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Calibrating annual sedimentation in a glacial lake
Lake Linné, Svalbard, Norway

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Introduction

The advent of climate change throughout the next century makes it critically important to study and understand current environmental patterns for a better understand of the consequences of recent climate variations (IPCC, 2007). The Arctic is considered an ideal location to study contemporary climate change due to the natural systems that enhance the effects of climate change in these high latitude areas (Fig. 1) as well as the untouched and anthropogeneticly isolated character of these areas.

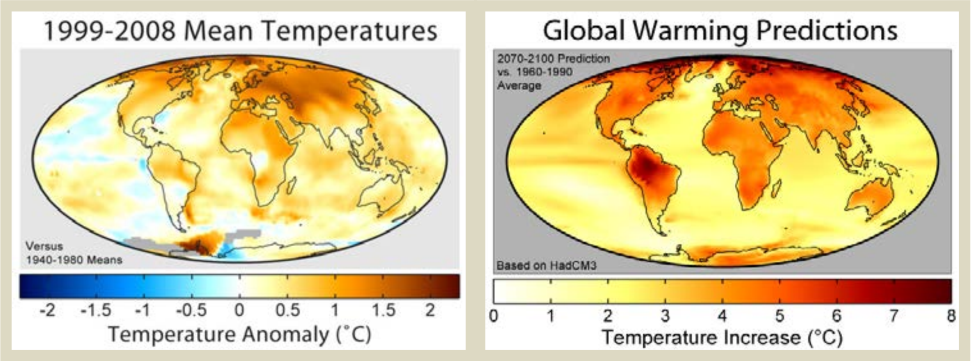


Figure 1. The Arctic is considered an important location to study contemporary climate change due to the natural systems that enhance the effects of climate change in these high latitude areas. Note the increased projected warming of the Arctic. (IPCC, 2007)

Sedimentation in Arctic lacustrine environments is dependent on the characteristics of the surrounding watershed. The winter snowpack, precipitation, and in glacial systems, and the amount of glacial ablation, govern the volume and timing of sediment laden water that is deposited in the lake environment. Arctic lakes are subject to seasonal sedimentation patterns which consequently lead to the formation of varves. Conventional belief suggests seasonal varves consist of couplets, two distinct layers that represent high-flow, high-energy summer events and calm, low-flow winter environments for sediment deposition (Ashley, 2002; Richards, 1982). In reality these annual couplets are complicated by sediment availability, lake currents and timing of seasonal precipitation.

On a seasonal scale, glacial regimes, precipitation events, lake currents and sediment availability will govern the sediment supply present for transport and deposition throughout the year. Consequently, studies in High Arctic environments focus chiefly on modern sedimentation patterns with the ultimate goal of interpreting the paleo-climate environmental conditions. Complicating the varved record however, are sediment characteristics of the contributing watershed as well as the timing of the deposition due to regional weather patterns.

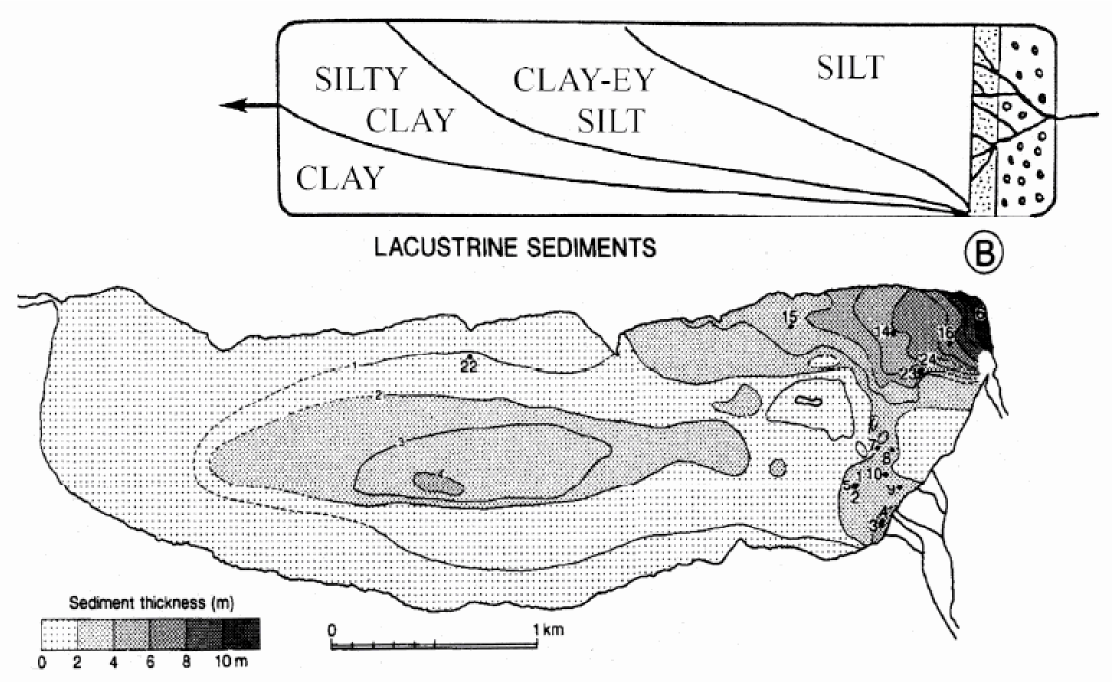


Figure 2. The lacustrine sediment thickness in Lake Linné. Notice that the sediment thickness is deeper in the southern end of the lake near the inlet for Linné River. Note that thickness also contours the eastern side of the basin. Sediment grain size likely follows the trend in the top illustration. Figures from Smith & Ashley (1985) and Svendsen (1989).

Lake Linné is a glacier-fed lake in Svalbard, Norway. Year after year sediment is introduced to the lake and deposited on the bottom. The estimated volume of sediment that fills the Linné basin likely encompass the past 9,000 years of annual deposition (fig. 2) (Magerud & Svendsen, 1990). In order to thoroughly understand the vast record held within Lake Linné, the Linné valley environmental system has been monitored in great detail. Many studies of stratigraphy, composition, and grain size of seasonal deposition from lake cores have been scoured and compared to weather data and other environmental conditions (McKay, 2004, Motley, 2006, Roop, 2007, Corbin, 2008).

Past studies in arctic lake environments have determined that seasonal varves indicate characteristics of annual climate and weather within the watershed of the catchment basin (Leeman & Niessen, 1994, Magerud & Svendsen, 1990, Snyder et al, 2000). In this way, the sediment record is called upon as a proxy for climate realities. The purpose of the following study is to continue this record by conveying contemporary sedimentation characteristics in the High Arctic system of Lake Linné, Svalbard, Norway.

This study will focus on the most recent depositional year, fall 2010 through summer 2011. The study is a continuation of previous projects and investigates modern sedimentation in Lake Linné in order to formulate a relationship between sedimentation and environmental climate variables. Not only was the amount of total accumulated sediment anomalously low during last season, but the proportions of sediment attributed to fall deposition and the spring melt season were unconventional. Sediment varves from the most recent atypical depositional year have the potential to complicate the extensive varve record. Misinterpretations of seasonal varves may therefore convolute the record of past environmental conditions, thus a clear understanding of this contemporary record is essential to correctly interpreting past High Arctic climate conditions.

Location

The Arctic is commonly defined as the land above the Arctic Circle, which encompasses the area above 66°N. As a result of high latitude, the Arctic receives heightened amounts of solar radiation and is distinctly affected by climate variation. The island of Spitsbergen lies in the Norwegian archipelago of Svalbard, located within the Arctic Circle between 74° and 81° north and 10° to 35° east (fig. 3). The group of islands is surrounded by the North Atlantic Ocean and is on average 60% glaciated (Ingolfsson, 2004). On the western coast of the largest of the islands, Spitsbergen, Kapp Linné protrudes and is bordered to the north by the main fjord of Isfjorden that flows into the Atlantic. There is a research and radio relay station located on Kapp Linné that serves as a base for science expeditions. The glacial valley study area is 5 km east of the Isfjord Radio base station, within the Linné valley.

It has been suggested that subsequent to the Late Weichselian glaciations, the Linné valley became a fjord roughly 9000 years ago (Mangerud et al 1992). The Linné valley remained a freshwater tributary of the main fjord, Isfjorden, until becoming isolated as a result of the formation of a marine terrace due to long shore drift (Mangerud & Svendsen, 1990). Besides long shore drift, isostatic rebound as a result of deglaciation has also been noted as cause for the isolation of the Linné valley. Over all, the relative sea level for the Linné valley area has dropped 60 m over the past 12,000 years (Sandahl, 1986).

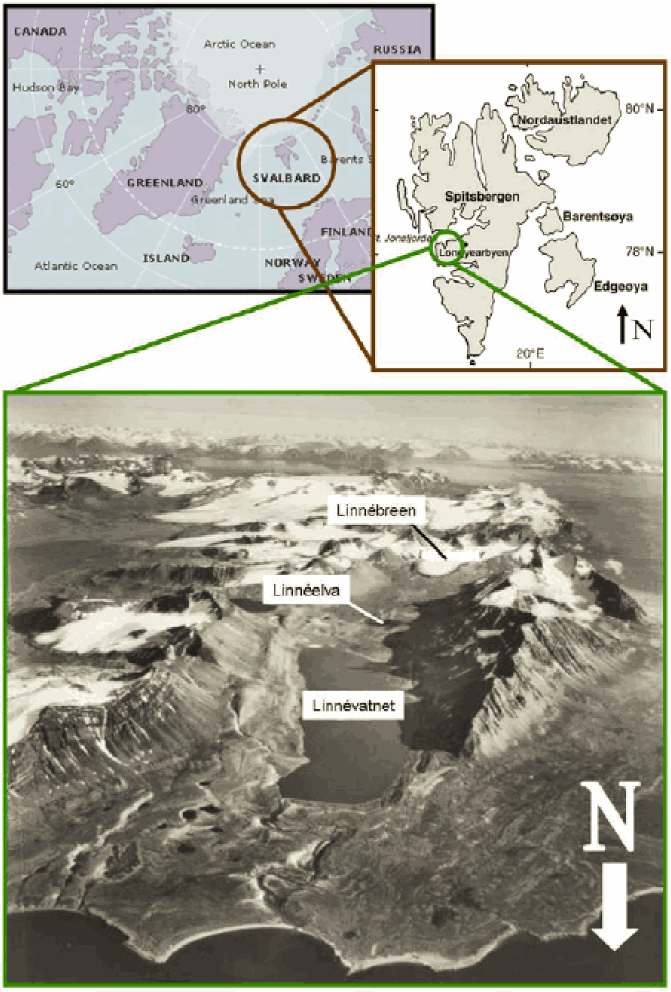


Figure 3. Simplified from Corbin 2008 (Oblique aerial Courtesy of Norsk Polarstitutt).

Within the Linné valley, roughly an hour's walk from Isfjord research station, Lake Linné occupies the regional topographic depression (fig. 4). The deposition-laden lake measures about 1.3 km wide to about 4.7 km long (McKay, 2005), and is oriented roughly north-south, bounded by steep glacial valley walls to the east and west. On average the lake is roughly 12 m above sea level (McKay, 2005). During the arctic winter, from September to July, the lake is completely capped by ice. When the lake surface is exposed, wind occasionally promotes significant turbulence, generally from the northerly or southerly directions since the substantial valley walls protect against wind from the east or west.

At the southern-end of the lake, the primary inflow stream feeds freshwater into the lake system. The inflow stream is perpetuated by melt from the up valley glacier, though is spiked by local rain events, karst drainage and seasonal melting of snow pack on the surrounding landscape. Arnold (2009) and others have suggested that changes in gradient allow the stream to act as a sediment storage area, since the braided plain section of the stream may act as alluvial storage. The effect of this storage is not confirmed, however may play a role or help explain seasonal fluctuations in sediment volume that is delivered to the lake.

Linné River drains a 27 km^2 watershed, melt water and sediment from every corner is collected and channeled into Lake Linné. Once in the lake, the extraneous water may interact with any one of the three main bathymetric basins, the deepest of which is 37m (McKay, 2005) and is most distal to the inflow channel. Within each of the three basins, marine sediments underlie lacustrine sediments, a signature of the areas geological, environmental and climatic history (McKay, 2005). The thicknesses of sediments throughout the lake vary, though thickens toward the inflow stream (McKay, 2005). According to previous work on sedimentation over the last 10,000 years in Lake Linné, the average depositional accumulation range from 0.1 to 1.0 mm/year (McKay, 2005). The laminations inherit in annual deposition indicate the sediment record is seasonally driven, therefore reflects erosion rates and sediment transport.

The location of Svalbard in the arctic and the weather patterns that affect the archipelago create a polar desert ecosystem. Snow is the dominate type of precipitation, precipitation on the order of 200 – 600 millimeters w.e. (water equivalency) can be expected per year (Ingolfsson, 2006; Arnold, 2009). As the hydrological melt season begins, albedo decreases concurrent with decreasing snow on the landscape. This effect promotes further heat absorption by the ground surface in a positive feedback manner, accelerating further melting of the subsurface active layer and ambient snow (Kane et. Al, 1993; Arnold, 2009). Sedimentation into arctic lake environments such as Lake Linné varies directly as the amount and timing of precipitation fluctuates, thus arctic lake sedimentation is very sensitive to regional climate patterns.

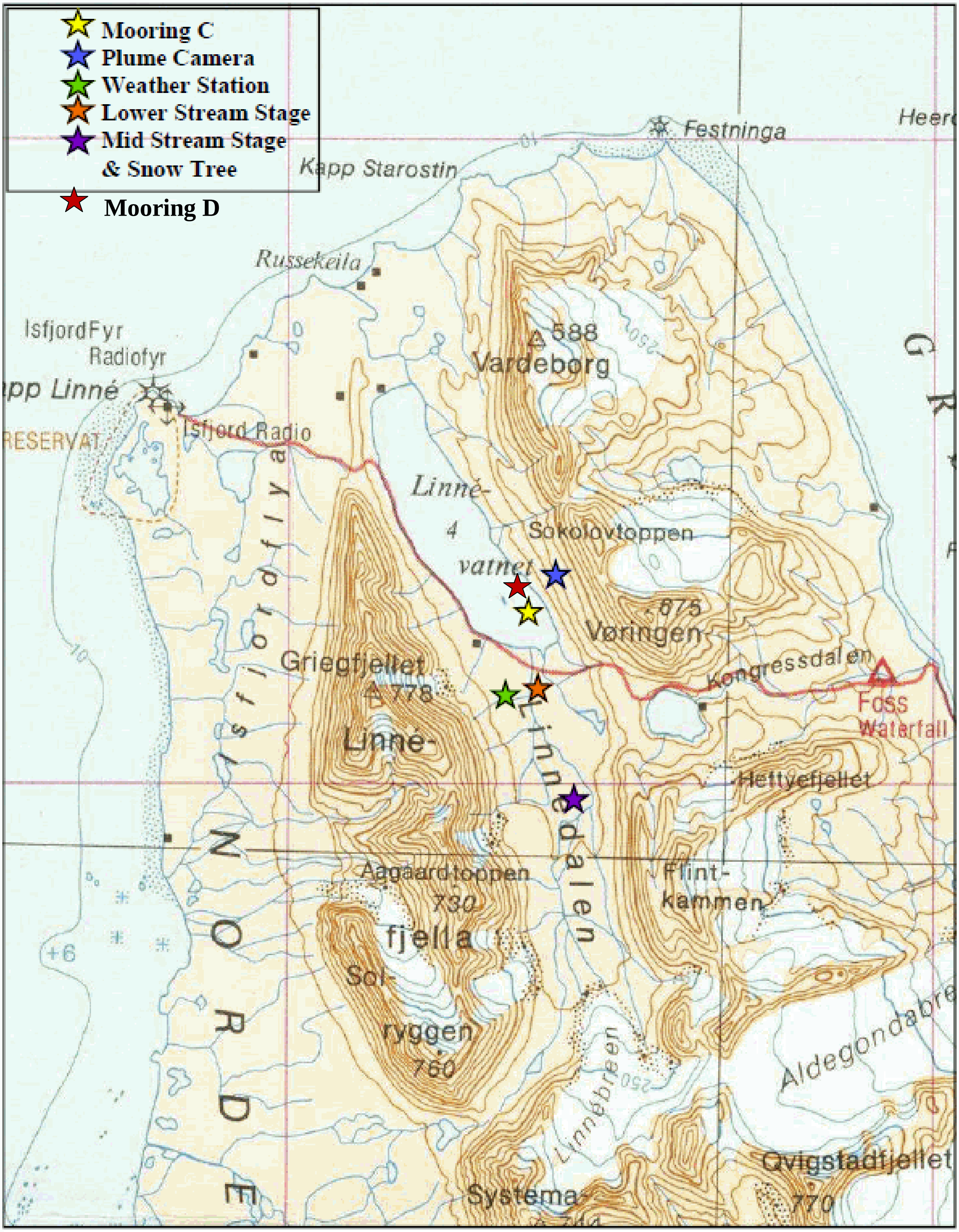


Figure 4. Location map for all environmental monitoring stations including mooring sites, weather stations and plume cameras. The map itself is a 2004 Norsk Polar Institute map of the study region showing Lake Linné, the Linné river, and finally the Linné glacier. (From Motley, 2006)

The water column of Lake Linné can be effectively studied by isolating the various characteristics of the lake, such as density, temperature or conductivity. For the subsequent review, temperature of the inflow stream will act as a proxy for density of extraneous water introduced into the water column. The lake temperature varies from the surface to the bathymetric basins; Smith and Ashley (1985) suggest this is a result of solar heating and heat transfer and circulation. In this way the surface water and bottom water are stratified based on temperature gradations and corresponding densities.

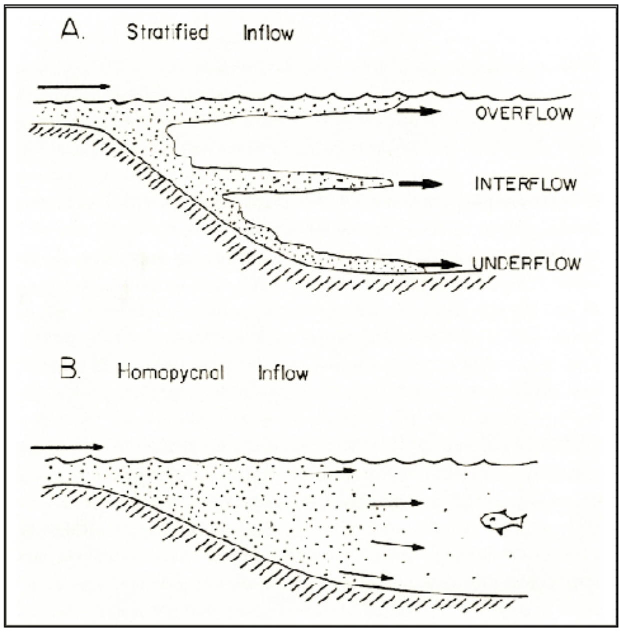


Fig 5. Depiction of the four types of inflows which depend on relative densities between inflow water and water column density. (Smith & Ashley, 1985)

The effect of temperature variation in the water column determines how input from the inflow stream will interact with the lake. Smith & Ashley (1985) and others propose the density of both waters play an important role in how they will ultimately mix depending on the temperature, conductivity and sediment volume entrained in the inflow plume. The conventional understanding is that density of the inflow stream water will promote an overflow, underflow or homopycnal flow (fig. 5). Inflow fluxes that are less dense then the lake water will travel over the lake surface as an overflow. Water from the inlet plume that is more dense then the water column will plunge under the water column and travel along the bottom of the lake as an underflow. Likewise, and interflow occurs if the inflow water is less dense then the bottom water but more dense then the surface water. Finally, a homopycnal flow will occur if the water column density and the inflow stream density are equivalent. In this scenario both water masses will mix and the extraneous water will disseminate throughout the water column.

The distribution of water inflow is also governed by environmental factors. The flow of the plume is affected by wind and waves as these factors generate temporary current flow patterns (Smith and Ashley, 1985). Similarly, the eastern side of Lake Linné may experience more sedimentation and plume deposition because of the Coriolis Effect that deflects sediment-laden water and currents to the right as a result of the Earth's rotation (Smith and Ashley, 1985). As a result of currents and plume movement in the Lake Linné water column, suspended sediment supply settle out differentially. The fine grained sediments increase with distance from the inflow stream, whereas coarser grained sediments “fall-out” of the water column more proximal to the southern inlet (Svensdsen et al 1989). In this fashion the sediment thickens across the lake bottom closer to the inflow stream and likewise the average grain size also increases (fig. 2).

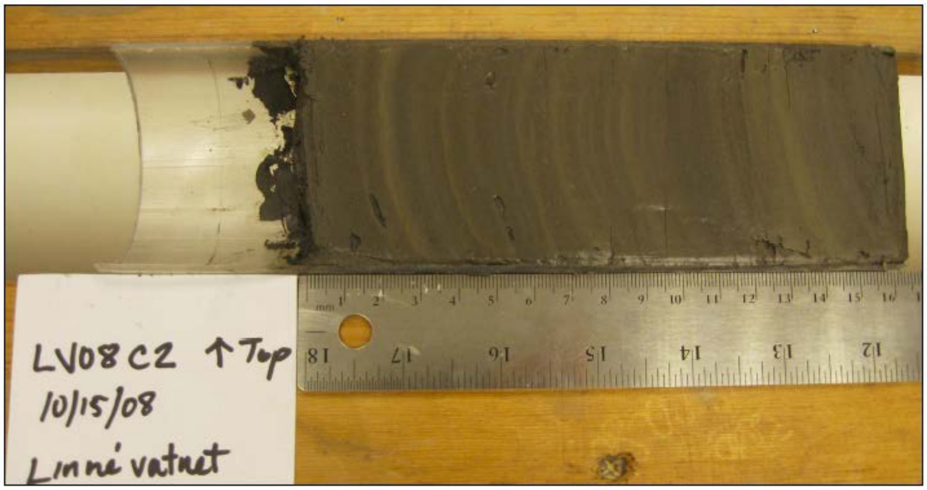


Figure 6. Preservation of seasonal sediment deposition in Arctic proglacial settings form varved sediments. This sediment core was recovered from Lake Linné in 2008 (Arnold, 2008).

As eluded to above, sedimentation in Arctic lakes preserve unique characteristic called varves (fig. 6). These varves are laminated duel couplets that record annual sedimentation. Conventional understanding suggests varves can be divided into two layers, a summer and winter layer distinguishable by average grain size (Strum, 1979; Arnold, 2009). The coarser silt and sand particles are attributed to summer deposition while the finer grained clay sediments indicate winter sedimentation

(Smith and Ashley, 1979). Just as tree rings can be counted as a proxy for the passage of time, the annually deposited sediment varves record seasonality in the past. Moreover, the characteristics of the varves express environmental conditions at the time of deposition, precipitation and temperature being to more informative (Leemann & Niessen, 1994). Since varve characteristics allow an annual resolution reconstruction of sedimentation, it is critical that a detailed understanding of the sedimentary response to environmental parameters in the watershed is attained in order to regenerate a high resolution record of past arctic climate.

Methods

In order to better understand the seasonal deposition within Lake Linné, this project implemented and analyzed simple plastic funnels with attached receiving tubes to intercept suspended sediment introduced from the inflow stream as it descended through the water column. A total of nine sediment traps were recovered during the 2011 summer field season, including those traps left suspended for the entire years are well as those deployed for the collection of the spring melt. The visual stratigraphy for each was documented with a photograph, later the samples were analyzed for grain size using specialized equipment, a Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyzer located at Bates College in Lewiston, Maine. The subsequent section chronicles the field and laboratory methods.

Mooring/ sediment trap design

Moorings with sediment traps and temperature loggers were deployed during the 2010 field season into the lake basins. Mooring C was located most proximal to the inflow delta at a depth of around 15 meters. Mooring D was located just northeast of mooring C, within the eastern side basin, suspended in 15 meters of water. There is a bathymetric high that “separates” the east and a west basin in the southern half of Lake Linné, Mooring E presides over this ridge suspended in only 5 meters of water. Mooring F was deployed in the southwestern side of the lake while mooring H was placed fairly central to the lake in 33 meters of water. Lastly, mooring G was the most distal to the inflow stream in approximately 35 meters of water (fig. 7).

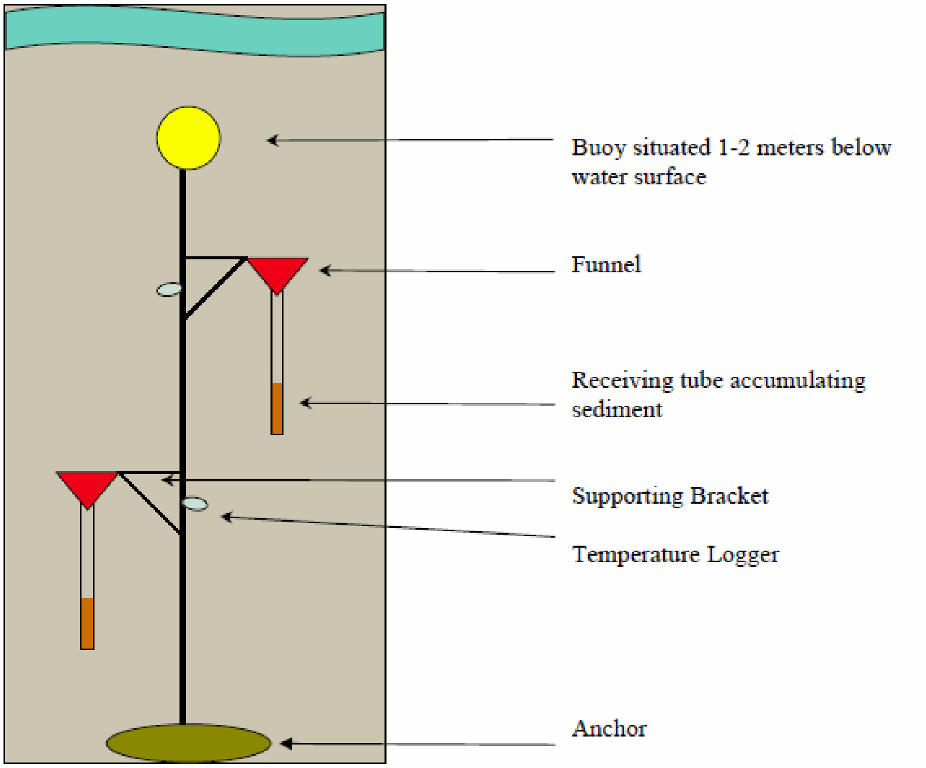


Figure 8. Diagram of mooring set up. The overall number of traps depends on the depth of the water at each location around the lake (Arnold, 2008).

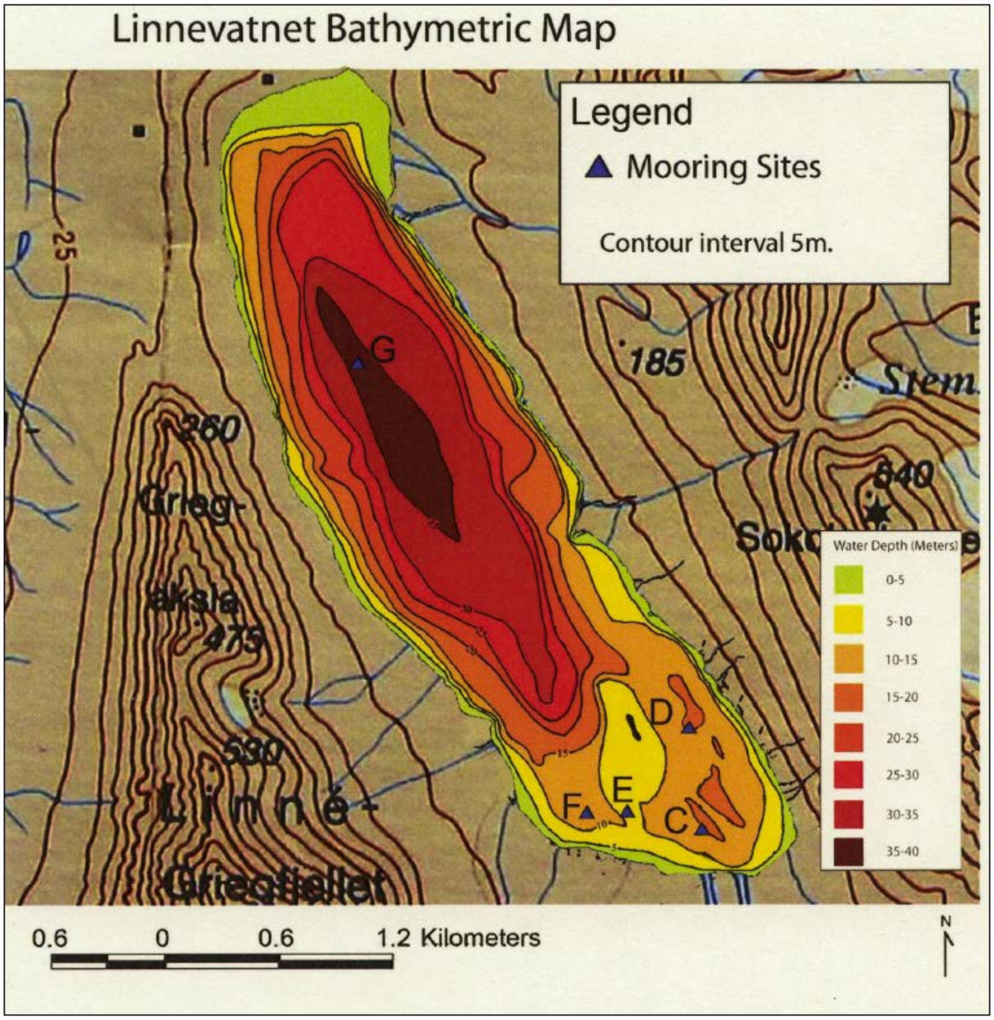


Figure 7. This bathymetric map of Lake Linné delineates the three basins into which the mooring lines are deployed. (McKay, 2005).

Each of these moorings are designated as “year-long” traps and remained suspended in the water column until they were retrieved during the week of July 13th through July 21st, 2011. Similarly, separate moorings that were deployed at mooring C, D and H before the spring melt season were recovered within the same time interval in July. These moorings are designated as “spring-traps” and were deployed while the lake was still caped with ice. The difference between the two trap designs are their funnel dimensions. The year-long traps use funnels with a diameter of 10.16 centimeters while the spring traps have a diameter of 20.23 centimeters. Deploying the spring traps provides a tentative timing and volume gauge for the spring melt season when compared critically to the year-long sediment record.

From the bottom of the lake to the surface, the mooring lines consist of several distinct parts (fig. 8). A large rock anchor acts as the holdfast for the contraption, attached to the rock is a nylon line and a buoy. The line is kept vertical because of the buoy, though it is important to note that the buoy does not breach the lake surface. Annual wind and ice action at the interface between Lake Linné and air could negatively disrupt the sediment traps and temperature loggers that are attached to the nylon mooring lines if the buoy extended to the surface. Depending on the depth of the lake, between 2 and 5 sediment traps were attached and deployed on the mooring lines. Regardless of the total number of traps on the line, the first trap was attached 1 meter above the lake bottom. Along with sediment traps, each mooring also had a network of Onset HOBO loggers that recorded temperature. Attached above the plastic sediment trap bracket, a logger was placed at every meter of depth.

The design of the sediment traps has changed and been improved upon after each subsequent field season. The most recent and most efficient design consists of a plastic funnel to collect settling sediment. The spout of the funnel is secured into a polycarbonate receiving tube attached for collecting the accumulating sediment. The bottom of the receiving tubes is sealed with an efficient cap to prevent any leakage and loss of sediment. Covering the top of the plastic funnel is a baffle array of 1 cm squares to protect against re-suspension after the sediment had settled in the receiving tube (Knight, 2011). Finally, the whole system was attached to the mooring line at specific intervals with a plastic bracket necessary to support the trap and keep them vertical for the sedimentation year.

A GPS as well as radio antenna signals were used to locate the different mooring around Lake Linné. Once sited a chain was suspended below the motor boat, wrapped around the buoy and used to pull the mooring into the craft. As each sediment trap breeched the lake surface it was detached from the mooring and carefully situated vertically so as not to disturb the accumulated sediment. Later the same day after all sediment had settled any visual stratigraphy was photographically documented and the height of the accumulated sediment marked on the receiving tube. The attached funnel was then removed and a corresponding cap to the ones at the bottom of the receiving tubes was placed on the top for the duration of the commute back to Isfjord base station.

Once back at Isfjord base station, the caps were removed and the remaining water in the receiving tubes was siphoned out. The receiving tubes were then cut a few centimeters above the sediment and allowed to dry even further next to a heater. In order to remove as much of the 'standing water' from the surface of the sediment, paper towels were used to wick water away leaving the accumulated sediment in the receiving tubes slightly moist. For transportation, paper towels were stuffed into the traps to preserve the sediment and protect against mixing and shifting.

The environmental climate data for the Linné valley was recorded by Onset HOBO weather station and level logger technology. The main weather station is located roughly a kilometer up valley from Lake Linné, there is another weather station located at the top of the Little Ice Age moraine even further south and another on the glacier at the highest altitude. The main weather stations measures precipitation, wind speed and direction, solar radiation, ground temperature and air temperature. The amount and duration of precipitation as well as air temperature are the most important records as they most directly affect the glacial melt and fluvial systems, thus tributary stream discharge, and consequently the amount and timing of possible sediment influx into Lake Linné.

The In-Situ Incorporated 9000 Pro XP/e Troll was deployed at mooring site C, just a meter above the lake bottom. This instrument recorded temperature, conductivity, turbidity and depth for the spring melt season. Once calibrated with variation in barometric pressure, this record produced a characteristic picture of the lake level for the year.

Another instrument deployed approximately one meter above the lake bottom at mooring C was the intervalometer. This instrument, like the sediment traps, has a 10 cm funnel covered by a 1cm^2 baffle array that concentrates sediment into a receiving tube. The distinctive feature of the intervalometer is its ability to measure the rate of sedimentation through the use of light transmission (Arnold, 2009). The instrument works via an inverted Schmitt trigger, when the LED lights can beam through the receiving tube without being disrupted the trigger is on. Conversely, when the light source is blocked and the lights can no longer beam unimpeded through the receiving tube due to accumulated sediment, the trigger is switched on. Over time more and more of the LED lights are blocked as a result of sedimentation, as the vertical thickness increases so does the subsequent voltage from the instrument (Arnold, 2009).

The inflow river into Lake Linné was also closely monitored. Onset Optic Stowaway temperature loggers were deployed and recorded inflow temperature. This temperature record is a signature of extraneous inflow water when analyzing currents in Lake Linné. The loggers themselves were attached to rocks and placed in the deepest parts of the river to capture a record of annual river temperature.

Deployed at two separate locations within the valley were unique contraptions to measure snow depth. The contraption stands 1 meter tall and is adorned with “branches” in the form of horizontal dowels. Each “branch” is 10 cm above the previous one, starting at 10 cm from the ground and alternating sides till 100 cm. At the end of each “branch” an Onset HOBO temperature logger was attached and recorded temperature and solar radiation at set intervals of time. When the snow would fall and begin to accumulate, the loggers would in turn become buried. First the 10 cm logger then 20 cm, all the way up to the 100 cm logger that would indicate that the snow had accumulated over 1 meter in the valley. As one can imagine, variations in the record are a result of rapid snow accumulation followed by settling and melting between precipitation events, then more accumulation. These “snow trees” are interpreted as proxies for snow accumulation and volume in the valley as well as the timing and volume of melt water introduced into the river system and thus into Lake Linné. A parallel study by Mount Holyoke College student, Taylor Bennett, explores and analyses the snow tree data in greater detail then in this analysis.

The most captivating and visually stunning environmental data was recovered from the automated time lapse camera situated on the eastern slopes of valley facing south – southwest, overlooking the delta where the inflow river empties into Lake Linné. The camera captured two images a day, one in the morning and one in the afternoon, which when strung together; provide a perceivable record of hydrologic activity within the valley.

Results

Year-Long Sediment Traps

D4 Trap Data – Mean (fig. 9A)

Starting from the bottom of Trap D4, the mean grain size begins at 10 microns and slightly increases over the first 3.5 centimeters to 13.6 microns. Three points over the interval from 0.75 to 1.25 cm had drastically uncharacteristic grain sizes and have been indicated as red data markers. Similarly two data points (at 3.25 and 4.25 cm) located at the transition from gradually increasing to gradually decreasing grain size are marked as uncharacteristic. From 3.5 centimeters to 6.75 centimeters the grain size gradually decreases to 8.1, indicating roughly a 0.59 micron decrease per quarter centimeter over the interval. After 6.75 centimeters the mean grain size begins to increase, reaching a maximum of 14.9 microns at 8.5 centimeters from the bottom of the trap. Mean grain size remains relatively consistent for the remaining portions on the trap, hovering at an average of 14.7 microns. The total amount of accumulated sediment was 10.75 cm for the bottom trap of mooring D.

D4 Trap Data – Median (fig. 9B)

The plotted median for the bottom trap of mooring D maintains the shape of grain size curve for Trap D4 mean. However, all grain size values appear to be shifted toward smaller microns, shifting the entire plot to the left relative to the D4 mean plot. The grain size begins at 8 microns on at the bottom of the trap, decreases the first 2 cm to 5.8 microns, then begins to increase to maximum of 10.9 microns for 2 cm. From here the plot indicates a gradual decrease in grain size over 3 cm, culminating in a finer grain size of 6.2 microns. The rate of gradual decrease is approximately 0.64 microns per centimeter over the particular interval. The top portion of the grain size plot indicates an increase of grain size, culminating in a maximum of 12.9 microns, though an 11.2 micron average for the remaining 3.75 cm of sediment.

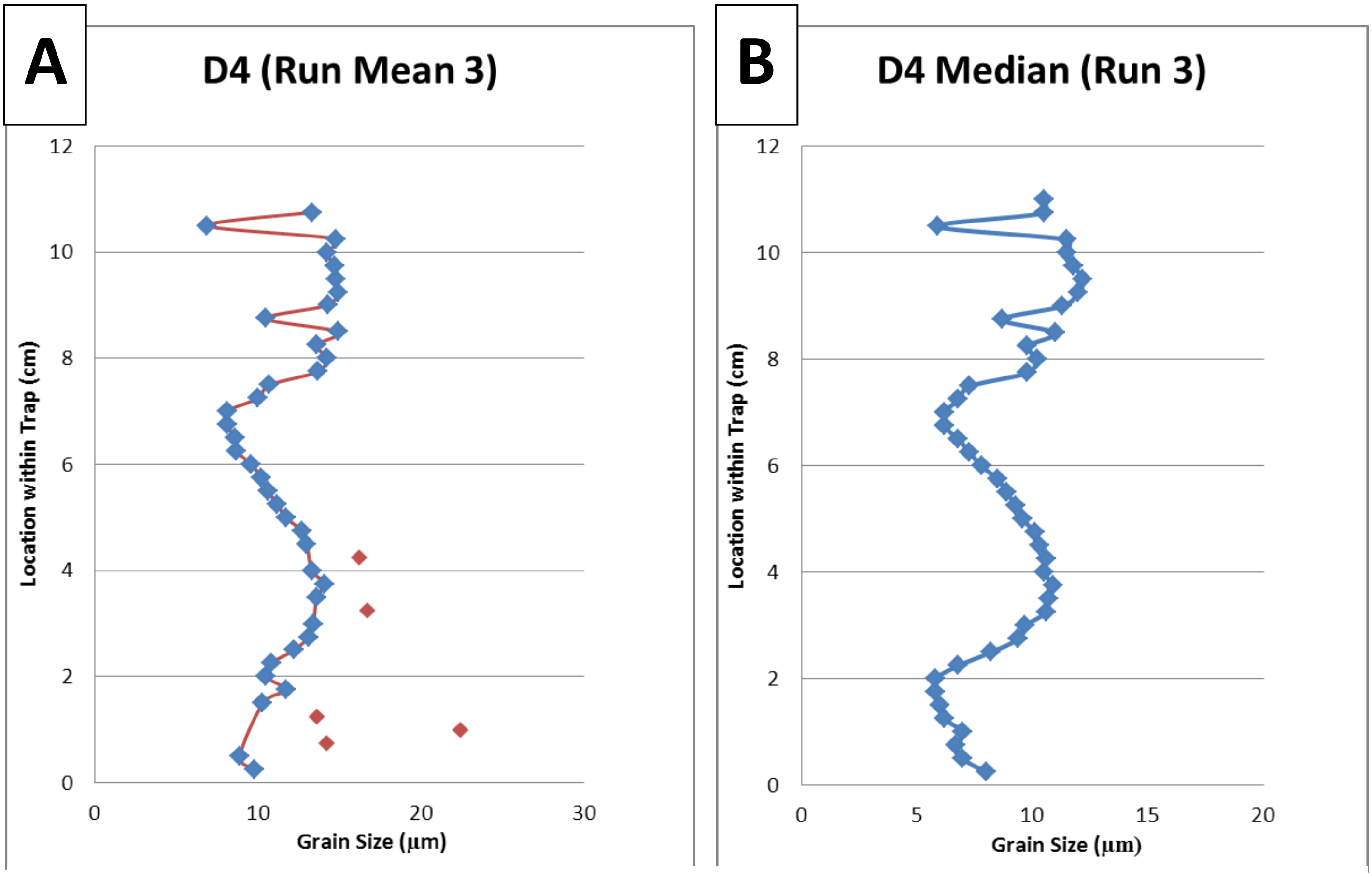


Figure 9. The grain size plots above represent the entirety of accumulated sediment at D4 for the 2010-2011 depositional year. Each point in figure 9A is a result of averaging 3 separate runs of the same sample to get the most representative grain size for that interval. The resolution of the grain size data for the receiving tubes is every quarter centimeter. The plot in figure 9 B utilized the same data from #A, only represents the median values of the 3 separate runs for each sample.

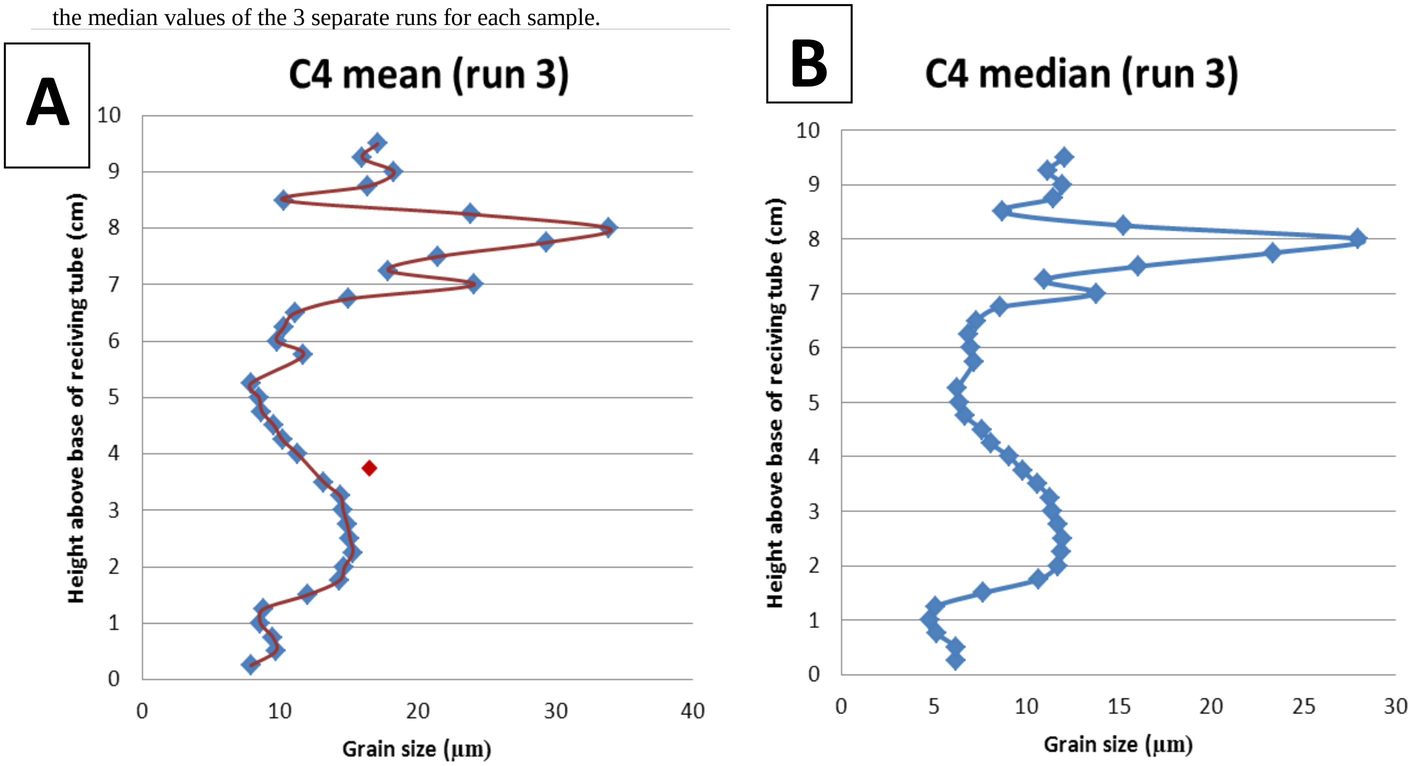


Figure 10. The grain size plots above represent the entirety of accumulated sediment at C4 for the 2010-2011 depositional year. Each point in figure 10A is a result of averaging 3 separate runs of the same sample to get the most representative grain size for that interval. The resolution of the grain size data for the receiving tubes is every quarter centimeter. The plot in figure 10B utilized the same data from #A, only represents the median values of the 3 separate runs for each sample.

C4 Trap Data (fig. 10A)

Starting from the bottom of Trap C4, the mean grain size begins at 7.9 microns and increases over the first 2.5 centimeters to 15.1 microns. The interval from 2.5 to 5.25 centimeters shows a gradual decrease in grain size to 7.9 microns, indicating roughly a 0.61 micron decrease per quarter centimeter over the interval. One point over the interval from 2.5 to 5.25 cm had a drastically uncharacteristic grain size and is indicated as red data marker. After 5.25 centimeters the mean grain size begins to coarsen rapidly, reaching a maximum of 33.9 microns at 8.0 centimeters from the bottom of the trap. Mean grain size remains relatively consistent for the remaining portions on the trap, hovering at an average of 14.7 microns. The total amount of accumulated sediment was 9.5 cm for the bottom trap of mooring C.

C4 Trap Data – Median (fig. 10B)

The plotted median for the bottom trap of mooring C maintains the shape of grain size curve for Trap C4 mean. However, all grain size values appear to be shifted toward smaller microns, altering the entire plot left relative to the C4 mean plot. The grain size begins at 6.2 microns on at the bottom of the trap, and then begins to increase to maximum of 11.9 microns at 2.25 cm from the bottom of the trap. From here the median plot indicates a gradual finning in grain size over 2.75 cm, culminating in a grain size of 6.4 microns. The rate of gradual decrease is approximately 0.62 microns per quarter-centimeter over the particular interval. The top portion of the grain size plot indicates a rapid increase of grain size with a maximum of 28 microns. The final portion of the sediment trap varies from 8.7 to 12.1 microns at the top.

Spring Sediment Traps

Sping D base Trap Data (fig. 11)

The bottom-most trap on spring mooring D had a total of 2.5 cm of accumulated sediment. The initial sedimentation includes grain sizes of 6 microns. The coarsest grain size was recorded half a centimeter from the base and indicated 13.6 microns. The final 2 centimeters had an overall decrease in grain size from 13.6 to 6.4 microns.

Spring C base Trap Data (fig. 12)

The bottom-most trap on spring mooring C was suspended at 14 meters depth. The initial sedimentation includes grain sizes of 37.6 microns. The rather coarse grain sizes remain for the first 2 centimeters of the trap then a fining of the sediment occurs. For the top 3 centimeters of the spring trap the grain size decreases from 38.4 to 10.7 microns. The total amount of accumulated sediment for spring trap C was 5 cm.

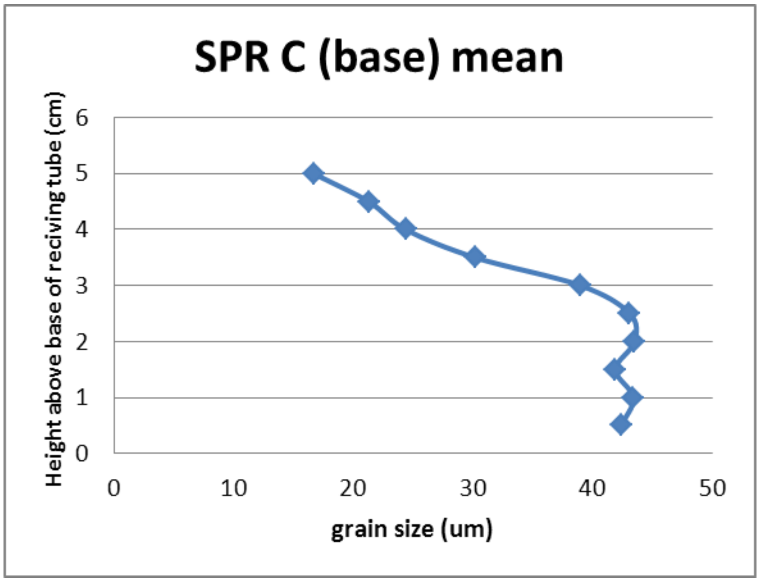


Figure 12. The grain size plot above represent the entirety of accumulated spring sediment in the bottom spring trap at mooring C for the 2011 melt season. Each point represents an averaging 3 separate runs of the same sample to get the most representative grain size for that interval. The resolution of the grain size data for the receiving tubes is every half centimeter.

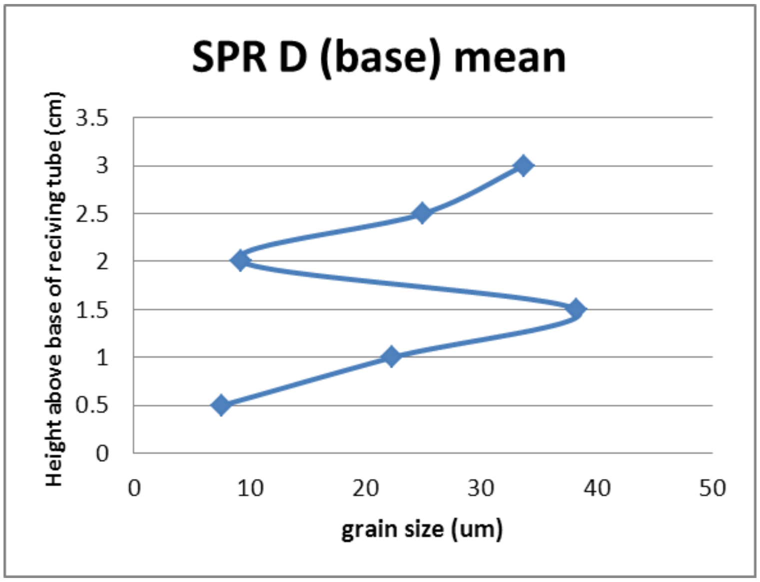


Figure 11. The grain size plot above represent the entirety of accumulated spring sediment in the bottom spring trap at mooring D for the 2011 melt season. Each point represents an averaging 3 separate runs of the same sample to get the most representative grain size for that interval. The resolution of the grain size data for the receiving tubes is every half centimeter.

Mean Grain size versus Median

Many previous studies have used the mean grain size data from the Beckman Coulter Particle Analyzer to evaluate the sedimentation process in Lake Linné, a practice this study has continued. To ensure a correct interpretation of the grain size plots, a comparison of mean, median plots and a reconstruction of select grain size histograms for trap C4 and D4 were made. While the median grain size plots show finer overall grain size characteristics for both C4 and D4 year-long traps, the same shifting grain size patterns are observed.

At the base of both mean and median plots of year-long trap D4 the shape of the curve begins at a finer grain size and coarsens upwards of by around 4 cm from the base. Similarly, the gradual fining in grain size is also represented. By 6.75 cm, both plots have returned to the grain size represented at the base of the sediment trap. Lastly, the grain size pattern is further mirrored in the mean and median plots even at the top of the sediment traps. Though a different overall grain size pattern is represented for the year-long C4 sediment trap, the correspondence of the median and means plots are the same as seen in D4.

The median grain size was plotted alongside the mean because calculations of the mean are affected to a greater degree by outliers. In contrast, the median expresses grain sizes that incorporate the bulk size of the tested sample. As a result, the median grain size plots are shifted toward finer grains; however the relative shape of the plot maintains its integrity and is used as a base for identifying outliers in the plot of mean grain size. For example, the sample analyzed 1 cm from the bottom of the year-long D4 trap shows a grain size of 22.4 microns, when compared to the same sub-sample on the median plot the drastic jump in grain size does not appear. The comparative analysis between mean and median grain size run for both C4 and D4 traps flagged several possible outliers and motivated a deeper analysis into the discontinuities.

Reconstruction of Grain size Histograms

A reconstruction was done of the raw grain size data contributed from the Beckman Coulter Particle Analyzer. Samples along the mean grain size curves for C4 and D4 year-long traps that indicated a deviation from the overall pattern were highlighted and analyzed. The reconstructed grain size histogram for the deviation at 3.25 cm from the bottom of trap D4 is represented in figure 13. Plotted along with the 3.25 cm sample are the two samples run directly before and directly after. All three particle diameter plots follow a similar histogram, indicating bulk of the grains within the sample are centrally located around 10 microns. After the 10 micron bulk in all three samples, the number of larger grain sizes decreases. The histograms for at 3 cm and 3.5 cm indicate that grain sizes do not exceed 50 microns for these samples. The histogram for samples taken at 3.25cm indicates that grains of within the range of 350 microns exist in the sample. Several other comparative histogram plots created for the samples that diverged from the pattern seen in the median graphs conveyed similar patterns of excessive grain sizes.

D4

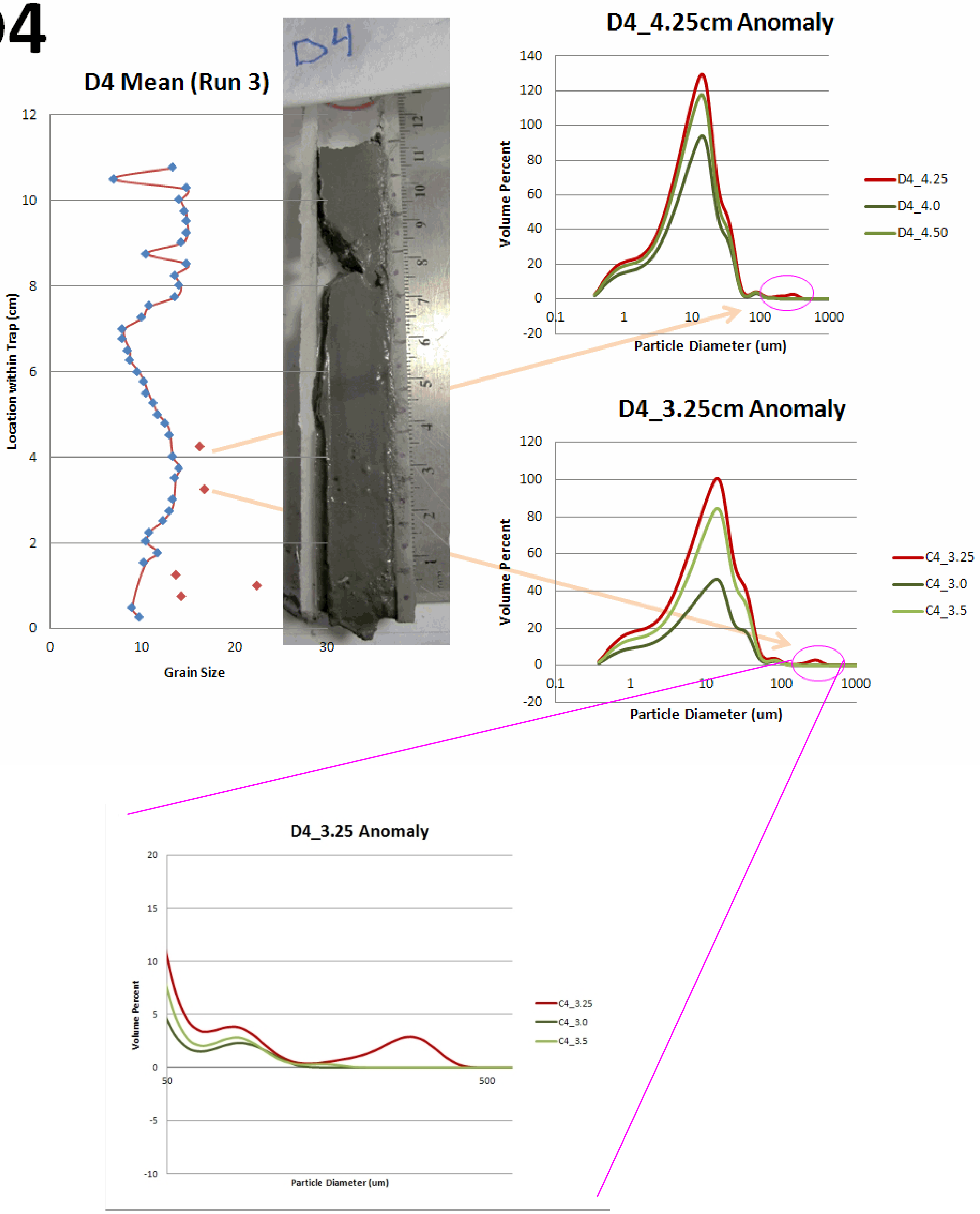


Figure 13. The figure above explains the anomalies found through the reconstruction of grain size histograms. Data points in marked in red on the grain size plot of D4 were scrutinized for their viability by reconstructing the histograms on the right. The lines in red represent the sample under question. The enlarged plot of the 3.25 cm anomaly indicates a significant volume of anomalously large grains in the sample.

Weather Station

Air Temperature

Between July 31, 2010 and July 14, 2011, the air temperature in the Linné valley ranged from -18.3° F to 52° F with an average of 23.5° F. During the field season air temperature ranged from 39.3° F to 44° F (fig. 14).

Precipitation

Approximately 339.3 mm of rainfall was recorded in the Linné valley between July 31, 2010 and July 14, 2011. Approximately 0.6 mm of rain was recorded during the field season (fig. 15). Of the 41 precipitation events recorded within the valley, 18 occurred after February 21, 2011. All precipitation events recorded comprised of 0.2 mm or more of rain. The highest accumulated precipitation was 21.2 mm over 15 hours between March 15, 2011 and March 16, 2011.

Lake Temperature

Temperature loggers on all year-long mooring lines recorded water column temperatures since July of 2010. They revealed distinct seasonal characteristics (fig. 16 and 17). In September, the lake began a gradual cooling period until mid-October when the lake began to freeze over. The top layer of the lake was frozen from late October until late April. In late April, the ice began melting and was completely gone by mid-July. Lake Linné was thermally stratified in the winter, however mixing during the cooling in the fall/winter transition as well as the spring/summer transition occurred.

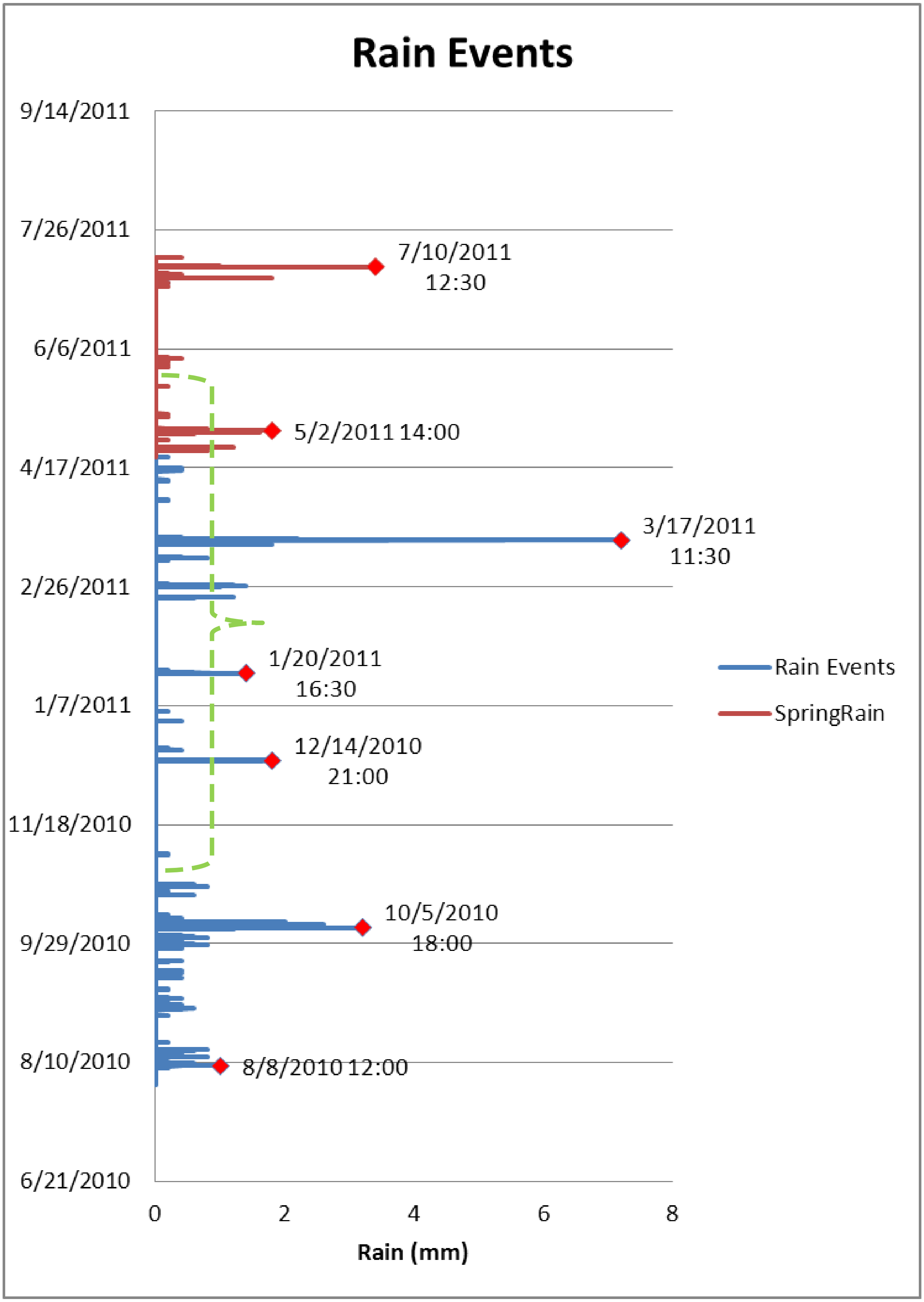
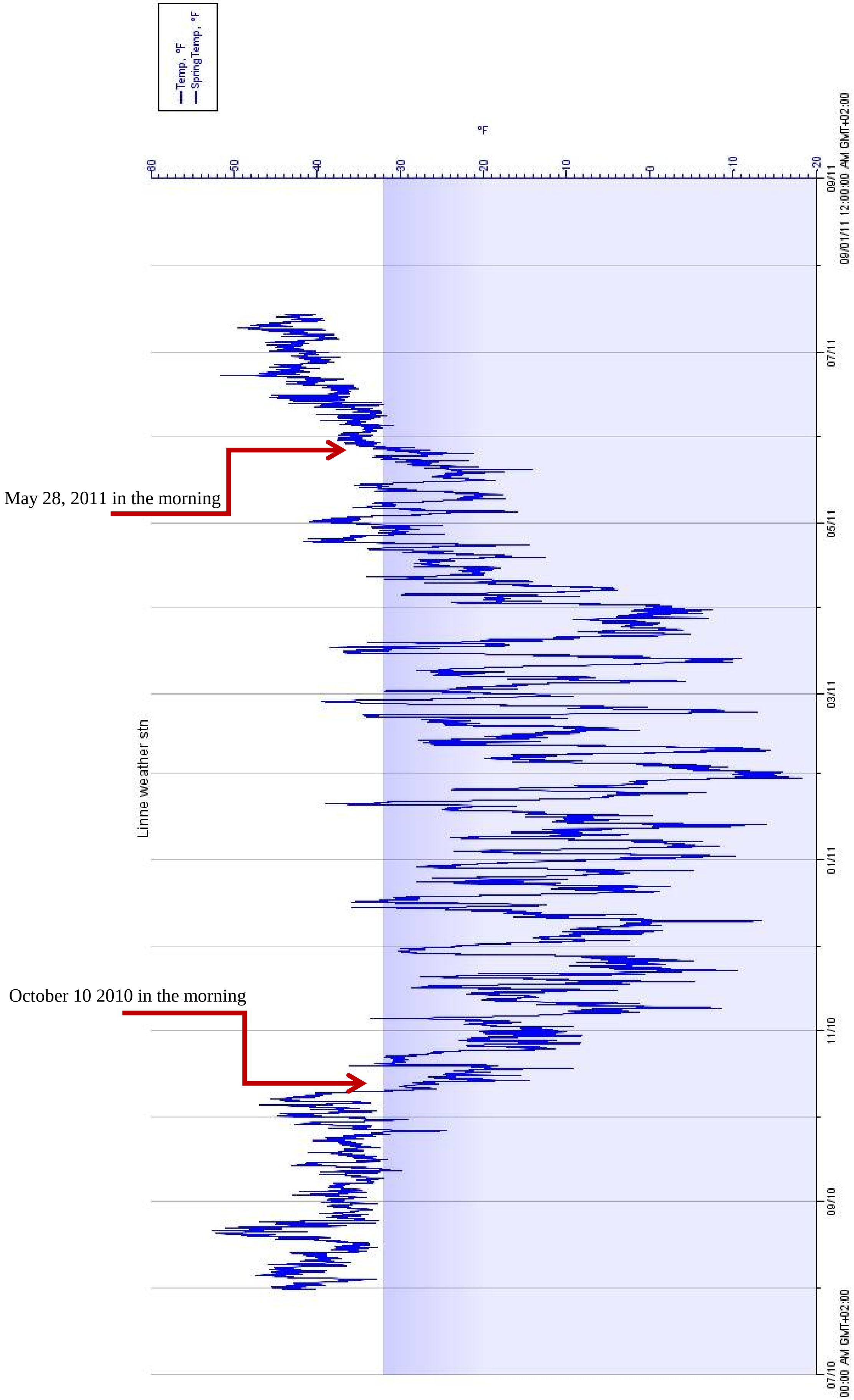


Figure 15. The figure above shows all the precipitation events from August, 2010 through July, 2011. The difference in colors of the fall/winter and spring precipitation is a result of downloading and then resetting the weather station prior to the spring melt season. The green dashed line represents the interval of time in which the inflow stream was below 0°C and consequently was frozen.



May 28, 2011 in the morning

October 10 2010 in the morning

Figure 14. The figure above is the raw air temperature data at the main weather station south of Lake Linné. A low alarm was added to the data to aid in the visualization of when the Linné valley was frozen and when it was thawing.

Temperature loggers along Mooring C

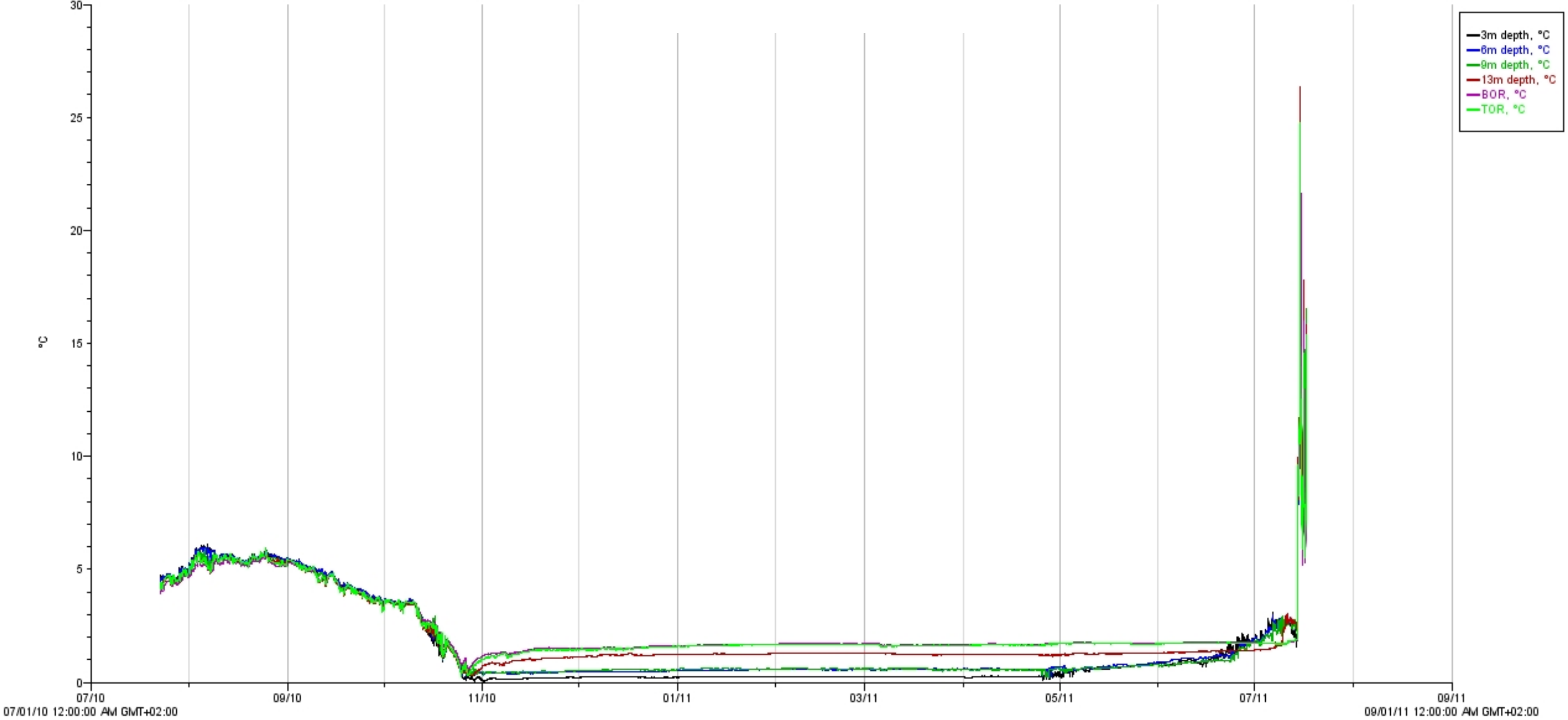


Figure 16. Temperature loggers along mooring C. TOR = Top of anchor rock, BOR = Bottom of anchor rock.

Temperature loggers along Mooring D

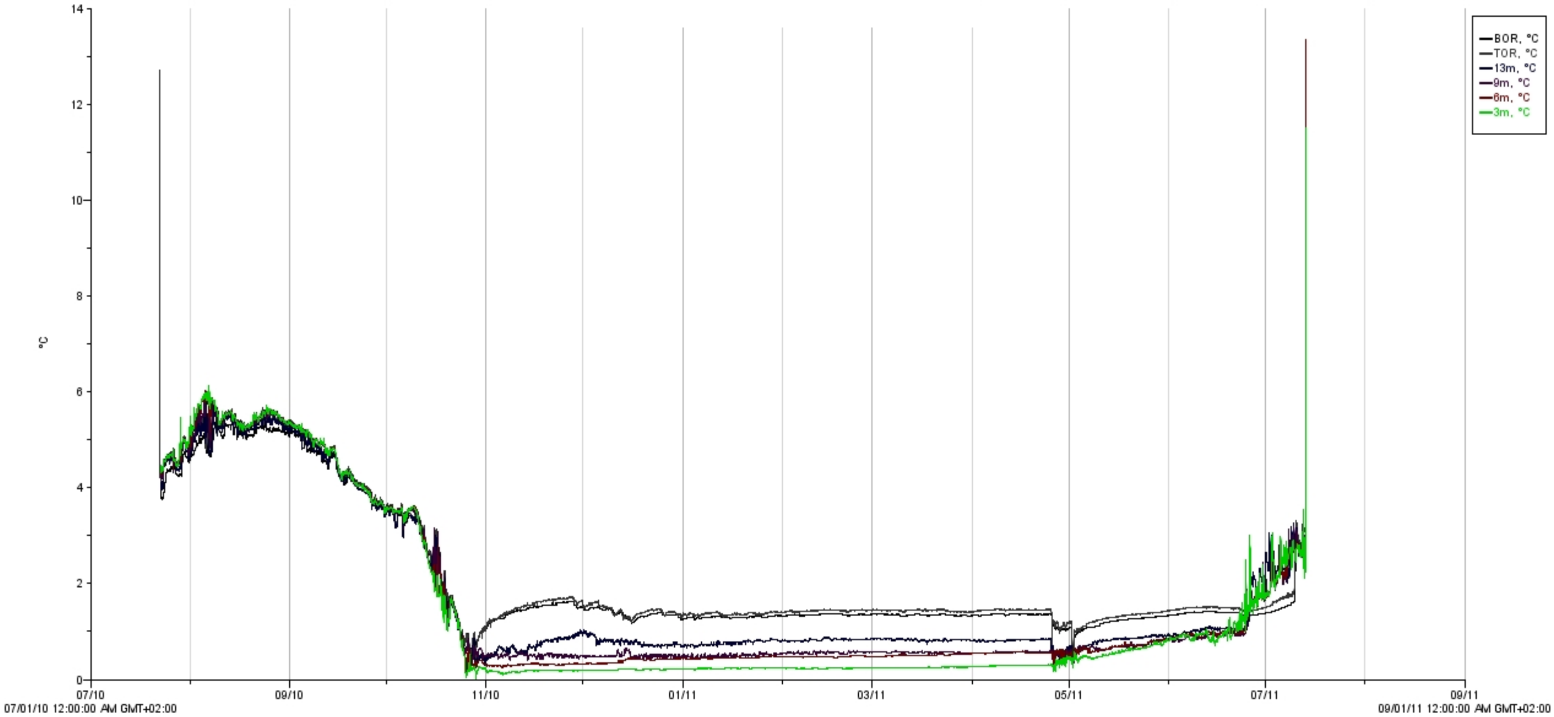


Figure 17. Temperature loggers along mooring C. TOR = Top of anchor rock, BOR = Bottom of anchor rock.

For the purposes of this study we will focus on the lake temperatures in the fall and spring seasons at locations for mooring C and mooring D. Water temperatures recorded at mooring C began at 6° C on average in early August and gradually decreased to approximately 0.5° C at the end of October. Between October 13, 2011 and October 21, 2011, temperature loggers located at the top and bottom of the anchor rock recorded lake temperatures of approximately 2.5° C whereas the logger located closest to the surface recorded temperatures of 1° C colder on average. At the end of October, the temperature in the lake shows stratification. Beginning in late April, water temperatures recorded at mooring C fluctuate from 0.2° C to 3.1° C, with a broad trend of increasing temperature (fig. 16).

Water temperatures recorded at mooring D started at between 4.7° C and 5.7° C on average in early August and gradually decreased to approximately 0.5° C at the end of October. Between October 15, 2011 and October 20, 2011, temperature loggers located at the top and bottom of the anchor rock recorded lake temperatures of approximately 3.1° C whereas the logger located closest to the surface recorded temperatures of 1.89° C average. By the later afternoon of October 20, 2010, the temperature stratification at mooring D returned to early October characteristics. At the end of October, the temperature in the lake shows stratification. The stratification continues until April 25, 2011 when all temperature loggers record an abrupt decrease in temperature of between 1° C and 0.5° C. The encompassing temperature reduction for all loggers continues until on May 1, 2011 through May 2, 2011 the loggers attached to the top and bottom of the anchor rock on mooring D record a sharp decrease in temperature again. The temperature decrease is between 0.8° C and 1° C. Just as quickly as the temperature dropped the evening of May 1, 2011, the lake regains previous stratification over 3 hours during the late afternoon on May 2, 2011. The temperature loggers above the top of the anchor rock do not show significant change over the interval. Continuing after the beginning of May, water temperature at mooring D begins a broad increasing trend. The loggers on the anchor rock join the gradual increasing temperature trend on June 10, 2011 with a jump from on average 1.7° C to 2.4° C over the course of 13 hours (fig. 17).

Lake Temperature and Meteorological Conditions

Lake temperature, Air temperature and Precipitation Conditions

An attempt was made to find correlation between meteorological conditions and lake stratification behavior. The following data includes a comparison of both mooring C and mooring D to ambient air temperature of Linné valley as well as precipitation events over the course of the sedimentation year. No strong correlation was found between mooring C or D lake temperature and air temperature (fig. 18 and 19). Conversely, the prominent fall rain event from October 4 till October 8 corresponds with the temperature increase for the bottom loggers on both mooring C and mooring D. The early May temperature drop at mooring D also correlates with a significant rain event that occurred over a corresponding timeframe.

Despite the absence of a single principle factor that orchestrates lake temperature in Lake linne, there is an encouraging link between precipitation events and air temperature and lake temperature. Furthermore, the comparison between mooring C and mooring D expresses significant differences between the two sites. Both sites recorded an increase in bottom logger temperature over the early October interval that corresponds with a rain event. However, the more proximal mooring site C did not record the significant temperature decrease in late April, felt so strongly by mooring D.

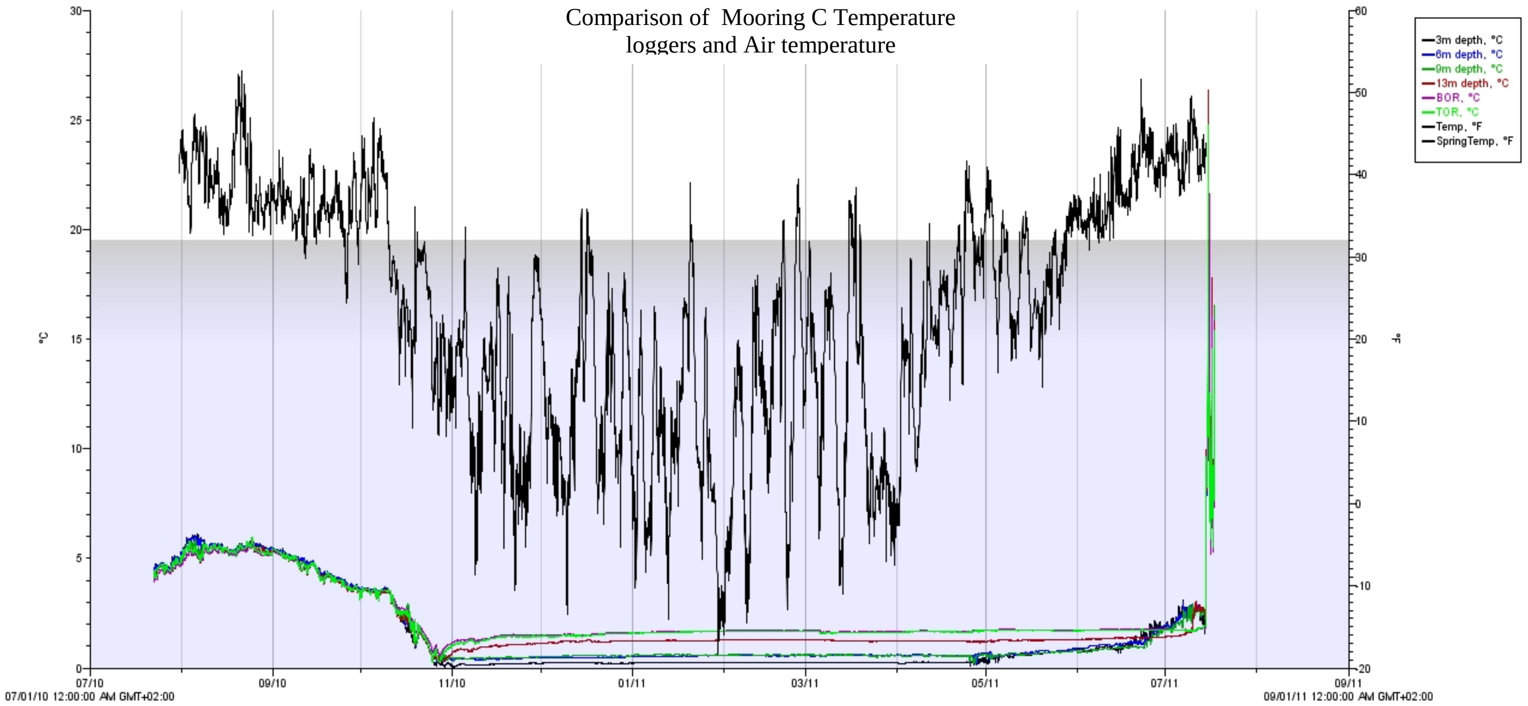


Figure 18. Comparison of Mooring C Temperature loggers and Air temperature.

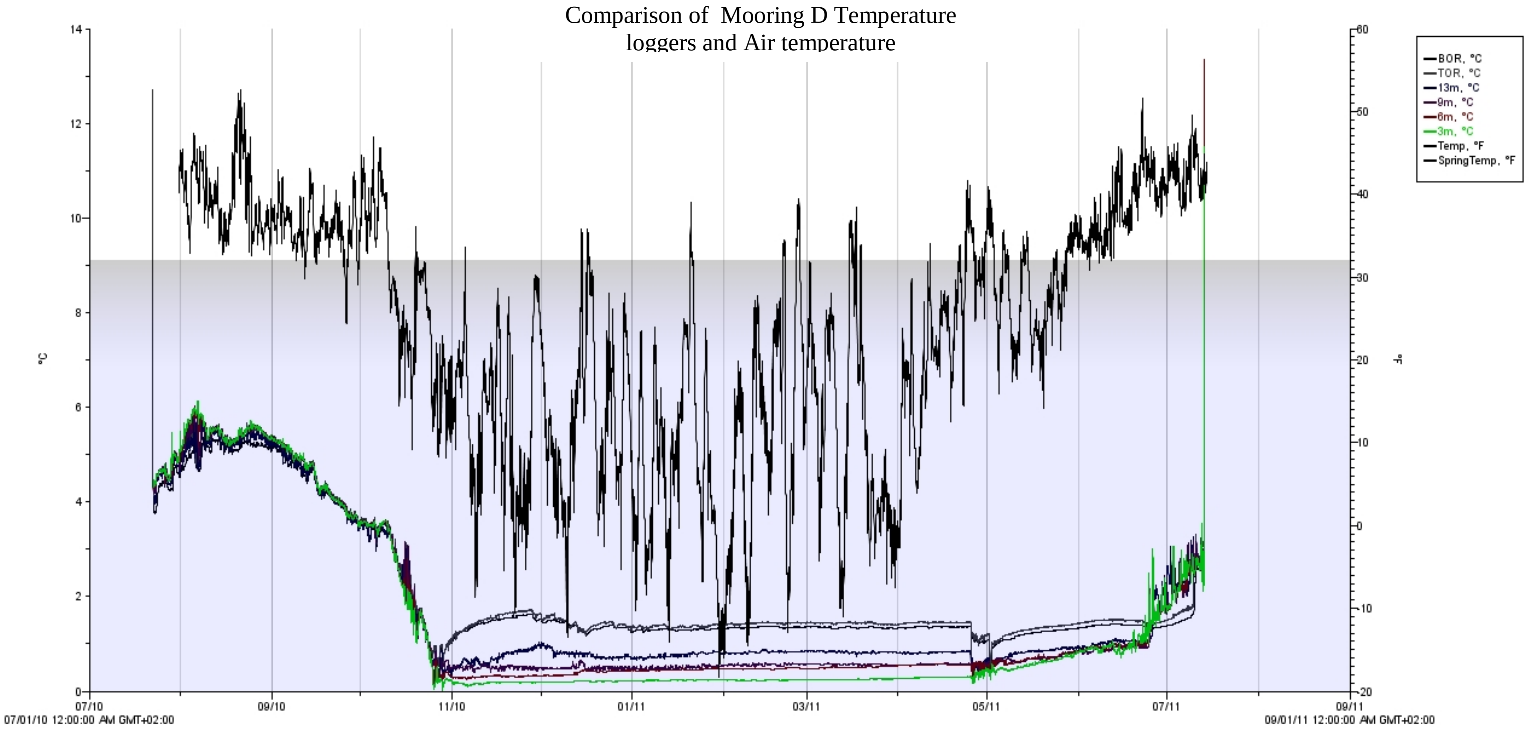


Figure 19. Comparison of Mooring D Temperature loggers and Air temperature.

Timing of Sedimentation – Intervalometer

The intervalometer showed sedimentation accumulation beginning August, 12, 2010 (fig. 20). The first major sedimentation event began August 16th and continued until August 31st. After a brief calm the second fall event began October 12th and gradually continued until November 14th. The tremendous spike during the spring occurred the day and time that the intervalometer was pulled from the lake environment and so is null. Similarly, the lack of sedimentation events recorded by the intervalometer during the spring suggests the instrument malfunctioned since other environmental records suggest deposition did occur over the spring interval.

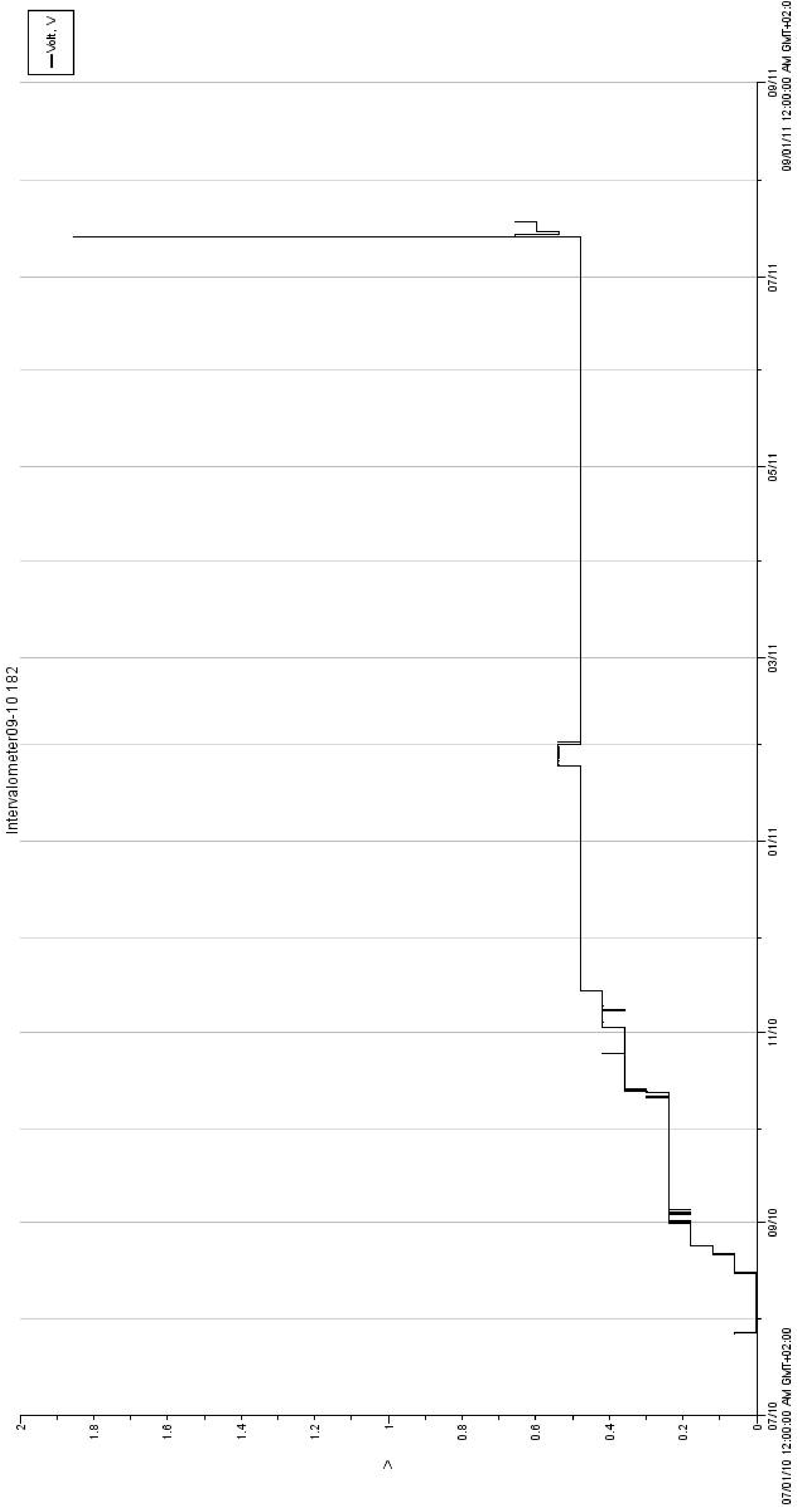


Figure 20. The intervalometer showed sedimentation accumulation beginning August, 12, 2010 though did not record spring sedimentation due to instrument malfunction.

Spring Turbidity and Temperature

Mooring C (fig. 21)

The In-Situ Troll was deployed at 14 meters at Mooring C and collected measurements of turbidity and temperature. Turbidity from April 26th through the end of May remained consistently between 0.05 and 0.1 NTU. From the end of May through the beginning of July turbidity very gradually increased to 2.3 NTU. From July 4th to July 10th the turbidity at C increased more rapidly to levels of 9.8 NTU. Over the interval from July 10th – 11th NTU values spiked to 49 over the course of 9 hours. Again in the morning of July 11th the NTU values dramatically increased to 86 then decreased to values previously seen in early July, all in the span of 5 hours. The last spring turbidity event occurred in the afternoon of the same day, July 11th, in the evening. Over the course of 3 hours, turbidity spiked to 46 NTU and then returned to values of on average 2.7 NTU.

The temperature record at mooring C remained consistently at around 1.6° C from April 26th through July 5th. After early July the temperature began to gradually increase, on July 7th the temperature jumped to 2° C then recovered. Most dramatically, the temperature increased 2° C from July 7th through July 10th and warmed approximately another degree with each pulse of turbidity in the record.

Mooring D (fig. 22)

The In-Situ Troll deployed at Mooring D collected measurements of turbidity and temperature from the end of April till July 15th, 2011. Compared to turbidity recorded at mooring

C, turbidity at mooring D did not remained consistent from April 26th through the end of May. Specifically, on May 2nd in the early morning a spike in turbidity reached 38.9 NTU, following this event, turbidity returned to average values between 1.6 and 3, NTU. From this event onward turbidity at mooring D remains noticeably higher than at mooring C. Beginning the evening of July 10th, turbidly increased dramatically to maximum values of 162.2 NTU. By early morning of July 11th the NTU values decreased, in total mooring D recorded a total of 39,608 NTU over the course of the 16 hour turbidity event. In comparison mooring C had recorded 19,107.2 NTU. For the remainder of the spring turbidity record, mooring D shows relatively consistent turbidity readings.

The temperature record at mooring D remained consistently at around 0.5° C from April 26th through June 24th. The only interruption to the constant temperature was on May 2nd when the temperature dropped to 0.010° C for 11 hours. After June 24th the temperature record at mooring D began to increase. Maximum temperatures of 3.1° C were reached in the early morning of July 10th. Following the overall maximum temperature, the record at mooring D cooled to 2.2° C before warming once again to almost record highs by the evening of July 10th. The temperature record after this event remained constant for the remainder of the deployment.

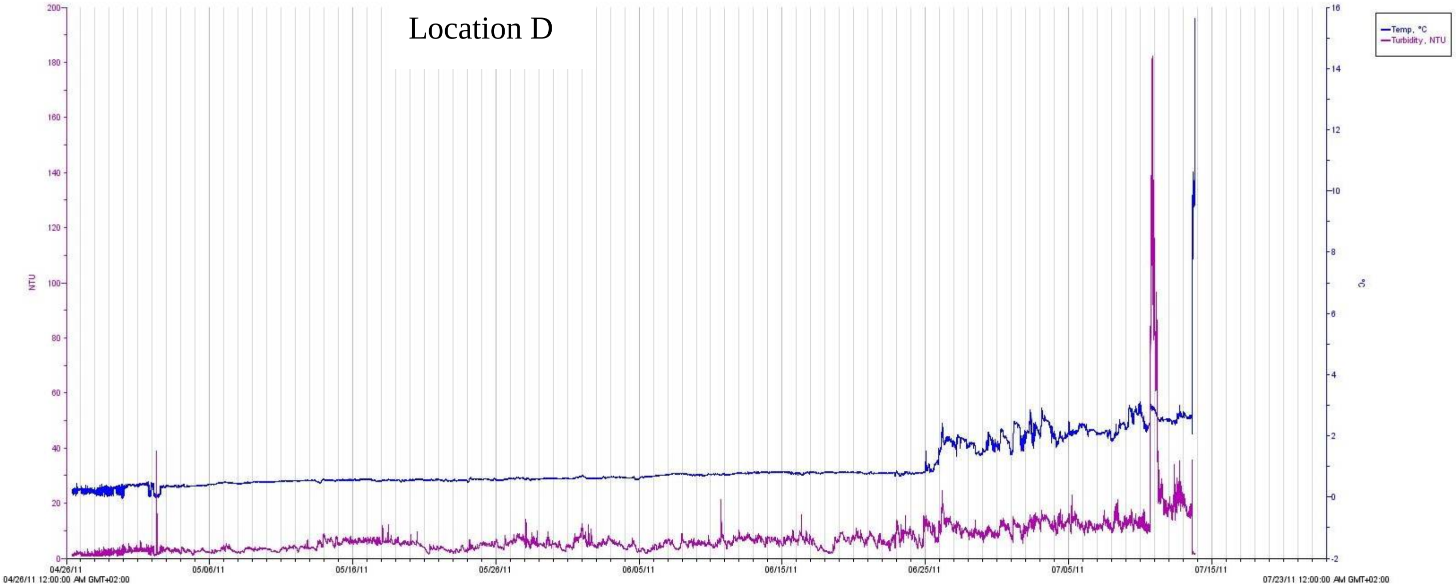


Figure 22. Spring Turbidity and Temperature at location D

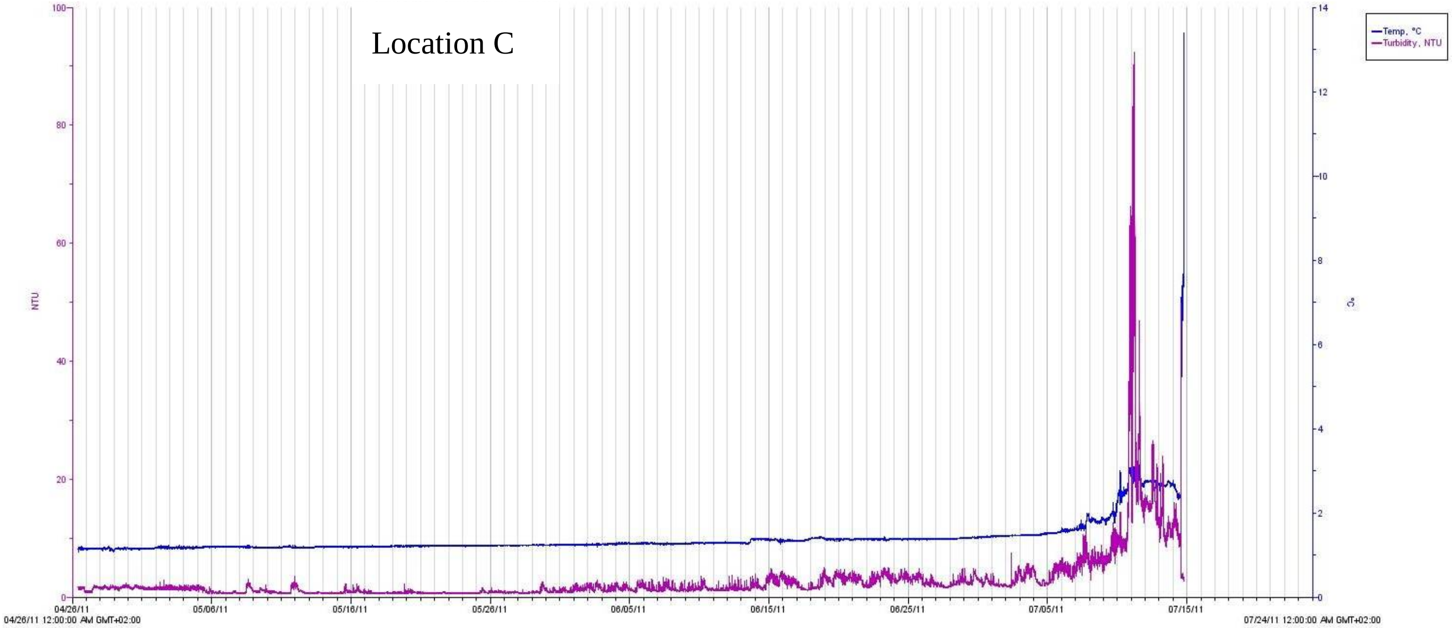


Figure 21. Spring Turbidity and Temperature at location C

River Stage Temperature Data

The stream temperature was fairly high (5 - 9° C) throughout August, 2010. The diurnal pattern was expressed by a range of approximately 2 - 6° C between day and night temperatures. On August 17th, temperature dropped dramatically to 0.27° C, on August 20th the river temperature spiked to 9.8° C. Finally, on October 10th the temperature in the river reached 0° C and remained throughout the winter.

Beginning June 14th, 2011 the stream temperature reached 0.3° C for the first time since October 2010. The stream quickly warmed in a diurnal pattern to 1° C on June 18th, then to 2° C on June 20th, 3° C on June 22nd and finally past 4° C on June 24th. The stream reached its maximum temperature of 10.3° C on July 9th in the evening.

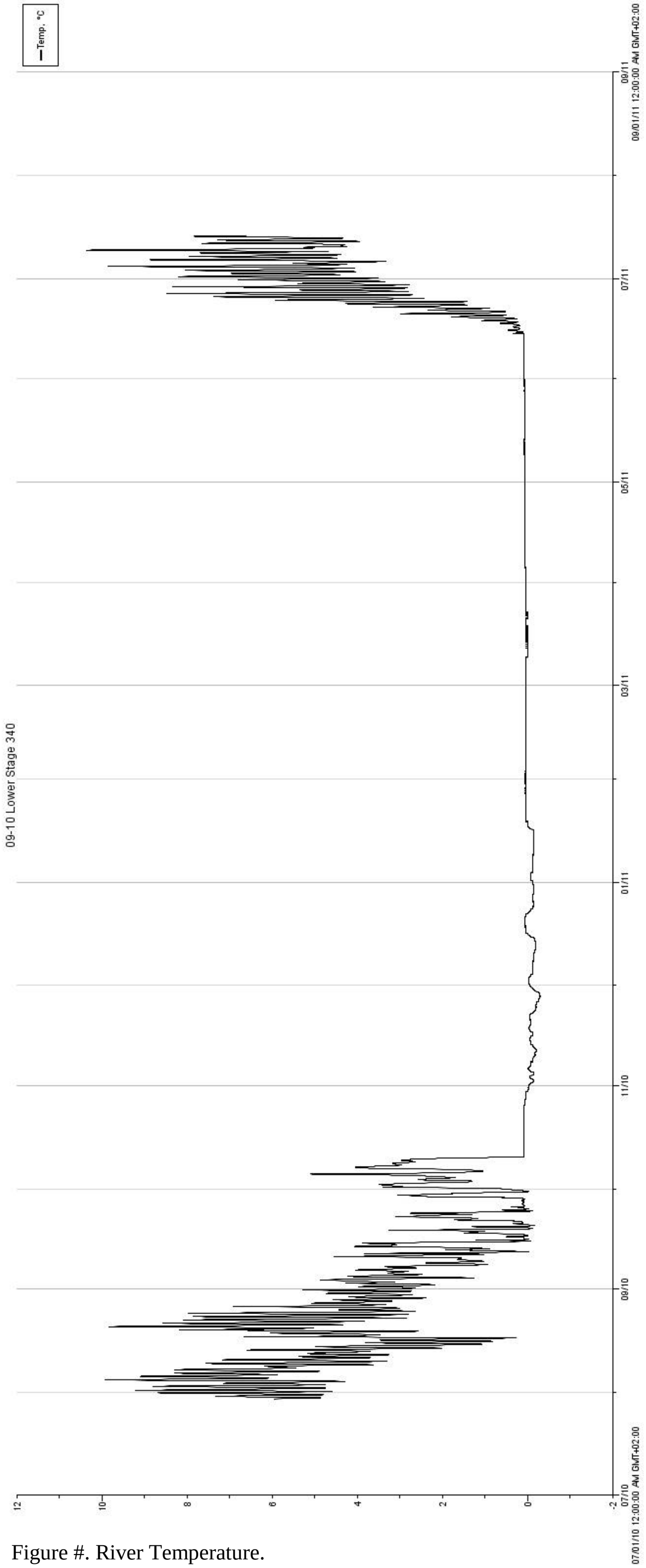


Figure #. River Temperature.

Automated Camera

Two groups of automated remote camera images were consulted for the purposes of this project. Images of the fall into winter transition were consulted for 2010. Similarly, 179 images of the southern end of Lake Linné were consulted from April 21 through July 13, 2011. The images reveal weather conditions, wave conditions on the lake, and surface sediment plume extents. The camera images serve as an accompanying data set to visually represent the many environmental factors that influence the Lake Linné inflow regime.

The extent of the surface sediment plume in the lake near the mouth of the inflow varied greatly. Overflow turbidity currents noted in both fall and spring generally migrated in a counter-clockwise fashion, as a result of lake currents and the influence of the Coriolis Effect. The event pictured in figure 23 illustrates an individual migration of the single surface plume event during the spring melt season. On July 10th, 2011, a visible plume dominated the eastern side of the southern portion of the lake. The plume progressed and continued into the evening of the 10th. By the morning of July 11th the over flow retreated. An important note is that while wind conditions do pick up on July 11th, the lake surface is placid for the introduction of the spring plume into the lake basin. This is the only spring sediment plume event recorded by the automated camera.

The event pictured in figure 24 is one of the two plume events that were captured by the automated camera in the fall of 2010. Similarly to the spring events, the influence of wind on the circulation of surface sediment plumes was negligible as the surface of the lake appears glassy.

Figure 24. The second of two fall plume events documented by the automated camera.

Figure 23. Above is a series of images recording the only sediment plume event documented by the automated camera during the spring melt.

Interpretations and Discussion

The differences in sediment fluxes from year to year attest to the variability in sedimentation characteristic in the Linné valley (fig. 25). With this in mind, we begin to understand that the valley does not warm in the same way every year. The variability in environmental factors govern how much and of what type of grain size are deposited each year.

Many previous studies have suggested that despite variability in sediment flux from year to year, patterns of grain size increases and decreases are common. For example, Corbin (2008) cites that mean grain size graphs for C4 from 2005-2006 as well as 2006-2007 increase in the middle portion and is preceded by a finer grained section. Year-long trap C4 for this sedimentation year similarly has a coarsening section at the top of the sediment trap, though is preceded by an, albeit less dramatic, coarser grain size section. Similarly, year-long trap D4 has a coarser section preceded by a substantial depositional portion of coarser grained material.

The grain size plots from yearlong mooring C and D are interpreted with the weather data results simultaneously in the following section. Each portion of the sediment record is described with environmental data as well as temperature logger data with the goal of determining the driving force of each event.

Weather Station – Air temperature and Precipitation

The weather station data from the fall and winter indicate a significant difference between in the fall/winter season and the spring/summer season. Temperature recordings from the main weather station indicate by the early morning of October 10, 2010, ambient air temperature in the valley was plunging in to arctic winter. On three separate occasions in the fall the weather station recorded temperatures in the valley dipped slightly below 0°C, however, after the October 10th date, the system cascades into winter. After this point the fluvial system is frozen for the winter season and no new sediment deposition is capable of being introduced to the lake.

Just five days prior to the October 10th ‘deep freeze’ date, the largest rain event for the fall introduced 35.6 mm of rain to the Linné valley. The effect of the precipitation was recorded and visually documented by weather and environmental loggers around the valley including the automated plume camera. The record of the fall rain events will be discussed as we investigate each instrumental data separately. The October 5th rain even was not however, the only rain event in the fall. Six other scattered rain events fell previously producing 53.8 mm of rain that fell in the Linné watershed. Conversely, the reality of only having one spring rain event (July 11th, 2011) after the air temperature reached above freezing indicates increased fluvial activity occurred in the fall.

In the spring, the ambient air temperature warmed more gradually then the converse plunge into cold air temperatures for winter. For example, there were six separate occasions that the air temperature in the valley exceeded 0°C before the system was completely out of winter. Between October 10, 2010 and May 28, 2011, precipitation in the Linné Valley would have contributed to the valley snow pack. The effect of isolated warming periods in the spring before the fluvial system was fully active may affect the influence of the fluvial system and thus decrease the volume of the sediment load carried by the system.

Sediment Trap Record - Fall

Through comparison of year-long trap stratigraphy with corresponding spring trap stratigraphy, it is clear that the spring record does not contain a complete record of sediment from the spring melt. Similarly, a significant bulk of the accumulated sediment in year-long traps C4 and D4 is fairly fine-grained. The first and only coarse spike is determined to have occurred as a result of the single precipitation event. Consequently, the gradual coarsening of grain size observed at the bottom of both C4 and D4 sediment traps is a result of increased fall sedimentation followed by a gradual settling out of suspended sediment during the winter.

The first sections of the sediment trap include first, the gradual coarsening of sediment from 0 – 4 cm in D4 and from 0 – 2.25 in C4 range from 8.1 - 14.8 microns. In the fall, the intervalometer data shows evidence of two significant sediment pulses at mooring C. The air temperature at the main weather station had started to show a decrease temperature trend with greater diurnal variability however had not crossed 0°C during the first pulse event registered in the intervalometer. However, during the second sedimentation event registered by the intervalometer, between October 12 – 14, the air temperature data indicates the Linné valley was in full winter conditions and frozen.

The rain event on October 5, 2010 and corresponding sediment plume captured by the automated cameras indicate the fluvial system was still transporting sediment right up until the river froze on October 10, 2010. Furthermore, the visual evidence of both the rain event and the transported plume reveals that fall sedimentation is substantial. The interpretation of sedimentation by the intervalometer even after the river system had shut down suggests the plume may have been and over-flow or homopyncal flow and thus particle high in the water column took longer to settle out, accounting for the delayed response for the intervalometer.

Similarly to the air temperature data, the fluvial system indicates the inflow stream into Lake Linné was decreasing in temperature during the first fall sedimentation event in august. Subsequently, during the second fall sedimentation beginning October 12, 2010, the fluvial system had already been frozen for two days. The delayed response of the of the temperature logger data from the mooring lines at both C and D show that by October 14, 2010 the loggers attached to the anchor rock showed a slight warming. The lag-time response of the lowest loggers to the introduction of the fall plume further suggest the plume was an over flow and thus had to settle out of the water column. The gradual coarsening of the sediment record in both C4 and D4 are a further expression on the differential settling times on suspended plume sediment.

Transport of sediment to the lake environment for the 2010-2011 sedimentation year continued right up until the Linné valley began the winter deep freeze. Therefore, the bottom interval of increased grain size found in both the C4 and D4 sediment traps could have been introduced to the lake by increased fall precipitation and non-frozen reality of the valley.

Sediment Trap Record – Spring

Spring sedimentation during the 2010 melt season increased from 7.9 – 33.9 microns for C4 and 8.1 – 14.9 for the less dramatic D4 spring sediment trap. The sedimentation event was shown in the turbidity data from each mooring line C and D, on July 10, 2011. May 28, 2011 marked the transition of high winter air temperature and the subsequent temperatures that followed had an increasing trend with lower diurnal variability. Stream temperature behaved similarly to air temperature and began increasing in temperature June 13, 2011. The lack of precipitation at this time suggests that the inflow stream was driven by snow pack melt due to the warming and increased solar insolation. Images from the automated plume camera during this melting period also suggest melting of the valley snow.

Following a period of no precipitation as the Linné valley began to thaw from the arctic winter, the first and only spring rain event occurred on July 10, 2011. The automated plume camera shows the weather system and low hanging clouds creeping through the valley on July 9th, by July 10th in the morning a plume entered the lake and spread up the southeastern side of Lake Linné. Interestingly, the automated camera also captured an image of an ephemeral stream entering the eastern side of the lake, creating a sub-plume. The integrity and effect of the minor inlet is unknown, and most likely does not compete with the governing effect of the Linné river. However, understanding that there may be extraneous sources of sediment may explain why D4 has more overall accumulated sediment this sedimentation year since it is more proximal to the eastern edge of the lake.

The signature temperature of the lower stage during the turbidity events on July 10, 2011 was between 3 – 5°C. The temperature loggers suspended at mooring C and D recorded similar temperatures before, during and after the event even though the turbidity monitor recorded dramatic shifts. The implications of similar inflow and lake temperature suggest the sediment plume entered the lake in a homopycnal manner, disbursing to all levels of the lake and traveling as an un-stratified mass.

Comparison of Sediment from Previous years - What this year's record may look like as a varve

The accumulated sediment record is given for the last six years from 2004 – 2010 in figure 25. The composite of grain sizes is of the lowest trap at mooring C. The most recent year, shows a unique and distinct pattern. The first 3 – 4 cm indicates a coarsening grain size peak followed by a steady decrease in grain size and finally a second spike in grain size occurring at the top half of the sediment trap. Without full comprehension of the facts, the most recent record could easily be interpreted as two summer events and a low energy winter event in between. The ability to effectively utilize laminated stratigraphy as a chronology is based on interpreting the record precisely. Sedimentation characteristics of the 2010-2011 year have added further complication to the process of interpreting seasonal varves.

Two studies by Pratt (2006) and Arnold (2009) interpreted thin sections of lake sediment cores and showed coarser layers as summer deposition while darker, fine-grained layers represent winter. The two studies measured and calculated the thickness of each lamina as well as the couplet. In the end the two studies attempted to correlate collected and analyzed sediment traps from previous years with the varved core record. Logically the thickest layer in the thin section should have corresponded to the thickest sediment accumulation in the traps. Success in correlating sediment traps and core samples was minimal, however, possibly with interpretation of this year’s coarse fall and spring sedimentation pattern, interpretation of such sediment core records may be more successful.

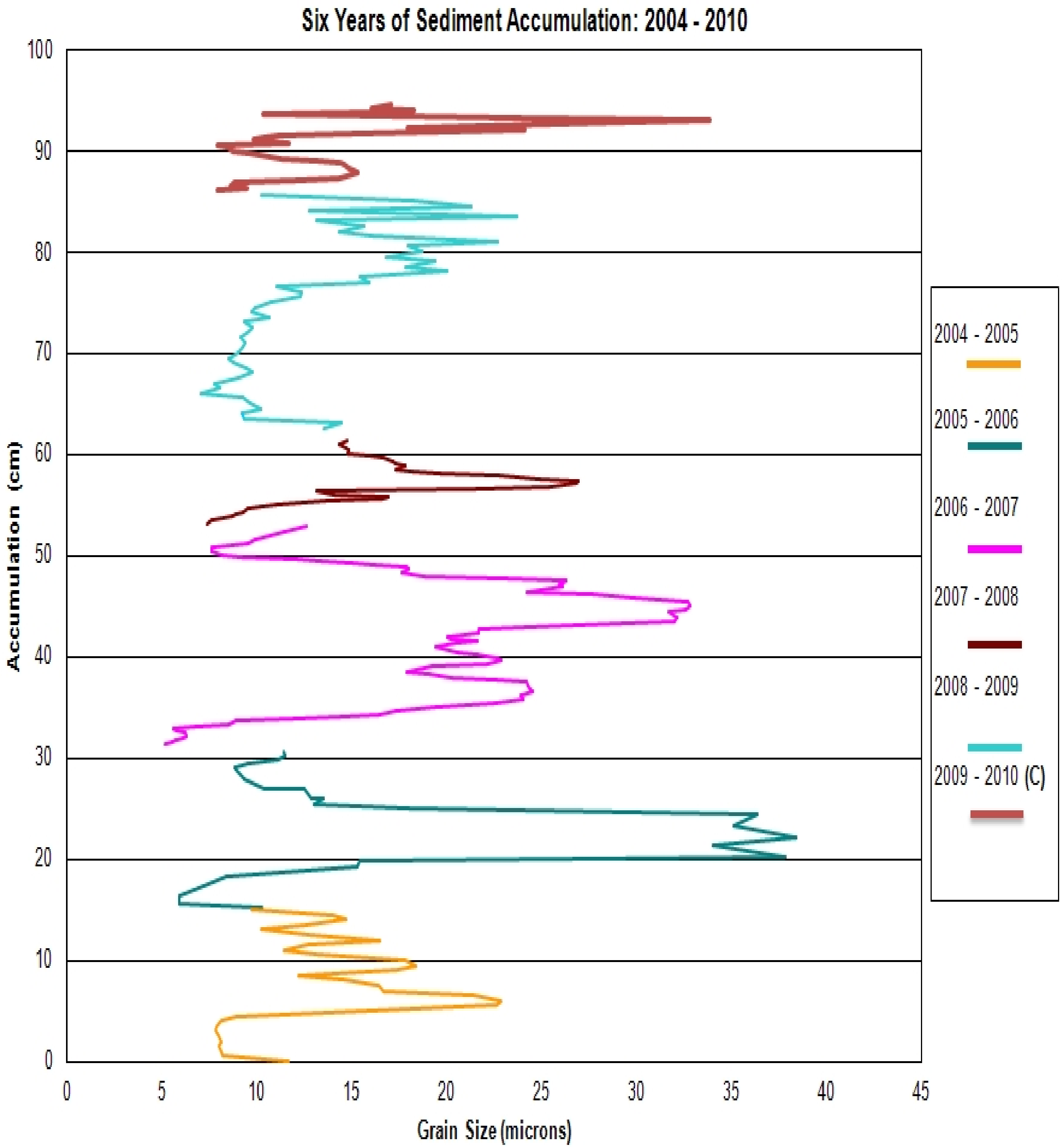


Figure 25. The accumulated sediment record is given for the last six years from 2004 – 2010. All records are from the bottom trap of mooring C.

Conclusions

Sediment trap stratigraphy is greatly controlled by the environmental characteristics of the surrounding watershed, therefore by variable seasonal sedimentation. Contrary to many studies, the winter sedimentation can be coarse-grained if the weather patterns promote precipitation and prolonged relative warm conditions followed by a sharp transition into winter environments. The spring and summer layers tend to be approximately 20 – 35 microns, and are strongly influenced by air temperature, precipitation and the availability of transportable sediment. In the sediment record, fall sedimentation has a signature of gradual grain size changes. Sediment deposited as a result of spring environmental conditions have a signature of rapid changes in grain size.

The comparison of year-long traps C4 and D4 describe the sedimentation for the 2010 – 2011 depositional years. The differences in overall accumulated sediment volume are first, the possible effect of strong lake currents causing sediment plumes to skirt the eastern coastline and second, the possibility of ephemeral streams introducing supplementary sediment to D4. The complex yet significant boundary between the gradually fining bottom sediment and the low-volume is found in both C4 and D4.The existence of two distinct coarse sediment sections indicates varved sediments have the ability to be easily misinterpreted.

The grain size characteristics of C4 and D4 compared to weather and environmental data indicate that the first (August 8th – 10th, 2010) and second (October 5th, 2010) major sediment flux into the system occurred in the fall. These events were likely over flows. The third major sediment flux occurred as the only spring depositional event from July 10th – 11th, 2011. The spring event was likely a homopycnal flow.

The sedimentation accumulation for 2010 – 2011 deposition years was small with only 9.25 mm as compared to 230 mm in 2007 – 2008 and 138 mm for 2006. Air temperature and precipitation were comparable with previous years.

Previous studies have suggested correlation between recent varve thickness and weather data do not reveal significant trends with in the Linné valley. The added knowledge of increased fall sedimentation has the ability to increase the correlation by understanding that coarser fall and winter records do occur. The goal of this project was to determine the influences of environmental factors with in the Linné valley for the purpose of calibrating stratigraphic lamellae with in the pro-glacial lake Linné sediment record. Ultimately a more succinct, though complex understanding of the environmental factors that affect seasonal deposition facilitates the understanding of paleo-climate and paleo-environmental realities has been achieved.

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