SEDIMENTATION IN SMALL BLACK HILLS PONDS: DETERMINING VOLUME
AND ACCURACY OF MEASUREMENTS WITH GIS

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SEDIMENTATION IN SMALL BLACK HILLS PONDS

Sedimentation in small Black Hills Ponds: Determining Volume and Accuracy of Measurements with GIS

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Sedimentation in Small Black Hills Ponds

Abstract

Sedimentation of local waters is a problem for all reservoirs in the Black Hills of South Dakota. As a precursor to working on sediment removal, a survey on the extent of the sediment needs to be taken. Four sample lakes were used to determine which of three interpolation methods gave the most accurate results. Inverse Distance Weighted was the most accurate interpolation method followed by spline and kriging. This study also attempted to determine if fewer samples could be taken while still providing similar results. The smaller samples would mean less field time and thus lower costs. Subsamples of 50%, 33% and 25% were taken from the total samples and evaluated for the lowest Root Mean Squared Error and Relative Root Mean Squared Error values. These results were inconclusive as some lakes were more accurate with the 33% or 25% subsamples while others were more accurate with the greater subsamples. However, when these volume estimates were expressed with a dollar value for removal other results became more obvious. In most cases, the dollar amount for removal was underestimated when using the lower sample sizes. Values of this underestimation ranged from $7,525 to $132,425 for total sediment removal compared to what the total samples produced. It is suggested that future sediment surveys gather as much data as is reasonably possible in order to have the most accurate results. Inverse Distance Weighted is the preferred interpolation method for these studies, but in some cases spline proved nearly as accurate. Results from these surveys are used in prioritization of available funds for reclamation activities.
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<thead>
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<th>Full Form</th>
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<tr>
<td>ac</td>
<td>Acre</td>
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<tr>
<td>ANN</td>
<td>Artificial Neural Networks</td>
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<tr>
<td>BHNF</td>
<td>Black Hills National Forest</td>
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<tr>
<td>CCC</td>
<td>Civilian Conservation Corps</td>
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<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>ha</td>
<td>Hectare</td>
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<tr>
<td>IDW</td>
<td>Inverse Distance Weighted</td>
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<tr>
<td>LIDAR</td>
<td>Light Detection And Ranging</td>
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<tr>
<td>MSE</td>
<td>Mean Squared Error</td>
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<tr>
<td>NRCS</td>
<td>Natural Resources Conservation Service</td>
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<td>RMSE</td>
<td>Root Mean Squared Error</td>
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<td>RRMSE</td>
<td>Relative Root Mean Squared Error</td>
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<tr>
<td>SCS</td>
<td>Soil Conservation Service</td>
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<td>SDGFP</td>
<td>South Dakota Game, Fish and Parks</td>
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<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
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<td>USFS</td>
<td>United States Forest Service</td>
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CHAPTER 1
INTRODUCTION

Arising from the northern plains of North America is a small mountain range called the Black Hills. The Black Hills are an elliptically domed area in southwestern South Dakota and northeastern Wyoming, about 125 miles long and 65 miles wide. The uplift of the Black Hills probably occurred towards the end of the Cretaceous and continued into the early Tertiary, between 65 and 48 million years ago (Trimble 1980), during the Laramide Orogeny. The Laramide Orogeny occurred as a series of tectonic pulses, between 75 and 35 million years ago. Major features created during the orogeny are found from Canada to northern Mexico, with the Black Hills being the easternmost extent of mountain-building (English and Johnston 2004).

The oldest geologic units in the study area are Precambrian metamorphic and igneous rocks, exposed in the central core of the Black Hills. These rocks were formed during the Trans-Hudson Orogeny, 2.0-1.8 billion years ago, where still older sedimentary rocks were metamorphosed by the intrusion of the Harney Peak Granite. The granite portions can be seen today in areas such as Harney Peak (highest point in South Dakota at 7,242 ft.) and Mount Rushmore. Outside of the central core are areas of increasingly younger rock formations (Paleozoic, Mesozoic, and Cenozoic) that encircle one another. In ascending order these include the Cambrian Deadwood Formation, Ordovician Winnipeg Shale and Whitewood Formation, Devonian Englewood Formation, and Mississippian Pahasapa Limestone, the Pennsylvanian-Permian Minnelusa Formation and Permian Opeche Formation and Minnekata Limestone. The
youngest rocks include the Triassic Spearfish Formation and Jurassic Sundance Formation, Unkpapa Sandstone and Morrison Formation. The sedimentary units typically dip away from the central core, and extensive erosion of these rocks since the uplift has given the Black Hills their present form.

Most of the limestone and some sandstone units are important in a hydrologic aspect, making the Black Hills unique in that few surface streams flow from the region, and still fewer streams have natural “lakes”, often just small pools. This occurs in part from a semiarid climate and in part from infiltration of rainwater on the outcrop and from stream water infiltrating into aquifers in the limestones, due to the existence of an extensive karst systems in these units (Hortness and Driscoll 1998). The Paleozoic Minnekahta, Minnelusa, Pahasapa, and Deadwood aquifers are four of the five major aquifers in the region (Strobel et al. 1999). The near lack of glaciation and deposition of impermeable clay-rich surface till sheets, has also limited the existence of natural bodies of water within the Black Hills.

Permanent water sources occur in fractured sections of the limestone formations as subsurface aquifers intersect the land surface as coldwater springs (Carter and Driscoll 2003). The nearly 800 miles of free flowing streams are the only surface hydraulic component within the Black Hills of South Dakota. Naturally ponded waters are small, limited in number and usually only occur when beavers (*Castor canadensis*) build their dams and alter habitats (Harris and Aldous 1946). These beaver ponds are modified during high stream flows from heavy summer thunderstorms that are common in the area, and the dams may be completely washed away (Butler and Malanson 2005, Doyle et al. 2005). Since most streams are ephemeral, readily available ponded waters are almost
nonexistent and the technology to extract water from aquifers did not exist, efforts by early settlers to have long-term water sources available began to be developed. Most of the efforts were the construction of artificial dams to capture surface runoff.

Many of these small lakes have earthen dams that entrain water for a short distance upstream. These waters are normally small in nature and range from less than 0.8 hectare (2.0 acre) to 12.1 hectares (30 acres) in size. While not typically needed for water sources today, they do play an important part in recreation in the Black Hills, especially for sportsmen. Over 5,239 hours of recreational use were seen at two small lakes in one summer (Simpson 2009). To accommodate this use, the South Dakota Game, Fish and Parks annually stocks catchable rainbow trout into these small waters.

1.1 Research Background and Justification

The Civilian Conservation Corps (CCC) and the U.S. Forest Service (USFS) constructed many small dams within the Black Hills starting in the 1930’s. Today these waters are nearly seventy years old and have reached a level of “maturity” by limnology (the study of inland waters) standards. Aging of these waters, including sediment influx (siltation), naturally occurs over time, but can be accelerated by upstream influences such as overgrazing by livestock and road building practices (Matyas and Rothenburg 1986, Radoane and Radoane 2005). The impact of siltation is easily seen by the public and often results in phone calls to governmental agencies asking for positive changes. These actions can place some importance on the speed in which the work could be done, but there is also a matrix system that provides an unbiased approach for the order of reclamation projects. As with any work, the timing and extent of projects are directly
linked to the monies available. Removal of the sediment has been costly in past projects and many unknowns come up in the bidding process. Development of a process to determine the extent of sediment accumulation in a lake is needed to improve the estimates for sediment removal. By providing needed data for cost estimates, public agencies and private enterprises could forecast expenditures, and will save time and money by reducing last minute contract changes. Public decision makers can also use these estimates to aid in determining how these expenditures rank in regards to other projects and appropriate areas for spoil deposits.

The problem of sediment accumulation in any specific lake is determined by land use practices, soil development, slope of the land and the amount of runoff in the watershed above the lake. Small lakes or ponds, of this age group typically experience more aging effects that are accelerated with poor land use practices within the watershed, than do larger lakes (Murphy and Meehan 1991). Unlike large waters, methods used to determine sediment volumes in small lakes is not commonly found in published literature, so determining the extent of sediment influx in the study area lakes has proved to be difficult. Local biologists considered that Geographical Information System (GIS) might be a tool that could solve these difficulties. One could use the interpolation processes within the GIS environment to estimate the volume of sediment within any small lake.

Using GIS was only one step of the total process. Besides the computer program, another need was data and how it was to be collected. There are several different ways this data can be gathered. First, it was acknowledged from the outset that there would likely be little chance of obtaining this data from outside sources, based on the particular
data needed (sediment depths) and the small size of the waters. Second, it was identified as important that the resources for collecting the data had to be reasonable in cost. Lastly, it was known that in these small waters there would be a need to collect samples in shallow portions of the lake. Each of these criteria was used to identify the best approach in data collection.

Based on the options available and criteria above, it was decided to collect the data “in house” on a lake by lake basis. The process entailed the use of physical measurements and interpolation options within ArcGIS working in combination to estimate the volume of water and sediment in area lakes. This study looked specifically at the issues within the data collection process and answers which of the interpolation methods might provide the best estimate for Black Hills lakes. Results of this study will include recommendations towards the interpolation method that should be used in Black Hills small lake sediment studies, and suggestions as to the minimum required number of samples needed for meaningful results.

1.2 Research Objectives

The objective of this study is to determine which of three commonly used interpolation methods provides the best accuracy and the minimum number of samples needed to obtain reasonable accuracy of sediment accumulation in these small lakes. This research will utilize a smaller number of sample points, which would be more cost efficient, to generate results that are similar to a higher number of sample points.

The best interpolation method will be determined and demonstrated with this project. This study determines the most accurate interpolation method by two phases of
analysis. Evaluation of sample points with each interpolation method (IDW, spline and kriging) is performed within ArcGIS. A first step is to see the visual effects of the interpolation and compare each method against one another. Further analysis of the data using Root Mean Square Error (RMSE) and Relative Root Mean Square Error (RRMSE) also determine which of these interpolation methods yielded the most accurate results to the original data source. In this sense, the product from the model (via the best interpolation methods) is tested against true sample points. The sediment volume estimates is passed along to habitat biologists and administrators for determining the cost of reclamation projects and prioritization of these projects.

1.3 Study Area

All waters used in this study reside within the boundary of the Black Hills National Forest (BHNF) under the management of the U.S. Forest Service (USFS) (Figure 1). Most of the watersheds in the Black Hills share a common characteristic of being heavily forested with ponderosa pine (*Pinus ponderosa*) along with stands of Black Hills spruce (*Picea glauca*), aspen (*Populus tremuloides*) and bur oak (*Quercus macrocarpa*). Even with this forested environment, there are numerous road networks throughout the forest and small towns located within its confines.

Four small waters from within the Black Hills forest boundary were selected for determination of sediment accumulation, accuracy of interpolation methods and in the development of a running GIS model that allows for more widespread use of the process. Each lake has impacts in their respective watersheds that has affected the amount of sediment inputs into the inlet areas and other parts of the lake. In order of increasing
size, the lakes researched in this study were: Dalton Lake (1.2 hectare), Major Lake (1.6 hectare), Lakota Lake (4.5 hectare), and Bismarck Lake (10.1 hectare).

The CCC constructed Dalton Lake in 1935 (Driving Hawk Sneve 1973). Located in the central Black Hills, it has a small creek with numerous road crossings above the lake. Major Lake was built for public use by a combined effort between the USFS and the CCC. At only 5- acres, Major Lake was important due to its location within the small town of Hill City.

Built in 1963, Lakota Lake was originally constructed by a private individual and later sold to the USFS. Road crossings and runoff after forest fires have contributed to the inputs of this southern Black Hills Lake. Lastly, Bismarck Lake located in the central Black Hills adjacent to Custer State Park, is owned by the USFS, but it was originally constructed in the 1930’s by the USFS and the CCC. Bismarck Lake was named after “Bismark Annie”, a local boarding house owner who also did placer mining along the creek leading to Bismarck Lake.

These four lakes were selected because each lies within a separate watershed. This was one criterion in selecting the waters as no one impact (ex. runoff after a forest fire) would be a potential major influence to all sampled waters. Several common factors exist among these four waters as road development, livestock grazing practices and “hobby” farming occurs almost ubiquitously across much of the intertwined private landholdings within the forest boundaries.
Figure 1. Study areas in the Black Hills of South Dakota
CHAPTER 2
LITERATURE REVIEW

Soon after the construction of dams across the United States, there were some concerns about the life expectancy of these structures and evaluations on the rate of sedimentation began (Gottschalk 1948, Wang and Hu 2009). How one goes about gathering data for determining changes within the lake has been determined in different ways.

2.1 Early Studies

Churchill (1948) first attempted the use of empirical curves to relate reservoir capacity loss to hydrodynamic processes. Working for the Tennessee Valley Authority (TVA), Churchill described a method to predict future rates of reservoir silting. Using what he described as a “Sedimentation Index of Reservoir” was a relationship between the length of retention (how long the water is in the reservoir) to the transit velocity (how fast the water is moving into and out of the reservoir). It was a ratio between these two characteristics, period of retention to transit velocity, which Churchill and others with the TVA used as a measure of sedimentation efficiency within the reservoir. Further, as a pond fills with sediment, its Sedimentation Index value would be lowered and there would be a greater incoming load that would be passed through. However, there was some early debate on the extent of how this would be applied to small ponds (stock dams) compared to larger reservoirs.
Gottschalk (1948) stated that out of the extensive study the Soil Conservation Service (SCS) had performed, sediment studies on fewer than 5% were small waters. He felt that the “laws of sediment deposition” would be irrelevant to the reservoir size. The rates of the sedimentation would be controlled more by the operation of the reservoir, watershed conditions and climatic conditions. Jones (1948) commented that the size of the reservoir may actually cause a greater degree of variability with expected sedimentation rates. His suggestion stemmed from the idea that smaller waters could either be located high in the watershed or lower in a watershed. The waters that were higher in the watershed would be more likely to have less of a chance for sediment influences, where a pond that would be further down in the watershed may have a greater unit drainage area. Thus, according to Jones (1948) the smaller waters might have a greater degree of variability in sedimentation rates. While the size of the water might be important to the overall sedimentation rate, other factors such as the condition of the watershed above the lake might be directly involved in what is able to be transported.

Gottschalk (1948) first proposed that the rate of the sedimentation depends on the climatic conditions, nature of the soil type in the watershed, slope of the land, topography and land use. While this list of impacts was good for its day, there are greater impacts and unique situations that are not covered in such a short list. For example, land use is a general term that has many variables. Classifying an area as “rural” may not take into account the direct influence of only a few instances of streamside livestock grazing or poorly managed road construction that could further erode the stream channel and contribute to sediment effects downstream. In other words, it only takes a few small instances acting in concert, to allow for a greater rate of sedimentation within any one
watershed. So while Gottschalk (1948) and others had some preliminary work in this venue, they were also hampered by the lack of computer resources we take for granted today. Modeling and other factors had not yet developed to a level where one could expect more accurate sedimentation forecasts.

Later studies then began to look at the actual impact of sediment on the reservoirs themselves. Sampling equipment was developed that allowed users to establish sediment rating curves, which are used to compute suspended sediment discharge into reservoirs (Dendy 1974). This work was necessary in the design of structures as there needed to be a known “life” of the reservoir (normally 50 or 100 years). Known as “trap efficiency” of a reservoir, Dendy (1974) developed a prediction equation that showed how a small reservoir would fill with sediment based on a sediment index. Lastly, he suggested that installing structures that could control a C/I (capacity/average inflow) greater than 0.1 could prevent from 80-95% of the particles from depositing during a floodwater event. These studies concentrated on small, dry reservoirs throughout the U.S.

2.2 Recent Studies

The Soil Conservation Service (now called the Natural Resource Conservation Service) has performed more recent work. Seemingly more concerned with suspended sediment, bedload sampling was also an impacted variable that was tested by this agency (Edwards and Glysson 1999). Many of these attempts at measuring sediment were quite lengthy, requiring set base points and profiles along the same transects in subsequent years. In addition, a “pre-filled” reservoir profile was needed for comparison to sampled values. Jothiprakash and Garg (2009) used artificial neural networks (ANN) in a
modeling process in order to determine sediment loading. They achieved better results from specific processing of the ANN than from simple linear regression alone. The results of these works has been promising, but they all point towards the real issue that these manmade reservoirs are in constant change and predicting their life cycle is important in their management.

Additional options, such as the use of Light Detection and Ranging (LIDAR) can be used to determine fairly accurate depths (up to one foot resolution); however, this technology again requires a “pre-reservoir” profile in which to compare sample values (Gao 2009). Some researchers have had some success using LIDAR in determining sediment depths, but this has only been performed in shallow water bays that have good water clarity. The use of LIDAR has been noted to be expensive. According to Romgough (2010), the estimated costs for this project was rough quoted to be between $20,000 to $25,000 for all of the lakes in this study. Other options exist such as using depth finders to determine the ocean or lake bottom and the gray line of the depth finder to determine the extent of sediment at a given point (Thorne and Hanes 2002, Odhiambo and Boss 2004). This was especially useful when the depth finder was linked to a GPS where the two worked in concert to derive the grayline sediment depth to a geographical position (Agarwal and Idiculla 2002). Grayline is a feature programmed into depth finders that allows the user to distinguish between strong and weak echoes. It "paints" gray on targets that are stronger than a preset value and allows you to tell the difference between a hard and soft bottom. A soft, muddy bottom returns a weaker symbol which is shown by a narrow gray line. A hard bottom or less sediment would return a brighter signal or thicker gray line.
GPS technology has also been incorporated with GIS. Prasad et al. (2005) developed GIS tools to analyze the impact of forest roads on streams. Their overall goal was to determine the best fish passage status of the different stream crossings. GIS has also been a key component for sedimentology studies where flow accumulation was a consideration (Schauble et al. 2008).

2.3 Interpolation Alternatives

Utilization of GIS has been seen with the incorporation of interpolation methods. Li and Heap (2011) discussed over 72 different interpolation methods that were used in published environmental GIS studies. Of these different modeling efforts, Inverse Distance Weighting (IDW), ordinary kriging, and ordinary co-kriging were the most frequently used methods. Differences between the selected methods and their attributes used in this study were discussed, but it is important to first consider the distribution of data points and the phenomena being studied in the final decision on which method was used (Childs 2004).

Inverse Distance Weighting estimates the value at unknown points using the distance and values from nearby known points (Caruso and Quarta 1998). Incorporated in this method was that items near each other will tend to have traits more similar than those areas further away from each other (Tobler’s Law). The IDW method has been called an exact interpolation as the known values are used at the sample points. The surfaces produced from IDW have been characterized as smooth. However, IDW may produce some artificial peaks and valleys between data points due to the averaging inherent in this technique (Longley et al. 2005). Other noted problems with IDW are its
particular sensitive nature to the weighted aspect of its function, and that it can be affected by uneven point distribution, and its predictive properties are limited to the minimum and maximum of inputs (Caruso and Quarta 1998).

Spline has been referred to as a flexible ruler that makes smooth curves through the sample points (Bolstad 2005). Spline functions are flexible in that the division lines pass through the points, but this can also lead to artifacts where the points are located or in between the sampled points. The spline interpolation has constraints set to the function so that the entire line remains smooth and the slope of the line changes equally across its length.

Kriging has been a commonly used interpolation model, which has a statistical based estimate of the predicted measures (Bolstad 2005). At the heart of the kriging method was the computation and interpretation of the semivariogram. The semivariogram measure the degree of spatial correlation among observation data points as a function of distance and direction between the data points (Hu 1995). Kriging interpolation uses information from the semivariogram to present unbiased estimates of points that have minimum variance. Since there are known variances, one can compute confidence limits on the estimates, which cannot be done with other methods. Kriging interpolation produces a smooth graphic (Longley et al. 2005). One negative of kriging is that the original data points are seldom honored (Hu 1995). This can be problematic if contours generated from the interpolated surface appear on the wrong side of observed data points. In this case, the semivariogram may not always be a true estimator of the data set. The analysts must be familiar with the data to know if the selected semivariogram was correctly used based on the features. Furthermore, Hu (1995) noted
that kriging is not a suitable model when there are numerous pits and spikes in the dataset. One should not take the easy route, or take the first, or the most commonly used method without first stating experimental and evaluation criteria (Caruso and Quarta 1998).

One possible alternative that has been used with kriging within some software products is adjusting the sill and nugget values. Burrough and McDonnel (1998) defined the sill as the portion of the semivariogram curve that starts to level off and is indicative of lessening spatial dependence between datapoints because of sample separation distance. The nugget was noted as the portion of the semivariogram that represents the measurement errors of spatial variation at low values. Certain software packages allow use of these mechanisms to fit the semivariogram to the data. By first exploring the data, a researcher can look for outliers and examine for normality, or spatial autocorrelation before the selection of the interpolation model is made.

2.4 Evaluation

Evaluation of the interpolation techniques used in studies varies. Willmont (1982) suggested using root mean squared error (RMSE) or mean square error (MSE) as being the best to summarize the differences between observed values and model-predicted values. Others have used descriptive statistics to compare the distribution of data in both univariate (mean, median and mode of residual distribution close to zero) and bivariate (scatter plot) patterns (Hu 1995). There are some issues with outliers that can affect RMSE evaluation (Li and Heap 2008). To compensate for these possible errors, relative root mean square error (RRMSE) has been used as it is not as severely
impacted by extreme influences of outliers. Finally, a researcher can also leave out a single or multiple specific known point data, run the interpolation and then compare the predicted value to the known value.

From this study, a recommendation for the most accurate interpolation method for sediment surveys in the Black Hills was presented. This study determined if lower amounts of data, equaling lower costs, could occur while obtaining the same relative accuracy. The outcome of this work would provide researchers with a background for further work while also giving some guidance towards costs associated with fieldwork. These are topics not recorded in literature and are important for future work.
CHAPTER 3

CONCEPTUAL FRAMEWORK AND METHODOLOGY

There are three areas included in the methods and materials section. Data collection simply refers to the process of gathering the data. Once the data was collected, some management of the information was needed. This project relied heavily on the different interpolation processes. In the two sections on data analysis, the processes are detailed. Finally, the exact subsamples and how the data was spread across each lake for these subsamples are presented.

3.1 Data Collection

Due to financial and logistic factors, uses of LIDAR and depth finders were not chosen for this work. LIDAR was discounted based on cost and that there were no “preexisting” maps or profiles of these small lakes. Depth finders were considered as well, but perceived issues in shallow waters was a realistic concern. It is known that shallow waters (< 6 inches) would be encountered at some sampling points. Thus, an alternative was chosen that would allow for shallow water measurements while keeping costs low.

This study attempted to resolve the issues noted above in regards to cost and logistics, by applying a simple method of sediment measurement at intervals along transects. Field data were collected during the winter when ice was sufficient to support the field crews. Holes were drilled through the ice with gas powered augers in a systematic fashion so that all habitat types and practical areas were represented. The
distance between sample points was measured by twenty-five long steps (average 5.2 meters) between holes and between transects. Due to differences in lake size and shoreline complexity, each lake had a different number of total sample points (Table 1). A four-inch diameter, ten foot long, PVC pipe with an end cap was fashioned to determine the lake water depths. The end cap provided a definite “feel” when the lake bottom was reached. The sounding rod was constructed from 10-foot sections of regular conduit to which a tape measure was attached. Extra pipe sections were added to extend the entire length, but there were limits to what workers can physically manage.

The entire sequence of measuring occurred in this fashion: the PVC pipe was slowly lowered until it reaches the bottom of the lake, sounding rod was pushed through hole in the end cap with sufficient force to be pushed through the sediment (mud). Final sediment depths were determined when the rod became significantly hard to push any further, the depth of sediment was measured off the attached tape measure. Measurements were made to the nearest inch. All depths were recorded and labeled in a consecutive order. GPS locations were taken at each sample location. The GPS used in this study was a Trimble Geo3, although any GPS unit could be incorporated to work effectively.
Table 1. Total number of sample points taken at each lake.

<table>
<thead>
<tr>
<th></th>
<th>Number of points</th>
<th>Surface Hectares</th>
<th>Mean distance (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total number</td>
<td>50%</td>
<td>33%</td>
</tr>
<tr>
<td>Dalton Lake</td>
<td>73</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>Major Lake</td>
<td>80</td>
<td>40</td>
<td>26</td>
</tr>
<tr>
<td>Lakota Lake</td>
<td>270</td>
<td>135</td>
<td>89</td>
</tr>
<tr>
<td>Bismark Lake</td>
<td>317</td>
<td>159</td>
<td>105</td>
</tr>
</tbody>
</table>

3.2 Data Management and Incorporation

Sediment and water measurements were joined with GPS locations at each sampling site to provide a spatial component to the sediment measure. The depth measurements were imported into the data table for the GPS locations. These values were in inches due to the measure units on the tape measure. Fields to the data table were added and were populated with the conversions of the inch measurements to meters. Separate fields were needed to include the depth of the water, depth of the sediment and a combination of depth of water and sediment. The steps used in the process were done in a fashion as depicted in Figure 2.

The effort increased with the number of holes or data points collected. A smaller number of sample points would decrease time and associated total costs for any future work to be performed. To determine the number of points needed for similar results at each lake, one half of the total number of samples from each lake, 33% of samples and
25% were taken as subsamples from the total samples collected. These data were combined for further analysis.

Figure 2. Overall interpolation and sample size models in ArcGIS.
3.3 Interpolation Process

All available points were used to determine the most accurate interpolation method. There were numerous options for each of these interpolation methods. In order to keep the parameters as close as possible, the same search radius and number of points to include were kept similar. Inverse Distance Weighted interpolation was based off the variable search radius. This option was chosen as there are areas around a lake where a specified number of points may occur a far distance from the area of interest. This option limited this distance at the sacrifice of uniformity. Ordinary kriging methods were used in analysis, as there was no constant mean of the sediment variable. Regularized spline interpolation was used over tension as it gives a clearer presentation product.

To determine if sample size made any difference or if a smaller sample could be taken while keeping errors small, ten randomly selected points were taken from the overall dataset of each lake. The randomization of ten points was used due to differences in overall sample sizes between waters and for comparisons across waters, if needed. Determining the particular locations for subsamples was performed via a random number generator in Excel. These subsample data were then selected within each lake dataset and made into their own subset. Final interpolations of the full dataset and smaller subsets were performed in ESRI ArcGIS with the Spatial Analyst extension. IDW, spline and kriging interpolations were made on the ten subsamples for each lake.
3.4 Data Analysis

Data from each of the lakes were analyzed for the lowest RMSE (Equation 1) and RRMSE (Equation 2). The lowest value from each lake was determined to be the most accurate interpolation method for sediment analysis in this study. Ultimately, any differences in sediment estimates were used to determine if 50%, 33% or 25% of the total points would be sufficient to get similar results. The “Cut/Fill” command was used to determine the final total volume of sediment from the sediment raster. This process determines the difference between two rasters, one of the current lake bottom and the second of the lake bottom with sediment removed.

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (y_j - \hat{y}_j)^2}
\]

Equation 1

where:

- \(y_j\) = depth from known measure
- \(\hat{y}_j\) = predicted depth from interpolation
- \(n\) = sample size

Hernandez-Stefanoni and Ponce-Hernandez (2006) suggested that RMSE is sensitive to outliers and it places a lot of weight on large errors. To compensate for this sensitivity, efforts to establish criteria have been established using a new method called the relative root mean squared error (RRMSE) (Haberlandt 2007). The RRMSE are reported in this study for comparison with RMSE results.
RRMSE = \[ \left( \frac{1}{n} \sum_{i=1}^{n} \left( \frac{p - o}{o} \right)^2 \right)^{\frac{1}{2}} \]

Equation 2

where:

\( p \) = predicted depth from interpolation,
\( o \) = observed value
\( n \) = sample size or samples.

Residuals are the differences between the observed value of the dependent variable and the predicted value (McGrew and Monroe 2000). Residuals, when graphed against the independent variable describe patterns of independence and fit to the regression line. These scatterplots also indicate the difference between the projected points (regression) to those observed and they give an orientation of the model values.

Data from ten randomly selected points were used in the analysis of subsample accuracy. Accuracy of the subsamples was determined from the identification of point depth at the random sites. The values from the three different subsamples were compared to the known true value at the random site. The RMSE for the ten points was used to get an overall comparison value and to determine the sample size needed to obtain similar results. The volume of sediment was estimated from these rasters.
3.5 Description of Data Sources

The author collected the primary data (water depths, sediment depths, and GPS positions) for this research project with the assistance from coworkers of South Dakota Department of Game, Fish and Parks. Permission for using these data for this research was been granted by the supervisory staff.

Numerous alternatives towards data collection were investigated for this study. Options such as Light Detection and Ranging (LIDAR) and depth finders were eliminated because of costs or other factors. It was decided that a simple option of physical measuring combined with GPS measurements was the most practical as it provided the needed accuracy, low cost and could be repeated to determine changes in the future.

The use of low cost, easily obtained materials meant there could be modifications to the system until a final process and materials list could be determined. The use of GPS technology was used as a way to determine the location of the sample and could also be used as a storage device if needed.

3.5.1 Dalton Lake sample points

Dalton Lake, the smallest of the sample lakes had 74 samples taken during the initial survey (Table 1). The subset of 50 % of the total number of sample points for Dalton Lake yields 37 points that were used during the interpolation analysis at this level (Figure 3). 24 sample sites were used at the 33% subset and 18 at the 25% subset.
Figure 3. Location of total sample, and randomized 50%, 33% and 25% points for Dalton Lake used in interpolation analysis.
3.5.2 Major Lake sample points

Major Lake had 80 samples taken (Table 1). 40 of them were used to determine the 50% subsample interpolation, 26 for the 33% subsample and 20 for the 25% subsample (Figure 4).

3.5.3 Lakota Lake sample points

The third lake in this study was Lakota Lake, which is located on the outskirts of the nation’s largest state owned park (Custer State Park). An extensive sampling effort was performed at this lake with 270 total sampling locations taken (Table 1). Over 4.2 surface hectares, this averaged a sample taken every 11.7 meters (roughly every 38 feet). The 50% subsample included 137 points (Figure 5). The 33% and 25% subsamples had 89 and 68 points, respectively. Gap of sample points in the central portion of the lake are due to the water depths being beyond the measurement capabilities of the sampling system.

3.5.4 Bismark Lake sample points

This U.S. Forest Service owned lake was the largest lake (10.1 hectares) used in this study. There were 317 total sample points taken at this lake which took a crew of five persons two days to complete (Table 1). Subsamples at 50%, 33% and 25% were determined via randomization (Figure 6). Bismark Lake was one of the sample lakes where not all the sample points could be physically sampled due to water depths. This specific sampling procedure has limits to the maximum depth that can be effectively measured. The practical limits are dictated by the measuring device. The length of
typical conduit is 10 feet in length. Two equal sections of conduit are normally connected together to form a total of 20 feet of length. This length has proved to be the practical maximum that can be physically managed between sample sites and for measurement of the lake bottom. Additional length beyond the twenty feet is cumbersome and extremely tiring for field crews to manage.
Figure 4. Location of total sample, and randomized 50%, 33% and 25% points for Major Lake used in interpolation analysis.
Figure 5. Location of total sample, and randomized 50%, 33% and 25% points for Lakota Lake used in interpolation analysis.
Figure 6. Location of total sample, and randomized 50%, 33% and 25% points for Bismark Lake used in interpolation analysis.
Three interpolation methods were used to determine which produced the best accuracy to the original points of sediment loadings in small lakes in the Black Hills of South Dakota. The best method was determined from the lowest RMSE and RRMSE between the original point and that same point for each interpolation process. Subsamples (50%, 33%, and 25%) from each of the total points were randomly separated. These subsamples were processed through the same interpolation methods. Priority of result interpretation was placed towards that interpolation process that had the lowest RMSE and RRMSE from the earlier effort. The analysis of these efforts provided the background for answering the key questions as to which interpolation method works best and how many sample sites were needed for relatively producing the same results.

4.1 Sediment Profiles

Interpolation of the sediment values was the first step in the process of determining which method would be the most accurate. Maps showing the differences between these interpolation efforts are illustrated in the following sections.
4.1.1 Dalton Lake

The smallest of the sample waters, Dalton Lake had differences in appearances between the separate interpolation methods. Inputs of sediment into Dalton likely come into the lake from the inlet that enters the lake from the left side in these depictions (Figure 7). Expectations might be that there would be larger amounts of sediment towards the inlet than further around the lake. However, high flow can alter these expectations and the size of the deposition material itself can have a large impact on where these materials settle down in the lake. In each of the interpolations there appeared to be a major deposition of sediment around the inlet with a plume that traverses towards the dam (far right). There are no gauging stations on Elk Creek (inlet creek to Dalton Lake) nor were sediment samples taken to determine any size classifications of the material in the lake. Those topics are beyond this study and reflect possible future work.

4.1.2 Major Lake

Major Lake is unique amongst the study lakes in the fact that it is urban in nature. Also, the watershed while having some similarities to the other lakes in regards to forested areas, does experience the greatest impact from livestock grazing adjacent to the stream course. Aptly named, Horse Creek flows into Major Lake from the northwest corner in the depictions and flows out at the easternmost point of the lake (Figure 8). Sediment levels in Major Lake seem to have two “hot spots” towards the middle of each side. This was seen with each interpolation method, but seems more accentuated in the IDW and spline methods.
Figure 7. Dalton Lake interpolation maps from full data points.
Figure 8. Major Lake interpolation maps from full data points.
4.1.3 Lakota Lake

Lakota Lake has a unique configuration as it is rather narrow and long with one shorter arm offshoot to the northwest (Figure 9). Water enters the lake from the narrow arm (southwest) and exits at the northeast point. All three interpolation methods showed a good deposition of sediment towards the inlet areas. Sediment levels were mostly located around the inlet area and about 1/3 of the way up the lake. It should also be noted that the lake did reach depths that prevented sediment measures in the deepest portion. These measurements were not taken, as equipment would not reach to the bottom of the lake. While this may seem problematic, in reality it may not have a large impact as most of the sediment had settled out before reaching this area. From a practical standpoint, it is unlikely that this section of lake (deepest portion) will ever be considered for sediment removal, as it would have water in it during drawdown.

4.1.4 Bismark Lake

Bismark Lake, like Lakota Lake, reached depths that were prohibitive towards data collection (Figure 10). This occurred in the area towards the dam and spillway area. Water primarily enters Bismark Lake from the north and water exits towards the southwest. A small stream comes in from the east and flows into the southern arm. Much of the sediment deposited around the inlet area of each arm, but did travel out into the lake. Limited sediment influences occurred around other parts of the shoreline and may be due to a stabilized shoreline. Bismark Lake had one area that was not able to be sampled due to water depths being beyond the length (20 feet) of the sampling equipment.
Figure 9. Lakota Lake interpolation maps from full data points.
Figure 10. Bismark Lake interpolation maps from full data points.
4.2 Accuracy of Interpolation Methods

Overall, the results from these four sample lakes had the best and most consistent accuracy when IDW interpolation was used (Table 2). In all the study lake examples, either the IDW or spline produced the lowest RMSE from the observed to the predicted depths. Kriging was the most variable of the three interpolation methods used. At Lakota Lake, the kriging interpolation method had the second lowest RMSE. At the other three lakes kriging interpolation had the highest RMSE, and thus it was the least preferred for accuracy.

RRMSE is less sensitive to extreme outlier data points than RSME. IDW interpolation had the lowest RRMSE of the methods used in this study (Table 3). In all but one case, Lakota Lake, spline interpolation was second in performance of interpolation methods. Similar to the RSME results, kriging provided the second best interpolation results from Lakota Lake.

A high RMSE value indicates that the predicted value (from each interpolation method) produced values that were further away from the mean or regression line. Lower RMSE values indicate that the predicted values are closer, relatively, to the mean and provide a measure as to the accuracy of the interpolated measurement.
Table 2. Root Mean Squared Error (RMSE) for four sediment survey study ponds within the Black Hills.

<table>
<thead>
<tr>
<th>Lake</th>
<th>IDW</th>
<th>spline</th>
<th>kriging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.0705</td>
<td>0.0775</td>
<td>0.0949</td>
</tr>
<tr>
<td>Major</td>
<td>0.0763</td>
<td>0.0883</td>
<td>0.1742</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.0389</td>
<td>0.0507</td>
<td>0.0400</td>
</tr>
<tr>
<td>Bismark</td>
<td>0.2439</td>
<td>0.3026</td>
<td>0.7573</td>
</tr>
</tbody>
</table>

Table 3. Relative Root Mean Squared Error (RRMSE) for four sediment survey study ponds within the Black Hills.

<table>
<thead>
<tr>
<th>Lake</th>
<th>IDW</th>
<th>spline</th>
<th>kriging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.2005</td>
<td>0.2204</td>
<td>0.2700</td>
</tr>
<tr>
<td>Major</td>
<td>0.1451</td>
<td>0.1680</td>
<td>0.3314</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.0693</td>
<td>0.0903</td>
<td>0.0713</td>
</tr>
<tr>
<td>Bismark</td>
<td>0.0662</td>
<td>0.7521</td>
<td>1.8823</td>
</tr>
</tbody>
</table>
4.3 Accuracy of Subsamples - IDW Interpolation

Determining if there was a difference when sample size was taken into account, random samples (50%, 33% and 25%) were taken from each lake. RMSE values from this portion of the study showed some variability for many of the lakes (Table 4 and Figure 11). In three of the four cases, Bismark Lake being the lone exception, the 33% subsample had higher RMSE values. The random sample from Lakota Lake also produced RMSE values from the 50% and 33% subsamples that were abnormally high.

It was interesting to note the previous interpolation analysis did not show these same trends. It might be that the unique shape of Lakota Lake (long, narrow with one arm) presented a unique difficulty for the interpolation process. Lakota Lake also had a large deposition of sediment towards the long, narrow inlet and this may have caused difficulties with the interpolation methods.

![Figure 11. Root Mean Squared Error (RMSE) for ten random points at different sample sizes (50%, 33%, and 25%) using IDW interpolation.](image-url)
Typically, one might expect that having more data would provide for a more accurate interpolation process. This research pressed to find if there was a trade-off between effort expended and accuracy of results. Using RMSE and RRMSE as a measure of the accuracy of each IDW interpolation, these expectations were not met (Tables 4 and 5). RMSE values determined from ten random sample points showed that in many cases the sample size of 25% nearly equaled or was better than when twice as many values were collected (Table 4, Figure 11). An example of this near similarity occurred with the subsamples from Major and Dalton Lakes. In these two instances, the RMSE value for 25% (using IDW interpolation) was relatively similar to that of the 50%. This was surprising as the subsample points taken at the 50% and 25% appear to be well distributed (Figures 3 and 4). RMSE values of the 33% subsample was close to the other values from Dalton Lake and was the lowest (= most accurate) at Bismark Lake.

<table>
<thead>
<tr>
<th>Lake</th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.0123</td>
<td>0.0229</td>
<td>0.0179</td>
</tr>
<tr>
<td>Major</td>
<td>0.0311</td>
<td>0.0726</td>
<td>0.0332</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.1647</td>
<td>0.2227</td>
<td>0.0123</td>
</tr>
<tr>
<td>Bismark</td>
<td>0.0696</td>
<td>0.0260</td>
<td>0.0290</td>
</tr>
</tbody>
</table>
Table 5. Relative Root Mean Squared Error of Inverse Distance Weighted interpolation methods for differing sample sizes at four Black Hills reservoirs.

<table>
<thead>
<tr>
<th>Lake</th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>1.3435</td>
<td>1.3186</td>
<td>1.4584</td>
</tr>
<tr>
<td>Major</td>
<td>1.2748</td>
<td>2.1637</td>
<td>1.8487</td>
</tr>
<tr>
<td>Lakota</td>
<td>1.7945</td>
<td>2.0643</td>
<td>1.3435</td>
</tr>
<tr>
<td>Bismark</td>
<td>1.4618</td>
<td>1.2459</td>
<td>1.6474</td>
</tr>
</tbody>
</table>

Major Lake and Dalton Lake had similar RMSE values from 50% and 25% subsamples (Figure 11). Data from Bismark Lake produced values that were much greater for the 50% subsample, and the 33% and 25% values were consistent for this lake.

RMSE values are good for comparing each of the actual interpolated values. Using residual plots can also reveal how the points are interpolated from the surveyed to the predicted. The residual is the difference between the surveyed values of the point to the predicted values, and is a reflection on the magnitude that the points disperse from a trendline. Residual plots for the ten random points taken at 50%, 33% and 25% revealed how these points were interpolated compared to the original Dalton Lake data (Figure 12). Values close to the zero mark were small in their residual differences. The further away the values drift from the zero indicates that the model is predicting values with greater error. If the residual value is positive, then the predicted value is greater than the regression line, and it indicates that the interpolation method has underestimated the
sediment value at that point. If the value is negative (or below the regression line), then
the interpolation model is overestimating the sediment depth. Values on the Y axis show
the magnitude of the overestimate or underestimate. The 50% IDW model had good
clustering with shallower depths. When the depth measurements were high, the residual
error drifted from the regression line.

The RMSE values from the IDW interpolation for Lakota Lake were high in
comparison to the other lakes (Table 4, Figure 11). Residual plots for this Lakota Lake
(Figure 13) and IDW interpolation shows fairly good clustering at the 50% subsample,
but some deviation at the greater values (= deeper sediment depths) (Figure 9). The
residual plot of these ten random points did indicate that the larger value at 25% IDW
interpolation was relatively close to the zero. This occurrence would tend to reduce the
overall RMSE that was observed and might be the reason why the smaller sample size
was overall very good in accuracy.

In the Lakota Lake example, the residual plot showed how there were some
outlier points that occur around the 2.4-2.5 depth for the 50% and 33% subsamples. This
means that the interpolation method had difficulty producing an accurate reading at these
greater depths. Additionally, this might be the influencing factor on why the Lakota Lake
example had the largest RMSE value. As mentioned earlier, RMSE is sensitive to high
values and outliers. These outliers may have an impact in the RMSE. Knowing this
information may be beneficial for future work and determining how to include or exclude
these values as an option. RRMSE values were smallest for the 50% subsample with a
slight increase with the 25%, and the 33% subsample ranking last for describing the
influence of outliers (Table 5).
RMSE values from the 50%, 33%, and 25% subsamples were consistent for the 50% and 25% Major Lake subsample (Figure 11). The greatest RMSE value was with the 33% subsample. Residual plots of these data (Figure 14) show that one point within the 33% subsample was over 0.2 away from the trendline. This one value indicates a poor interpolation of one single value and would be considered an outlier. This was further evidence towards the need to know and understand the data within an experiment as just one poor reading can cause great error. RRMSE values showed a large value at the 33% subsample as well (Table 5).

Bismark Lake had an RMSE that was higher at the 50% subsample size than those from 33% or 25% (Figure 11). The points at the 50% subsample had greater dispersion at the lower samples (Figure 15). One value in particular was nearly -0.2 away from the regression line. Dispersion of interpolated values at the 33% and 25% subsamples were much lower. The lower values observed in the residual plots appear to be the reason for the lower RMSE with the 33% and 25% subsamples (Figure 11).
Figure 12. Residual plots for different subsamples (50%, 33%, and 25%) using IDW interpolation for data from Dalton Lake.
Figure 13. Residual plots for different subsamples (50%, 33%, and 25%) using IDW interpolation for data from Lakota Lake.
Figure 14. Residual plots for different subsamples (50%, 33%, and 25%) using IDW interpolation for data from Major Lake.
Figure 15. Residual plots for different subsamples (50%, 33%, and 25%) using IDW interpolation for data from Bismark Lake.
4.4 Accuracy of Subsamples - spline interpolation

Differences were also observed among the subsamples at each lake when the spline interpolation method was used. All RMSE values of Major Lake were low and appear to show good approximation of the data regardless of the sample size used (Table 6). Dalton Lake and Bismark Lake had their lowest RMSE value with the 33% spline subsample (Figure 16). The lowest RMSE value for Lakota Lake was observed with the 25% subsample. The random samples of 50% and 33% at Lakota Lake had the highest RMSE value of any of the waters using the spline interpolation method.

As with the IDW interpolation method, Lakota Lakes’ unique shape may point out that spline becomes inexact when confines are narrow with the added complexity of higher sediment levels located in this narrow arm. The fact that Major Lake (an oval shaped lake) had relatively consistent values regardless of the sample size helps to support this finding that with spline interpolation, shape might matter or that quick changes can cause problems with interpolation accuracy.

One of the tenets of this review on spline interpolation is the suggestion that more points should provide a better accuracy to justify the cost of gathering the data. RMSE and RRMSE were again used as a measure of the accuracy of each spline interpolation (Tables 6 and 7). The expectation that increasing samples across the entire lake would provide a more accurate interpolation was not an accurate assumption. In two of these four study waters there was lower RMSE values at the 25% subsample compared with those of greater sample sizes (50% and 33%) (Table 6, Figure 16).
Table 6. Root Mean Squared Error of spline interpolation methods for differing sample sizes at four Black Hills reservoirs.

<table>
<thead>
<tr>
<th>Lake</th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.3620</td>
<td>0.1325</td>
<td>0.1717</td>
</tr>
<tr>
<td>Major</td>
<td>0.1567</td>
<td>0.2424</td>
<td>0.1939</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.9601</td>
<td>1.3259</td>
<td>0.2091</td>
</tr>
<tr>
<td>Bismark</td>
<td>0.3420</td>
<td>0.1178</td>
<td>0.1346</td>
</tr>
</tbody>
</table>

Table 7. Relative Root Mean Squared Error of spline interpolation methods for differing sample sizes at four Black Hills reservoirs.

<table>
<thead>
<tr>
<th>Lake</th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.7867</td>
<td>0.4327</td>
<td>0.5640</td>
</tr>
<tr>
<td>Major</td>
<td>0.6578</td>
<td>0.5419</td>
<td>0.4368</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.4760</td>
<td>0.6200</td>
<td>0.7867</td>
</tr>
<tr>
<td>Bismark</td>
<td>5.1774</td>
<td>2.1459</td>
<td>0.5036</td>
</tr>
</tbody>
</table>

Figure 16. Root Mean Squared Error (RMSE) for ten random points at different sample sizes (50%, 33%, and 25%) using spline interpolation.
Major Lake stands out as the one example of where all sample sizes were relatively equal in their RMSE value. Dalton Lake and Bismark Lake shared one similarity when the spline interpolation was used; a high RMSE value at the 50% level with lower values for the smaller sample sizes (33% and 25%).

The residual plots of ten random points from each sample size at each lake revealed how the interpolated samples differed from the predicted values (Figures 17, 18 19, and 20). At Dalton Lake the values were close to the trendline for lower sediment depths and a slight deviation at some of the lower sediment values for the 50% subsample (Figure 17). Interpolated values of the 33% and 25% subsamples indicated dispersion from the trendline across the spectrum of these samples.

Residual plots for Lakota Lake support the statements that were first identified with the RMSE and RRMSE values noted earlier (Tables 6 and 7). Small values of sediment depth were identified with good accuracy but as the sediment depths increased there was an increasing difficulty of accurately predicting these greater depths (Figure 18). It is unknown if the problem with spline interpolation being able to predict these values is based on the sudden changes in sediment depth or from the shape of the lake. The magnitude of many sample points deviated much less with the 25% subsample than with either the 50% or 33% subsamples (Figure 18). The points close to the trendline indicate that the smallest sample size (25%) happened to have samples that were close to those predicted.

RMSE values from the 50%, 33%, and 25% subsamples were consistent for the 50% and 25% Major Lake subsample (Figure 19). Although the RMSE values at Major Lake were similar, the largest value was with the 33% subsample. Residual plots of all
the subsamples show a slight deviation of the values over much of the range with some lower dispersion points in the middle of these random points and some higher outlier points. In each of the subsamples a single point is extreme from the others and might be considered as an outlier and provides an example of the need to understand the data as this could cause great error for predictions.

Bismark Lake had the highest RRMSE of the sample lakes when spline interpolation was used (Table 7). The RMSE of the 50% subsample from Bismark Lake was higher than those from 33% or 25% (Figure 20). Dispersions from the trendline are seen at the Bismark Lake residual plots for all subsample levels. Several of the random sample points demonstrate a scattering of high predictions for low sediment points of many different sediment depths.
Figure 17. Residual plots for different subsamples (50%, 33%, and 25%) using spline interpolation for data from Dalton Lake.
Figure 18. Residual plots for different subsamples (50%, 33%, and 25%) using spline interpolation for data from Lakota Lake.
Figure 19. Residual plots for different subsamples (50%, 33%, and 25%) using spline interpolation for data from Major Lake.
Figure 20. Residual plots for different subsamples (50%, 33%, and 25%) using spline interpolation for data from Bismark Lake.
4.5 Accuracy of Subsamples – kriging interpolation

Kriging was the third interpolation method used in this study. One general trend held constant throughout the three interpolation methods: the RMSE values did not increase as samples sizes decreased (Tables 4, 6, and 8). Lakota Lake RMSE values were lowest with the 25% subsample. From the Lakota Lake data the 33% value was highest of the three subsamples. This phenomenon was observed earlier in the IDW and spline interpolation methods. As was mentioned previously, it is unknown whether the interpolation processes had difficulty with the narrowing of the lake and estimating depths from the selected points or that the greater changes in sediment depth around this area made the interpolation difficult. Another explanation might be that the interpolation procedure has problems accurately predicting values when nearing the edge of a polygon. The residual plots of the kriging method for Lakota Lake show close approximations for lower values and only greater deviations when the sediment values increased for the 50% and 33% subsamples (Figure 21). The ten random points of the 25% subsample had smaller differences from the trendline compared to the 50% and 33% subsamples.

The variability of RMSE and RRMSE did not show the anticipated trends of increasing values with the lower sample sizes in all cases (Tables 8 and 9). This was expected as it would be predictable that fewer samples may produce larger errors. The fewer samples would be a tradeoff due to less time required to collect data and thus a lower cost. There were some increases of these parameters, but only in a few notable cases (Major Lake RMSE and Lakota Lake RRMSE).
Table 8. Root Mean Squared Error kriging interpolation methods for differing sample sizes at four Black Hills reservoirs.

<table>
<thead>
<tr>
<th></th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.1308</td>
<td>0.0970</td>
<td>0.2059</td>
</tr>
<tr>
<td>Major</td>
<td>0.1312</td>
<td>0.4721</td>
<td>0.6502</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.5331</td>
<td>0.9251</td>
<td>0.1308</td>
</tr>
<tr>
<td>Bismark</td>
<td>0.3701</td>
<td>0.5610</td>
<td>0.4585</td>
</tr>
</tbody>
</table>

Table 9. Relative Root Mean Squared Error of kriging interpolation methods for differing sample sizes at four Black Hills reservoirs.

<table>
<thead>
<tr>
<th></th>
<th>50%</th>
<th>33%</th>
<th>25%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>0.6197</td>
<td>0.3901</td>
<td>0.5533</td>
</tr>
<tr>
<td>Major</td>
<td>0.6468</td>
<td>1.1518</td>
<td>1.4408</td>
</tr>
<tr>
<td>Lakota</td>
<td>0.4937</td>
<td>0.5036</td>
<td>0.6197</td>
</tr>
<tr>
<td>Bismark</td>
<td>7.6159</td>
<td>11.3052</td>
<td>2.4947</td>
</tr>
</tbody>
</table>
Figure 21. Residual plots for different subsamples (50%, 33%, and 25%) using kriging interpolation for data from Lakota Lake.
Trends of kriging interpolation are unclear. Each subsample (50%, 33% and 25%) had the lowest RMSE value, but at different lakes (Figure 22). The 50% subsample was lowest at Major Lake and Bismark Lake, 33% was lowest at Dalton Lake and 25% was lowest at Lakota Lake. Major Lake and Dalton Lake had similar RMSE values from 50% and 25% subsamples (Figure 22). Data from Dalton Lake were the most consistent of any of the sampled waters using kriging interpolation.

Figure 22. Root Mean Squared Error (RMSE) for ten random points at different sample sizes (50%, 33%, and 25%) using kriging interpolation.
Residual plots revealing how the surveyed values compare to the predicted values for Dalton Lake are depicted in Figure 23. The 50% and 33% subsample had the least deviation from the trend line of the three subsamples at Dalton Lake when kriging interpolation was used. A few points (outliers) may be affecting the 25% subsamples. In these cases the interpolation seems to be affected at some of the smaller sediment depths. This might be indicating that utilizing some of the smaller subsets are not appropriate for the kriging procedure.

Major Lake RMSE values when using kriging interpolation showed an increasing trend of point spread from the trendline as the sample size decreased (Figure 24). The 50% subsample was close to the trendline for all of the values. This occurrence would tend to reduce the overall RMSE that was observed and might be the reason why the larger sample size was overall very good in accuracy. Increasing values between 0.5 and 0.6 inflated the RMSE value for the 33% subsample. Outliers may be affecting the 25% subsample or the kriging procedure had difficulty interpolating these points accurately with the smaller sample size. RRMSE values, which are not as sensitive to outliers, showed an expected trend as the decreasing sample sizes had an increasing tendency (Table 9).

Residual plots for Bismark Lake indicate that interpolated points were slightly different between the subsamples (Figure 25). For all three subsamples, most of the dispersion from the trendline was only for the values around 0.5 and higher. In the case of Bismark Lake, using kriging interpolation, most of the spreading was mixed between overestimation and underestimation of sediment levels.
Figure 23. Residual plots for different subsamples (50%, 33%, and 25%) using kriging interpolation for data from Dalton Lake.
Figure 24. Residual plots for different subsamples (50%, 33%, and 25%) using kriging interpolation for data from Major Lake.
Figure 25. Residual plots for different subsamples (50%, 33%, and 25%) using kriging interpolation for data from Bismark Lake.
4.6 Volume Comparisons

One focus of this research was to determine if fewer samples would produce similar results. Estimated volume of sediment was determined for each lake. These processes were run for the different subsamples (50%, 33% and 25%) (Table 4). In Dalton and Major Lakes, the effect of sample size was evident. As fewer data were used in the interpolation process, their volume estimates tend to drift further away from the full sample estimate. Lakota Lake followed a similar trend until the 25% subsample that was actually closer to the full sample estimate. Bismark Lake had a closer estimate with the 33% subsample than from the 50% subsample.

It would be expensive if one were to reach the unrealistic goal of removing all of the estimated sediment (Table 10). At each lake, the total estimates and subsample estimates show how the disparity was realized when dollar amounts were calculated to the volume of sediment. At Dalton Lake, if a comparison between the full estimate and the 25% subsample were used then that would yield a difference of $41,700. The largest cost error was seen with the 33% subsample from Lakota Lake where the cost difference was over $132,000. There was one cost overestimate from Bismark Lake (33%) as the sediment amount was higher from the subsample than when the entire data points were used.
Table 10. Estimated volume of sediment and subsample estimates from four Black Hills ponds and the associated removal costs.

<table>
<thead>
<tr>
<th></th>
<th>Estimated Volume (cu/m)</th>
<th>Removal Costs</th>
<th>Cost Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3,435</td>
<td>$112,325</td>
<td>--</td>
</tr>
<tr>
<td>50%</td>
<td>3,129 (91%)</td>
<td>$102,325</td>
<td>($10,000)</td>
</tr>
<tr>
<td>33%</td>
<td>3,205 (93%)</td>
<td>$104,800</td>
<td>($7,525)</td>
</tr>
<tr>
<td>25%</td>
<td>2,160 (63%)</td>
<td>$70,625</td>
<td>($41,700)</td>
</tr>
<tr>
<td>Major</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8,781</td>
<td>$287,125</td>
<td>--</td>
</tr>
<tr>
<td>50%</td>
<td>8,327 (95%)</td>
<td>$272,275</td>
<td>($14,850)</td>
</tr>
<tr>
<td>33%</td>
<td>7,561 (86%)</td>
<td>$247,225</td>
<td>($39,300)</td>
</tr>
<tr>
<td>25%</td>
<td>6,371 (73%)</td>
<td>$208,325</td>
<td>($78,800)</td>
</tr>
<tr>
<td>Lakota</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>81,593</td>
<td>$2,668,000</td>
<td>--</td>
</tr>
<tr>
<td>50%</td>
<td>79,524 (97%)</td>
<td>$2,600,325</td>
<td>($67,675)</td>
</tr>
<tr>
<td>33%</td>
<td>77,531 (95%)</td>
<td>$2,535,575</td>
<td>($132,425)</td>
</tr>
<tr>
<td>25%</td>
<td>80,427 (99%)</td>
<td>$2,629,850</td>
<td>($38,150)</td>
</tr>
<tr>
<td>Bismark</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>31,131</td>
<td>$1,017,950</td>
<td>--</td>
</tr>
<tr>
<td>50%</td>
<td>30,321 (97%)</td>
<td>$991,450</td>
<td>($26,500)</td>
</tr>
<tr>
<td>33%</td>
<td>32,038 (103%)</td>
<td>$1,047,600</td>
<td>$29,659</td>
</tr>
<tr>
<td>25%</td>
<td>30,429 (98%)</td>
<td>$995,000</td>
<td>($22,950)</td>
</tr>
</tbody>
</table>

(Note: Percent in parentheses are the estimates of the subsample compared to the total estimated volume for each lake. Costs figured at $25/cu. yd. Cost difference is the difference between the calculated dollar amounts of each subsample compared to the total sample dollar amount. Dollar amount in parentheses notes that the cost differences were estimated below the total sample value and those without the parentheses denote that the estimated cost differences were above the total sample value.)
CHAPTER 5
CONCLUSIONS

The aim of this research was twofold. First, it was to recommend the most accurate interpolation method for sediment samples in small lakes. Of the various interpolation methods available, it is not easy to decide which would be better simply by looking at contour lines or general depictions as there can be a great deal of difference among the various methods. A second aim of this research was to determine if fewer sample points would lead to similar results. Fewer needed points would allow for quicker sampling and less money expended during field exercises. Both of these results would provide direction for future work needed in the Black Hills when sampling sediment levels in small lakes.

If a researcher wants to judge the methods simply by visual means (i.e. appealing curvature of contour lines), then the results may look nice but could have poor representation in analysis of variables. In the case of this particular research, the final outcome was simply not an appealing map, but the results have a real world application. The application of this work was to provide an estimate of sediment volume. This data was forwarded, along with an appropriate map of the location of the sediment in the lake, to habitat biologists and administrators that use the information for project prioritization and to allow for more accurate bids on projects by private contractors.

The first part of this project was to determine the accuracy of three interpolation methods based on how well they predicted the values at the known points. The best method produced the least error as measured by RMSE. In all of the sample waters, IDW
had the lowest RMSE, with spline being a close alternative. Kriging ranked third in accuracy for point value prediction.

It was interesting to note that in cases, Bismark Lake in particular, where sampling was not performed due to physical constraints of the apparatus used there were differences between the methods. In this instance spline interpolation indicated sediment depths that were greater in areas where sampling was not used. IDW also indicated that there were sediment depths that were greater in this area but not to the extent of spline. Spline may have produced these inaccuracies due to the fewer number of data points available in the region in which to derive the interpolation and also that this area was on an edge of the sampling area.

Other researchers have noted that RMSE can be sensitive to outlier or extreme measures in a dataset. To offset this occurrence, the measurement RRMSE was developed. This statistic removes the effects of measurement units and is not sensitive to changes in measurement unit or scale (Li and Heap 2008). In all of the study waters, the RRMSE was lowest using IDW interpolation followed by spline and kriging. These results again suggest that IDW interpolation was the most accurate of the methods sampled in this study. Kriging in this study was used as a parameter by itself without any further geostatistical procedures. The researcher could also use options within the kriging procedure to improve the accuracy of the model including the alteration of the semivariogram, sill and nugget location. These options could be diverse and were not tested in this study.

Determining how many sample points are needed across these four study lakes allows for more efficient sampling. The methodology used for field collection requires
personnel to commit to assisting for several days. If this fieldwork can be reduced while still obtaining similar results, then money in the form of time expended, could be saved during data collection. Analysis for this aspect came from two different processes.

RMSE was again employed as a measure of interpolation accuracy, but in this case, it was with the subsamples (50%, 33% and 25%). Information from these tests was somewhat inconclusive. There was an original premise that there would be greater accuracy when more sample points were taken. While this was not apparent with the subsample analysis it did become more evident when actual dollar amounts of the estimates were observed. These values showed their importance of having the best accuracy especially when one considers the impact these could have on prioritization of projects and needs to project amendments.

A second process was used via the application of the data subsets into residual plots. These figures depict where possible outlier points reside and how they might be affecting RMSE accuracy. Throughout this study, many of the interpolation methods suffered in managing higher sediment values. When values were low or at least consistent, the interpolation methods all functioned well, but IDW was consistently the best alternative.

The original objectives of this study were to determine a good interpolation method for sediment surveys in the Black Hills and if sample size could be reduced while keeping accuracy. Inverse distance weighted performed best of the interpolation methods chosen. Spline and kriging also did well in some instances, but they were consistently behind IDW in regards to accuracy. Subsample analysis showed that there were differences when the smaller samples were used. These seemed to have a large impact on
the overall costs when they were calculated with this consideration. It is recommended to capture as much data as possible when performing sediment surveys in the Black Hills to ensure the most accurate estimates.

5.1 Limitations of the Research

As with any research, the addition of more data could always help to validate the process used. In this case, the expansion of even more small lakes would help to establish and prove if the findings were consistent across even more waters. Beyond the sheer number of waters needed for fine tuning this research, there were areas where the water depths were too deep to sample effectively. New methods or perhaps new or different sampling equipment design would help to collect data in these deeper water portions of area lakes. In the current study, there were sections of two of the larger lakes where depths were prohibitive to collect data. By adding a new data collection process or method, one could collect these data and improve the overall accuracy of the interpolated estimate. Also there might be confounding impacts on the process by not having some of these deeper samples. Missing data would obviously have an impact when interpolation methods involve estimating data where points were not taken.

5.2 Potential Future Research

Future work associated with this research may come in a variety of steps. A more in depth analysis of the data gathering process, specific alterations when using kriging interpolation, alternative steps to evaluate the interpolation methods and validate the sampling results are all possible future needs associated with this research.
There are additional considerations for future investigations in the evaluation of interpolation methods. Taking into account the shape of the lake may dictate that there are some interpolation methods that are superior to others in predicting the precision of the overall estimates. After the initial research analysis there could be indicators that point to a more preferred method of interpolation based on bottom shape or profiles. Additionally, if a researcher were to do some pre-survey work on the lake in question then this might also dictate which interpolation method might be a better use later on in the process.

Although the IDW and spline interpolation methods proved to be superior when working on sediment depths in this research, some modifications can be done to kriging interpolation that may improve its overall results. Use of adjusting the semivariogram modification to the interpolation model can better fit the data, which might help. Within ArcMap and the Geostatistical Analyst extension one can experiment with the sill and nugget to improve the fit of the data to a regression line. These areas can be researched in the future to potentially improve the accuracy of the kriging interpolation method when using sediment data.

Within the sample size evaluation there are several alternatives that can be investigated further. In this study there were some inconclusive results in regards to the best sample size based on the RMSE statistic. In several cases there were extreme values when the 33% subsample was utilized and other instances where the lowest sample size (25%) had the best precision. This study evaluated each subsample with a single sample. By increasing the number of iterations there might be a reduction in this error or the
results may be more in line to original expectations that larger sample sizes would be more accurate.

This study utilized RMSE as an evaluator towards the interpolation method to determine the best accuracy. An alternative to this approach may include comparing interpolated surfaces from the full sample and then compare other interpolated surfaces with a one or a few points removed. The evaluation would then be what the predicted values were at the location where the points were eliminated. This method might provide some additional insight towards determining the best interpolation method.

Lastly, studying the effects of flow into these small dams and monitoring the sediment pluses from storm or runoff events is another area of future research. Determining the size of particles and mapping their dispersal along with runoff can increase the knowledge of sediment loading and aid in determining the expected life of these small reservoirs.
REFERENCES


