Groundwater attenuation of summer stream temperatures favors deeper intrusion depths into Lake George, NY

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ABSTRACT

Groundwater inputs to two major streams along the southern end of Lake George attenuate summer temperatures resulting in deeper lake intrusion depths relative to other major streams. Between late April and early October, East and West Brook baseflow water temperatures generally were cooler than other major streams by ~4 °C in mid-summer. Historical data for West Brook confirmed that the trend occurred as far back as 1970. As a consequence of cooler spring and summer temperatures coupled with higher salinity, deeper lake intrusion from these streams was hypothesized based on density calculations. Warmer streams entered the lake as overflow through late spring while East and West Brook intruded into the lake at depth. Upon stratification, East and West Brook intrude at or below the metalimnion while other monitored streams generally intrude at or above the metalimnion; by mid-August/early September all streams intruded below the metalimnion. High-resolution profiler data identified the presence of underflow during a fall storm event in 2014. Deeper intrusion depths of East and West Brook would supply organics and oxygen to the Caldwell Sub-basin hypolimnion which can potentially have both negative and positive effects on hypolimnetic oxygen depletion.

Key words | baseflow, groundwater, intrusion depth, Lake George, NY, temperature

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INTRODUCTION

Temperature is one of the most important factors to consider when evaluating how streams function because of its influence on physical, chemical, and biological processes. Temperature is negatively related to water density and viscosity, which can impact stream intrusion depth into a lake (Laborde *et al.* 2010; Cortés *et al.* 2014), sediment infiltration rates (Constantz & Murphy 1991), and stream discharge (Constantz *et al.* 1994). Warmer water reduces gas solubility while enhancing biological oxygen demand (BOD), which can mobilize phosphorus (Liikanen *et al.* 2002) and trace metals from sediment in reduced conditions (Von Gunten *et al.* 1991). Since nearly all aquatic organisms are ectothermic, temperature influences metabolic rates similarly throughout trophic levels (Gillooly *et al.* 2001) with enzymatic activity approximately doubling with each 10 °C rise in temperature (Black 2012).

Many streams derive the majority of their discharge from groundwater and thus the headwater temperatures are similar to groundwater with water temperature trending toward air temperature with downstream flow (Sullivan *et al.* 1990). The extent of the temperature change depends on climate, riparian vegetation, stream morphology, and groundwater inputs (Sullivan & Adams 1991). Climate often is the dominating factor influencing water temperature

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with absorption of solar radiation being the primary source of warming (Morin & Couillard 1990; Webb & Zhang 1997; Evans *et al.* 1998; Johnson 2003). Riparian vegetation can insulate small streams by shading the water and the adjacent landscape (Sweeney 1993; Dong *et al.* 1998; Johnson 2004); however, the insulating effect of shading diminishes as stream width increases (Poole & Berman 2001). Stream morphology changes the surface area to volume ratio and can promote the exchange of stream water with the hyporheic zone (Brunke & Gonser 1997; Poole & Berman 2001; Webb *et al.* 2008). Hyporheic water temperatures generally are warmer than stream temperatures during the winter and cooler during the summer because a portion of the water originates from groundwater, which maintains a consistent year-round temperature that approximates the mean annual air temperature (Brunke & Gonser 1997; Hayashi & Rosenberry 2002). Streams heavily influenced by groundwater inputs exhibit attenuated year-round temperatures (Holmes 2000).

Ultimately, it is the combination of these factors that determine stream temperature, and the temperature difference between a stream and its receiving waterbody will dictate the stream intrusion depth (Fischer *et al.* 1979; Killworth & Carmack 1979). When stream inputs are warmer and less dense than the lake, they intrude as overflow. When stream inputs are cooler and thus denser, they intrude as underflow until a level of neutral buoyancy is reached (Alavian *et al.* 1992). In a well-mixed lake, all inputs will be mixed regardless of intrusion depth. During periods of stratification, however, intrusion depth will dictate at what depth in the water column stream constituents become available (MacIntyre *et al.* 2006; Cortés *et al.* 2014).

Intrusion depth in Lake George is of great interest because it may impact the regular occurrence of hypolimnetic oxygen depletion in the Caldwell Sub-basin, the southernmost sub-basin of the lake. The land surrounding the Caldwell Sub-basin is the most developed area in the Lake George watershed, based on property tax records from the eight towns and villages within the Lake George watershed; with roughly half of the ~9,000 total buildings in the Lake George watershed located in this area. Greater urbanization coupled with the south to north flow of the lake has resulted in a consistent phosphorus and chlorophyll gradient in the lake that decreases as water flows north (Boylen *et al.* 2014). The higher nutrient concentration in the Caldwell Sub-basin and subsequent increased phytoplankton biomass has been indicated as a contributor to hypolimnetic oxygen depletion (Boylen *et al.* 2014). The greater organic biomass reaching the sediment surface enhances the BOD, lowering the hypolimnetic oxygen concentration during stratification with the lowest oxygen concentrations observed in October and November just before fall turnover. Oxygen depletion in Lake George becomes a concern when dissolved oxygen (DO) concentrations fall below 4 mg/L because at ~10 °C, which is roughly the hypolimnetic temperature during early fall, 4 mg/L dissolved oxygen is equivalent to 35% saturation. Fish sensitive to low dissolved oxygen will avoid such areas (Arend *et al.* 2011) and oxygen concentrations ≤30% saturation result in the release of sediment-bound phosphorus (Eichler & Boylen 2011). In addition, for lakes classified AA-Special in New York State, including Lake George, 'at no time shall the DO concentration be less than 4.0 mg/L' (6 CRR-NY 703.3). Minimum hypolimnetic oxygen concentrations in the Caldwell Sub-basin were ≥4 mg/L during five years between 1980 and 2010 and for three of those years the minimum oxygen concentration was 4 mg/L.

The goal of this research was to determine: (1) if thermal regimes vary among the major streams entering Lake George, and if so, identify the factors that may be primarily responsible for the observed differences; (2) estimate the intrusion depth of each stream based on density; and (3) identify possible impacts of varying intrusion depths to the hypolimnetic oxygen depletion in Lake George. A better understanding of intrusion depth, entrainment, and mixing during stratification has broader implications on nutrient availability, primary production, and food web dynamics that could be applied to all waterbodies.

METHODS

Study site

Lake George, located in the southeast portion of the Adirondack Park (NY), is a large (110 km^2, 2.1 km^3), long (51.5 km), oligotrophic lake with a dominantly forested

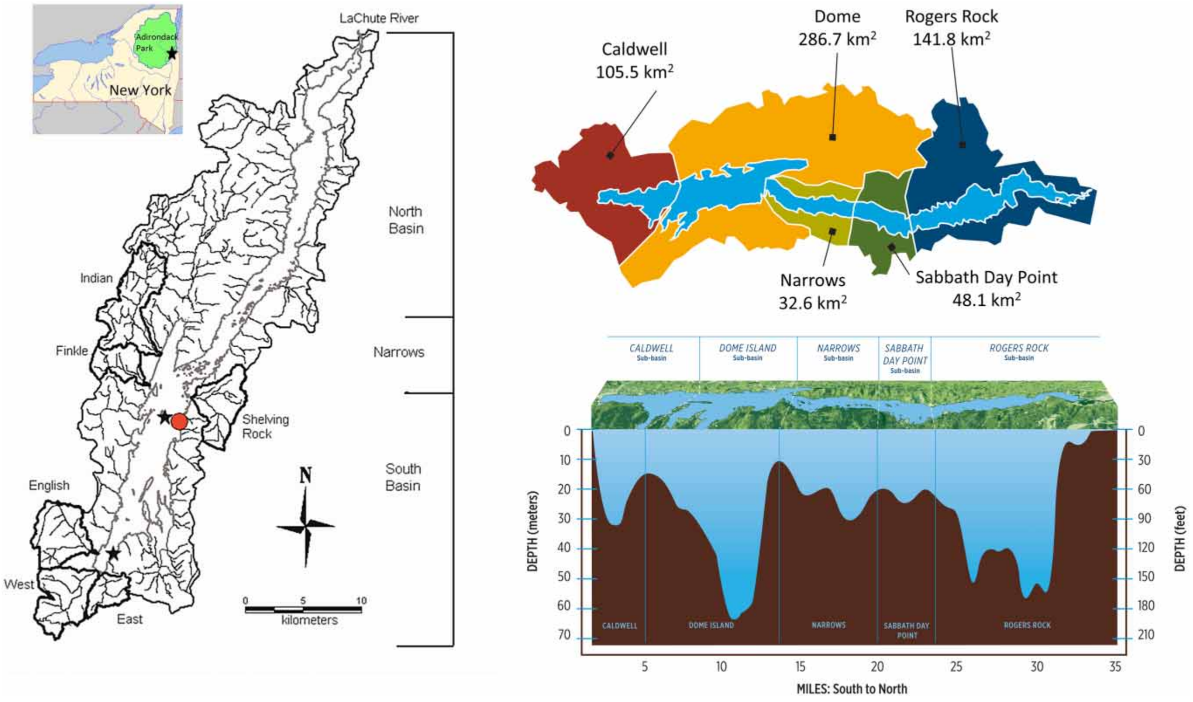

Figure 1 | (Left) The Lake George Basin along with streams and the monitored sub-watersheds outlined in black. In-lake sampling locations, Tea and Dome Islands, identified by stars; Tea Island is the most southern location. Profiler location indicated by circle. (Right) The five major sub-basins of Lake George and their land catchment are identified accompanied with a side-view of the deepest points along the length of Lake George based on Boylen & Kuliopulos (1981).

watershed (Figure 1; Boylen & Kuliopulos 1981; Shuster *et al.* 1994). Lake George surface water is maintained by the LaChute Hydro Company, Inc. at an elevation of 97.5 m. The highest point in the watershed, Black Mountain, reaches 800 m. Mean annual precipitation (2000–2008) was 114.7 ± 18.8 cm with an average precipitation from May to October of 64.3 ± 35.7 cm (Eichler *et al.* 2009). Precipitation in 2007 and 2008 between May and October was below average at 48.0 cm and 55.9 cm, respectively. The 141 streams surrounding Lake George (Sutherland *et al.* 2001) supply the lake with 57% of its annual hydrologic budget with precipitation directly on the lake and groundwater discharge in the lake accounting for 25% and 18%, respectively (Shuster *et al.* 1994). The lake has a relatively small watershed with a 4.6:1.0 land to lake surface ratio and a residence time of 5.5 and 6.8 years based on volume and conserved solutes, respectively (Shuster *et al.* 1994).

The lake has chemically distinct South and North basins that are separated by a shallow sill in the Narrows, ~18 km from the south end. The South Basin, which is the focus of this study, consists of two sub-basins, Caldwell and Dome Island. The headwater and most southern sub-basin, Caldwell, has a maximum depth of 31 m and receives discharge from East, West, and English Brook (Figure 1). The Dome Island Sub-basin is the largest sub-basin with a maximum depth of ~60 m (Boylen & Kuliopulos 1981) and receives discharge from Finkle, Indian, and Shelving Rock Brook. These six brooks are a sub-set of the 10 largest tributaries entering Lake George and drain 23% of the entire watershed (Swinton *et al.* 2015). The level of development ranges from the most impacted in East and West Brook watersheds to no development in the Shelving Rock Brook watershed. All the tributaries are relatively narrow with tree canopy covering the majority of the stream length.

During the last glaciation, the Laurentian Ice sheet stripped away most of the soil cover from higher elevations and deposited a greater proportion of sand in the southern end of the watershed with finer clays deposited in the North Basin. Upland deposits of sands and gravels are sporadic and infrequent with varying thickness overlaying fractured bedrock. Lower elevations have more consistent sandy tills overlaying fractured bedrock which near lake level is overlain by varved silts and clays. Kamic terraces composed of sandy to gravelly sediments are common in tributary valleys. Lake George bedrock is a mix of dominantly granitic gneisses, charnockitic gneisses, garnet-biotite-quartz-plagioclase gneisses, quartzites, metaanthrosites and metagabbros with smaller quantities of marble, calcsilicates, and amphibolites (Shuster *et al.* 1994).

The effects of repeated glacial encroachment and retreat in the Lake George watershed resulted in varying soil types (Table 1) and thus sub-watersheds exhibit different hydraulic conductivities. The greater deposition of sand in the south end resulted in East and West Brook exhibiting the highest infiltration rates while Shelving Rock, the only watershed monitored on the east side of the lake, is characterized by steeper slopes and shallow/exposed bedrock limiting infiltration rates. The remaining watersheds (English, Finkle, and Indian) have soils primarily composed of type B and C soils which exhibit intermediate infiltration rates.

Sampling

The six major tributaries of this study were monitored for temperature and chemical composition between 2007 and 2010. Sampling occurred monthly between December and March with the sampling rate increasing to 2-week intervals between April and November. Temperature measurements were taken during baseflow conditions from March to December using a Raytek Mini Temp IR thermometer, which was routinely checked against National Institute of Standards and Technology (NIST) certified thermometers. Water temperature measurements were taken while either in the stream or on the stream bank with the angle primarily vertical. West, English, and Finkle Brook measurements were taken near the mouth of the streams while East, Shelving Rock, and Indian Brook measurements were taken within 0.5 km of the lake. Shelving Rock and Indian Brook were dominantly shaded by riparian vegetation between the sampling location and the lake; a wetland was located downstream of the East Brook sampling location. Raw temperature measurements are presented along with relative water temperature difference, calculated as the individual stream temperature minus the average temperature of all streams sampled on a specific date.

Table 1 | Percent of soil types in the monitored Lake George sub-watersheds

Sub-watershed	A	B	C	D
East	25.4	48.9	24.0	1.7
West	23.8	49.9	24.0	2.3
English	6.1	58.5	33.4	2.0
Finkle	4.8	41.3	48.3	5.6
Shelving Rock	2.1	37.5	0.2	60.3
Indian	3.9	50.6	42.8	2.7

Data obtained from the Lake George Association and Warren County Soil and Water Conservation District. Type A: <10% clay with >90% sand and gravel; B: 10–20% clay with 50–90% sand; C: 20–40% clay with <50% sand; D: >40% clay with <50% sand (USDA 2009).

The Offshore Chemical Monitoring Program sampled mid-lake locations from May to November during 2007 and 2008. Prior to stratification, sampling occurred every 2 weeks with monthly sampling during summer and 2-week sampling reinstated during fall. The two locations utilized in the South Basin were Tea Island in the Caldwell Sub-basin and Dome Island in the Dome Island Sub-basin (Figure 1). Vertical temperature profiles were recorded at set intervals of 0, 1, 2, 3, 5, 10, 15, 20, 25, 30 m with additional measurements taken within depth ranges exhibiting large temperature changes. Measurements were recorded using a YSI temperature probe (various models), which was routinely checked against NIST thermometers. Samples were collected for analytical chemistry in the epilimnion (0–10 m; hose-integrated) and hypolimnion (1 m off the bottom; grab). Sodium, calcium, magnesium, and potassium were analyzed by atomic absorption spectrophotometry using a Perkin Elmer AAnalyst 5000 (Creed *et al.* 1991); chloride and sulfate were analyzed by ion chromatography using a Lachat 8000 QuikChem (Pfaff 1993). Alkalinity was measured by Titration Method 2320 B (Clesceri *et al.* 1989). Standard quality assurance and quality control protocols included blanks, duplicate samples, spikes, and external check standards every ten samples. Additional description of sampling methods for the stream and lake monitoring can be found in Swinton *et al.* (2015).

Water density was calculated for both the lake and streams using temperature and salinity (comprising sodium, chloride, calcium, magnesium, potassium, sulfate, and bicarbonate). Although both epilimnetic and hypolimnetic lake samples were taken and their calculated salinities were within 5% of each other, only the epilimnetic value was used in the calculation as it was more representative of the water column (0–10 m) than a grab sample 1 m off the bottom, which could be influenced by underflow. While bicarbonate was not measured directly during the 2007–2008 stream study, it is estimated as being equivalent to calcium on a weight basis. Based on preliminary West and Finkle Brook 2015 data from the Jefferson Project, calcium and alkalinity (reported as calcium carbonate) exhibited a strong correlation ($r^2 > 0.93$, $N = 6$) during baseflow conditions with calcium comprising 37–60% of the calcium carbonate. Therefore, bicarbonate was estimated as an equivalent mass of calcium. Alkalinity measurements were taken for the lake sampling locations and were included in the salinity calculations.

McCutcheon *et al.* (1993) defined water density as:

$$\rho_s(kg\ m^{-3}) = \rho_o + AS + BS^{3/2} + CS^2$$

ρ_o, A, and B are based on temperature, C is a constant, and S is salinity (g/kg).

Stream intrusion depth was based on density calculations for each stream and the corresponding sub-basin, Caldwell or Dome Island. Isopleths were constructed using SigmaPlot and because density was interpolated between sampling dates and within individual profiles some static instabilities may be present. Isopleths contours are depicted using the oceanographic sigma or density anomaly measurement which is the water density difference from 1,000 kg/m^3.

Previous stream projects

To verify the temperature trends observed in this stream study, previous stream studies that included West or East Brook and any of the other four streams included in the 2007–2010 project were examined for comparison. Fuhs (1972) sampled a total of 18 streams from July 1970 to July 1971; temperature data from West, English, Finkle, and Indian Brook are included here for comparison. The Nationwide Urban Runoff Program (NURP) focused on streams having different levels of watershed development at the south end of the lake from July 1980 to June 1982, and therefore only includes West and English Brook (Sutherland *et al.* 1983). Sutherland (unpublished data) sampled from August 2002 through November 2005 on West, East, English, Finkle, and Indian Brook.

High-resolution profile data

A YSI 6950 vertical profiler equipped with EXO 2 sonde capable of recording temperature and chloride profiles at 1-m resolution every 90 minutes was deployed near the deepest location (53 m) in the Dome Island Sub-basin during the fall of 2014 as part of the Jefferson Project. The water temperature probe had a resolution of 0.001 °C with an accuracy of 0.01 °C between −5 and 35 °C. The chloride probe had a resolution of 0.01 mg/L with accuracy ±15% of reading or 5 mg/L between 0 and 1,000 mg/L. Air temperature was measured using the Vaisala Weather Transmitter WXT520 attached to the vertical profiler platform. The air temperature measurements had a resolution of 0.1 °C with an accuracy ranging from 0.2 at −20 °C to 0.4 at 40 °C. The Jefferson Project is a collaboration among Rensselaer Polytechnic Institute, IBM Research, and the FUND for Lake George with the goal of combining multiple high-resolution data from weather, stream, and in-lake sensors to create meteorological, hydrologic, hydrodynamic, and food web models to better understand the effects of anthropogenic development and climate change on the health and function of Lake George.

Statistical analysis

Statistical analyses were conducted in SPSS or SigmaPlot. Normality and equal variance were conducted on baseflow stream data to determine if parametric or nonparametric analyses were appropriate. Significance of main factors was determined using analysis of variance (ANOVA) with the Holm-Sidak method used for pairwise comparisons when data were normally distributed. Data that were non-normally distributed required the non-parametric counterparts: Kruskal–Wallis and Dunn's methods to determine significant differences between main factors and pairwise comparisons, respectively. Correlations were conducted using the Spearman rank order when data distribution was non-normal.

Seasonal components were based on solstice and equinox dates: spring (March 21–June 20), summer (June 21–September 22), and fall (September 23–December 20).

RESULTS

Comparing baseflow temperatures among the six streams identified two main findings: (1) East and West Brook temperatures were cooler than other streams during summer months (Figure 2) and (2) a seasonal trend of the relative water temperature difference for East and West Brook indicates a greater proportion of discharge originates from groundwater than other streams in the study (Figure 3).

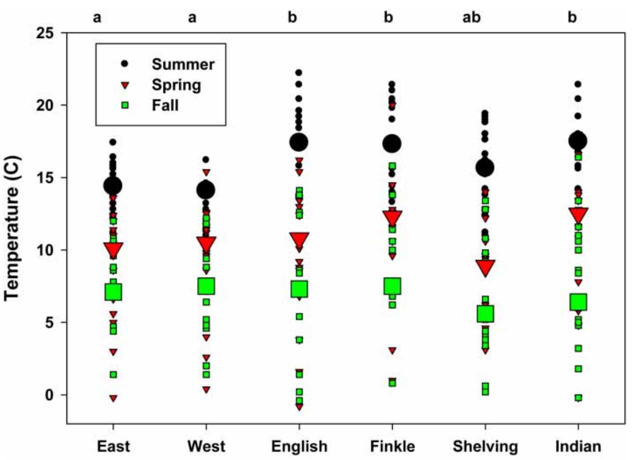

Figure 2 | Baseflow stream temperatures recorded in six major streams to Lake George between 2007 and 2010 separated by season. Larger symbols represent the seasonal median (summer and spring) or mean (fall) for each stream based on normality and equal variance. Different letters represent significant differences between streams during summer (Dunn's method). Streams are listed based upon location from south to north.

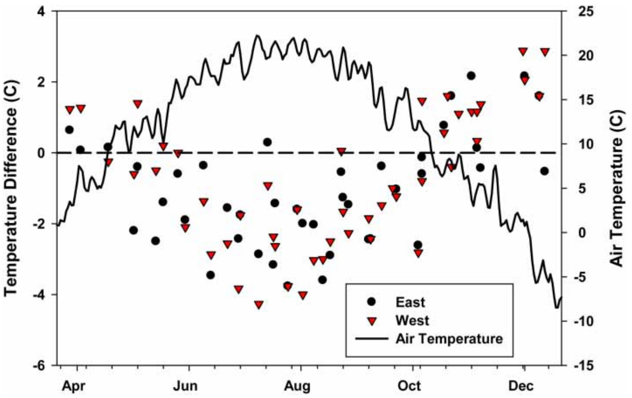

Figure 3 | Relative temperature difference for East and West Brook between 2007 and 2010 exhibit a strong seasonal component. Between mid-April and mid-October, East and West temperatures were generally cooler than the average temperature of all monitored streams entering Lake George. Daily air temperature data were obtained for the NOAA Glens Falls Airport (KGFL). Air temperature is the daily average from 2007 to 2010 smoothed using a 3-day average.

Comparing baseflow stream temperatures by season indicated only summer temperatures were significantly (Kruskal–Wallis, $p < 0.05$) different among streams with pairwise comparisons showing East and West Brook being significantly (Dunn's method, $p < 0.05$) cooler than English, Finkle, and Indian Brook (Figure 2). Shelving Rock Brook temperatures while not significantly different from other streams were consistently cooler than all other streams in spring and fall.

To reduce inter-annual variability and thus enhance statistical rigor, the relative water temperature differences were compared among streams. Comparing the relative stream temperatures strengthened the differences observed during summer and resulted in new significant comparisons during the spring and fall. Along with East and West Brook, significant summer water temperature differences now included Shelving Rock being significantly cooler than English, Finkle, and Indian Brook. During the spring, East, West, and Shelving Rock Brook were significantly (Dunn's method, $p < 0.05$) cooler than Finkle and/or Indian Brook. During fall, Shelving Rock Brook was significantly (Holm-Sidak, $p < 0.05$) cooler than West, English, and Finkle Brook.

The relative water temperatures of East and West Brook illustrate the seasonal effect on stream temperatures with cooler temperatures between late April and early October, peak differences reached ~4.0 °C in July. By early October, East and West Brook temperatures transitioned to generally warmer temperatures (Figure 3). The transition between warmer and cooler relative temperatures in the spring and fall occurred between 5 and 10 °C for both the water and air (Figures 3 and 4). When water and air temperatures were below 5 °C, East and West Brook generally were warmer than other major streams and when the temperatures were above 10 °C, their temperatures generally were cooler than other major streams. Stream temperature data from the early 1970s (Fuhs 1972), 1980s (Sutherland *et al.* 1983), and 2000s (Sutherland unpublished) verified the seasonal trend (Figure 4). The transition range from 5 to 10 °C is near that of groundwater for the Lake George area, which is ~8.3 °C year-round (USEPA 2013). Groundwater temperature remains relatively constant year-round and approximates the average annual air temperature for a region (Brunke & Gonser 1997; Hayashi & Rosenberry

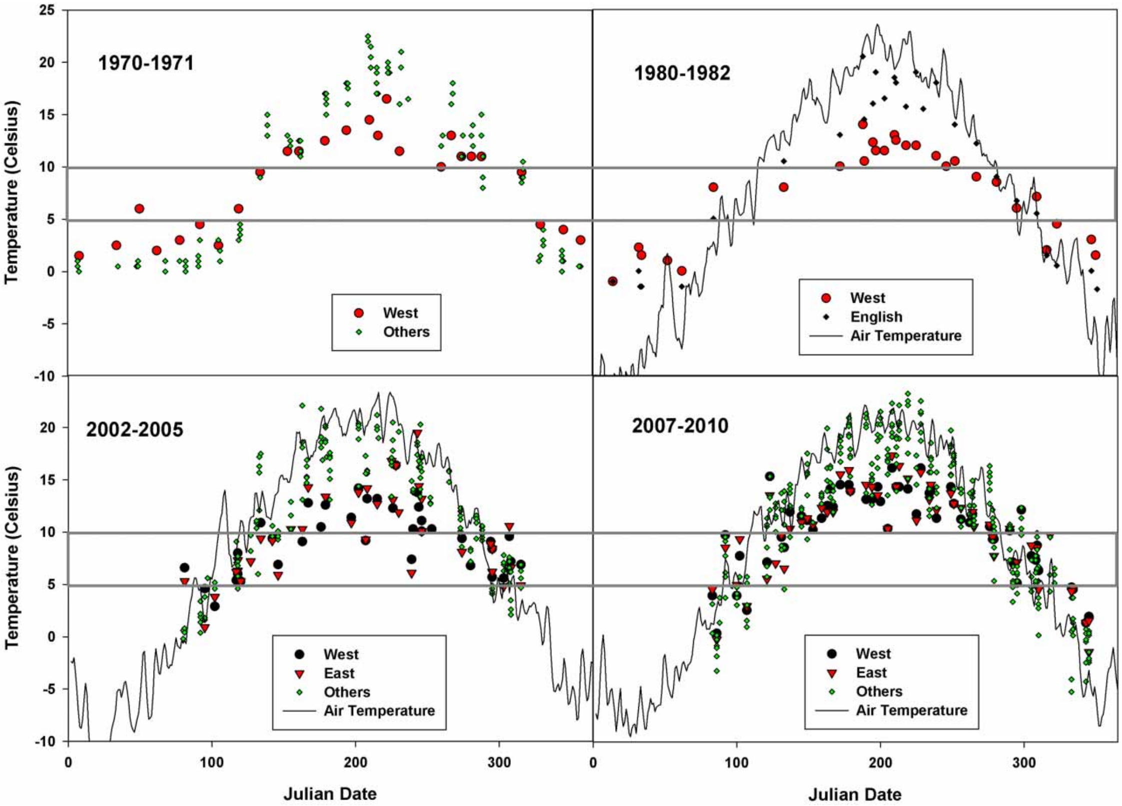

Figure 4 | Stream temperatures indicate the seasonal trend of East and West being warmer in cold months and cooler in warm months as was evident in all earlier studies. The transition between warmer and colder temperatures occurred in mid-spring and mid-fall between 5 and 10 °C, which is in the range of groundwater temperature for the region. Daily air temperature data were obtained for the NOAA Glens Falls Airport (KGFL). Air temperature is the daily average for the years indicated in each graph smoothed using a 3-day average.

2002). Between 2007 and 2010 the average annual air temperature ranged from 7.2 to 8.8 °C based on data from the National Oceanic and Atmospheric Administration station at Glens Falls Airport (KGFL).

Intrusion depth

Stream intrusion into a lake or reservoir is dictated by the relative density difference between the stream and lake/reservoir. In the Lake George watershed, temperatures among streams can vary substantially on an individual day resulting in colder water intruding deeper in the lake. Prior to the establishment of the thermocline in 2007, intrusion depths of East, West, and English Brook ranged from near surface to underflow (Figure 5). Between the onset of stratification and mid-August, East and West Brook entered the lake as interflow at the deeper portion of the metalimnion while English inserted in the shallow portion of the metalimnion. In early August, the thermocline tended to break up into a double layer thermocline with East and West Brook entering the deeper portion, and English entering the shallow portion. By late August, East and West Brook intruded into the hypolimnion, while English Brook inserted at the deeper portion of the metalimnion, with all three streams entering the hypolimnion through turnover.

In early May 2008, English Brook entered the lake near the surface and East Brook as underflow (Figure 5). Establishment of a strong thermocline was delayed allowing East, West, and English Brook to intrude at ~15 m in mid-June compared to ~10 m at the same time in 2007. East, West, and English Brook generally inserted between 10 and 15 m until August with a tendency for East Brook to intrude the deepest and English the shallowest. Through

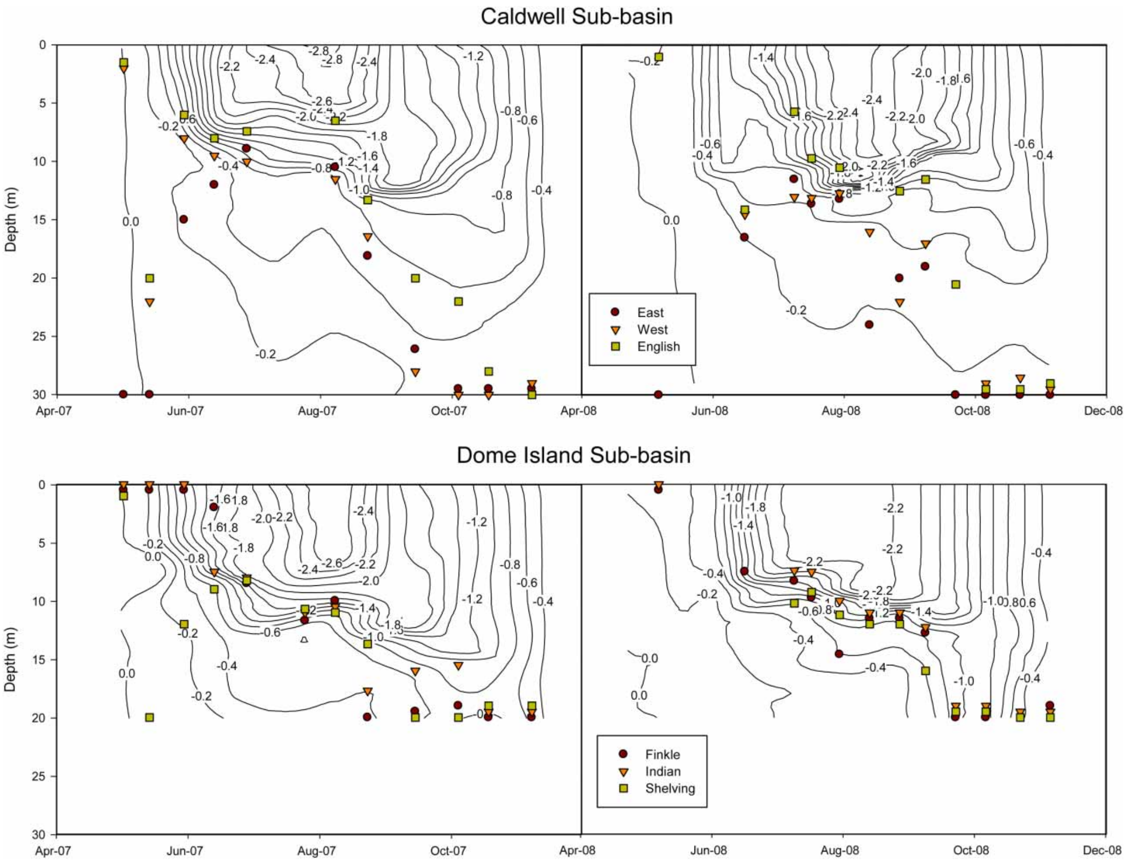

Figure 5 | Lake density (kg/m^3) isopleths for the Caldwell and Dome Island Sub-basins during 2007 and 2008 determined from temperature and salinity. The calculated intrusion depth for each stream was based on the relative density difference between lake profiles and stream discharge. The cooler water temperature in East and West Brook indicates intrusion during summer is within metalimnion or hypolimnion, limiting its incorporation to the SML.

September, English maintained the 10 to 15 m intrusion depth with East and West entering between 15 and 25 m. By October, all were intruding as underflow.

Streams entering the Dome Island Sub-basin had a tendency to insert either above or within the metalimnion until late August or September during 2007 and 2008, respectively, with the exception of Shelving Rock in early 2007 (Figure 5). Finkle and Indian Brook inserted at the lake surface through May 2007 while Shelving Rock Brook tended to enter as underflow or interflow. Between June and early August, all streams inserted within the metalimnion, with intrusion below the metalimnion beginning in mid-August. By mid-September, stream inputs intruded as underflow. Similar patterns were observed during 2008.

Streams intrusion depth into Lake George was dominantly influenced by temperature with the dissolved ion composition (salinity) having a minimal impact on most streams. To illustrate this point, stream densities were compared to the average lake density (0–2 m) of the receiving sub-basin with density differences attributed to temperature and salinity quantified (Figure 6). East and West Brook show consistently denser stream discharge for both temperature and salinity with peak differences reaching ~2.0 kg/m^3 in mid-summer. Finkle and Indian Brook show that warmer water temperatures in late spring resulted in the overflow observed in 2007 and 2008. The lack of development in the Shelving Rock Brook watershed resulted in the stream water comprising fewer dissolved ions and thus the salinity component always resulted in the stream discharge being less dense than the lake; however, the cooler water temperatures overwhelm the impact. Finkle Brook was the stream most impacted by dissolved ions because of the high salt concentrations that are believed to be a result of a previously uncovered road salt

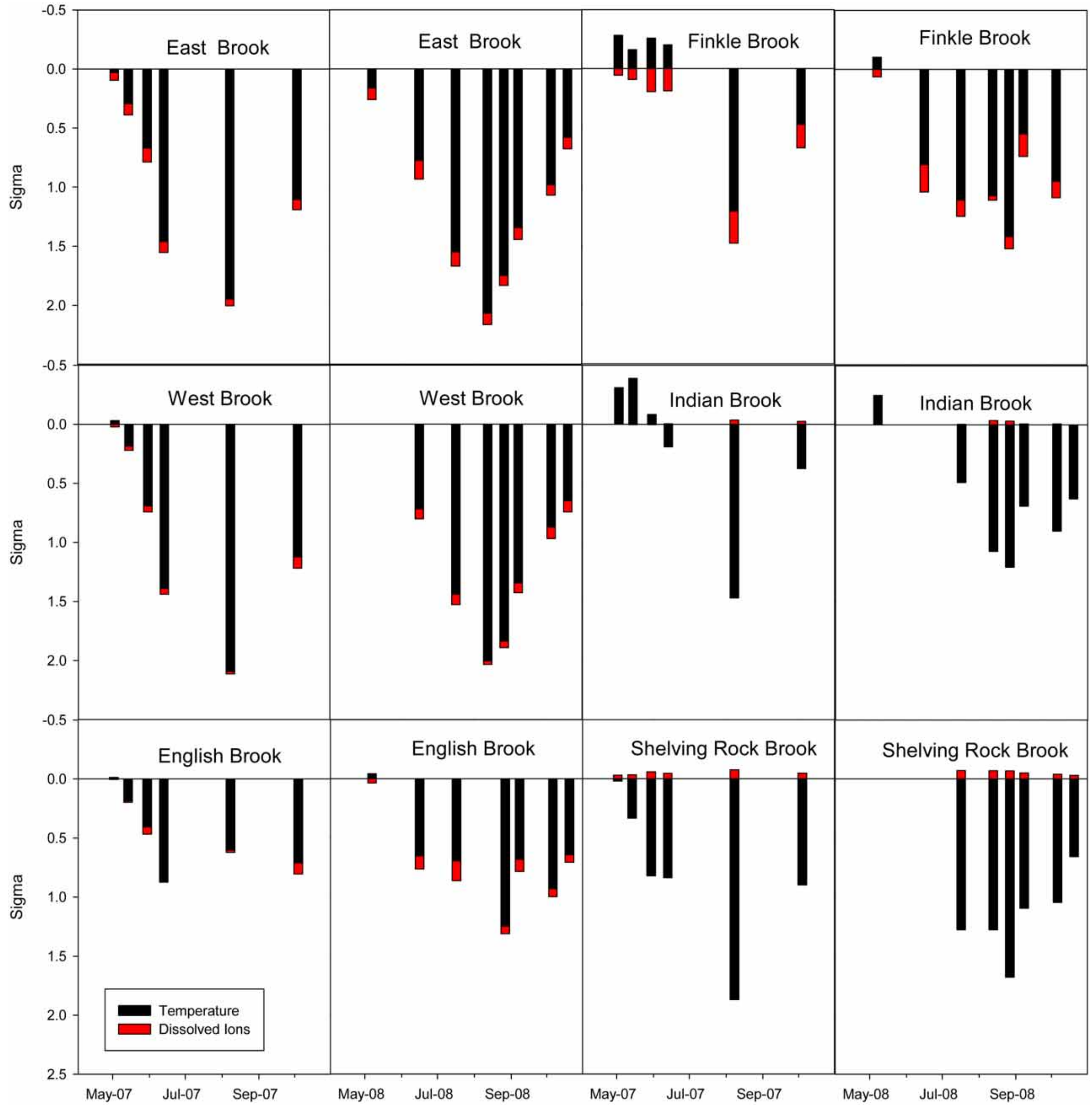

Figure 6 | Relative density between stream discharge and the lake surface (0–2 m). The contribution of temperature and dissolved ions (salinity) are quantified. Values below the zero line indicate the stream discharge is denser than the lake surface and values above indicate the stream discharge is less dense.

storage facility (Swinton *et al.* 2015). However, the maximum density difference measured in August 2007 attributed $<0.3\ \mathrm{kg/m^3}$ to salinity with the temperature accounting for a density difference of $1.2\ \mathrm{kg/m^3}$; the gradient on the isopleths is $0.2\ \mathrm{kg/m^3}$.

Initial high-resolution profile data from the Dome Island Sub-basin illustrated a cold-water, less saline underflow during a fall storm event in 2014. A storm system beginning on November 24 and ending on November 26 had a cumulative rainfall of 2.31 cm distributed between two events. The first event on November 24 resulted in bottom water (53 m) decreasing temperature by ~1 °C and chloride by ~2 mg/L (Figure 7). Decreases in both temperature and chloride below 40 m are visually detectable shortly after precipitation fell on November 24 indicating that the underflow was entrained in water below 40 m. The second event on November 26 did not exhibit the same magnitude of change because the air temperature had dropped ~20 °C between the two events resulting in the second event being a mixture of rain and snow.

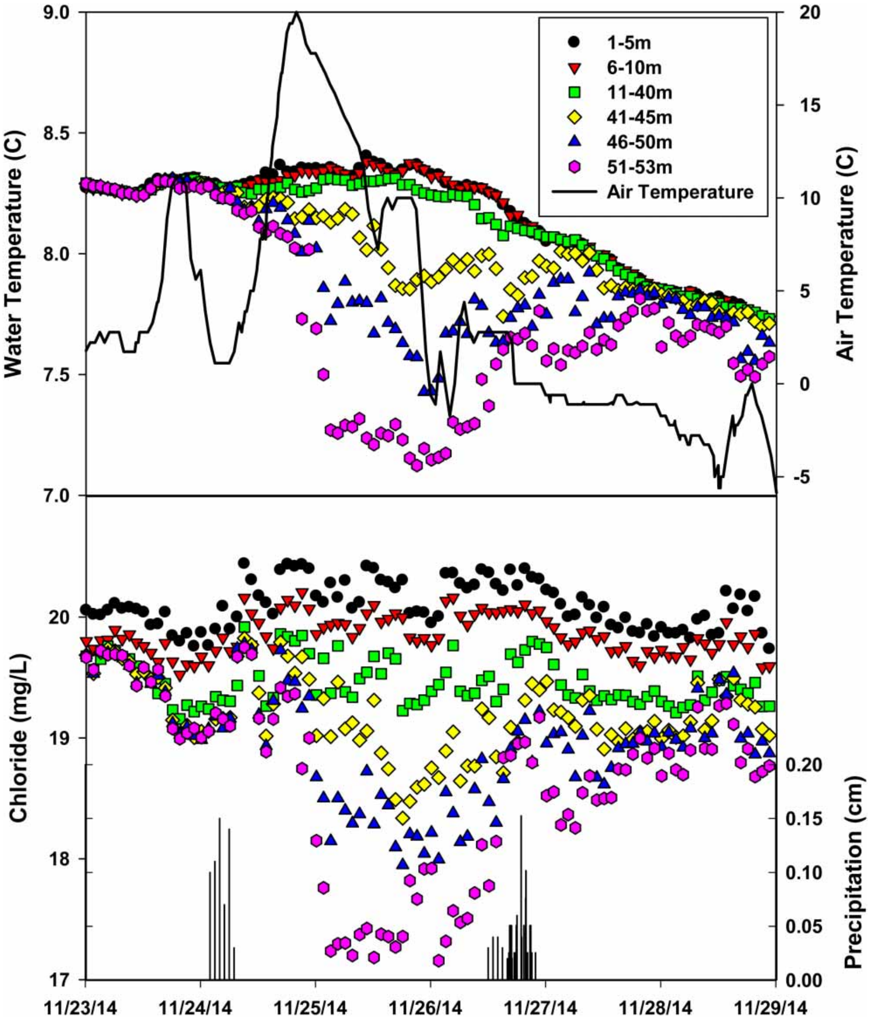

Figure 7 | Temperature and chloride data collected using a YSI vertical profiler near Shelving Rock during a November 2014 precipitation event verifying stream discharge entering the lake as underflow with entrainment dominantly below 40 m. Air temperature was measured using the weather station on the vertical profiler.

DISCUSSION

Summer baseflow temperatures in East, West, and Shelving Rock Brook clearly were cooler than other major streams monitored, and based on historic West Brook studies, this is not a new phenomenon. Therefore, the discussion will focus on: (1) how soil composition may influence the different seasonal thermal regimes observed; (2) how deeper intrusion depths may incorporate organics and oxygen into the hypolimnion; and (3) the implications of hypolimnetic intrusion on the oxygen depletion regularly observed in the Caldwell Sub-basin.

Seasonal thermal regimes

Three distinct seasonal temperature patterns exist in the six major streams monitored around Lake George between 2007 and 2010 that can be explained in part by the soil composition within each watershed. The most common thermal regime is representative of English, Finkle, and Indian Brook. Median summer baseflow temperature among these streams was very consistent ranging from 17.3 to 17.5 °C (Figure 2). However the spring (average) and fall (median) temperatures differed by 1.7 °C and 1.1 °C, respectively. These streams are located along the west side of the lake with >83% of the soils comprising type B and C (Table 1) having an infiltration rate between

0.05 and 0.30 in/hr (Guo 2006). Since soil type and topography are similar, the influence of groundwater should be fairly consistent among the streams, as seen in the average summer temperatures. Stream temperatures in the spring and fall experience increased variation because the influence of groundwater and canopy cover diminish, enhancing the effect of climate and stream morphology.

The cooler summer temperatures in East and West Brook can be explained by the greater proportion of fast infiltrating soils; ~75% of soils in these two watersheds comprise type A and B soils. These soils consist primarily of sand and gravel which result in infiltration rates between 0.15 and 0.45 in/hr (Guo 2006); the faster infiltration rate means groundwater seepage into the streams can occur more readily. The assumption that a greater proportion of discharge from these streams originates from groundwater is supported by the cooler water temperatures in warm months and warmer water temperatures in cold months. Since groundwater in the region remains ~8.3 °C throughout the year, it acts as a temperature buffer during summer and winter. The interaction between stream water and groundwater is well documented (Castro & Hornberger 1991; Stanford & Ward 1993; Evans *et al.* 1998; Malcolm *et al.* 2002) along with its ability to buffer stream temperatures (Holmes 2000; Malcolm *et al.* 2002; Johnson 2004). One of the most compelling studies by Shepherd *et al.* (1986) combined three studies along the Pacific Northwest coast of the United States varying in watershed size, discharge rate, and temperature during different decades using different methodologies and having different goals: all documented that intra-gravel temperature was warmer in the winter and cooler in the summer than the stream temperature with the transitions occurring around March and October.

Shelving Rock Brook, the only stream monitored on the east side of the lake, is characterized as undeveloped forest with steeper slopes and a greater proportion of shallow/exposed bedrock relative to the other watersheds monitored. Shelving Rock Brook temperatures generally were cooler than the other streams with the exception of East and West Brook during summer. Shelving Rock Brook temperatures did not exhibit a seasonal component when analyzing relative temperature differences, indicating groundwater inputs were not the primary influencing factor. While the heavily forested watershed may aid in maintaining cooler water temperatures, it is likely not a principal factor because the Indian Brook watershed also is heavily forested but exhibited a different thermal regime. The most probable explanation is the greater proportion of shallow/exposed bedrock. Shallow streams with bedrock bottoms can transfer up to 25% of the energy absorbed by the streams to the bedrock resulting in a dampening of diurnal temperature (Brown 1969). Additionally, the stream corridor is predominantly shaded providing insulation by limiting energy absorption from solar radiation. Small stream temperatures are difficult to predict because they respond more rapidly to energy inputs and watershed characteristics than do larger streams (Smith 1972), making it necessary to have continuous temperature measurements and energy flux calculations among the streams and their substrates to fully understand the different thermal regimes observed throughout the Lake George Basin.

Intrusions

As stream discharge enters a lake it will intrude according to its density relative to the water column. If the stream discharge is less dense than the lake, the discharge enters as overflow and becomes incorporated into the surface mixed layer (SML). This was the case for Finkle and Indian Brooks through late spring of 2007. If the stream discharge is denser than the lake, as is often the case for East, West, and Shelving, the flow will propagate down the slope of the lake. As the flow continues down the slope of the lake, a head begins to form at the front of the flow; it is this region of the flow that mixes with the lake water (Simpson 1982). The extent of mixing and entrainment of the head depends on the velocity, density difference, and the degree of slope. As any of these parameters increase, mixing between the head of the flow and the lake water also increases (Simpson 1982). The flow will continue down the slope until it reaches a depth of neutral buoyancy, at which time it begins to propagate horizontally (Alavian *et al.* 1992). Prior to stratification, the water column is well mixed and while East and West Brook may intrude at varying depths, all inputs will likely become mixed throughout the water column.

Once the thermocline develops, intrusion depth will dictate the region of the water column where the discharge will incorporate. If the discharge intrudes above the metalimnion, the flow will become incorporated into the SML (Cortés *et al.* 2014). However, if the intrusion is within the metalimnion, it likely will not become incorporated into the SML quickly, due to the rate of vertical mixing within a thermocline being on the order of heat diffusion (Quay *et al.* 1980; Fee *et al.* 1994). Therefore, stream discharge intruding into the metalimnion will dominantly remain in the metalimnion for an extended period of time, possibly creating a nutrient-rich layer for primary producers to utilize. If the discharge is denser than the metalimnion, the flow continues to propagate down the slope into the hypolimnion (Cortés *et al.* 2014). East and West Brook intrusion depths during the summer and fall imply the inputs would predominantly be maintained in the metalimnion or hypolimnion with little incorporating into the SML until fall turnover.

High-resolution profiler data confirmed that underflow does occur during fall at the deepest depths of the Dome Island Sub-basin. Initial data identified a colder, less saline pulse of water entered the sub-basin during a storm event in November 2014 (Figure 7). Streams entering the lake in this area have watersheds that primarily are forested and are representative of Shelving Rock Brook, which is located ~1.5 km away from the profiler. Shelving Rock Brook chloride concentration was ~1 mg/L (Swinton *et al.* 2015) with November baseflow temperatures measured between 2007 and 2010 ranging from 0.6 to 6.6 °C. The colder and less saline inputs entered the lake as underflow with entrainment affecting water below 40 m; little temperature change was detected in the top 40 m of the water column. The high-resolution data illustrate the power to identify complex hydrodynamic mixing during storm events. An additional profiler was deployed in the Caldwell Sub-basin, near East and West Brook during the 2015 season, which should allow us to test the hypothesis that cooler stream temperatures insert into the hypolimnion as implied by the calculated intrusion depth. The high-resolution data can additionally identify if intrusion depths vary throughout the day and how temperature changes during summer storm events influence intrusion depth and mixing patterns, assuming that the inputs during baseflow conditions can be detectable at these offshore locations. The inputs may simply be too small to detect and, if that is the case, installation of static CTD sensor strings near shore could benefit future studies.

Implications to hypolimnetic oxygen depletion

The depth of stream intrusion is of great importance when studying or managing a lake because the nutrients, sediments, gases, and pollutants incorporated in the discharge will be available at specific levels of the lake during periods of stratification. The primary concern with deeper intrusion depths in the Caldwell Sub-basin of Lake George deals with seasonal hypolimnetic oxygen depletion. In the Caldwell Sub-basin, the hypolimnion regularly experiences oxygen depletion below 4 mg/L during late summer/early fall (Boylen *et al.* 2014). This is the only sub-basin of the lake where oxygen depletion this severe has been documented and may be impacted by deep intrusion of nutrient-rich oxygenated stream discharge. East and West Brook are two sub-watersheds at the south end of Lake George with high residential and commercial development associated with tourism. West Brook has been known since the late 1960s–early 1970s to contribute elevated levels of nitrogen and chloride (which also affects water density) to the lake that originate from the local waste water treatment plant (Aulenbach & Tofflemire 1975) and a previously uncovered road salt storage facility. Since at least the early 1980s, East Brook and an adjacent small sub-watershed have contributed high levels of phosphorus to Lake George through stormwater runoff (Sutherland *et al.* 1983). When these nutrient-rich oxygenated inputs are incorporated into the hypolimnion, they can have both positive and negative effects on the dissolved oxygen levels. The addition of organic material could negatively affect the oxygen levels by elevating the microbial activity and thus promote hypolimnetic oxygen depletion. On the other hand, the input of oxygen-rich stream discharge could attenuate the seasonal hypolimnetic oxygen depletion. An in-depth study on how stream discharge impacts hypolimnetic oxygen concentration is required to determine the extent and importance of supplying both organics and oxygen to the hypolimnion during stratification.

CONCLUSION

Soil type variability within the Lake George watershed resulted in distinct stream temperature regimes that influenced intrusion depth into the lake. Streams receiving a large proportion of groundwater or more shallow/exposed bedrock exhibited cooler summer temperatures dictating deeper intrusion depths that could isolate stream inputs to the hypolimnion during periods of stratification. High-resolution profiler data confirmed underflow intrusion during the fall of 2014 and merit additional data collection to determine if the stream discharge is able to penetrate the thermocline to incorporate into the hypolimnion. If so, this deeper intrusion could have both negative and positive impacts on the hypolimnetic oxygen depletion that occurs in that sub-basin of the lake. The addition of high-resolution profiler data throughout the lake as part of the Jefferson Project will answer questions similar to these and progress our understanding of the hydrodynamics in Lake George as well as the field of hydrodynamics.

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