



A Review of Lake Vertical Profile Monitoring in the Southwest Alaska Network

Recommendations for Future Efforts

Natural Resource Technical Report NPS/SWAN/NRTR—2013/689



ON THE COVER

Sockeye salmon, Kijik Lake, Lake Clark National Park and Preserve.
Photograph by: Claudette Moore)

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Recommendations for future efforts

Natural Resource Technical Report NPS/SWAN/NRTR—2013/689

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Abstract

The Southwest Alaska Inventory and Monitoring Network monitors freshwater systems in five national park units: Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Lake Clark National Park and Preserve (LACL). To date, most of our efforts have focused on field testing and modifying protocols for water quality and hydrology monitoring on high priority lake systems. In this report we evaluate two aspects of water quality sampling collected from vertical profiles in Lake Clark National Park and Preserve. First we evaluated the ability of field sampling methods to produce precise measurements, and then we evaluated the efficiency of the sampling design for smaller lakes.

Water quality sampling was initiated in Lake Clark in 2008 and expanded to other lakes in the subsequent years. Sampling was conducted at ten sample sites in each lake basin (there are three basins in Lake Clark, and one in smaller lakes) using a multiparameter instrument (sonde) to record four water quality parameters (temperature, pH, dissolved oxygen, and specific conductivity). Sampling is conducted at 18 depth categories along the thermal gradient to a maximum depth of 50m. This method created ten vertical profiles of each parameter for each lake basin. Parameter measurements were recorded twice at each depth class, once when the sonde was descending, and again when it was ascending.

We used repeated measurements collected from each sample location in Lake Clark to evaluate measurement precision, and found statistically significant differences between repeated measurements; especially in measurements of pH. These differences were likely due to *in situ* equilibration protocols, and resampling procedure. We suggested changes to field protocols that will improve the quality of data obtained from lake sampling. We then evaluated the necessity of sampling all lakes with a minimum of 10 spatial replicates. We found that in small lakes with homogeneous basins, water quality estimates were well represented by a single measurement collected from near the center of the lake. Based on this outcome, we suggest using mid-lake sampling for small lakes with uniform lake basins. These changes will enable SWAN staff to improve data quality, and increase the sampling frequency for tier 2 lakes.

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We express our deep gratitude to Dan Young and Ginger Irvine, Lake Clark National Park and Preserve; Troy Hamon, Bob Peterson, Imes Vaughn, Jonathan Campbell, Mark Heiser and Vera Gilliland, Katmai National Park and Preserve; Dean Tucker, WRD; Chuck Lindsay, and James Walton, Southwest Alaska Network, for their continued logistical support and assistance in completing monitoring activities. We are indebted to the professionalism of pilots Allen Gilliland (KATM) and Leon Alsworth (LACL). Document review by Paul Burger and Jeff Shearer greatly improved earlier versions of this document.

Introduction

One objective of the Southwest Alaska Inventory and Monitoring Network (SWAN) is to monitor freshwater systems in five national park units: Alagnak Wild River (ALAG), Aniakchak National Monument and Preserve (ANIA), Katmai National Park and Preserve (KATM), Kenai Fjords National Park (KEFJ), and Lake Clark National Park and Preserve (LACL) (Figure 1). The goal of SWAN freshwater program is to document natural variability and to monitor for potential influences of large scale anthropogenic impacts, such as climate change, on large lake systems. One of SWAN's primary objectives is to monitor water quality and hydrologic parameters in large lake systems, including associated tributaries and outlets, to describe the current status and trends of limnological conditions.

The NPS Water Resources Division staff recommended that a set of core water quality parameters: water temperature, dissolved oxygen, pH, and specific conductivity, be measured in all NPS I&M Network park units as part of the national aquatic vital signs monitoring efforts (NPS 2002). These metrics were chosen for both their ecological significance and sensitivity to stressors (Shearer and Moore 2010). To date, much of SWAN's freshwater monitoring efforts have focused on protocol testing for monitoring these core water quality metrics. Specifically, methods were explored to document variability of core water quality parameters (e.g., temperature, pH, dissolved oxygen, and specific conductivity) during the ice-free season (May – October).

Water quality data collected along a vertical profile provide a snapshot of lake conditions in the upper water column during an index period defined as late July – August (Shearer and Moore 2010) when lake productivity is high and thermal stratification is most pronounced. Of the four parameters, water temperature is a dominant forcing factor affecting the three remaining core water quality parameters. It responds to seasonal ambient air temperature which provides stable and somewhat predictable annual and season ranges; however, it is also subject to sudden short-term temperature shifts associated with seasonal weather as noted in the results. Dissolved oxygen and pH values correlate strongly with temperature as well as productivity rates, resulting in variation with depth along the thermal gradient. Conductivity is a measure of a water body's ability to carry an electrical current and is predominantly controlled by the weathering rate of minerals and the presence of dissolved solids. Specific conductivity is a unit used to standardize raw conductivity values to a temperature of 25° C. Specific conductivity is the most stable of the four parameters along the vertical profile because it is a reflection of the entire watershed, and not dependent on depth, temperature, or light intensity.

The objectives of this report are to: 1) critically examine our protocols for collecting discrete core water quality samples using a multi-parameter instrument; and 2) evaluate the sampling intensity required to describe water quality at small lakes. We evaluated bias in field water quality sampling methods using the information contained within the descending and ascending measurements recorded at every sampling location. If measurements were unbiased, then we would expect that the differences between the descending and ascending measurements would not be different. We used simulations of 2010 data to evaluate the number of sample locations required to describe water quality within two Tier 2 lakes (Lachbuna Lake and Crescent Lake) in LACL. We then present recommendations to improve sampling methods based on the results of our statistical analyses.

Study Area

Lake Clark (Figure 2) is a glacially-carved oligotrophic lake that is 66 km long and 5–8 km wide (31,337 ha) with an average depth of 103 m, and a maximum depth of 280 m (Young and Woody 2007). It is located in the Kvichak River drainage in southwest Alaska. Six tributaries contribute the majority of runoff into the lake of which three are glacially fed, two are clear, and one is organically stained (Brabets 2002). Seasonal runoff from glacial tributaries is highest between June and September, which creates a turbidity gradient along the length of the lake. (Brabets 2002, Wilkens 2002). Lachbuna Lake (Figure 2) is a non-anadromous glacial system located in the Kijik River watershed. It has a surface area of 333 ha. The 1520-ha Crescent Lake (Figure 2) is an anadromous glacial lake located within the Crescent River system, which is in the eastern portion of LACL, flowing into the Cook Inlet.

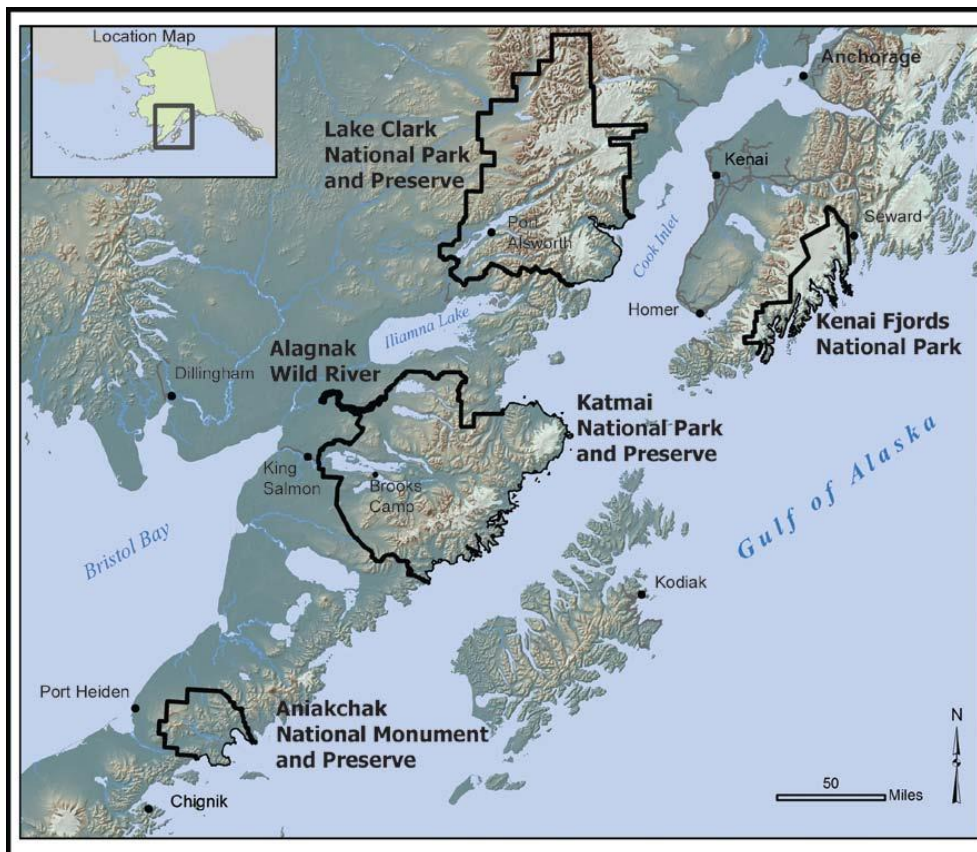


Figure 1 National Park units included in the Southwest Alaska Inventory and Monitoring Network, Alaska, USA.

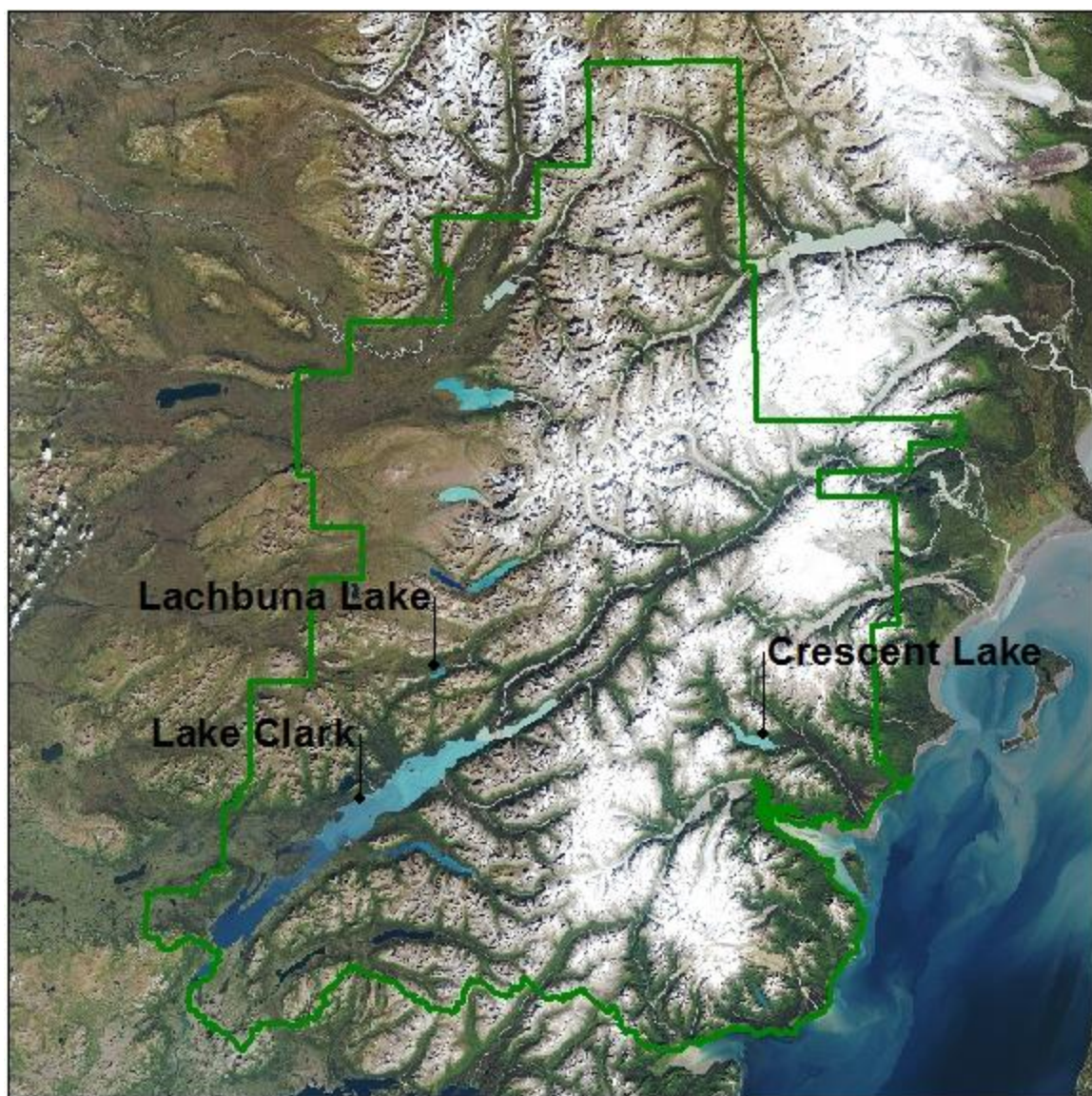


Figure 2. Study area in Lake Clark National Park and Preserve, Alaska, USA. Temperature, pH, dissolved oxygen, and specific conductivity were sampled in Lake Clark, Crescent Lake, and Lachbuna Lake.

Methods

Sample Design

The sample design proposed in the draft SWAN Freshwater Protocol identified a three tiered strategy in which high priority Tier 1 lakes were scheduled to be sampled annually, Tier 2 Lakes were scheduled to be sampled twice every ten years and Tier 3 lakes would be sampled once every 10 years. Table 1 shows the proposed sampling schedule for the lakes included in this report. The Tier 1 lakes such as Lake Clark were generally large complex systems, which required intensive sampling to understand water quality spatial and temporal variation. Tier 2 and 3 lakes were generally smaller and could be described with less sampling intensity. In 2009 water quality monitoring was fully implemented in Lake Clark, and was expanded to Tier 2 lakes in 2010.

Sampling locations were placed using general random tessellation stratification (GRTS) methods (Stevens and Olsen 2004). GRTS points were created in ARCMAP 9.2 by overlaying a 1 km² grid of cells on each lake. Points were placed within each grid cell using the GRTS algorithm (see SWAN SOP 2 for more detail). These points became candidate sample site locations. A 100 m edge buffer was applied prior to the grid analysis to excluded points in shallow areas of the lakes. The result was a list of randomly selected, spatially balanced sample locations for collecting lake profile data.

Ten sampling locations were placed in each lake basin. In order to account for spatial heterogeneity, Lake Clark was divided into three basins (upper, middle and lower) to consider the effects of the turbidity gradient so that 30 sample points were distributed across the lake. Lachbuna and Crescent Lakes each received ten sample locations. Lachbuna Lake was too small to fit 10 sample locations using the 1 km² initial grid, so the grid size was reduced to accommodate 10 sampling locations; as was the practice for all lakes that were too small to fit 10 sampling locations using the 1 km² grid.

Table 1. Initial sampling frequency for tier 1 and tier 2 lakes in Lake Clark National Park and Preserve, Alaska, USA.

Tier	Water Body	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10
Tier 1	Lake Clark	x	x	x	x	x	x	x	x	x	x
Tier 2	Lachbuna Lake	x	x								
	Crescent Lake	x	x								

Field Methods

Annual lake sampling was conducted between late July and mid-August defined as the index period when the thermal gradient is greatest (based on previous lake temperature monitoring). Water quality sampling for core parameters was recorded using Yellow Springs Incorporated (YSI) multiparameter 600 model sondes. Measurements of water temperature (°C), pH (unitless), dissolved oxygen (mg/L and % saturation), and specific conductivity (µS/cm), collectively referred to as core parameters were measured along a vertical profile from the surface up to a depth of 50 meters. Once the sonde was placed in water and readings equilibrated, core parameters were recorded on both the descent and ascent. Measurements were collected every meter from 0 m, to 5 m, and every 5 meters from 5 m to 50 m or the bottom, whichever was reached first. The repeated measurements were intended to evaluate the range of measurement error expected by using the instrument in difficult field conditions. Prior to field sampling, a series of calibrations and error checks for each metric were performed on each sonde. Post-trip error checks were conducted after each daily sampling trip.

Analysis of descending and ascending measurements

To test for sampling bias, we used descending and ascending temperature, pH, and dissolved oxygen data from 30 sample locations in Lake Clark collected in 2009-2011. All measurements from the 30 sampling locations in Lake Clark and 18 depth categories were included. We did not perform the analysis using specific conductivity data because there was little variation in the measurement.

Repeated measures analysis of variance (Proc GLM, SAS) was used to test the following two hypotheses regarding the descending and ascending data: 1) were the measurements of core water quality measurements recorded on the way down (from 0 to 50 m) different from those recorded on the way up; and 2) were descending and ascending measurements unbiased with respect to depth and site?. The direction by depth interactions were visualized using boxplots that were generated in program R (version 14.1.0).

Analysis of Tier 2 sampling intensity

We used a simulation exercise to estimate the number of subsample readings needed to represent the true value of pH. Crescent and Lachbuna Lakes were selected for this analysis because data were available at the time of the analysis. Ten sample locations in Lachbuna and Crescent Lakes were sampled during August of 2010. We chose to use pH recorded at 5 m depth as the variable of interest for this exercise, because analysis of vertical profiles from the previous analysis of Lake Clark showed that pH was quite variable, and the parameter most subject to recording error. The simulation exercise measured the total amount of variation expected to be observed from different numbers of subsamples of lakes with distributional parameters identical to those observed in the two lakes tested.

We assumed the within-lake variation of pH could be characterized by a normal distribution with a mean and standard deviation equal to that of the 10 samples recorded during the 2010 survey at each lake. With this assumption in place, we randomly drew 10 values from the 2010 distribution for each run of the simulation, to represent a virtual sampling event. We then sampled (with replacement) between 1 and 9 points from the 10 simulated values. The mean of each sample was used as the measure of pH recorded for each model run (nsim = 100), and for each sample size (1-9). The simulation was repeated 100 times for each lake, generating two 100-row by 9-

column matrices, where each row represented a single draw of 10 random values, and each column represented the mean of a sample that ranged in size from 1 to 9.

We compared the mean value generated from each simulation to the value recorded at the most central location of the lake. This was done because many lake water sampling protocols use only one reading taken from the geographic center of the lake (e.g. Goransson et al. 2004). We also displayed the overall variance described from the Monte Carlo simulations using boxplots. Simulations and visualizations were conducted in R version 2.14.0.

Results

Descending/ascending measurement bias

For all statistical tests we chose a conservative significance criterion ($P = 0.01$). We found that the mean differences between the descending and ascending data were small but statistically significant for pH in all years (Table 2). A significant direction by depth interaction was observed in all years (Table 2), indicating that the difference between the two measurements changed by depth. These results can be seen most clearly on the box plots for pH (Figure 3). The box plots also show that outliers and larger variances occur primarily on the downward trip of the sonde. Influential outliers were observed for many observations (Figure 3). These outliers are typically only recorded on one of the two measurement events (down or up), and are likely largely responsible for the significant differences between the depth classes. Outliers were left in for this analysis with equal weight to illustrate potential patterns related to use of the sonde to record data measurements. The plots also show directional bias between measurements (Figure 3), which illustrates the statistical direction by depth interaction.

There were statistically significant differences between the descending and ascending measurements for temperature in all years (Table 2). However, these differences tended to be very small ($\sim 0.10^\circ \text{C}$). The depth by direction interaction was only significant in 2009 and 2011 (Table 2). There were no significant differences in dissolved oxygen in all three years (Table 2), and by definition no significant depth by direction interactions in dissolved oxygen.

Table 2. Results from repeated Analysis of Variance test of measurement bias in Lake Clark National Park and Preserve, Alaska, USA. Comparisons test the difference between measurements recorded on ascending and descending trips of a multiparameter instrument.

Metric	Year	<u>Up and Down difference</u>		<u>Depth by Direction Interaction</u>	
		F statistic	P value	F statistic	P Value
Temperature	2009	66.98	< 0.0001	5.42	< 0.0001
	2010	93.33	< 0.0001	1.80	0.0370
	2011	206.70	< 0.0001	3.20	< 0.0001
pH	2009	2212.94	< 0.0001	34.59	< 0.0001
	2010	470.04	< 0.0001	3.35	< 0.0001
	2011	429.32	< 0.0001	35.62	< 0.0001
DO	2009	5.38	0.021	1.73	0.0478
	2010	0.39	0.533	0.95	0.5064
	2011	1.66	0.198	1.38	0.1607

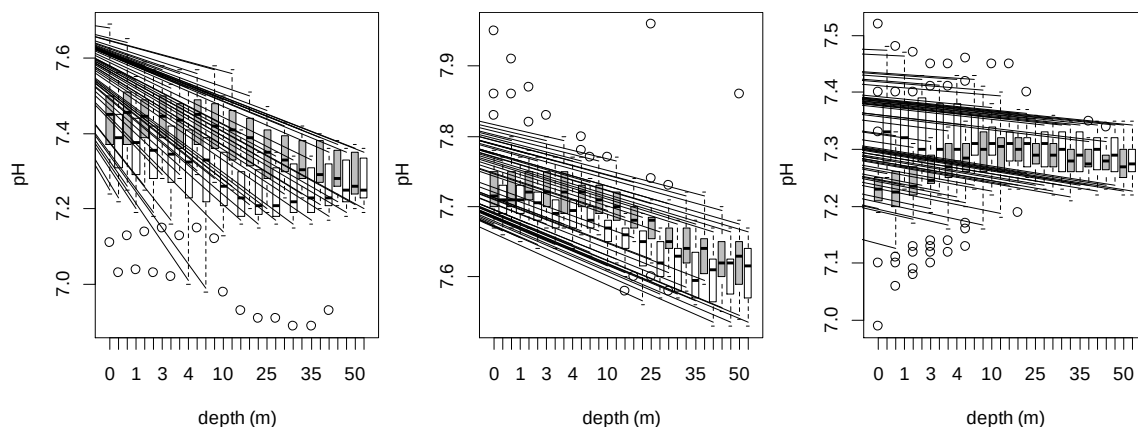


Figure 3. Box and whisker plots of pH measurements from Lake Clark in Lake Clark National Park and Preserve, Alaska, USA in 2009-2011. Measurements were made at 30 sites in Lake Clark with a multi-parameter sonde at each of 15 depth classes. The pH was recorded on the way down (shaded box), and again on the way back up (white box). Each box shows the inter quartile range (IQR), and whiskers denote $1.5 * IQR$. Open circles denote outliers.

Tier 2 sampling scheme

The mean pH based on 10 readings was 7.67 (SD = 0.0135) and 7.15 (SD = 0.075) for Lachbuna, and Crescent Lakes, respectively. It is not surprising that the overall variation for Crescent Lake was slightly higher than Lachbuna Lake because Crescent Lake is larger. Examination of the histograms generated by the 10 readings in each lake shows little evidence of normally distributed error structure (Figure 4), but the mean and median were virtually identical (red and blue lines in Figure 4), which is expected from normally distributed data. Of interest is that the value of pH obtained from the sample point closest to the center of the lake was similar to the measures of central tendency obtained by all ten readings in both lakes (Lachbuna = 7.68, and Crescent = 7.15).

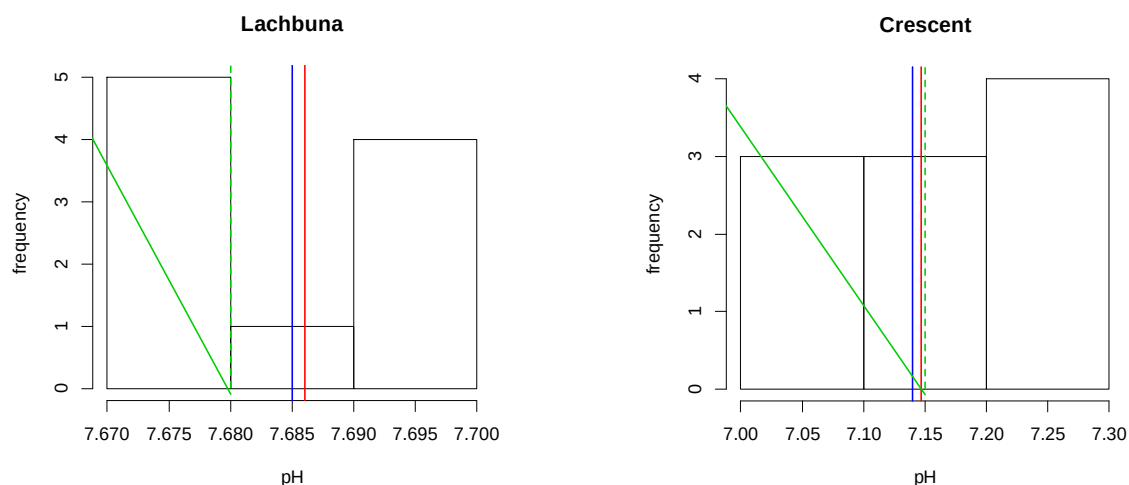


Figure 4. The histograms represent the distribution of 2010 readings of pH at 5m depth from Lachbuna and Crescent Lake, Lake Clark National Park, Alaska, USA. The red and blue solid lines represent the mean and median of the 10 readings, and the green dashed line represents the reading from the sample point closest to the center of the lake.

The interquartile range of pH estimates for both lakes was contained within the 95% confidence interval of the 2010 sampling occasion for sample sizes ranging from 2 to 9, and within the first standard deviation for all sample sizes (Figure 5). All but the most extreme estimates of pH from all sample sizes fall with 2 standard deviations of the mean (Figure 5). It was expected that the total variation present in the sample would be reduced as the number of subsamples used to generate the estimate increased. Percent coefficients of variation of the estimated means for all sample sizes were less than 2 for both lakes (Figure 6), indicating high precision in measurements regardless of the number of subsamples taken. There was little precision to be gained from sampling more than 2 (Crescent) or 3 (Lachbuna) subsamples (Figure 6).

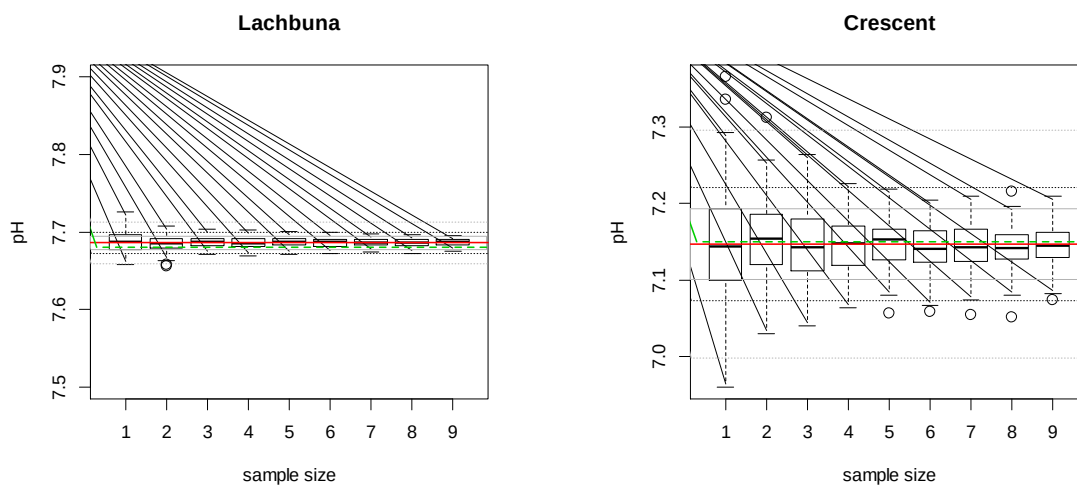


Figure 5. Boxplots of simulated parameter estimates of pH generated from 100 simulations of sampling of two lakes in Lake Clark National Park, Alaska, USA. The Box plots summarize results from 1 to 9 random samples per sampling event in two lakes. The green dashed line represents the value drawn from the sample point closest to the center of the lake. The shaded box represents the confidence interval generated from the 2010 sampling occasion. The red line indicates the mean pH from the 2010 sampling. The black and gray dashed lines represent the 1st and 2nd standard deviation (respectively) from the 2010 sampling occasion.

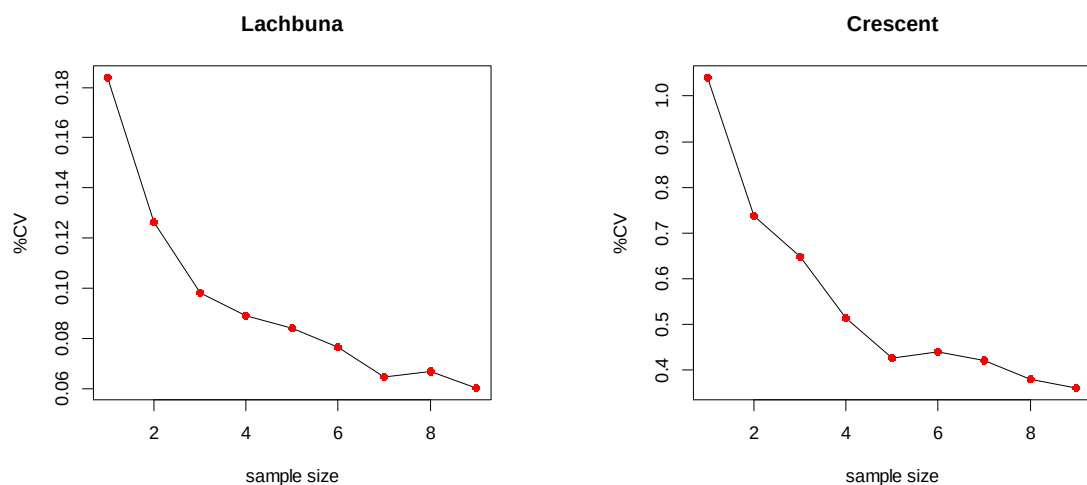


Figure 6. %CV of simulated parameter estimates generated from 100 simulations of sampling of two lakes in Lake Clark National Park, Alaska, USA. Percent CV was presented for back-transformed model output (pH) because pH is the unit of interest for change-detection. In doing this the values of the %CV were changed, but the shape of the curve was not. Using raw numbers, %CV for Lachbuna ranged from 3 to 1, and Crescent Lake ranged from 19-7 (3 points are necessary for %CV <3).

Discussion

Using existing data

We found statistically significant bias in the descending data, especially for pH. Variance was typically larger in the downward measurements, suggesting a problem with either field technique, multiparameter instrument equilibration, or both. The differences between the measured values were not large, but the results indicate directional drift, and therefore room for improvement in our field protocol. The directional biases observed are non-random, suggesting that the median of the ascending and descending measurements may be a poor representation of true values. Therefore, when using the 2009-2011 vertical profile data for future analysis, we suggest using only the ascending data, rather than the mean of the ascending and descending data. This will cause subtle changes in water quality values compared to those that were published previously, but will more closely reflect the true values.

Field sampling methods and protocol

Improved field practices will ensure high-quality data collection. Lakes in southwest Alaska tend to be cold, and have low ion concentrations. These are difficult conditions for automated probes. We suggest that the sonde should be placed in a bucket of lake water and left in run mode between sampling locations. This will allow the sensors to properly equilibrate to the cold, and low ionic conditions present in most lakes, which should improve the accuracy of measurements, especially pH. Upon arrival at a sampling location, the sonde should be lowered to a depth of 5 meters and left to equilibrate *in situ* for five minutes prior to sampling. After five minutes, sampling should begin at the surface, and continue to a maximum depth of 50 m.

Of course variation in field measurements can come from various sources. While our data supports the idea that field practices contributed to observed measurement bias, calibration practices could also contribute. Therefore, changes to the pre-field calibration protocols will improve the quality of the vertical profile data. Calibration practices would be improved if prior to sampling, sondes were calibrated using temperature corrected pH standard. Field personnel began doing this in 2010, but it was never applied universally until 2012, likely contributing to some of the variation observed in the descending and ascending data.

Errors associated with recording and archiving data could also contribute to the types of variation observed in our analysis of data from Lake Clark. Vertical profile data should therefore be reviewed in the field by technicians to identify any anomalies in the data. Displaying raw data in the field will provide some indication of how well the meter is performing. In Lake Clark where multiple samples are collected, vertical profile data should be compared between sites for consistency. Although some variability is expected due to the complexity of the lake, vertical profile data across sample locations is expected to be relatively homogeneous in a given year. If feasible to do so, mid-day calibration checks can also be performed using a known multiple parameter solution, as suggested by USGS (2005, chapter 8.6). Field personnel should also note any problems or irregularities observed during sampling (e.g. the sonde contacts the lake bottom) so that data can be censored before they are entered into the database. The vertical profile data should be

reviewed, graded and certified by field personnel as they are entered into the AQUARIUS database. All missing data should be entered and notated as such. This should be done by field personnel because it is difficult for data analysis staff to know if widely deviant readings are real, or a result of measurement error.

Replicate sampling requires that both transect measurements occur in the same direction (USGS 2005, Chapter 6.8). From 2009-2011 in Lake Clark, replicate measurements were made along transects in opposite directions without repeating the equilibration protocol in between. While the repeated measurements taken from the descending and ascending sonde readings allowed us to assess bias in our observations, they did not represent a true replicate measure of a complete sampling cycle. This weakness should be remedied in future quality assurance assessments. In the future, repeated samples should represent an entire sampling cycle from arrival at the sampling location to completion. In other words, after the initial vertical profile reading is completed, the sonde should be returned to the bucket of lake water used during transit between sampling locations for at least five minutes before repeating an entire sampling cycle at the same location. Conducting replicate samples in this manner is time consuming, so we recommend sampling a subset of sites up to three times using the revised methods. This way, the precision and bias of the new methods can be evaluated. If there continues to be significant bias, alternative methods should be explored.

Tier 2 lake sampling

Our statistical simulations suggested that it was unnecessary to sample ten sites at some Tier 2 lakes. The gains in precision expected by adding additional data points decreased dramatically after sampling at three locations in the largest lake. Further, the expected coefficients of variation derived from sampling even one site were small compared to other ecological datasets. Mid-lake sampling has been shown to be representative of overall lake condition (Goransson et al. 2004) and provides a cost effective method for collecting data from lakes in remote areas. In 2010 the measurements recorded from the center of both Crescent and Lachbuna Lakes were very similar to the means and medians of the ten recorded sampling locations lending support this idea. Our analysis was based on just 2 lakes for which data were available at the time of analysis. This a small sample size, and may not be representative of all Tier 2 lakes. There could be significant spatial variation in water quality parameters for larger lakes, or lakes with heterogenous basins. Based on these results, we cautiously recommend that future sampling in SWAN tier 2 lakes be conducted at one mid-point site. In larger tier 2 lakes, additional sites may be sampled to ensure that the sample locations reflect the overall water quality within the lake.

Conclusions

Our analyses showed that there were opportunities for improvement in both field protocols and data collection efficiency for lake vertical profile sampling carried out by SWAN. Changes to the calibration, sonde transportation, and equilibration methods will improve the quality of the data collected, and reduce bias apparent in data analysis. In addition to improving data quality, changes to quality assurance protocols should streamline sampling effort, and reduce the overall cost of vertical profile sampling in the large Tier 1 lakes.

Similarly, changing the number of sample locations required for small lakes provides an opportunity to revise the original sample design for those lakes. The gains in efficiency with the revised sampling protocol will allow us to: 1) redefine the sample units and statistical population to be studied; 2) improve statistical inference by adopting a randomized sampling scheme; 3) increase the sample size to be more inclusive of all lake types in SWAN park units; and 4) control for confounding effects of latitude and location by sampling from every park unit every year. Our revised sampling scheme will also allow us to revise the questions addressed by sampling the tier 2 lakes, such as: how do anadromous fish runs affect lake water quality; Are water quality dynamics affected most by basin morphology, geology, or climactic factors? These improvements will allow SWAN to insure that vertical profile sampling occurs on a time schedule that is useful to park managers and leads to important ecological insights.

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