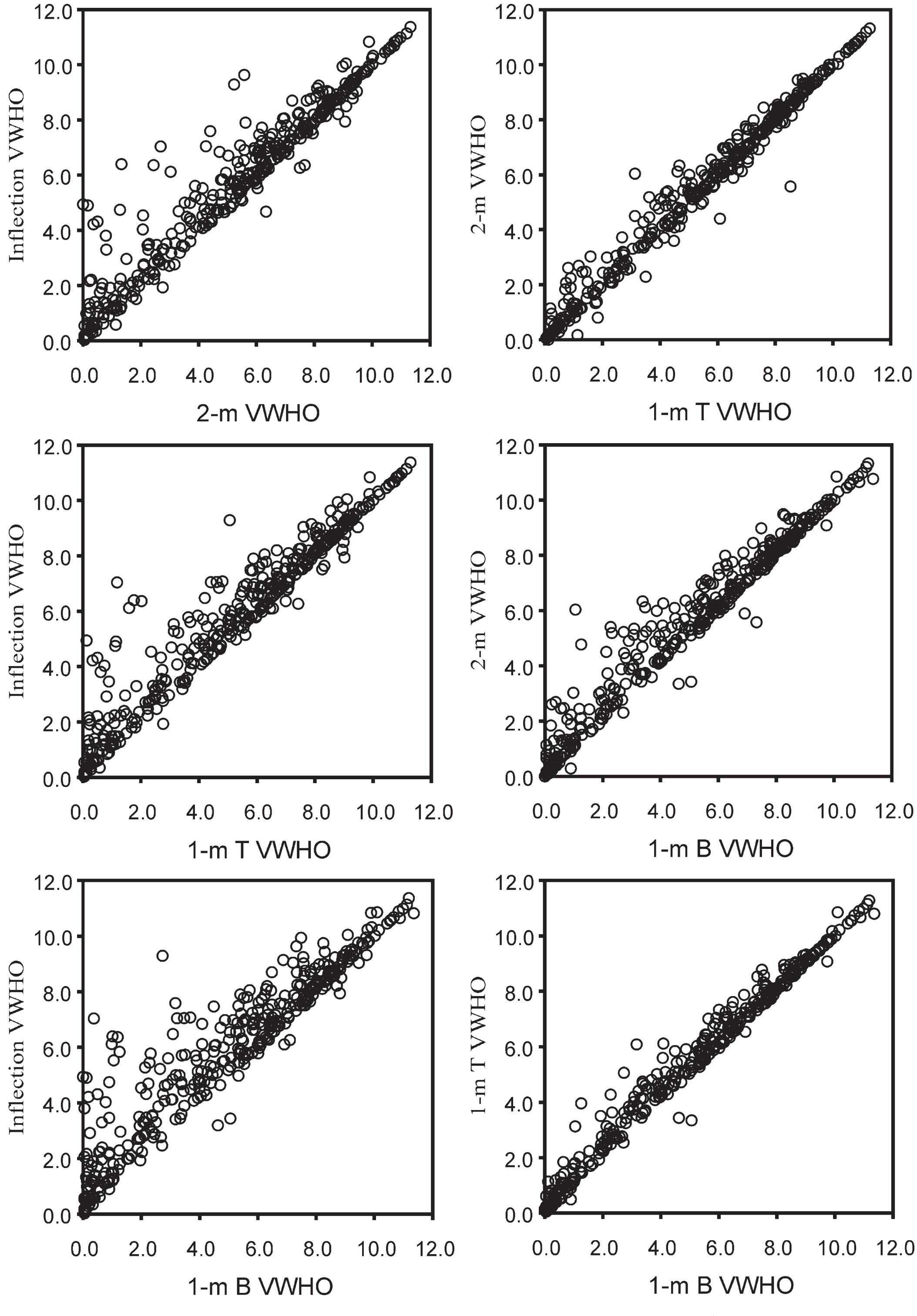

Figure 2. Comparison of volume-weighted hypolimnetic oxygen calculations (VWHO; mg O_2 L^{-1}) from profile data using the 2-m, 1-m T, 1-m B, and Inflection methods (n = 387).

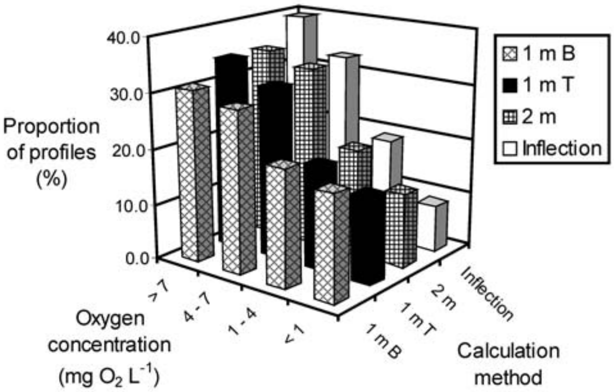

Figure 3. Proportion of profile data (%) in four oxygen concentration categories (< 1 mg O_2 L^{-1}, ≥ 1 to < 4 mg O_2 L^{-1}, ≥ 4 to < 7 mg O_2 L^{-1}, ≥ 7 mg O_2 L^{-1}) using each VWHO calculation method (n = 387).

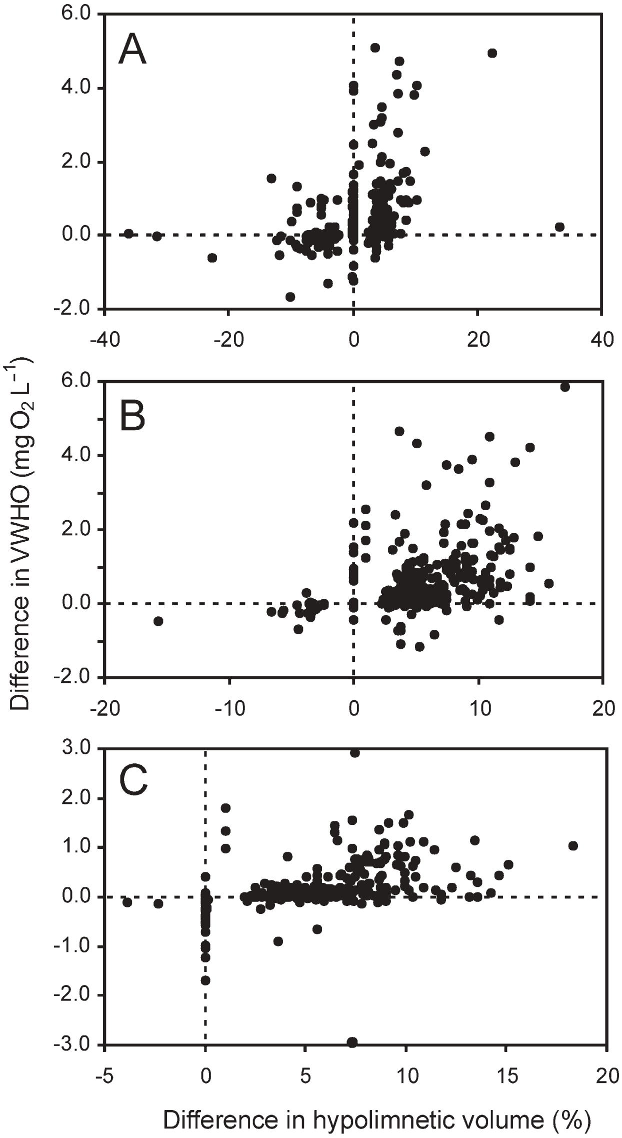

Figure 4. Differences in volume-weighted hypolimnetic oxygen (VWHO) values vs. differences in hypolimnetic volume (as a % of lake volume) determined by the A) Inflection vs. 2-m method, B) Inflection vs. 1-m T method, and C) 2-m vs. 1-m T method.

quently interpolated, will produce very similar VWHO values as 1 m resolution data. These two sampling resolutions can produce different estimates of hypolimnetic volume, and it is these hypolimnetic volume differences that produce many of the large differences between VWHO values in 2-m vs. 1-m T or 1m-B methods.

Differences were greatest in lakes with anoxic hypolimnia (very low VWHO values) where the addition of only one 1 m stratum could have a major impact on the total hypolimnetic oxygen mass and, consequently, the final VWHO value. Even when comparing the 1-m T and 1-m B methods, there were greater differences observed in lakes with lower VWHO values. Closer examination of individual profiles suggested that, in some anoxic hypolimnia, the oxycline was very steep with the top hypolimnetic stratum having an overlying oxygen measurement with supersaturated oxygen conditions, and the underlying oxygen measurement having hypoxic or anoxic oxygen conditions. As a result, even very similar methods, such as the 1-m T and 1-m B methods, can produce substantially different VWHO values in low-oxygen hypolimnia. Especially for low-VWHO lakes, the Inflection method could produce VWHO values that largely reflect mid-depth strata supersaturated in oxygen and not anoxic deepwater oxygen concentrations.

Lakes with oxic hypolimnia (8–12 mg O_2 L^{-1}) were the larger, deeper lakes in the study (Quinlan et al., 2003), and showed few differences in VWHO values among the different VWHO calculation methods. These larger, deeper lakes had much greater hypolimnetic volumes, and the inclusion of several additional metres of strata to the top of the hypolimnion in the Inflection or 2-m methods would add only a small proportion to total hypolimnetic volume. Profiles that tended to produce the greatest differences in VWHO values among methods were from smaller lakes where differences in hypolimnetic volume among methods were relatively large (Fig. 4).

These results suggest that the criteria used for defining the hypolimnion, and subsequent VWHO calculation method, warrants more consideration for shallower lakes with smaller hypolimnetic volumes relative to larger lakes. When we compared time series (1976–1995) of VWHO values for three lakes of varying hypolimnetic volume (Dickie Lake: $0.33*10^6$ m^3, Buck Lake: $1.54*10^6$ m^3, Harp Lake: $4.29*10^6$ m^3; volume represents average for 1-m T method, 1989–1992), the time series for the different calculation methods showed better agreement in the larger Harp Lake (Fig. 5). The results for Dickie Lake reflect the small, anoxic nature of its hypolimnion. The great disparity in results for the year 1989 are from the inclusion of a single top stratum oxygen measurement in

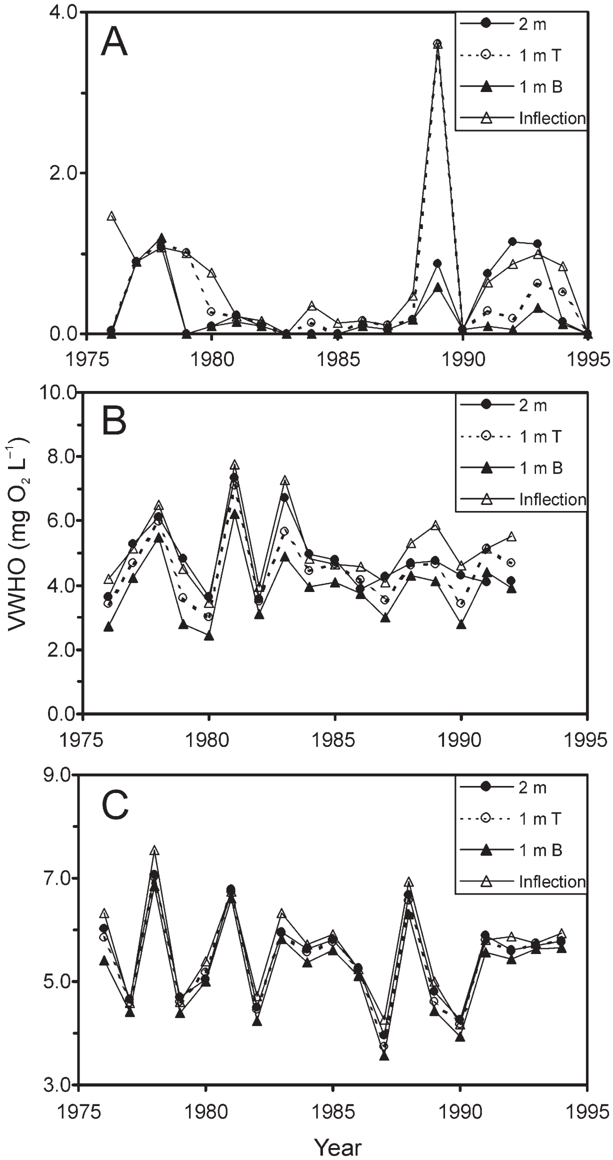

Figure 5. Volume-weighted hypolimnetic oxygen (VWHO) concentrations for the time period 1976–1995 for (A) Dickie Lake, (B) Buck Lake, (C) Harp Lake.

the Inflection and 1-m T methods that contributed a substantial majority of the oxygen mass to the VWHO calculation. When comparing long-term VWHO averages among calculation methods in these three time series, there was a difference of up to 72% in the long-term VWHO average in Dickie Lake (n = 22), versus differences of up to 24% and 7% in Buck and Harp Lakes, respectively (n = 16, n = 21, respectively). These results suggest that assessment of water quality using VWHO values will be more sensitive to calculation method in smaller, anoxic lakes compared to larger, oxic lakes.

While many of these results may be intuitive to limnologists, the differences in calculated VWHO values were substantial and surprisingly large (maximum differences of 3–7 mg O_2 L^{-1} between methods), particularly in smaller and shallower lakes. These large differences highlight the need to standardize temperature and oxygen profile sampling in lakes, particularly when the purpose of such sampling is to determine habitat quality values such as VWHO for keystone species like lake trout which are sensitive to VWHO declines. Volume-weighted hypolimnetic oxygen calculations using the visual inspection of inflection points in temperature profiles to determine hypolimnetic volume produced much higher VWHO values due to the inclusion of thermocline strata supersaturated in dissolved oxygen. When comparing 1 m and 2 m resolution sampling using a rate-of-change cutoff (< 1 °C m^{-1}), calculated values of VWHO were generally similar between 1 m and 2 m resolution sampling when calculated hypolimnetic volumes were similar. As it is not possible, *a priori*, to determine if hypolimnetic volume determinations would be the same in 2 m resolution sampling vs. 1 m resolution sampling, it is advisable that 1 m resolution be used until sampling crews are clearly beyond the rate-of-change cutoff.

As many sampling crews still use older-model analog oxygen meters with a ‘reading error’ of ±0.05 mg O_2 L^{-1}, coarser sampling resolution that produces less than a ±0.05 mg O_2 L^{-1} difference in VWHO values compared to 1 m profile resolution could be considered reasonably accurate. The depth beyond the top of the hypolimnion at which coarser sampling resolution could be used with reasonable loss of accuracy would be a function of hypolimnetic volume (or closely correlated variables such as maximum depth). An examination of 1 m resolution profiles from 24 lakes (maximum depth range 14–55 m), subsequently converted to 2 m resolution data (by removal of observed data) and then interpolated to re-create 1 m resolution data, indicated that VWHO for all lakes was within ±0.05 mg O_2 L^{-1} of original 1 m resolution profiles if 2 m resolution began 5+ m below the top of the hypolimnion. Results also indicated that VWHO differences exceeded ±0.05 mg O_2 L^{-1} in 42% of the lakes (10 of 24) if 2 m resolution began 1 m below the top of the hypolimnion, and these large differences occurred in lakes with maximum depth < 32 m. While we do not examine this scenario in this study, it is likely possible to conduct sampling with resolution coarser than every 2 m, with little loss of accuracy in VWHO calculation, if coarser sampling begins more than 5 m deeper than the top of the hypolimnion and/or the lake has a maximum depth ⩾ 32 m.

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