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Multi-temporal Assessment of Connecticut Lake Water Clarity Using Landsat Satellite Imagery

Progress Report
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RESEARCH PROBLEM

Connecticut has over 1,000 lakes and ponds larger than 5 acres in area. These water bodies provide important recreational opportunities, aesthetic values, and ecosystem services that contribute to the quality of life, environment, and economy of the state. Over the past 400 years, Connecticut has undergone significant alterations to its landscape. As a result of these mostly anthropogenic activities, including clearing of forests, agriculture, and urban and rural development, there have been significant impacts to the water quality of Connecticut's lakes and ponds. While a natural process, the eutrophication of lakes caused by excess nutrient export in runoff has been, and continues to be, a pervasive problem (Siver *et al.*, 1996). These conditions limit recreation opportunities, reduce the economical value of property, and diminish the ecological integrity of lakes" (CT DEP Lake Water Quality Management Program). An analysis conducted in Connecticut by Siver *et al.* (1996) found that 33 out of 35 lakes studied had shown a decline in water clarity, an indicator of water quality, since the 1930's.

Protecting lake water quality is a major concern for local, regional, and state agencies as well as citizens and non-profit organizations. Comprehensive water quality data are essential for improved management and policy decisions. It is, however, prohibitively expensive to monitor water quality for a significant number of lakes and ponds using conventional methods. As such, many lakes and ponds are not sampled throughout the region (missing potentially low water quality lakes and ponds), or under-sampled within the lake (missing the full, within lake, spatial extent of algal blooms and other phenomenon associated with the identification of lake trophic levels) resulting in the under-representation of the full extent of water quality issues (Mancino *et al.*, 2009). Over the years, several surveys have been undertaken to assess water quality in Connecticut, but the number of lakes and ponds included are minimal (Deevey, 1941; Norvell and Frink, 1975; Frink and Norvell, 1984; Canavan and Siver, 1994; 1995). Additionally, the U.S. EPA, USGS, Connecticut Agricultural Experiment Station (CAES), Connecticut DEP (CT DEP), academic and research institutions, and non-profit organizations periodically conduct water quality analysis. Although these surveys provide a hint at statewide water quality, no complete assessment has been conducted. Satellite remote sensing provides an efficient means by which to get at the *big* picture of statewide lake and pond water quality by enhancing *in situ* limnological measurements which can be applied to other lakes within the same satellite image and allow for the extension of the measured parameters collected from point locations within a lake to be applied to the entire lake surface (Mancino *et al.*, 2009).

INTRODUCTION

The primary goal of this project was to ***derive a multi-temporal assessment of lake water clarity at the state level from available Secchi Disk Transparency (SDT) data and archived Landsat satellite imagery dating back to the mid-1970s.*** To achieve this, we adopted the regression analysis procedures used successfully in the Northern Plains region of the United States (Lillesand *et al.*, 1983; Lathrop and Lillesand, 1986; Fuller *et al.*, 2002; Kloiber *et al.*, 2002a; 2002b). Ninty-five Landsat scenes covering portions of the years 1973-2010 for Connecticut were reviewed for applicability and numerous years of SDT data of Connecticut lakes were collected from the literature. Additionally, physical collection of SDT data was conducted from late July through August 2010 and applied to a 2010 estimation of Connecticut

lake water clarity. Based on these data, four dates of water clarity were estimated for the years 1980, 1993, 2005 and 2010.

DATA

Secchi Disk Transperency Data: Lake water clarity is typically measured by Secchi disk and the Secchi Disk Transparency (SDT) result serves as an indirect measure of a lake's trophic state. This data is directly comparable to the reflectance information collected by satellite imagery. For this project, transparency data was collected from the literature for lakes in Connecticut (Norvell and Frink, 1975; Frink and Norvell, 1984; Canavan and Siver, 1994; 1995; CAES, 2010). Data ranged from the years 1973 – 2009 which corresponds closely with the launch of the first Landsat satellite in 1972. All SDT data collected for this project are reported in Appendix A. Additionally, a team of students physically collected SDT data during the late July – August 2010 season. This data was used for the 2010 water clarity estimate.

Landsat Satellite Imagery: Connecticut is covered almost entirely by Landsat scene WRS Path 13 Row 31. This path row was, therefore, the only scene examined for this project dating back to 1973. The objective was to find cloud free imagery that corresponded closely with the available SDT data collection. A list of all Landsat data examined are provided in Appendix B. The preference is to have SDT data collected within plus or minus seven days of the Landsat image. Examining 95 satellite images, it was determined that the best dates for producing water clarity estimates would be August 29, 2010 (Landsat 7 ETM), August 21, 2010 (Landsat 5 TM), September 9, 2005 (Landsat 5 TM), August 22, 1993 (Landsat 5 TM), and April 6, 1980 (Landsat 3 MSS) although some of these dates resulted in extending beyond the preferred seven day span of SDT collection (see Appendix C). Some misregistration was identified in the 1980 and 1993 imagery which was shifted to match that found in the 2010 (Table 1).

Table 1. Required shift in the X and Y direction to geographically align with the 2010 Landsat image.

DATE	X SHIFT (meters)	Y SHIFT (meters)
6 April, 1980	-1667	-603
22 August, 1993	+ 3180	+17790

METHODOLOGY

Once the appropriate SDT and Landsat data had been acquired, the follow steps were performed to derive lake water clarity estimates.

Water Extraction: An unsupervised classification process (ISODATA in ERDAS IMAGINE) is applied to the Landsat imagery to identify water and other land cover pixels. Since water is spectrally unique from most other land cover features it tends to be easily identifiable. Thirty clusters are specified and labeled into water or non-water categories. These clusters are recoded into non-water (class 0) and water (class 1). A clump process is applied to the water pixels to identify groups of adjacent water pixels which represent waterbody features. Water clumps less than 3 acres in area are sieved from the clump layer to produce a feature layer of

waterbodies greater than three acres. This waterbody feature layer is used to extract water pixels from the original Landsat image which is then used in the regression model process.

Cloud and Cloud Shadow Removal: Some cloud and cloud shadow existed in the 1993 and 2005 Landsat TM images, however, these were minimal and did not significantly impact the identification of water pixels during the water extraction process. The August 21, 2010 Landsat TM image had significant cloud cover over the western half of the scene and could not be used for water clarity estimation. This area was substituted with the August 29, 2010 Landsat ETM image to derive the water clarity estimation. The April 6, 1980 Landsat MSS scene had no cloud issues.

Prepare Regression Model: Following recommendations found in the literature, the extracted water pixels from Landsat band 1 (blue) and band 3 (red) from the Thematic Mapper Sensor (2010, 2005, 1993) and band 1 (blue/green) and band2 (red) from the Multispectral Scanner (1980) are used to build the regression model. Using a statewide water polygon layer, the average response of each lake in band 1 and the ratio band 1/band3 is determined. Figure 1 provides examples of the derived Landsat data used to derive the data used in the regression model.

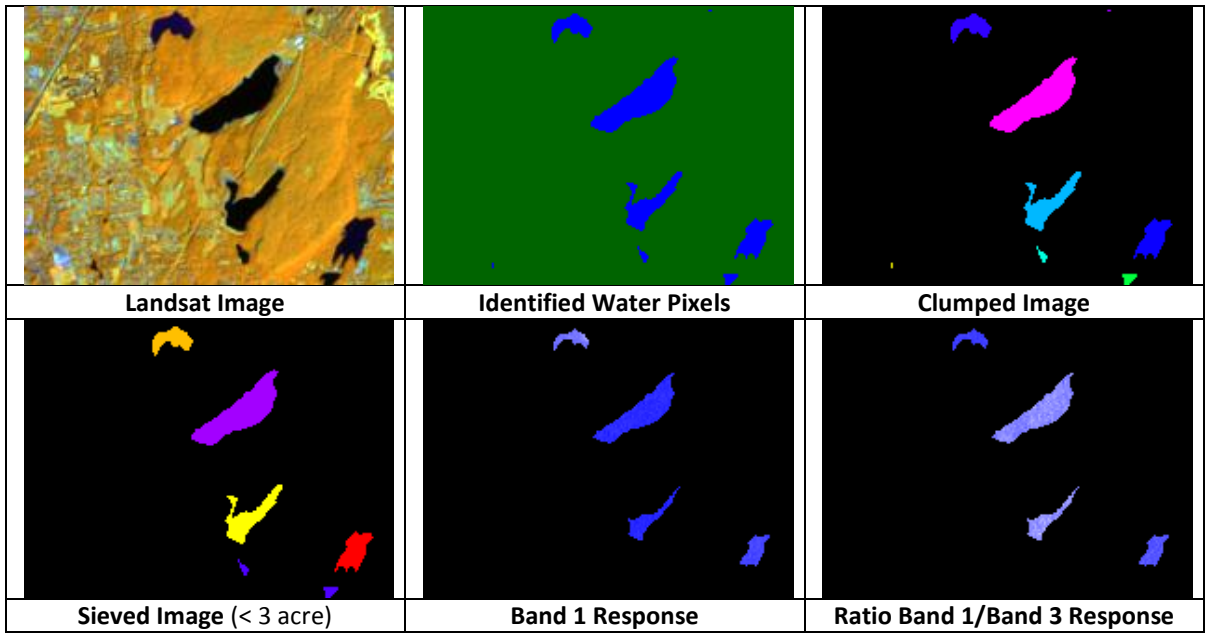

Figure 1. Example data layers created to build regression model.

Regression Model: The Landsat band 1 and the ratio of band 1/band 3 are used as the two independent variables in the model. The SDT data of sampled lakes for a given analysis year, log-transformed, serve as the dependent variable. The general predictive multiple regression equation used for the water clarity estimation is:

$$\ln(SD) = a(TM1/TM3) + b(TM1) + c$$

The resulting multiple regression equations independently derived for each analysis date are provided in Table 2. These models are applied, for each respective date, to the averaged band 1 and ration of band 1/band 3 Landsat data to derive the final lake water clarity estimate.

Table 2. Resulting multiple regression equations used for prediction of water clarity for each analysis date.

Estimation Date	Regression Equations
August 29, 2010	ln(SD)=1.29535(TM3/TM1) + (-0.04106)(TM1) + 0.69188
August 21, 2010	ln(SD)=0.40901(TM3/TM1) + 0.03047(TM1) + (-6.30695)
September 9, 2005	ln(SD)=0.13905(TM3/TM1) + 0.01899(TM1) + (-6.01691)
August 22, 1993	ln(SD)=0.07276(TM3/TM1) + 0.01722(TM1) + (-3.91417)
April 6, 1980	ln(SD)=0.55905(TM3/TM1) + (-0.03638)(TM1) + (-0.42668)

RESULTS AND DISCUSSION

An example of the final result of the water clarity estimation for 2010 is provided in Figure 2. For this particular date, 511 lakes are reported. For 2005, 1993 and 1980, 607 lakes, 550 lakes, and 459 lakes respectively were estimated. The number of lakes, and specific lakes, varied for each date depending on the amount of water pixels identified from the Landsat imagery for

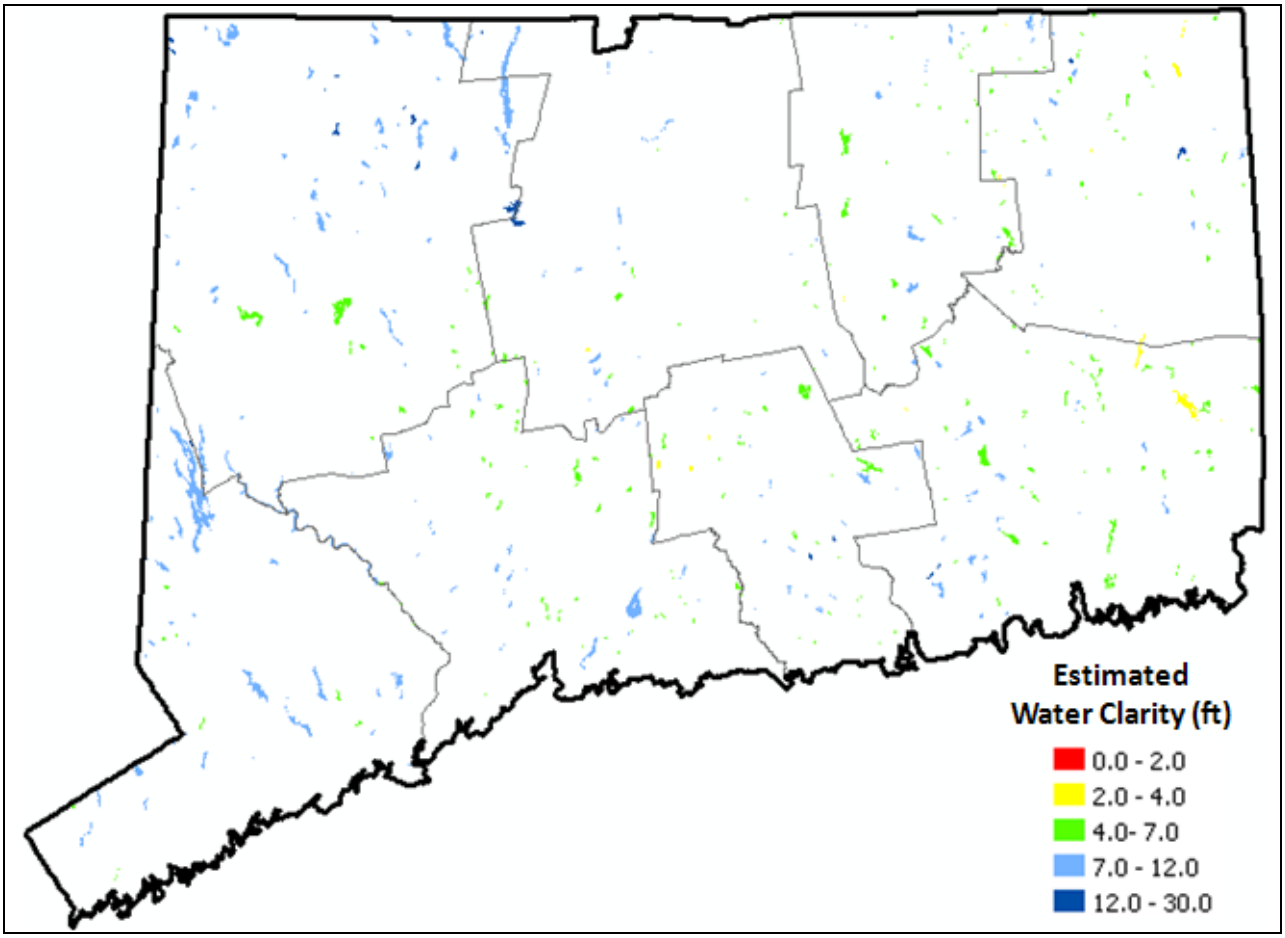

Figure 2. 2010 lake water clarity estimate. 511 lakes reported.

each date assessed. The map indicates differences in water clarity among lakes within the state, and the difference in water clarity is distributed throughout the state. The other dates of resulting water clarity estimation show similar trends. These will be made available online at the Center for Landuse Education and Research (CLEAR) website at http://clear.uconn.edu. Along with tablulature data for direct comparison among dates.

Additional statistical analysis provided in Figure 3 and Figure 4 seems to indicate a trend of decreasing water clarity overall from 1980 to 2010. In Figure 3, the median water clarity from 1980 is 8.44 feet (based on estimation of a springtime MSS Landsat image), 8.87 feet in 1993, 7.19 feet in 2005, and 6.83 feet for 2010. In addition, the maximum water clarity decreases as does the overall range. In Figure 4, most lakes have a slightly deeper water clarity of 7-12 feet in 1980 with this shifting to more lakes having a water clarity depth of 4-7 feet by 2010. Statistical analysis of the quality of the estimates still needs to be performed to determine if these are true trends or just artifacts of the models and imagery used. During the regression model development, 25 percent of the SDT samples, randomly selected, were maintained for validation purposes.

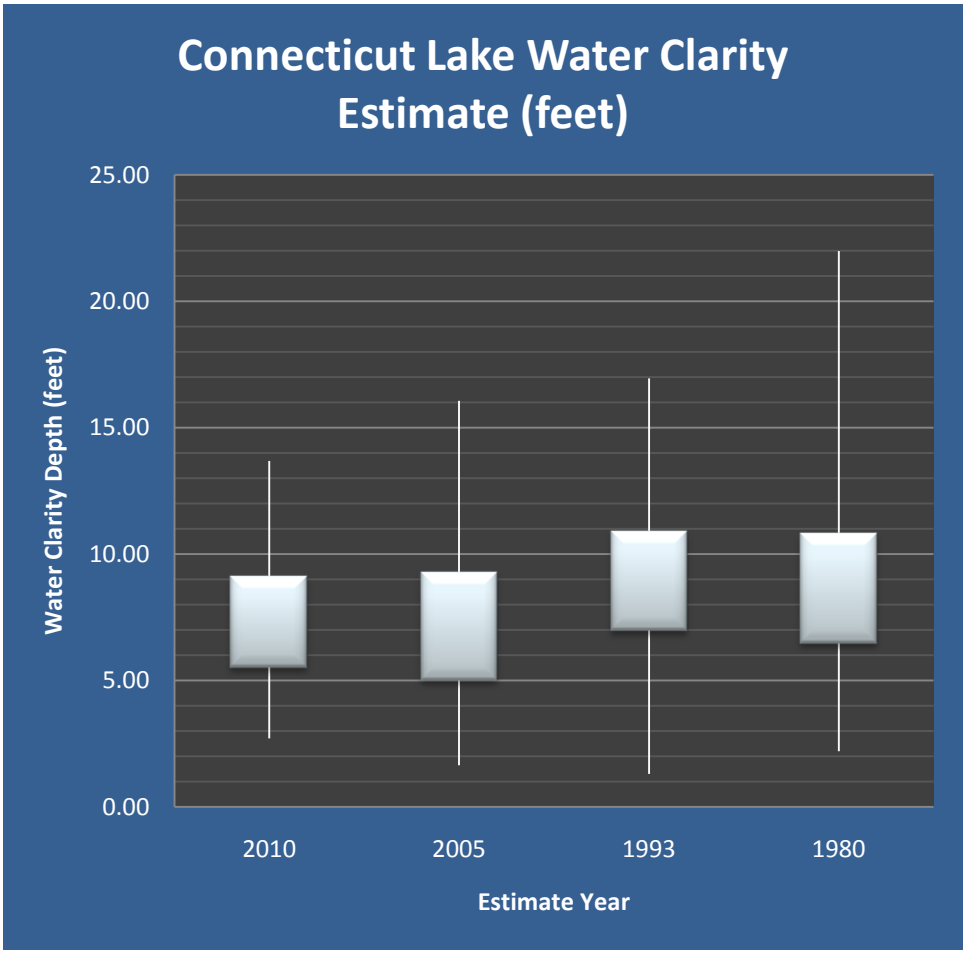

Figure 3. Box plot showing the median water clarity results, 25th and 75th percentile and minimum and maximum results for all lakes for each date assessed.

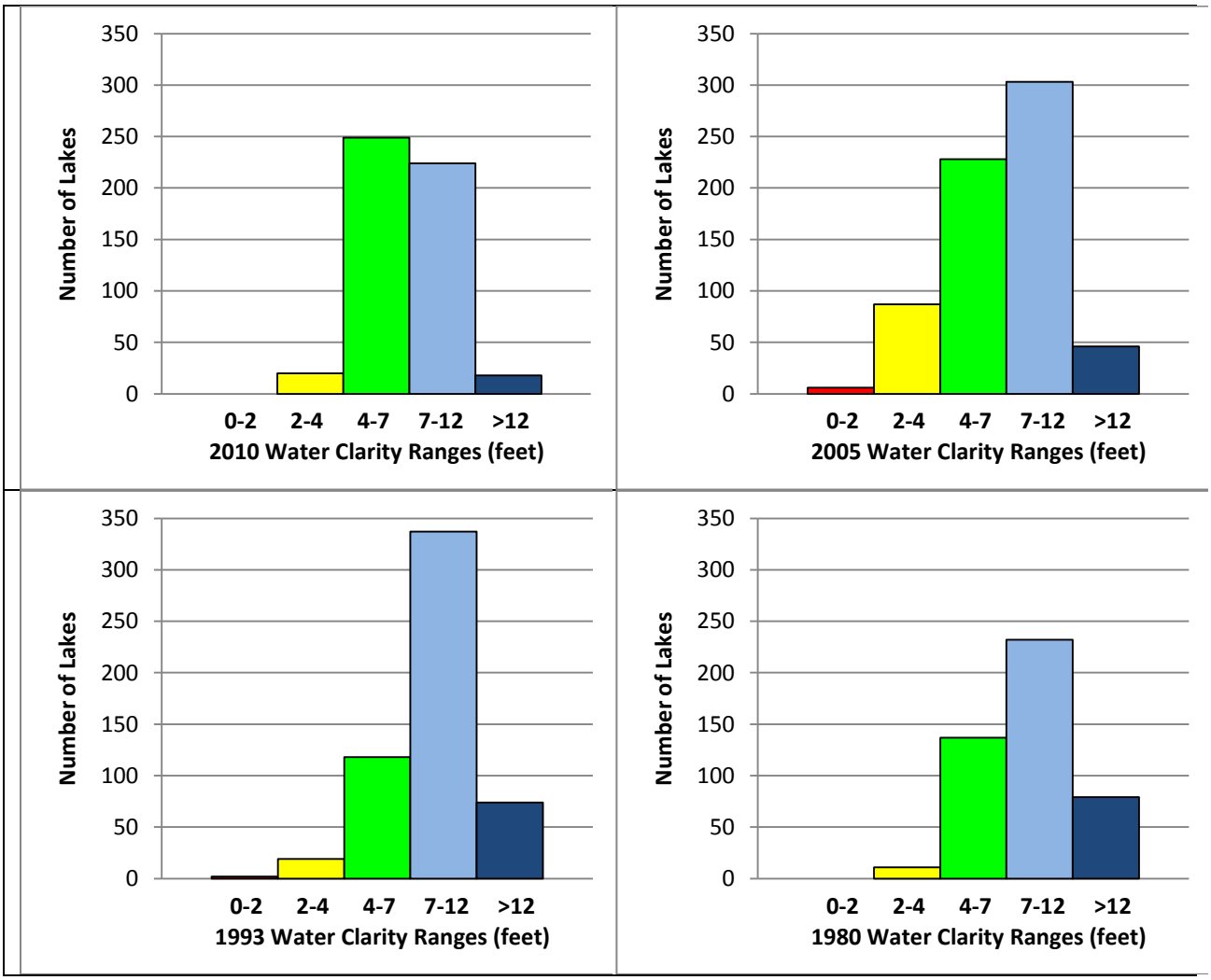

Figure 4. Water quality distribution of lakes in Connecticut for each of the four dates assessed.

FUTURE RECOMMENDATIONS

The following is a list of future research activities and needs:

- Comprehensive set of lake transparency data collected during the mid-July through mid-September time period as near the date of Landsat collection as possible. This can be problematic since we are unable to determine cloud cover until the day of the Landsat satellite overpass. If we can organize a large enough and active group of volunteers to be prepared to collect SDT data, we believe we can be successful at improving the lake water clarity estimates.
- Knowing specific coordinate location of lake transparency data collection will allow for more precision in model development. Currently point transparence data is applied to all water pixels making up the water body as opposed to just the single pixel and/or

immediate eight surrounding neighbors surrounding the area of data collection. Variability within the lake is likely to skew model results.

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APPENDIX A

Secchi Disk Transparency Data Collected

YEAR: 2010					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Wangumbaug Lake	3.7	7/22/2010	Long Pond	3.5	8/16/2010
Little Pond	1.6	7/29/2010	Dodge Pond	3.2	8/17/2010
Mansfield Hollow	2.2	7/30/2010	Gorton Pond	2.1	8/17/2010
Lower Bolton Lake	1.35	8/2/2010	Norwich Pond	2.4	8/17/2010
Middle Bolton	1.8	8/2/2010	Pattagansett Lake	2.7	8/17/2010
Bigelow Pond	2.3	8/4/2010	Powers Lake	4.1	8/17/2010
Black Pond	3.4	8/4/2010	Beseck Lake	0.8	8/19/2010
Mashapaug Pond	4.4	8/4/2010	Black Pond	2.6	8/19/2010
Lake Hayward	2.7	8/10/2010	North Farms Reservoir	1.25	8/19/2010
Moodus Reservoir	1.3	8/10/2010	Silver Lake	0.7	8/19/2010
Pickerel Lake	1.4	8/10/2010	Avery Lake	1.4	8/26/2010
Beach Pond	3.4	8/12/2010	Lantern Hill	2.5	8/26/2010
Glasgo Pond	1.3	8/12/2010	Gardner Lake	2.4	8/27/2010
Hopeville Pond	2.3	8/12/2010	Rogers Lake	3.5	8/27/2010
Pachaug Pond	1.9	8/12/2010	Uncas Pond	3.6	8/27/2010
Lake of Isles	2.4	8/16/2010			

YEAR: 2009					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Taunton Lake	1.5	6/10/2009	Gables Pond	2.6	8/3/2009
Rolling Ridge Pond	0.7	6/12/2009	Indian Lake	2	8/10/2009
Williams Pond	2.3	6/23/2009	Mill Pond Park	1.2	9/4/2009
Basserman Pond	1	6/25/2009	Cusick Pond	2	9/9/2009
Youngs Pond	0.3	7/1/2009	North Farms Rerervoir	1.1	9/9/2009
Redwing Pond	1.1	7/13/2009	Deer Lake	1.3	9/14/2009
Crystal Pond	2.3	7/16/2009	Deer Lake Reservoir	3.7	9/14/2009
Chaffee Lake	2.3	7/20/2009	Fall Mountain Lake	1.7	9/15/2009
Crystal Lake	1	7/20/2009	Fence Rock Lake	2	9/17/2009
Lower Moodus	1.5	7/20/2009	Wah Wah Taysee Pond	2	9/21/2009
Beaver Dam Lake	2	7/22/2009	Spring Lake	1.3	9/24/2009
H-H Camp Pond	1.5	7/23/2009	Hospital reservoir #3	4	9/30/2009
Town Mill Pond	2	7/30/2009			

YEAR: 2008					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Silver Lake	1	7/8/2008	Upper Guilford Lake	0.6	8/5/2008
Coventry Lake	3.3	7/15/2008	Andover Lake	2	8/14/2008
Moosup Pond	3.9	7/23/2008	Williamson Pond	1.8	8/18/2008

Beach Pond	5	7/31/2008			

YEAR: 2007					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Powers Lake	3	7/6/2007	Quaddick Reservoir	2.8	9/6/2007
Rolling Ridge Pond	0.5	7/20/2007	Forest Lake	1.8	9/13/2007
Winchester Lake	3	9/5/2007			

YEAR: 2006					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Ashford Lake	1.1	7/12/2006	Keley (Kelsey) Pond	0.75	8/8/2006
Rogers Lake	2.3	7/13/2006	Gladstone Pond	0.8	8/10/2006
Diamond Lake	2.5	7/14/2006	Pocotopaug Lake	0.5	8/16/2006
Oakwood Pond	1	7/14/2006	Ivoryton Pond	2	8/21/2006
Pattaganset Lake	2.3	7/18/2006	Amston Lake	3.5	8/22/2006
Clear Lake	3	7/19/2006	Bissonette Pond	1	8/28/2006
Gardner Lake	2	7/24/2006	Timbe Lake	2.7	9/7/2006
Amos Lake	2.3	8/1/2006	Mystic Seaport Pond	1.5	9/8/2006
Indian Lake	1	8/3/2006	Lower Pond	1.5	9/13/2006

YEAR: 2005					
LAKE NAME	**DEPTH (ft)**	**DATE COLLECTED**	**LAKE NAME**	**DEPTH (ft)**	**DATE COLLECTED**
Nichols Pond	0.9	6/29/2005	Chase Reservoir	2.7	8/8/2005
Pistapaug Pond	3.2	6/29/2005	Hayward Lake	2.2	8/9/2005
Mackenzie Reservoir	0.9	6/30/2005	Staffordville Rerervoir	3.2	8/11/2005
Long Meadow Pond	1.6	7/5/2005	Howells Pond	1.2	8/12/2005
Talmadge Ice Pond	1	7/7/2005	Mamanasco Lake	0.8	8/15/2005
Dayton Pond	1.4	7/8/2005	Messerschmidt Pond	2.8	8/16/2005
Lucky Pond	0.7	7/8/2005	Ball Pond	2	8/17/2005
Hidden Lake	1.9	7/11/2005	Black Hall Pond	2.8	8/18/2005
Housantonic Lake	2	7/12/2005	Millers Pond	4	8/22/2005
Alexander Lake	5.8	7/13/2005	Morey Pond	3.5	8/23/2005
Bigelow Pond	2.5	7/14/2005	Hamlin Pond	1.2	8/24/2005
Shelton Rerervoir #2	2.2	7/15/2005	Paderewski Park Pond	0.9	8/24/2005
Shelton Rerervoir #3	3	7/15/2005	Crystal Lake	2.9	8/25/2005
Ulbrich Rerervoir	2.6	7/18/2005	West Lake	2.5	8/25/2005
Upper Bolton Lake	0.8	7/18/2005	Tyler Lake	2.1	8/30/2005
Lower Bolton Lake	3.2	7/19/2005	Birch Pond	0.4	9/1/2005
Middle Bolton Lake	2.9	7/19/2005	Dunlop Pond	1.4	9/1/2005
Chalkers Mill Pond	0.5	7/22/2005	Tilleys Pond	0.8	9/1/2005
Crystal Lake	0.6	7/22/2005	Williams Brook (Highland Lake)	1.5	9/2/2005
Black Pond	3.8	7/25/2005	Winnemaug Lake	1.1	9/6/2005
Burr Pond	2.4	7/25/2005	Echo Lake	1.2	9/7/2005

Spring Lake	0.8	7/26/2005	Merriman Pond	1.5	9/8/2005
Cescent Lake	1	7/27/2005	Sylvan Lake	1.4	9/8/2005
Mills Pond, Lower	1	7/27/2005	Wampum Hill Pond	0.7	9/9/2005
Mills Pond, Upper	1	7/27/2005	West Side Pond	5.1	9/12/2005
Hummers Pond	1.5	7/28/2005	Mohawk Pond	5.4	9/13/2005
Schreeder Pond	1.7	7/28/2005	West Hill Pond	10.2	9/14/2005
Branford Suppy Pond (East)	1.5	8/1/2005	Billings Lake	5.4	9/22/2005
Halls Pond	3	8/1/2005	North Pond	1.3	9/23/2005
Cedar Pond	2.3	8/1/2005	Silvias Pond	1.1	9/26/2005
Great Hill Pond	2.4	8/1/2005	Bantam Pond	1.4	9/27/2005
Green Falls Reservoir	5.6	8/2/2005	Quonnipaug Lake	3.9	9/28/2005
Angus Park Pond	1.2	8/4/2005	Waubeeka Lake	2.4	9/28/2005
Horse Pond	2.6	8/4/2005	Avery Pond	1.2	9/30/2005
Salmon Brook	0.7	8/4/2005	Blissville Pond	1.7	9/30/2005
Dog Pond	2.5	8/5/2005			

YEAR: 2004

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Graniss Lake	4	5/11/2004	Terramuggus Lake	5.3	7/29/2004
Dooley Pond	1.7	6/18/2004	Kenosia Lake	2	8/2/2004
North Farms Rerervoir	0.5	6/21/2004	Crystal Lake	1.8	8/6/2004
Beseck Lake	2.5	6/24/2004	Wintergreen Lake	3.7	8/9/2004
Black Pond	4	6/25/2004	Highland Lake	3.25	8/10/2004
Cedar Lake	3	6/29/2004	Hammonasset Lake	1.8	8/11/2004
Higganum Reservoir	1.5	7/1/2004	Anderson Pond	1.4	8/12/2004
Silver Lake	1.8	7/6/2004	Batterson Park Pond	1.4	8/13/2004
Uncas Lake	3.3	7/7/2004	Canoe Brook Lake	3.6	8/18/2004
Norwich Pond	1.7	7/8/2004	Pinewood Lake	1.6	8/25/2004
Dodge Pond	2.2	7/9/2004	Bashan Lake	4.2	8/27/2004
Gorton Pond	1.6	7/12/2004	Maltby Lake #3	5.4	8/27/2004
Pickerel Lake	2	7/16/2004	Maltby Lake #1	2.8	9/2/2004
Manitook Lake	3.4	7/19/2004	Maltby Lake #2	8.3	9/2/2004
Saltonstall Lake	2.1	7/23/2004	Wononscopomuc Lake	4.2	9/15/2004
Holbrook Pond	1	7/27/2004			

YEAR: 1993

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Norwich Pond	2.4	6/1/1993	Beseck Lake	2.1	7/9/1993
Pataganset Lake	3.4	6/1/1993	Black Pond	3.8	7/9/1993
Powers Lake	3.2	6/1/1993	Amos Lake	2.3	7/13/1993
Rogers Lake	2.9	6/1/1993	Lantern Hill Pond	2.6	7/13/1993
Uncas Pond	3.5	6/1/1993	Long Pond	4.8	7/13/1993
Anderson Pond	1.4	6/2/1993	Norwich Pond	3.1	7/14/1993
Beach Pond	3.9	6/2/1993	Pataganset Lake	2.9	7/14/1993
Beachdale Pond	1.5	6/2/1993	Rogers Lake	4.6	7/14/1993

Billings Lake	3.6	6/2/1993	Uncas Pond	5.3	7/14/1993
Green Falls Reservoir	6.9	6/2/1993	Alexander Lake	5.6	7/16/1993
Pachaug Pond	2	6/2/1993	Killingly Pond	5.5	7/16/1993
Amos Lake	2.4	6/3/1993	Beach Pond	4.3	7/20/1993
Avery Pond	2.2	6/3/1993	Beachdale Pond	2	7/20/1993
Lantern Hill Pond	3	6/3/1993	Green Falls Reservoir	6.2	7/20/1993
Long Pond	3.2	6/3/1993	Pachaug Pond	2	7/20/1993
Wyassup Lake	4.3	6/3/1993	Linsley Pond	2.1	7/21/1993
Bashan Lake	5.8	6/8/1993	Crystal Lake	4.1	7/22/1993
Silver Lake	1.1	6/8/1993	Gardner Lake	2.6	7/22/1993
Crystal Lake	2.1	6/9/1993	Wamgumbaug Lake	2.8	7/22/1993
Gardner Lake	2.8	6/9/1993	Ball Pond	2.1	7/26/1993
Lake Hayward	4	6/9/1993	Kenoxia Lake	1.9	7/26/1993
Alexander Lake	5.6	6/11/1993	Bantam Lake	0.9	7/27/1993
Black Pond	4.2	6/11/1993	Lake Quassapaug	4.6	7/27/1993
Mashapaug Lake	3.3	6/11/1993	Lake Waramaug	2.3	7/27/1993
Ball Pond	3.1	6/13/1993	Tyler Lake	2.2	7/27/1993
State Lind Pond	1.6	6/14/1993	West Side Pond	4.7	7/27/1993
Beseck Lake	2.7	6/15/1993	Bigelow Pond	3.4	7/28/1993
Black Pond	3.6	6/15/1993	Black Pond	4.2	7/28/1993
Kenoxia Lake	2.4	6/16/1993	Mashapaug Lake	6.7	7/28/1993
Bantam Lake	3.3	6/22/1993	Highland Lake	4.2	8/2/1993
Lake Quassapaug	3.6	6/22/1993	Lake Winchester	3	8/2/1993
Lake Waramaug	1.4	6/22/1993	West Hill Pond	6.4	8/2/1993
Mohawk Pond	3.8	6/22/1993	Dog Pond	2.2	8/3/1993
Mount Tom Pond	4.9	6/22/1993	East Twin Lake	4	8/3/1993
East Twin Lake	4.3	6/23/1993	Mohawk Pond	4.9	8/3/1993
Emmons Pond	1.7	6/23/1993	Mount Tom Pond	3.8	8/3/1993
Highland Lake	4.4	6/23/1993	Wonoscopomuc Lake	4.9	8/3/1993
Lake Winchester	3.7	6/23/1993	Avery Pond	0.9	8/10/1993
Tyler Lake	2.5	6/23/1993	Lake Hayward	3.5	8/10/1993
West Hill Pond	9.4	6/23/1993	Anderson Pond	1.6	8/11/1993
West Side Pond	3.3	6/23/1993	Billings Lake	4.6	8/11/1993
Wonoscopomuc Lake	4.2	6/23/1993	Wyassup Lake	3.3	8/11/1993
Roseland Lake	0.6	6/28/1993	Squantz Pond	2.9	8/25/1993
Wamgumbaug Lake	4.8	6/28/1993	Candlewood Lake	2.7	8/27/1993
Quonnipaug Lake	4.6	6/29/1993	Linsley Pond	1.6	9/8/1993
Terramuggus Lake	4.8	6/29/1993	Quonnipaug Lake	3.4	9/8/1993
State Lind Pond	1.4	7/8/1993	Terramuggus Lake	5.6	9/8/1993
Bashan Lake	6.2	7/9/1993			

YEAR: 1992

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Gardner Lake	3.4	6/3/1992	Killingly Pond	5.2	6/30/1992
Lake Hayward	3.9	6/3/1992	Beseck Lake	2.6	7/10/1992
Pataganset Lake	2.8	6/3/1992	Black Pond	3.2	7/10/1992
Norwich Pond	2.7	6/4/1992	Crystal Lake	1.1	7/10/1992
Rogers Lake	2.8	6/4/1992	Silver Lake	1.7	7/10/1992

Uncas Pond	3.7	6/4/1992	East Twin Lake	2.9	7/20/1992
Lantern Hill Pond	1.9	6/5/1992	Lake Winchester	2.9	7/20/1992
Long Pond	3.1	6/5/1992	West Hill Pond	7.3	7/20/1992
Pataganset Lake	2.7	6/10/1992	Wonoscopomuc Lake	4.4	7/20/1992
Roseland Lake	1.2	6/11/1992	Candlewood Lake	2.1	7/21/1992
Bigelow Pond	2.1	6/12/1992	Lake Waramaug	1.8	7/21/1992
Mashapaug Lake	3.5	6/12/1992	Squantz Pond	4	7/21/1992
Black Pond	4.3	6/13/1992	Bantam Lake	2.3	7/22/1992
Amos Lake	1.9	6/16/1992	Dog Pond	2.1	7/22/1992
Avery Pond	1.6	6/16/1992	Mohawk Pond	4.3	7/22/1992
Beach Pond	4	6/23/1992	Mount Tom Pond	3.8	7/22/1992
Billings Lake	4.4	6/23/1992	Tyler Lake	3.4	7/22/1992
Pachaug Pond	1.8	6/23/1992	West Side Pond	3	7/22/1992
Wyassup Lake	3.4	6/23/1992	Dog Pond	2.8	7/30/1992
Bashan Lake	4.9	6/26/1992	Rogers Lake	3.4	9/4/1992
Crystal Lake	2.6	6/26/1992	Long Pond	4.2	9/10/1992
State Lind Pond	1.3	6/26/1992	Wamgumbaug Lake	3.5	9/17/1992
Wamgumbaug Lake	4.1	6/26/1992	Beach Pond	5.3	9/19/1992
Alexander Lake	6.2	6/30/1992	Bashan Lake	6.7	10/5/1992
Anderson Pond	1.3	6/30/1992	Pataganset Lake	2.4	10/5/1992
Beachdale Pond	1	6/30/1992	Long Pond	3.8	10/29/1992

YEAR: 1991

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Beseck Lake	1.9	4/12/1989	Beseck Lake	1.5	8/1/1989
Crystal Lake	2.3	4/12/1989	Gardner Lake	1.5	8/3/1989
Gardner Lake	1.7	4/14/1989	Dog Pond	1.8	8/9/1989
Lake Hayward	3.5	4/14/1989	Lake Winchester	2.1	8/9/1989
Lake Quassapaug	2.3	4/19/1989	Lake Quassapaug	1.5	8/10/1989
West Hill Pond	4.9	4/21/1989	West Hill Pond	7	8/17/1989
Alexander Lake	6.7	4/25/1989	Crystal Lake	2.4	8/21/1989
Killingly Pond	4.6	4/25/1989	East Twin Lake	4.6	8/24/1989
Avery Pond	2.3	4/26/1989	Wonoscopomuc Lake	6.1	8/25/1989
Beachdale Pond	1.5	4/26/1989	Alexander Lake	6.1	8/28/1989
Lake of Isles	3	4/26/1989	Killingly Pond	4.6	8/28/1989
Long Pond	3	4/26/1989	Lake Hayward	3.2	8/29/1989
Green Falls Reservoir	5.2	5/11/1989	Beachdale Pond	1.1	9/1/1989
Dog Pond	1.5	5/12/1989	Long Pond	4.1	9/5/1989
Lake Winchester	3.4	5/12/1989	Avery Pond	0.9	9/6/1989
East Twin Lake	4.3	5/17/1989	Green Falls Reservoir	7.5	9/6/1989
Wonoscopomuc Lake	3	5/17/1989	Lake of Isles	2.1	9/6/1989

YEAR: 1990

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Anderson Pond	1.1	5/9/1990	Dog Pond	2.9	6/15/1990
Lantern Hill Pond	3	5/9/1990	Lake Waramaug	2.7	6/15/1990

Red Cedar Lake	2.6	5/10/1990	Tyler Lake	4	6/15/1990
Lake Waramaug	1.7	6/5/1990	East Twin Lake	6	6/26/1990
Beach Pond	4.9	6/11/1990	Wonoscopomuc Lake	6	6/26/1990
Beachdale Pond	1.3	6/12/1990	Lake Waramaug	2.1	7/31/1990
Green Falls Reservoir	5.4	6/12/1990	Red Cedar Lake	2	8/9/1990
Pachaug Pond	1.5	6/12/1990	Mohawk Pond	5	8/17/1990
Avery Pond	1.9	6/13/1990	Anderson Pond	0.9	8/21/1990
Mohawk Pond	5.1	6/13/1990	Lantern Hill Pond	1.5	8/21/1990
West Side Pond	3.2	6/13/1990	West Side Pond	2.4	8/23/1990
West Side Pond	3.5	6/14/1990	Lake Waramaug	1.8	8/31/1990

YEAR: 1989

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Beseck Lake	1.9	4/12/1989	Beseck Lake	1.5	8/1/1989
Crystal Lake	2.3	4/12/1989	Gardner Lake	1.5	8/3/1989
Gardner Lake	1.7	4/14/1989	Dog Pond	1.8	8/9/1989
Lake Hayward	3.5	4/14/1989	Lake Winchester	2.1	8/9/1989
Lake Quassapaug	2.3	4/19/1989	Lake Quassapaug	1.5	8/10/1989
West Hill Pond	4.9	4/21/1989	West Hill Pond	7	8/17/1989
Alexander Lake	6.7	4/25/1989	Crystal Lake	2.4	8/21/1989
Killingly Pond	4.6	4/25/1989	East Twin Lake	4.6	8/24/1989
Avery Pond	2.3	4/26/1989	Wonoscopomuc Lake	6.1	8/25/1989
Beachdale Pond	1.5	4/26/1989	Alexander Lake	6.1	8/28/1989
Lake of Isles	3	4/26/1989	Killingly Pond	4.6	8/28/1989
Long Pond	3	4/26/1989	Lake Hayward	3.2	8/29/1989
Green Falls Reservoir	5.2	5/11/1989	Beachdale Pond	1.1	9/1/1989
Dog Pond	1.5	5/12/1989	Long Pond	4.1	9/5/1989
Lake Winchester	3.4	5/12/1989	Avery Pond	0.9	9/6/1989
East Twin Lake	4.3	5/17/1989	Green Falls Reservoir	7.5	9/6/1989
Wonoscopomuc Lake	3	5/17/1989	Lake of Isles	2.1	9/6/1989

YEAR: 1980

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Quonnipaug	3	4/1/1980	Quonnipaug	4.4	7/16/1980
Norwich	3.2	4/2/1980	Winnemaug	1.3	7/18/1980
Powers	3.5	4/2/1980	Powers	3.2	7/21/1980
Uncas	5.2	4/2/1980	Bashan	5.5	7/22/1980
Amos	2.6	4/3/1980	Ball	2.5	7/24/1980
Billings	5.2	4/3/1980	Moodus	2	7/25/1980
Bashan	6	4/7/1980	Long Meadow	1.3	7/28/1980
Moodus	2.1	4/7/1980	Norwich	3	7/30/1980
Columbia	3	4/8/1980	Uncas	5.4	7/30/1980
Waumgumbaug	3.6	4/8/1980	Kenosia	1.8	7/31/1980
Glasgo	2.8	4/9/1980	Columbia	5	8/5/1980
Ball	1.3	4/11/1980	Waumgumbaug	6.1	8/5/1980
Winnemaug	1.3	4/11/1980	Eagleville	1.5	8/6/1980

Long Meadow	1.1	4/14/1980	Squantz	3.4	8/7/1980
Kenosia	1	4/15/1980	Burr	2.7	8/8/1980
Squantz	5.2	4/15/1980	Amos	3.7	8/18/1980
Little	3.1	4/17/1980	Bigelow	2.5	8/19/1980
Quaddick	5.1	4/17/1980	Black (Woodstock)	3	8/19/1980
Bigelow	5.2	4/18/1980	Billings	4.5	8/20/1980
Black (Woodstock)	5.2	4/18/1980	Glasgo	2	8/22/1980
Burr	3.7	4/21/1980	Little	3	8/25/1980
Housatonic	2.1	5/5/1980	Quaddick	2.3	8/25/1980
Eagleville	2.3	5/9/1980	Housatonic	2	8/28/1980

YEAR: 1979

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Black (Meriden)	2.3	3/26/1979	Highland	6	8/2/1979
North Farms	1.5	3/26/1979	Beach	7.2	8/3/1979
Silver(Berlin)	2.5	3/26/1979	Dodge	4	8/7/1979
Cedar Lake	4.3	3/27/1979	Gorton	2	8/7/1979
Gorton	2.5	3/27/1979	Crystal(Ellington)	4	8/13/1979
Beach	6	4/4/1979	Mashapaug	8.2	8/13/1979
Wyassup	4.3	4/4/1979	Pachaug	3.5	8/14/1979
Mount Tom	3.5	4/5/1979	Cedar Lake	4.1	8/15/1979
Crystal(Ellington)	3.5	4/10/1979	Wyassup	4.3	8/16/1979
Mashapaug	6	4/10/1979	Tyler	3.8	8/17/1979
Highland	4.3	4/11/1979	Mount Tom	4.5	8/20/1979
Tyler	3.3	4/11/1979	Middle Bolton	2.5	8/21/1979
Lower Bolton	3.3	4/17/1979	Hitchcock	2	8/28/1979
Mamanasco	3	4/20/1979	Batterson Park	1.5	8/29/1979
1860 Reservoir	1	4/24/1979	Mamanasco	1.8	8/29/1979
Batterson Park	2.3	4/24/1979	Black (Meriden)	2.5	8/30/1979
Middle Bolton	2.5	4/24/1979	Silver(Berlin)	1.8	8/30/1979
Dodge	4.8	4/30/1979	Lower Bolton	2.3	9/1/1979
Pachaug	3	5/2/1979	North Farms	1	9/1/1979
Hitchcock	3	5/7/1979	1860 Reservoir	1	10/1/1979

YEAR: 1974

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Beseck Lake	2.2	4/3/1974	Candlewood Lake	5.7	7/15/1974
Cedar Pond	1.1	4/3/1974	Alexander Lake	6.3	7/17/1974
Linsley Pond	1.1	4/3/1974	Roseland Lake	2.5	7/17/1974
Long Pond	3.2	4/10/1974	Bantam Lake	1.5	7/23/1974
Pataganset Lake	3	4/10/1974	Beseck Lake	2.5	7/23/1974
Lake Pocotopaug	2.5	4/15/1974	Cedar Pond	0.9	7/23/1974
Terramuggus Lake	4.4	4/15/1974	Quassapaug Lake	7.5	7/23/1974
Quassapaug Lake	2.5	4/22/1974	Lake Lillinonah	2.5	7/25/1974
Shenipsit Lake	3	4/22/1974	Lake Hayward	3.3	7/29/1974
West Hill Pond	5.5	4/23/1974	East Twin Lake	6	7/30/1974

Bantam Lake	3	4/24/1974	Mudge Pond	3.8	7/30/1974
Gardner Lake	3.5	4/25/1974	Lake Zoar	2.5	7/31/1974
Lake Hayward	4.8	4/25/1974	Roseland Lake	3	8/1/1974
Taunton Pond	3.5	4/29/1974	Long Pond	4.8	8/6/1974
Mudge Pond	2.5	4/30/1974	Lake Pocotopaug	4.3	8/8/1974
Waramaug Lake	2	4/30/1974	Terramuggus Lake	6	8/8/1974
Roseland Lake	2	5/2/1974	Linsley Pond	3.5	8/9/1974
Alexander Lake	9.7	5/5/1974	Candlewood Lake	4.5	8/13/1974
East Twin Lake	5.3	5/7/1974	Taunton Pond	3.3	8/13/1974
Wononscopomuc Lake	1	5/7/1974	Shenipsit Lake	3.5	8/20/1974
Candlewood Lake	5.3	5/8/1974	Gardner Lake	4.8	8/21/1974
Lake Lillinonah	3.2	5/31/1974	Pataganset Lake	3	8/21/1974
Lake Zoar	2.2	5/31/1974	Bantam Lake	2.2	8/22/1974
Beseck Lake	4	6/21/1974	Waramaug Lake	3.2	8/22/1974
Bantam Lake	1.8	6/24/1974	West Hill Pond	7.2	8/22/1974
Quassapaug Lake	6.8	6/27/1974	Beseck Lake	2	8/26/1974
Shenipsit Lake	4.5	6/28/1974	Quassapaug Lake	6	8/26/1974
Gardner Lake	3.5	7/1/1974	Alexander Lake	8.2	8/27/1974
Pataganset Lake	2.5	7/1/1974	Mudge Pond	4	8/28/1974
Waramaug Lake	2.3	7/2/1974	Lake Zoar	2.1	8/29/1974
West Hill Pond	6.8	7/2/1974	East Twin Lake	5	9/4/1974
Lake Zoar	1	7/3/1974	Wononscopomuc Lake	8.2	9/4/1974
Lake Lillinonah	1.3	7/8/1974	Lake Pocotopaug	2	9/5/1974
Lake Pocotopaug	4.5	7/9/1974	Candlewood Lake	5.3	9/10/1974
East Twin Lake	5	7/10/1974	Lake Lillinonah	1.9	9/12/1974
Mudge Pond	4.5	7/11/1974	Lake Hayward	3.3	11/20/1974
Wononscopomuc Lake	7.3	7/11/1974			

YEAR: 1973

LAKE NAME	DEPTH (ft)	DATE COLLECTED	LAKE NAME	DEPTH (ft)	DATE COLLECTED
Bantam Lake	2	9/26/1973	Waramaug Lake	2	11/5/1973
Lake Zoar	1.5	10/4/1973	Mudge Pond	2.5	11/7/1973
East Twin Lake	6.2	10/17/1973	Cedar Pond	2	11/9/1973
Wononscopomuc Lake	4.3	10/17/1973	Linsley Pond	1.5	11/9/1973
Lake Lillinonah	2	10/19/1973	Gardner Lake	3.3	11/13/1973
Alexander Lake	5.7	10/23/1973	Pataganset Lake	3	11/13/1973
Shenipsit Lake	2.5	10/25/1973	Lake Pocotopaug	4.5	11/15/1973
Beseck Lake	2	10/31/1973	Terramuggus Lake	5.5	11/15/1973
Taunton Pond	4.5	11/2/1973	Candlewood Lake	5.2	11/20/1973
Quassapaug Lake	2.2	11/5/1973	Long Pond	3.2	11/20/1973

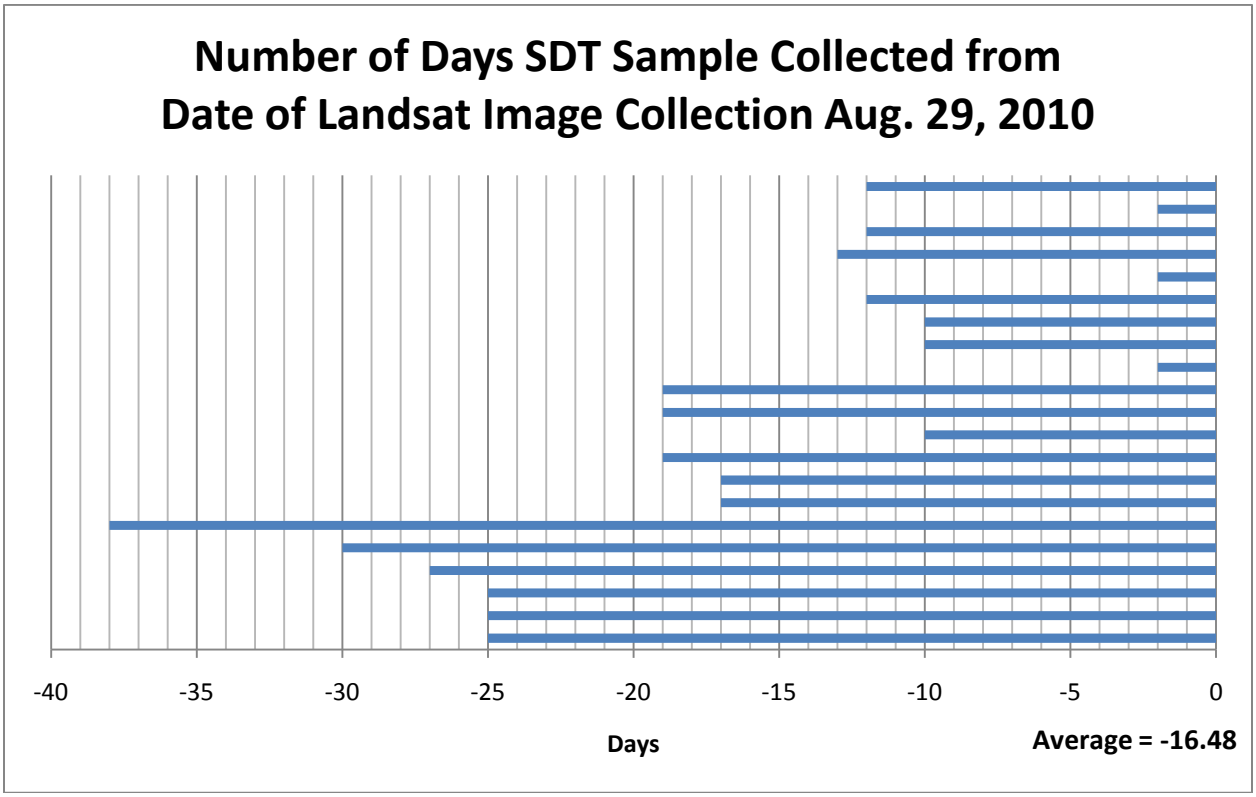
APPENDIX B

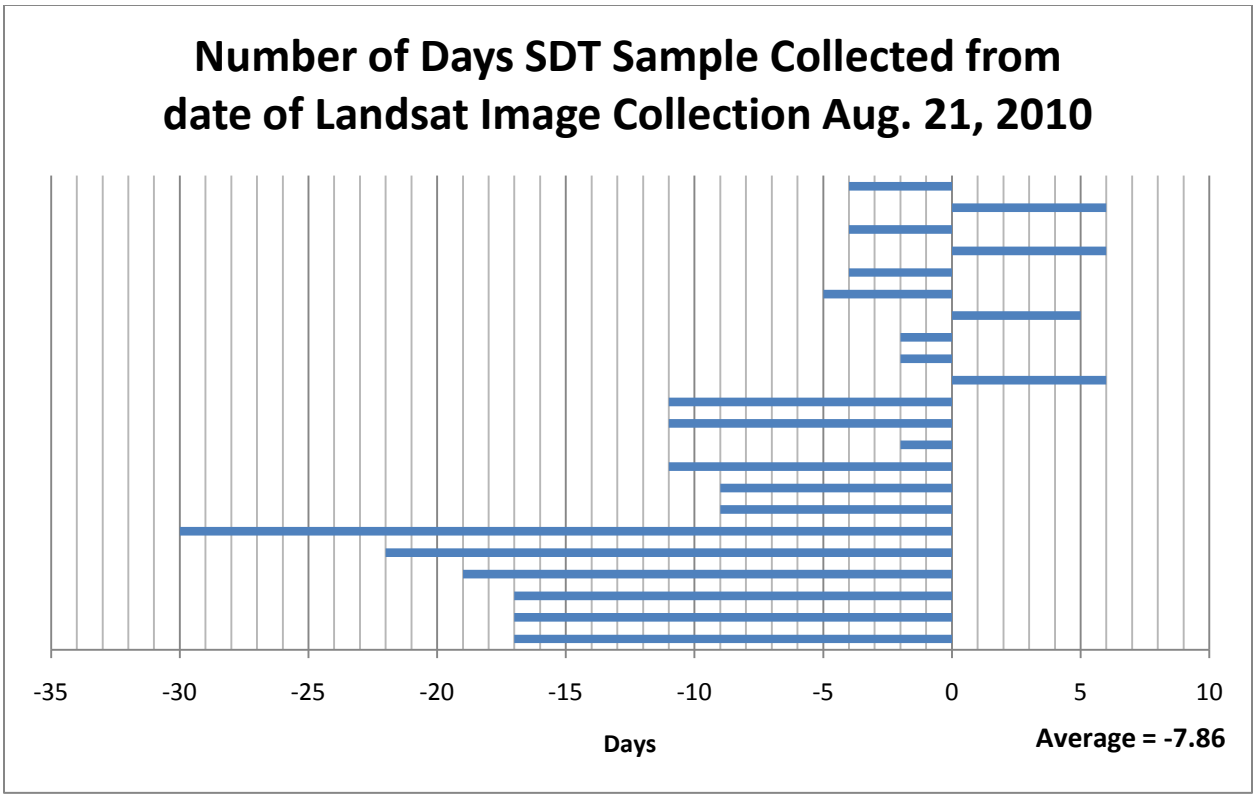
Landsat Satellite Imagery Examined

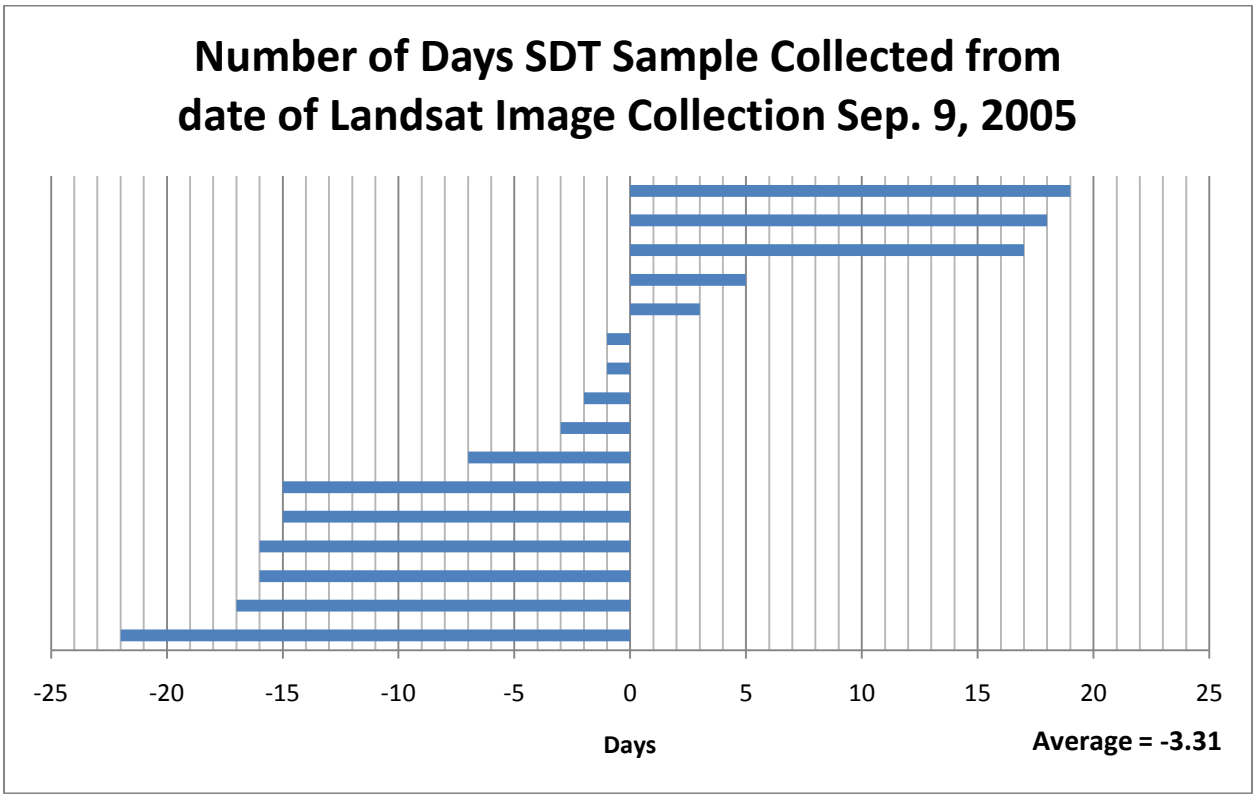
PLATFORM AND SENSOR	COLLECTION DATE	PLATFORM AND SENSOR	COLLECTION DATE	PLATFORM AND SENSOR	COLLECTION DATE
Landsat 5, TM	August 30, 2010	Landsat 7, ETM	October 26, 2007	Landsat 7, ETM	April 9, 2005
Landsat 7, ETM	August 29, 2010	Landsat 5, TM	September 30, 2007	Landsat 5, TM	October 7, 2004
Landsat 5, TM	August 21, 2010	Landsat 5, TM	September 7, 2007	Landsat 5, TM	August 29, 2004
Landsat 5, TM	August 14, 2010	Landsat 7, ETM	August 30, 2007	Landsat 7, ETM	August 28, 2004
Landsat 7, ETM	August 13, 2010	Landsat 5, TM	August 29, 2007	Landsat 5, TM	August 20, 2004
Landsat 7, ETM	August 6, 2010	Landsat 7, ETM	August 14, 2007	Landsat 5, TM	August 4, 2004
Landsat 5, TM	August 5, 2010	Landsat 7, ETM	August 5, 2007	Landsat 7, ETM	July 11, 2004
Landsat 7, ETM	July 28, 2010	Landsat 5, TM	July 12, 2007	Landsat 7, ETM	July 4, 2004
Landsat 7, ETM	July 21, 2010	Landsat 5, TM	June 26, 2007	Landsat 5, TM	July 3, 2004
Landsat 5, TM	July 20, 2010	Landsat 7, ETM	June 2, 2007	Landsat 5, TM	August 20, 2004
Landsat 5, TM	July 13, 2010	Landsat 5, TM	April 23, 2007	Landsat 7, ETM	June 9, 2004
Landsat 7, ETM	July 12, 2010	Landsat 5, TM	October 13, 2006	Landsat 7, ETM	May 8, 2004
Landsat 5, TM	July 2, 2010	Landsat 5, TM	September 11, 2006	Landsat 5, TM	August 22, 1993
Landsat 7, ETM	May 25, 2010	Landsat 5, TM	August 10, 2006	Landsat 5, TM	July 21, 1993
Landsat 5, TM	May 1, 2010	Landsat 5, TM	August 3, 2006	Landsat 5, TM	June 3, 1993
Landsat 5, TM	April 15, 2010	Landsat 7, ETM	August 2, 2006	Landsat 5, TM	September 20, 1992
Landsat 7, ETM	September 20, 2009	Landsat 7, ETM	August 2, 2006	Landsat 5, TM	August 19, 1992
Landsat 5, TM	September 19, 2009	Landsat 7, ETM	July 26, 2006	Landsat 5, TM	June 16, 1992
Landsat 7, ETM	September 4, 2009	Landsat 5, TM	July 25, 2006	Landsat 5, TM	October 4, 1991
Landsat 7, ETM	August 19, 2009	Landsat 5, TM	July 18, 2006	Landsat 5, TM	September 2, 1991
Landsat 5, TM	August 18, 2009	Landsat 7, ETM	July 17, 2006	Landsat 5, TM	August 17, 1991
Landsat 7, ETM	August 3, 2009	Landsat 5, TM	July 9, 2006	Landsat 5, TM	August 2, 1991
Landsat 7, ETM	July 25, 2009	Landsat 7, ETM	July 1, 2006	Landsat 5, TM	August 1, 1991
Landsat 5, TM	July 10, 2009	Landsat 5, TM	April 20, 2006	Landsat 5, TM	July 16, 1991
Landsat 5, TM	April 12, 2009	Landsat 7, ETM	October 2, 2005	Landsat 5, TM	June 14, 1991
Landsat 7, ETM	September 24, 2008	Landsat 5, TM	September 9, 2005	Landsat 2, MSS	June 26, 1980
Landsat 5, TM	August 31, 2008	Landsat 5, TM	September 1, 2005	Landsat 3, MSS	April 6, 1980
Landsat 5, TM	July 30, 2008	Landsat 5, TM	August 23, 2005	Landsat 2, MSS	September 12, 1979
Landsat 5, TM	June 12, 2008	Landsat 5, TM	August 16, 2005	Landsat 3, MSS	August 16, 1979
Landsat 5, TM	May 11, 2008	Landsat 7, ETM	July 30, 2005	Landsat 2, MSS	May 9, 1979
Landsat 5, TM	April 25, 2008	Landsat 5, TM	July 22, 2005	Landsat 1, MSS	July 1, 1974
Landsat 7, ETM	November 25, 2007	Landsat 5, TM	April 17, 2005	Landsat 1, MSS	October 22, 1973

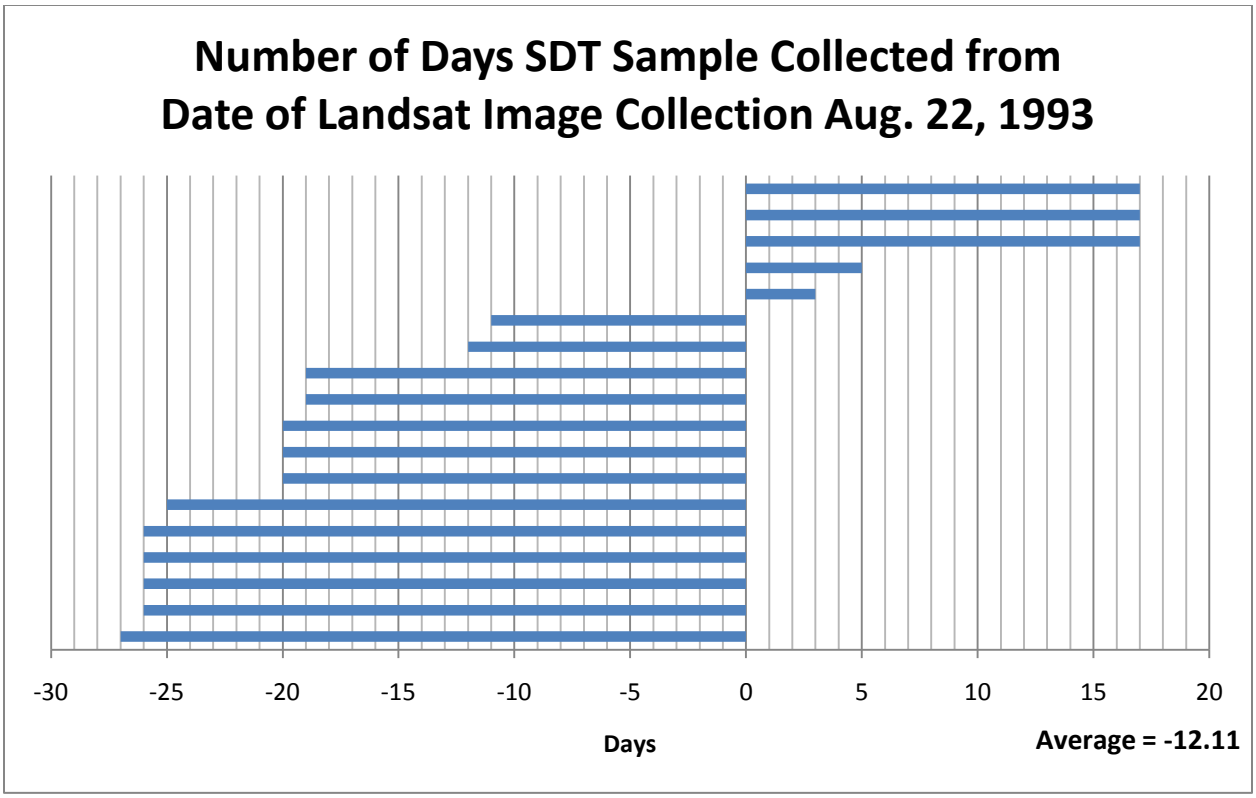
APPENDIX C

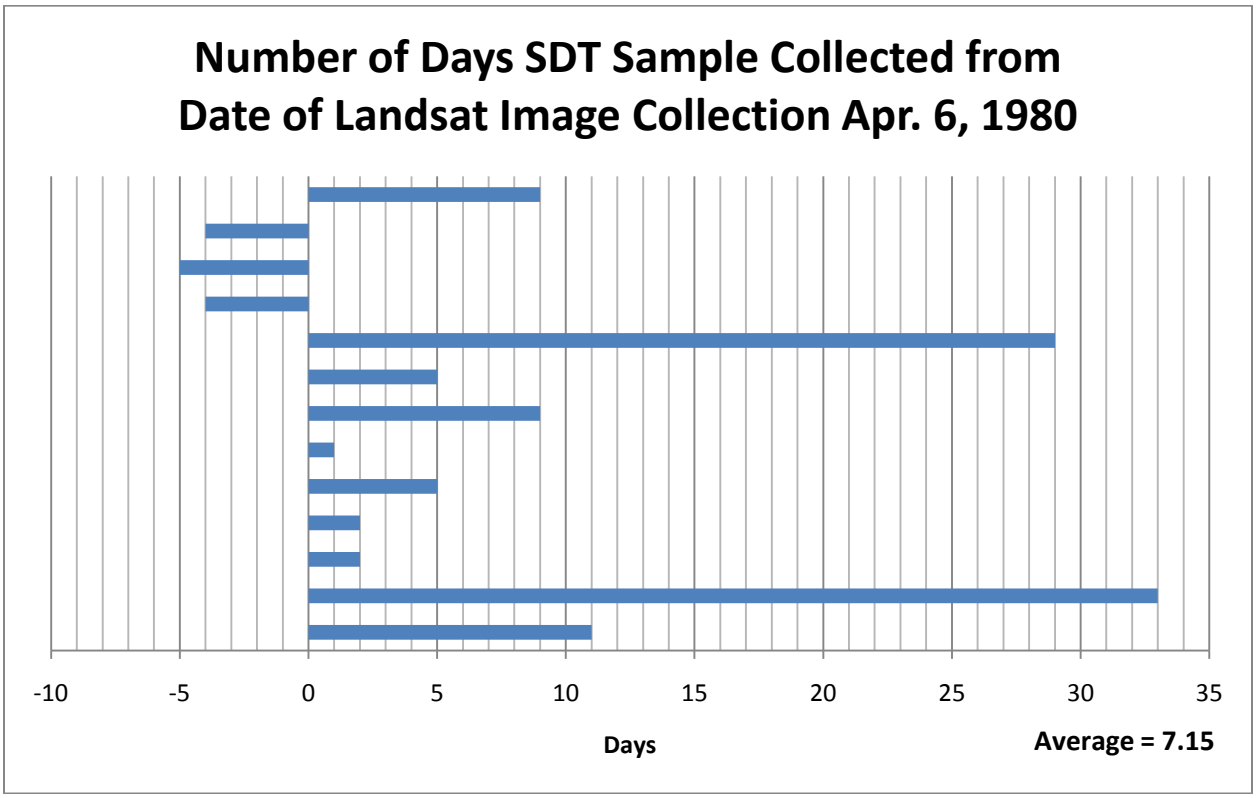
Number of Days between SDT Collection per Lake and Satellite Image Collection




Number of Days SDT Sample Collected from date of Landsat Image Collection Aug. 21, 2010
-35
-30
-25
-20
-15
-10
-5
0
5
10
Days
Average = -7.86


Number of Days SDT Sample Collected from date of Landsat Image Collection Sep. 9, 2005
-25
-20
-15
-10
-5
0
5
10
15
20
25
Days
Average = -3.31


Number of Days SDT Sample Collected from
Date of Landsat Image Collection Aug. 22, 1993
-30
-25
-20
-15
-10
-5
0
5
10
15
20
Days
Average = -12.11


Number of Days SDT Sample Collected from
Date of Landsat Image Collection Apr. 6, 1980
-10
-5
0
5
10
15
20
25
30
35
Days
Average = 7.15