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Method for Estimating Sediment Mass Movement from Delta Recutting: A Case Study Using Single Beam Sonar in Deer Creek Reservoir

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Received: 21 August 2019; Accepted: 22 October 2019; Published: 25 October 2019

Abstract: The recutting of delta sediments typically occurs during reservoir drawdown in the summer months. It can affect various reservoir processes and can impact water quality because of resuspending nutrients during warm periods supports phytoplankton growth. Quantifying this sediment movement is a key element for evaluating the life and quality of a reservoir. This study targets reservoirs in the intermountain region of the U.S. These reservoirs are filled in the spring, then drawdown through the summer to provide irrigation water. Incoming sediment loads are generally restricted to spring high flows, with little new sediment entering the reservoirs during the remainder of the year. As the reservoirs undergo drawdown, the sediment deposited in the delta region during spring flows is re-cut from the exposed delta and moved into submerged delta region. The majority of flow and sediment movement both above and below the water surface occurs in channels cut into the sediments during spring deposition. During recutting, channels in the exposed sediments often move, but the submerged channels are more stationary. Traditional single-beam sonar surveys are performed on a grid and changes are used to quantify sediment movements. This approach is not applicable to delta recutting as the grid resolution is not sufficient to resolve the relevant changes that occur in the narrow excised flow channels. This study explores the ability to quantify and monitor sediment mass movement in Deer Creek Reservoir (DCR) using a single beam sonar. Our method uses surveyed cross-sections across the flow channels. It is difficult to position boat passes exactly on previous survey lines, and small location differences in an up-stream or down-stream location can be significant because of the slope of the channel. To address this, we surveyed each line in two directions, then interpolated both the position and elevation data. We performed periodic surveys over a two-month period. We were able to document and quantify both sediment deposition and erosion areas. As expected, sediment movement was from the inlet areas toward the reservoir. The data showed both deposition and erosion depending on the distance from the reservoir head, which changed over the survey period. This method can be used to quantify sediment recutting and resuspension that can affect nutrient loads during critical warm, low-reservoir conditions, but is difficult to implement accurately.

Keywords: sediment delta; sediment recutting; nutrient cycling; quantitative sediment movement

1. Introduction

1.1. Background

The level of nutrients and pollutants in a reservoir has a profound effect on water quality and have numerous sources [1,2]. Deposited sediments have been identified as one potential internal nutrient source for reservoirs and can provide nutrients to the reservoir water column even when external sources are minimized. Studies conducted in reservoirs which reduced external inputs of nutrients have shown, that in some areas, external reduction had limited effect on eutrophication [3,4]. Excessive amounts of nutrients may increase productivity in ecosystems, leading to problems with water quality [5,6]. In addition to nutrients, bottom sediments can accumulate pollutants. The recutting and resuspension of sediments can mobilize these nutrients and pollutants and these physical processes are important mechanisms that control nutrient and pollutant concentrations in aquatic environments [2]. Understanding and quantifying these sediment mobilization processes in reservoirs will allow researchers to adequately maintain a sustainable source of water [5,6].

1.2. Nutrient Reclying

Nutrient (specifically, P) recycling is a complicated process with an extensive literature base, as it is affected by a variety of factors. For discussion, we will divided these processes into three types. First, P that can be released through geochemical processes. Second, sediment resuspension (potentially caused by a number of mostly mechanical factors) can affect internal nutrient cycling. This process can be characterized and quantified by sonar methods—the goal of this paper. Last, a number of other aspects (including temperature, organisms, etc.) may affect nutrient movement. We will not discuss these mechanisms or processes here, though they are important to understand. Fully understanding nutrient cycling in a reservoir would require the evaluation of all three process categories.

1.2.1. Geochemical and Biochemical Interactions

Chemically driven processes are responsible for a significant amount of P transfer between sediment and the water column. These include oxidation-reduction reactions involving iron (Fe) Fe-P complexes as well as reactions involving P, calcium (Ca), and pH in calcareous sediments [7]. Different P pools are released by different geochemical environments and processes.

Many very early studies have concluded that oxic sediment conditions retain P better than anoxic conditions, such as the work done by Einsele in 1936 (as reported in [7]) and Mortimer [8,9]. Subsequent literature has related Fe to the P cycle, based on oxygen levels. This relationship was first reported by Einsele in 1936, who noted that Fe compounds precipitated with the water was oxygeniated [7]. These Fe compounds precipitated in aerobic water were later shown to Fe(III) oxyhydroxide by Tessenow in 1974 [7] and Gunnars, et al. [10]. These iron-hydroxides absorb or co-precipitate large amounts of P. When sediment conditions become anoxic, Fe(III) is reduced to Fe(II), which forms much more soluble compounds and P is released. A minimum molar stoichiometric Fe to P ratio was found to be approximately 2 for precipitation of P [10]. If the ratio of ferrous Fe [Fe(II)] to phosphates is greater than 2, then P will only precipitate after oxidation and precipitation of all Fe present. If the ratio is less than 2, P remains in solution, which is the mechanism by which anerobic reservoir conditions can release P into the water column [10].

Ruban and Demare [11] found that P was not released if oxygen concentrations stayed above 0.5 mg/L. Below this, there was a change in redox potential which resulted in the release of both Fe and P. This follows chemistry principles which show that P can be bound by Fe mineral complexes.

Looking specifically at P releases from sediments Gibson, presented in [12], describes anoxic conditions in the hypolimnion which create the potential for P release. This is a positive loop, as allochthonous loading of P increases, autochthonous sources of P for sediment do likewise, which increases both carbon and P within sediments. This in turn increases oxygen demand and creates reducing conditions. Under reducing conditions, P is released, furthering the cycle.

This suggests that oxygenated water would result in lower P concentrations and releases. However, Gächter, et al. [13] found that oxygenated conditions in the hypolimnion did not affect P cycling at the sediment–water interface (see also [14–17]). Gächter and Müller [18] and others [13,19,20] have shown that this process is governed by benthic bacteria.

Researchers have evaluated other geochemical processes that can release P from sediments, this includes nitrate concentrations [21] and sulfates [22–24] which can disrupt the Fe–P complexes with ammonia, the impact of pH and Eh with carbon availably showed that effects depend on if the reservoir is calcareous [25] and photosynthesis rates [26]. Diffusion can also release P from sediments [27,28].

1.2.2. Resuspension and Other Factors

Resuspension is a mechanical process that allows deposited sediments to become suspended within the water column. Some of the well-recognized internal and external sources for resuspension include wind [29,30], wave action, ice, climate change [31], cold currents entering the reservoir from rivers or groundwater, and generation or regeneration in the water body. Disturbances by animals such as bottom-feeding fish [32] and chironomid larvae [33] may also cause significant resuspension. The suspended sediment have a profound effect on aquatic ecosystems [34]. Resuspension can introduce trapped nutrients into the water column, promoting the growth of algae and other aquatic organisms, adversely affecting water quality [5,33,35].

Sediment resuspension or recutting often occurs in the sediment delta regions of irrigation reservoirs as the reservoirs are drawn down to meet irrigation demands. As the reservoirs are drawn down, the sediment deltas are exposed and the inflow can cut or erode inflow channels through the delta sediments. The resulting recutting and nutrient inflows occur in the warm, summer period, a time when reservoirs are highly susceptible to algal blooms. Increased nutrient loads during this time period can have higher impacts on algal blooms than loads during other times of the year. There have been many studies on sediment movement and the effect it has on water quality [2,5,35,36]. These studies document various methods to monitor and quantify sediment movement along with impacts from these processes.

One method is to model or conceptualize the sediment movement is a sediment budget. A sediment budget is a quantitative inventory of all the sediment inputs, outputs, and storage within a defined system or area of the reservoir. The volume entering and exiting a particular section of a water body is monitored by determining and evaluating the sediment fluxes; the sources and sinks from different processes that give rise to additions and subtractions within a control volume. Another approach uses numerical models with various approaches, such as the finite element method, to predict reservoir sedimentation based on parabolized and laterally integrated forms of the governing equations [36]. This general approach is used in many computer models and calculations to predict sediment movement. This not only allows the calculation of the sedimentation rate, but also allows the prediction of the time evolution of bottom deposit structures, which is fundamental when analyzing the fate of pollutants [36]. Mass sediment movement monitoring is another method used to develop models of sediment mobilization, transport, and deposition. The use of Digital Elevation Models (DEMs) recorded by a laser scanner and the use of rare earth element oxides as tracers have both been proven as methods to trace mass sediment movement [37]. DEMs are used for measuring the movement outside of water bodies, while the use of rare earth element oxides can trace sediment movement both in and out of water.

This paper demonstrates the use sound navigation and ranging (sonar) to characterize and quantify mass sediment movement from delta sediment recutting in Deer Creek Reservoir (DCR). This approach is similar to developing DEM's with a laser scanner [37] but incorporated under water. Sonar has generally been used as a tool for marine geology, but in recent years, mainly through the interest in sediment problems of lakes and reservoirs, the use of sonar technology has been explored in bodies of fresh water [38]. Sonar uses sound reflection to detect objects on the bottom surface [39]. The basic principles on which sonar relies is that the sound moves at a steady rate through a given medium, water in this case, and reflects off objects in its path. In practice, sound velocity is changed by the temperature profile, which can be taken into account. By recording these echoes and measuring the time required for the echo to travel from the sound source to the receiving point, calculations can determine the distance to an object with reasonable accuracy. In some cases, sonar can be used to distinguish different sediment depositional environments; characterizing soft sediment layers from hard packed sediments [38,39]. This is useful for reservoir studies, since soft sediments are more prone to resuspension. In our study of DCR, however, we did not try to differentiate between the hard and soft sediments.

Sonar studies have been undertaken previously in fresh water reservoirs, but not for the use of monitoring sediment movement. The most common use is for bathymetry profiles and dredging management. Sonar has been used to detect mines on the ocean floor [40], monitor fish in shallow channels [41], create bathymetry profiles, and estimate sediment quantities in dredging projects. A group at the University of Illinois conducted a study using a multi-beam echo sounding to examine both the form and flow above a series of sand dunes in the Mississippi and Missouri rivers [42]. We show that sonar can be used to monitor and quantify short term, on the order of months, sediment movement in reservoirs that mostly occurs in submerged flow channels in delta sediments.

1.3. Study Objectives

Our objective for this work was to determine if we could develop a method to monitor and quantify sediment movement caused by sediment delta recutting. This was a challenge because the quantity of sediment moved, while significant for sediment and nutrient resuspension, is very small compared to the volumes or masses quantified using sonar-based methods for activities such as dredging. A secondary goal was to estimate sediment mass movement over the drawdown period at DCR. The long-term monitoring and characterizing sediment movement in the delta area is a longer-term objective. This initial work was limited to 6 surveys taken from 2 July to 11 August, a period of approximately 5 weeks. Reservoir drawdown was occurring during this period and sediment recutting and resuspension was taking place. We used the data collected to determine if single-beam sonar methods are appropriate and feasible for a longer term study focused on sediment characterization and to develop methods that could be used. These methods can be extended to other reservoirs that experience annual drawdown and sediment recutting and suspension. We also used this study to develop and refine methods for performing monitoring of sediment recutting over a longer time frame. The sediment delta in DCR is stable, it does not have a steep front, mostly because of annual drawdowns. Based on visual inspection when over 3 km (2 miles) of delta was exposed (Figure 1), it is apparent that while there is deposition over the entire delta, the majority of changes occur along the channels that are formed during drawdown.

Drawdown during a typical year is not as extensive as that during the dam reconstruction shown in Figure 1. In most years, the exposed delta only extends about 1.5 km (1 mile) or less, approximately half the distance shown in Figure 1. This repeated annual drawdown flattens the face of the sediment delta, as this face is continually moving because of changing water levels, and there is no sharp slope at the face of the sediment delta. Rather there is a relatively continuous slope in the delta sediment lacking a sharp face. Figure 1 shows that the sediment delta is cut by channels that resuspend the sediment. Changes during drawdown appear to be mostly confined to these channels. As the talweg of these channels wanders, it could also help eliminate a sharp sediment delta face and result in the more continuous slope that is observed. As Figure 1 shows, this process seems to continue in the submerged environment, as there is no clear demarcation line associated with the annual drawdown (which varies in extent from year to year).

During dam reconstruction, when the delta was exposed, we performed sediment sampling. We determined water soluble P for all 91 samples, and P in four other reservoirs or fractions for 19 samples. Results showed water soluble P in the range of 2.28×10^{-3} to 9.81×10^{-3}, KCl-P from 2.53×10^{-3} to 1.10×10^{-2}, NaOH-P from 5.30×10^{-2} to 4.60×10^{-1}, HCl-P from 1.28×10^{-1} to 1.34, and residual (mostly organic) P from 8.23×10^{-1} to 3.23 mg/g [5]. Figure 2 shows the sediment delta during samples. As noted, the sediment delta does not have an active gravity driven front, but is a relatively gradual slope. The image clearly shows sediment recutting or resuspension in the inlet channels.

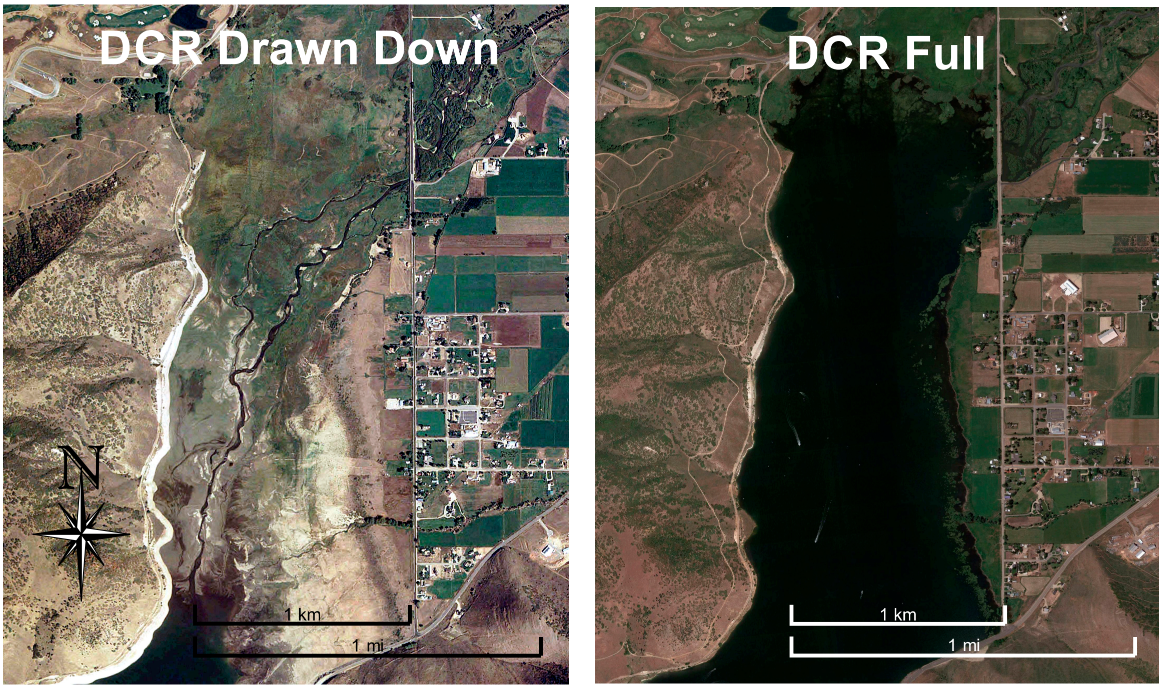

Figure 1. Exposed sediment delta showing the gradual slope and the incision by the influent streams. The left is approximately 3 km (2 miles) of delta that was exposed during a dam reconstruction project, the right image shows the lake with a typical pool elevation. The typical annual drawdown only exposes about half this amount, or about 1.5 km (1 miles) of the delta.

Figure 2. The exposed sediment delta during dam reconstruction showing sediment cutting in the inlet channel. Near the top of the photograph, vegetation can be seen in the portions of the delta that are regularly exposed due to annual drawdowns.

2. Study Area

DCR (Figure 3) is located 30 km (18.5 miles) above Utah Lake, on the Provo River below Heber Valley. DCR's main inflow comes from the Provo River, with other inflows from Snake Creek, Main Creek and Daniels Creek [43]. The contributing watershed is 700 km^2 (171,663 acres). The surface area of the reservoir is 1000 hectares (2680 acres) at full capacity with an annual inflow of 320,704,800 m^3 (260,000 acre-ft) from the Provo River. The reservoir is 10 km (6 miles) long and an average of 1.5 km (1 mile) wide. It has an average storage capacity of 187,488,960 m^3 (152,000 acre-ft) and is used to provide municipal and industrial power and irrigation flows to more than 20,000 hectares (48,000 acres) of farmland [35]. The reservoir is the main water supply to a large sector of the populated areas in Utah and Salt Lake Counties, serving an approximate population of 485,000 [43]. It is used for culinary water, providing 90,660,780 m^3 (73,500 ac-ft) of water annually for the water districts of Salt Lake City, American Fork, Lehi, Lindon, Pleasant Grove, Orem, and Provo [5,43]. This reservoir stores Provo River floodwater as well as surplus Weber River water diverted through the Weber-Provo Canal and water from the Duchesne River. The reservoir releases water for the Metropolitan Water District of Salt Lake City that flows 68 km (42 miles) through an aqueduct to Salt Lake City [35]. The stated beneficial use classifications for the reservoir include: culinary water, recreational bathing (swimming), boating and similar recreation (excluding swimming), cold water game fish and organisms in their food chain, and agricultural uses [43].

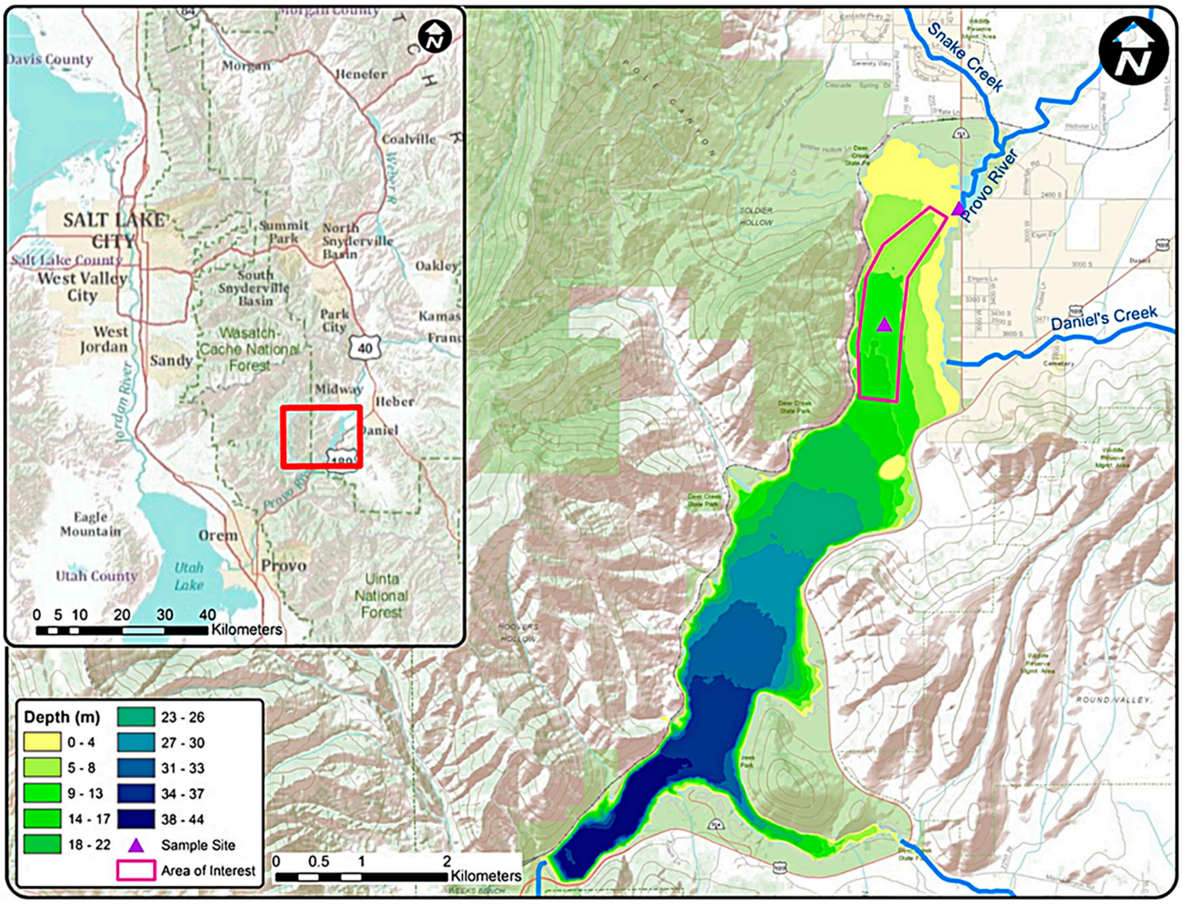

Figure 3. Deer Creek reservoir (DCR) with the study area, which is at the Provo River inlet, highlighted. The depths are relative to a full pool.

In recent years DCR has exhibited water quality problems including algae blooms and various taste and order issues that have been noted at water treatment plants receiving DCR water [44,45]. Eutrophication in the reservoir has caused a deterioration of water quality through increased algal growth. This excess growth is detrimental to a sustainable water supply and impairs the beneficial uses of the reservoir. As phosphorus (P) is the limiting nutrient for plant and algal growth in DCR, the key goal is to limit the amount of P entering the system. In some reservoirs where the input P has been reduced, eutrophication has not changed, potentially due to availability of nutrients from deposited and resuspended sediments. This is referred to as nutrient recycling, where nutrients previously trapped within the sediment become available through resuspension [34]. DCR sediment has a significant amount of available nutrients, more than 800 mg/kg water-soluble P, in the delta sediments [5].

DCR has greatly improved water quality after the reduction of external P loading; however, there are still large algal blooms as well as other water quality issues without clear attributable causes. One hypothesis is that sediment movement and resuspension plays a role in these problems, providing nutrients to the water column from the sediments [5]. To help understand this problem, we developed a method to monitor and quantify sediment movement in DCR using single-beam sonar. This addresses the first step to quantifying the amount of nutrients released to the water column which is to quantify sediment movements and resuspension.

3. Methods

3.1. Sonar Equipment

We used a single beam, dual-frequency Echotrac CVM Sounder with Hypack 2009 and Odom eChart software to perform data reduction and analysis. We used both programs for data collection and processing. Hypack 2009 supports data collection, survey planning, and log points, while the eChart displays real-time high and low frequency waves during the survey. We followed the manufacturer's instructions for calibration and water temperature profiling.

The basic conceptual survey model for this research used the sonar at selected locations to acquire data and then processed it using HYPACK 2009 software. To determine if sonar could be used to monitor and quantify sediment movements, we selected cross sections along the inflow of DCR and repeatedly surveyed those sections. The reservoir inflow delta is the part of the reservoir where sediments are most likely resuspended and moved. The raw data measured during each survey includes x and y coordinates obtained from the GPS, and depth measurements from the sonar.

The resolution of the sonar is 3 cm (0.1 ft) with accuracy of 0.03 cm (0.01 ft) ± 0.1% of the depth [39]. Using this information, an elevation profile of the reservoir bottom along each line was measured and plotted. Studying the plots and comparing each line with other lines at the same cross-section over time should give a graphical representation of the movement of the bottom sediment. The research was performed to determine if this method could provide the required information. Applicability depends on the precision and accuracy of the sonar and GPS measurements, the ability of the survey boat to return and measure the same cross section, and the ability to accurately analyze the resulting data.

3.2. Setup

To create a survey plan for DCR, we used the sonar system to survey sections across the entire reservoir near the inflow to locate any channels. This was done by using Odom eChart software to monitor the bottom profile during the survey. An example of the Odom eChart presentation is shown in Figure 4, which shows the survey line locations. Once we located a channel during the survey, we used the HYPACK 2009 software to mark these locations, created a map of these markers, and analyzed the map to determine the course of the subsurface channels. Using this map, we could see roughly identify where the channels were located and the route they traced along the lake bottom. We used these channel locations to create survey cross sections to monitor the channels for sediment movement. The final cross sections were chosen in locations that would be easy to find and repeat for each survey. This included both GPS locations, and shoreline markers to help with boat navigation.

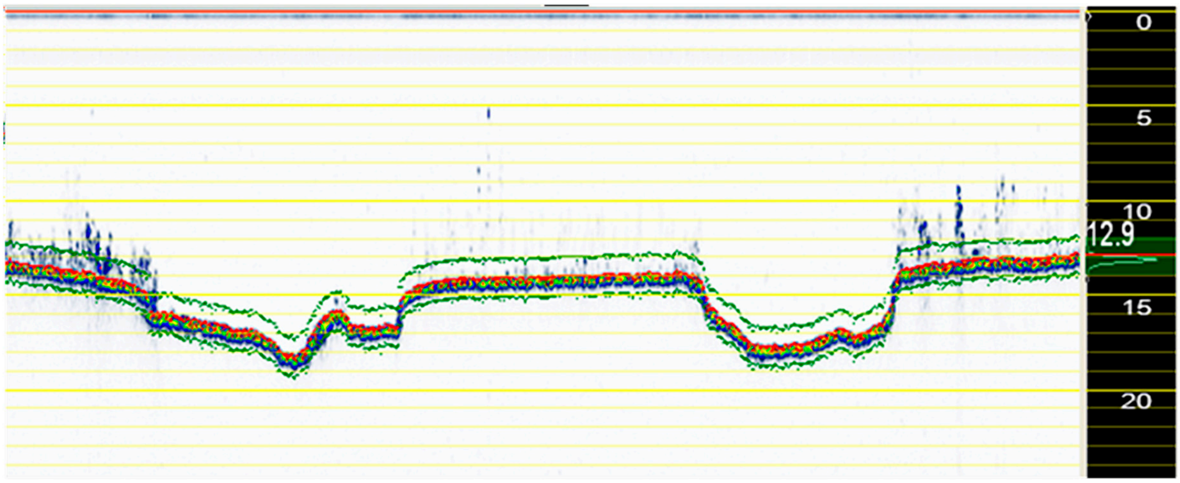

Figure 4. Example raw sonar data from Odom eChart software for a survey line showing a channel on the left side. The bottom shows as multiple sonar returns with significant noise.

We determined that even with GPS guidance during a survey, it was beneficial to have visible landmarks on the shore to help navigation. We created planned line profiles using the survey cross sections identified. Using both the GPS guidance system and the shoreline markers allowed us to survey the same profile lines each time. Figure 5 shows the profile lines created for this study. The starting points are represented with blue triangles and black numbers while each survey line with its associated number is shown in blue.

Figure 5 is a plot of the 7 survey lines, their location on the reservoir, and their relative distances and relationships. The top of the figure is near the inflow of DCR, while the starting point for each survey line is near the eastern shore of DCR. Profile Lines 1 through 4 began at Starting Point 1, Profile Lines 5 and 6 began from Starting Point 2, and Profile Line 7 began from Starting Point 3. Starting Points 1 and 2 are about 125 m (415 feet) apart, while Starting Points 2 and 3 are about 32 m (105 feet) apart. Table 1 lists the lengths of each profile line. Visual markers included items such as fence lines, structures, and other permanent objects that could be used to help keep the boat on line during the field data collections. These starting points were easy locations to identify and access with the boat, which aided the GPS positioning. While GPS guidance systems proved helpful, because of difficulty in recognizing small heading changes, it proved difficult to remain exactly on a survey line using only the GPS. Having visual markers on the far shore that could be used to help pilot the boat significantly helped accuracy.

Table 1. Length of the survey lines.

Line Number	Length m (ft)
1	605 (1986)
2	435 (1430)
3	703 (2308)
4	620 (2035)
5	697 (2288)
6	714 (2344)
7	720 (2362)

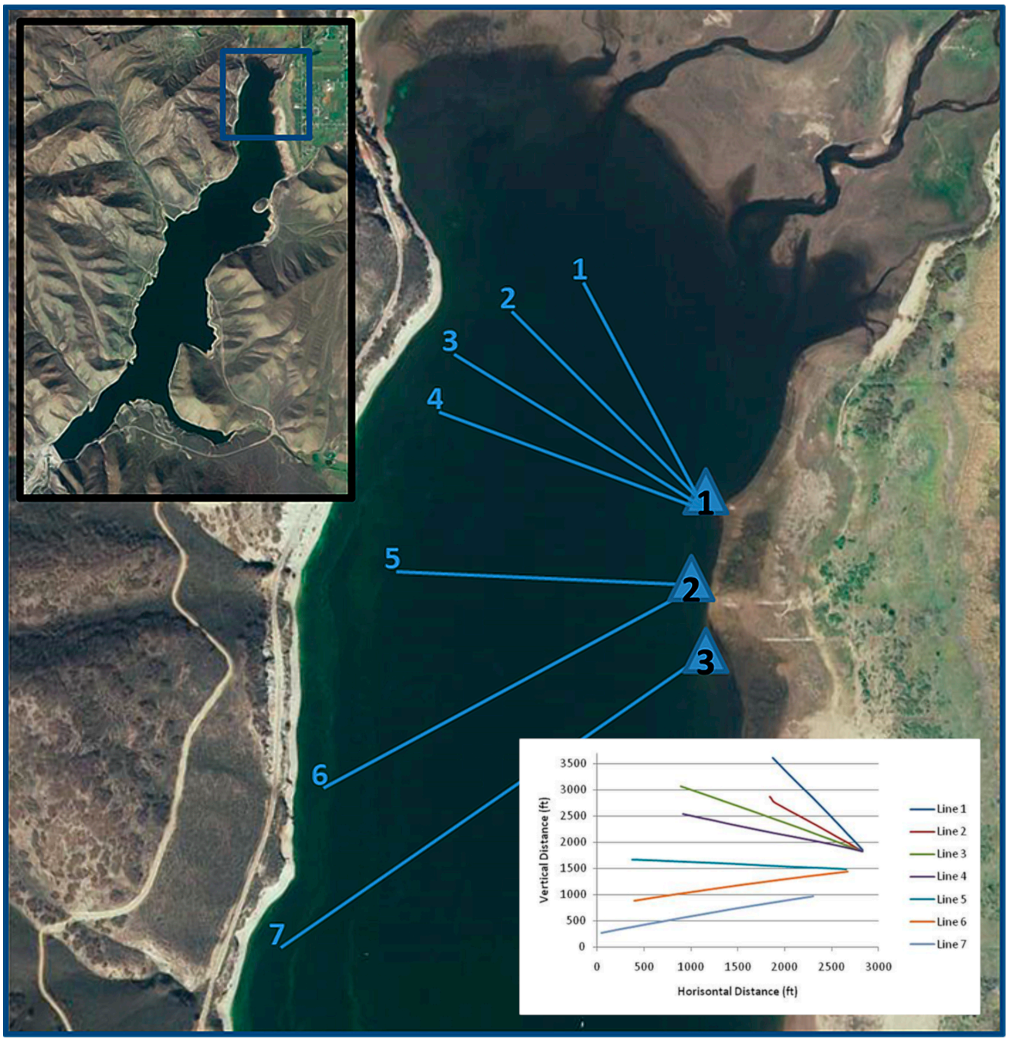

Figure 5. The 7 survey lines used in the projects. Lines 1, 2, 3, and 4 all begin at Starting Point 1, Lines 5 and 6 begin from Starting Point 2, and Line 7 begins from Starting Point 3. The inset in the lower right provides a scale for the lines, with Line 7 approximately 750 m (2500 feet) long.

3.3. Study Plan

We collected data along seven profile cross sections near the main inflow of DCR shown in Figure 5. Approximately every two weeks we re-surveyed the profile lines to create a time-series dataset of sediment movement. The field data collection consisted of seven survey lines with three starting points as indicated in Figure 5.

Before each survey, we used the ODM Digibar® to determine the water column sound velocity. We followed the manufacturer's recommended method for measurements. The resulting value was used by the Odom eChart® software as the initial sound velocity. We also entered offsets for the GPS unit and other relevant parameters.

Each survey began by positioning the boat on the starting point for the survey line and then piloting the boat along the planned line profile. We started logging data slightly before starting the line and continued as the boat moved along the survey line. We stop logging at the end of the line while we turned the boat around and re-started logging once the boat was positioned at the end of the line. We then re-surveyed the line going back towards the starting point. This allowed collection of duplicate data to support more accurate readings. The recordings were saved using HYPACK and organized by survey date and survey line.

We used Odom eChart software to collect the raw survey data at approximately 20 readings per second. Typical survey speeds were on the order of about 15 km (10 miles) per hour. We initially collected both low- and high-frequency data to identify hard and soft bottom sediments. We found that the delta area of DCR did not have significant amounts of soft sediments (or vegetation), and subsequently collected only high-frequency sounder data to identify the sediment surface. We performed all processing on these high-frequency data.

3.4. Field Data Collection

Field work started with the first trip on 2 July, and the last on 11 August, with a total of 6 field data collection trips. During the survey period, DCR was drawn down significantly with a surface elevation change of 2.28 m (7.47 feet). Only 5 of these trips were used to analyze sediment movement, as data from the first trip was used to locate and identify the underwater channels and design the survey lines.

Table 2 lists the six data collection trips, the date the trip was made, the lines surveyed, and DCR water elevation. Elevation is an important variable as the reservoir level lowers, more flow is concentrated into the channels, and in this case, the area of the upper survey lines became so shallow that surveys could not be accomplished. In this shallow water, even though the channel is completely submerged, the majority of flow is occurring in the submerged channel driving both sediment recutting at the inlet end and sediment deposition in the channel as flow slows in the deeper water.

Table 2. Sonar survey schedule for DCR showing the date of the survey trip, the lines that were surveyed, and the elevation of the reservoir surface obtained from the Bureau of Reclamation who operates the dam.

Trip Number	Date	Lines Surveyed	Water Surface Elevation m (Ft)
1	30/06/09	Preliminary survey	1651.18 (5417.25)
2	02/07/09	1, 2, 3, 4, 5, 6 ,7	1651.10 (5417.01)
3	16/07/09	1, 2, 3, 4, 5, 6, 7	1650.35 (5414.52)
4	23/07/09	4, 6	1649.74 (5412.53)
5	11/08/09	4, 5, 6, 7	1648.82 (5409.52)
6	03/09/09	4, 5, 6, 7	1648.21 (5407.50)

The number of lines surveyed for each trip varies. Trip 1 was the taken to located the channels and provide data to create the planned lines for the project. During Trips 2 and 3 all seven lines were surveyed two times, once heading down the line, and then coming back up the line. During Trip 4 only two lines were surveyed, however each line was surveyed four times to determine how repeatable the measurements were and to get more accurate results. Lines 1–3 were not accessible during Trips 5 and 6 due to drawdown of the reservoir.

4. Data Processing

We used HYPACK software to pre-process the raw sounder data and prepare the data to be exported for analysis. When we exported the data points from HYPACK, we did not use any of the various options to perform averaging or filtering on the data before exporting. We converted and exported raw measurement data as asci text in (xyz files from HYPAC) for analysis in Excel.

We transformed the coordinates to one-dimensional data representing distance along a line. We used the starting coordinate of the survey line as the initial point and we computed distance along the line as the distance from this point. This caused problems with some of our results as it assumes that each field collection followed the survey line exactly. This issue is discussed in more detail in Section 5.1.

We should have transformed the horizontal data, x and y, coordinates to separate coordinate systems for each survey line, where the transformed x-data represented distance along the line, with a value of 0 indicating the starting point for the line, and the y-data representing distance from the line, which ideally should be 0.

Using the transformed coordinates (i.e., distance from the starting point), we plotted depth versus distance for each survey line. As expected, these data exhibited measurement noise. We smoothed the data using a central moving window average with a width of eleven data points, five points on each side. We did not analyze the first and last five locations on each line as these points were a significant distance from the monitored channels and did not affect the results. Visual analysis showed that the data smoothing reduced the noise in the data. All subsequent analysis used these smoothed data as input.

After data smoothing, we interpolated the data to locations spaced at 0.076 m (0.25 feet) along each line. This allowed us to directly compare different survey times. Once the data had been interpolated, we computed the averaged elevation at each point using the data from forward and backward passes made on each line on the same day, occasionally more than one forward and backward pass was made, in this case we averaged all the passes from the same day.

Using the average data, we could characterize sediment movement using data from lines surveyed on different days. We used various methods including differencing and other quantitative comparison techniques.

5. Discussion

5.1. General Issues

The data showed sediment movement within the channels over time. The survey lines showed both deposition and erosion at different locations on various lines. In some cases, the changes did not appear to be from the result of physical processes, but were either the results of data collection errors, such as not surveying the identical location, or issues relating to the analysis.

The following sections describe trends within the channels for each survey line. In these discussions we explain the observed trends or changes and attempt to associate these trends with physical processes or attribute the changes to other issues; however, these explanations may not accurately represent what is actually happening due to the limited amount of data. While enough data were collected to determine if this approach is feasible, there were not sufficient data collected to adequately characterize all the various processes occurring in the channels, which was not an objective of this study.

The sonar data matched our expectations and what we know of the physical delta recutting that occurs at DCR. Figure 6 shows two channels in the exposed DCR sediment delta taken when the reservoir was significantly drawn down for dam repair. The left panel of Figure 6 shows sharp slopes resembles sonar geometry in the results from Lines 4 to 7 which show channels with sharp side slopes that are almost vertical (sonar results are shown later in Figures 7–10). These results closely matched channel shapes in the exposed delta area shown in the left panel of Figure 6. The right panel of Figure 6, from the same time period, shows a more rounded channel, similar sonar-delimited channels that appear in Lines 1 to 4 (sonar results are shown later in Figures 7 and 8).

Figure 6. Typical sediment recutting channel geometry from the exposed DCR delta. The left panel shows an exposed channel with near vertical side slopes, the right panel shows an exposed channel with a gradual slope on the left, and a steeper but non-vertical slope on the right. Sonar data reveals similar submerged channel geometry.

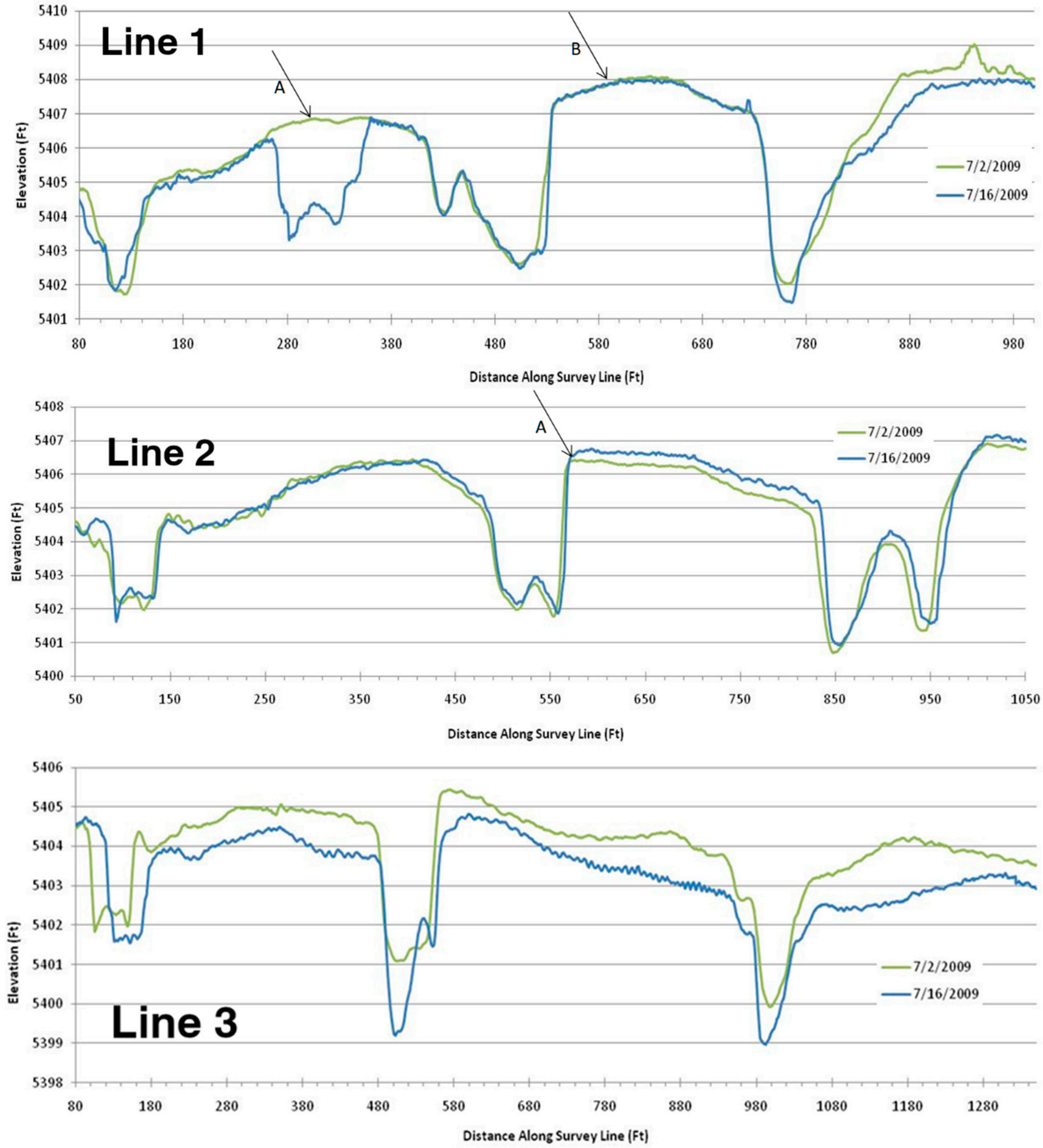

Figure 7. Survey results for Lines 1–3. These lines were only surveyed twice and reservoir drawdown made these areas unreachable because of how shallow the water was. The results show obvious errors resulting from various survey issues.

The data for all the lines showed that as the distance along the survey line increases, there is more apparent change in the sediment. That is, it appears that there is more sediment movement occurring at the end of the line than near the beginning. This occurs even in areas between the channels where we expected no, or little, change. Both the nature of these differences, increasing with increasing distance along the line, and changes occurring in regions we expect to have no or little change indicate that these changes were a result of a problem with our measurement or processing methods. These changes were not large, but were noticeable.

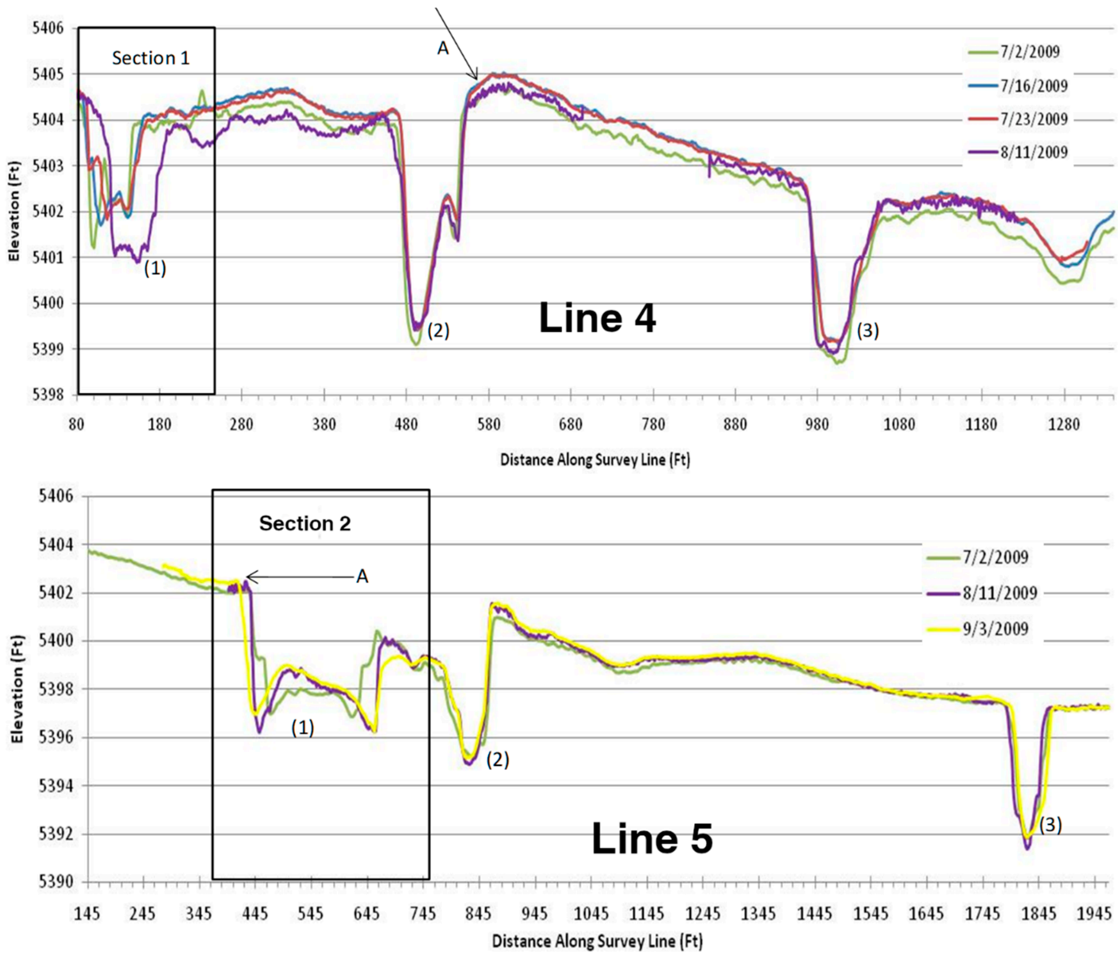

Figure 8. Results for Survey Lines 4 and 5. The left channel (Section 1) on Line 4 shows significant recutting with the channel moving deeper and to the right of figure.

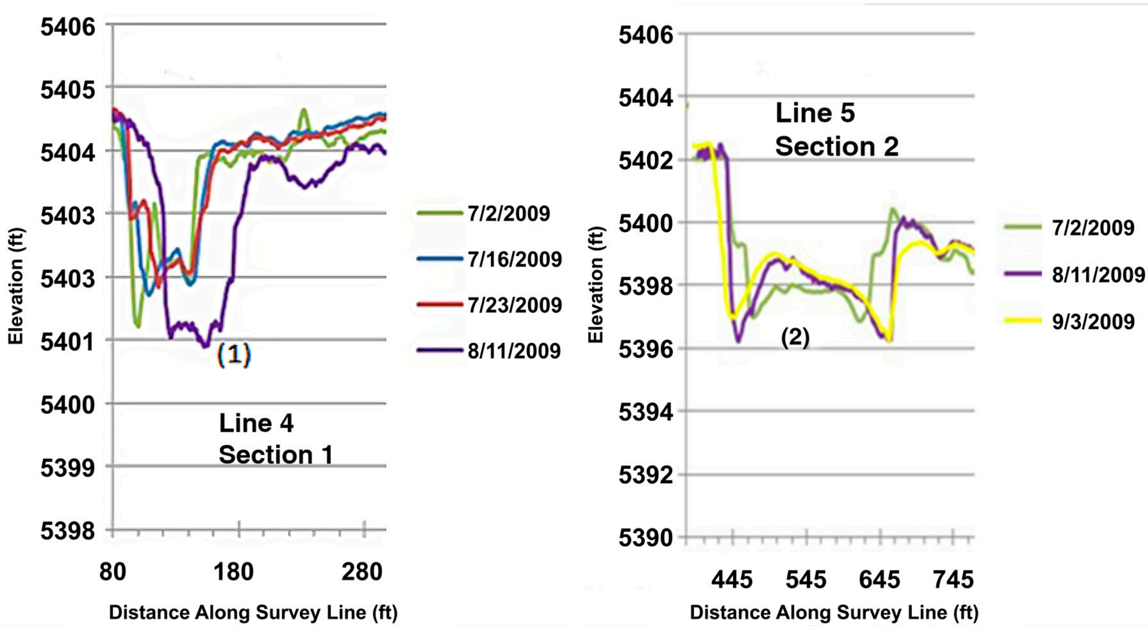

Figure 9. Detailed sections from Line 4 and Line 5 showing re-cutting and channel movement (Line 4) and both re-cutting with little channel movement (Line 5).

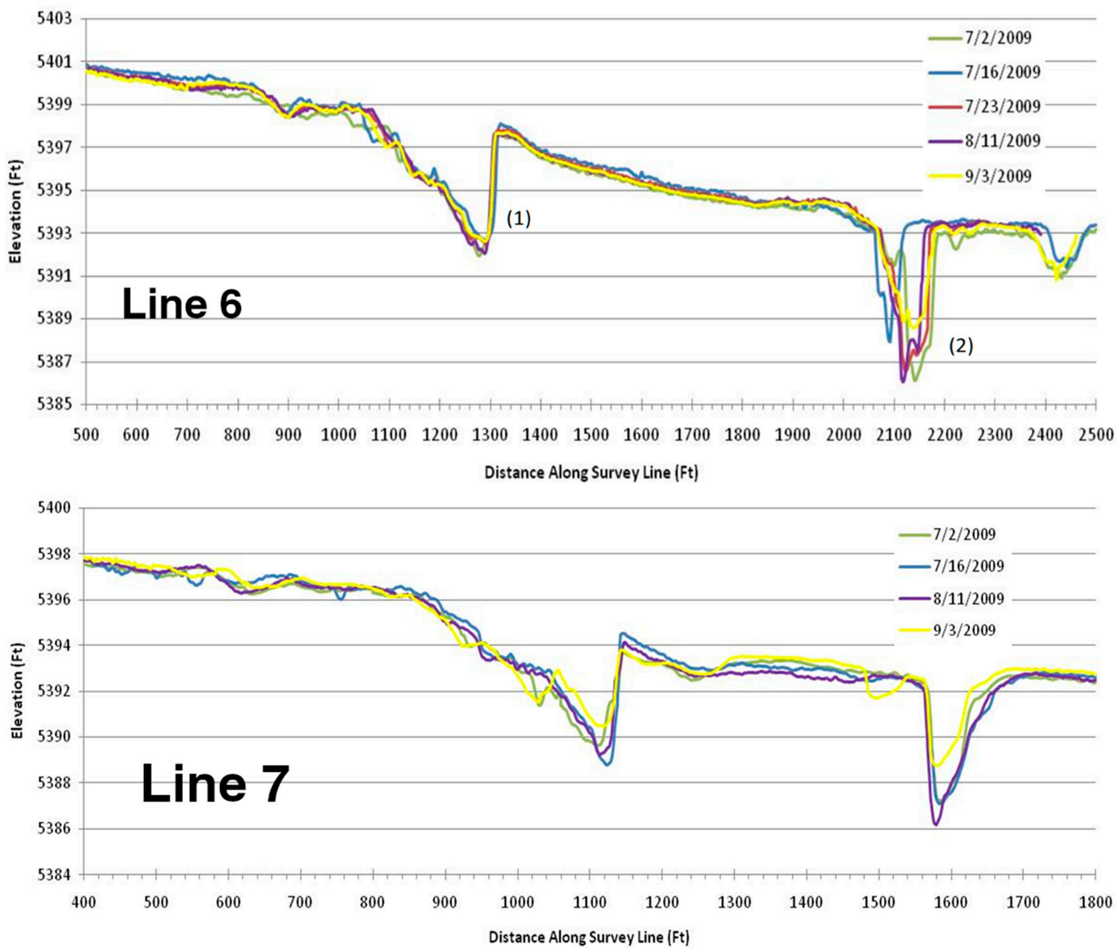

Figure 10. Results for Survey Lines 6 and 7. On both lines, the channel to the right of the figure exhibited the most change.

We determined that the most likely cause of these anomalies was the processing step where we converted the latitude and longitude readings (x and y data), to one-dimensional data representing distance along a line. In our method we used the starting coordinate of the survey line as the initial point and we computed distance along the line as the distance from this point. However, during field data collections, it was extremely rare (i.e., never) for the survey line to be perfectly straight during collection, as the boat occasionally moved slightly off the heading and was brought back on line. Thus the distance from the line origin to a sample point was not necessarily the distance along the line.

One potential way to address this issue would be to not to compute the distance between the line origin and a measured point, but to create a rotated coordinate system for each line with one ordinal direction matched to the line direction. Then the converted data would show distance from the starting point along the line (on-track distance) and the perpendicular distance of the point (off-track distance) from the line. This would have the added benefit of easier identification of measured points significantly off the survey line. This was an error in our method.

5.2. Discussion Survey Lines 1, 2, and 3

Lines 1, 2, and 3 (Figure 7), were only surveyed two times on 2 July and 16 July and because of reservoir drawdown this area was too shallow to access on the other trips. The data for these lines showed little change over this two-week period, but the data indicated several potential survey problems and small changes would not be evident. As these were to first two surveys, it is likely that there may have been problems with the sonar setup, as the sonar requires accurate off-set and other information that may have been entered incorrectly. Because we could not access these lines in subsequent surveys, we could not determine the cause or causes of the anomalies present in the data.

The data at Point A on Line 1 (Figure 7, top panel) does not show a channel, though one should exist. This anomaly is most likely caused by an error in the data and potentially caused by setting up the sonar incorrectly. At Point B (line 1, Figure 7), the elevation is the same for both surveys (2 and 16 July). This indicates that data for the two collections line up well and indicate no sedimentation movement, however the anomaly at Point A indicates a problem with one of the surveys.

Figure 7 (middle panel) shows the data from the two collections at Line 2. While there is an elevation difference, it is uniform along that line. We assumed that the elevation is incorrect and that there is no significant change in the sediment in the channel. This difference could have resulted from an incorrect sonar setup, or one survey line could have been slightly up- or down-stream, resulting in an elevation change. It is also possible, that this could have resulted from the data processing issue discussed as distances along the line were computed from a fixed beginning point. This can also cause errors in elevation.

Figure 7 (bottom panel) shows the data from the two collections at Line 3. The data seems to indicate that erosion occurred, however, the two surveys do not line up at any location. This may be due to errors while collecting the raw data using the sonar, GPS miscalculations, or errors in the elevation. The change in elevation between the two lines is about the same throughout the distance of Line 3, which implies that an error occurred, or that erosion took place along the whole channel which, again, is unlikely.

We concluded, based on an analysis of the data, that none of these three lines showed any sediment change over this two-week period but there is not enough data to draw firm conclusions. It is possible, but unlikely that sediment could have been deposited or eroded over the entire length of the lines, though this is unlikely as during July the Provo River carries little suspended sediment or bed load. Figure 7 demonstrates many of the challenges to using single-beam sonar for sediment monitoring.

5.3. Discussion Survey Line 4

We surveyed Line 4 four different times with two passes each time from early July through mid-August. During that period the reservoir surface elevation dropped 2.28 m (7.47 ft) and the water depth dropped from 3.7 to 1.4 m (12 to 4.5 ft) at Point A (Figure 8). This is significant as water inflow to the lake becomes more concentrated in the channel as there is less water over the flat portion of the reservoir bottom. Line 4 has three channels present.

Over the survey period, Channel 1 seems to have variation in movement, while Channels 2 and 3 exhibited less change. Channel 1 is much shallower then Channels 2 and 3, and for this reason the drawdown may explain the variation as the velocity in shallow water was most likely higher than that of deeper water in the other two channels. Figure 9 shows Section 1 in more detail. Also note that Channel 1 erosion patterns seem to be moving the channel in the direction of the steeper slope. This may indicate channel erosion similar to that shown in Figure 6, where the current cuts one bank, moving the channel in that direction. If the channel is moving due to bank erosion, the other bank usually sloths off filling that channel on the opposite side. While it is difficult to determine if this is taking place underwater, the plot does show the other side of the channel with a flatter slope.

Figure 9, which is a detailed plot of Channel 1 from Figure 8, shows a large difference between the first three surveys and the one taken on 11 August. Channel 1 has eroded with changes in both depth and width. As noted above, it has also apparently moved to the right of the figure. These changes can be explained by drawdown. Before the water drew down, the velocity of the water on the bottom of the reservoir and in the channels was relatively low as these channels were located far enough into the reservoir that there was little flow and the flow was distributed across the entire reservoir area. In addition, reservoir inflows were warmer than the deeper water, resulting in surface flow. There is also a lot of grass and bushes on the bottom of the reservoir away from the channel, slowing down any currents. Once the water dropped to only 1.2 m (4 feet) in depth, the velocity in the shallow channels had to increase because there was no other place for flow. This increase in velocity could explain the erosion in the first channel. This is a good example of delta sediment resuspension.

Channels 2 and 3 along Line 4 are deeper, so the sediment in the bottom did not change a large amount. Figure 8 shows some deposition in Channels 2 and 3. This is most likely from sediment cut further upstream in shallower sections.

In Line 4, the two main channels are undergoing different processes, one erosion and the other deposition. These processes can be better seen in the exposed sediment delta (Figure 7). The left panel of Figure 6 shows a channel with bank erosion that is moving due to erosion, similar to Channel 1 in Line 4. The right panel of Figure 6 shows a channel with sediment bed transport, similar to the other Channels 2 and 3 in Line 4.

5.4. Discussion Survey Line 5

The water surface depth at Point A on Line 5 dropped from 4.6 to 1.5 m (15 to 5 ft) over the first and last survey days for this line. Cross Section 1 from Line 5 is shown in Figure 8. This plot shows that Channels 2 and 3 of Line 5 received some deposition. These two channels have uniform walls, whereas Channel 1 edges increasing slough off as time increases. Line 5 exhibits mostly deposition, most likely from recutting upstream in Channels 2 and 3, with some bank erosion in Channel 1. This eroded material is most likely deposited further downstream in Channel 1.

5.5. Discussion Survey Line 6

Survey Line 6 (Figure 10) exhibited little change over the survey period. Channel 1 of Line 6 shows little change, while Channel 2 exhibits some deposition on the last survey, again most likely from recutting further upstream in the channel. Line 6 is in deeper water and located further from shore. This greater depth will cause less variation in the sediment movements as flow is not concentrated in the channels. The roughness of the lines in Channel 2 may be caused from the problems arising from an incorrect distance formula, discussed previously.

5.6. Discussion Survey Line 7

Survey Line 7 (Figure 10) exhibits both early and late changes from 2 July to 11 August with early erosion and later deposition. Line 7 is in deeper water. We hypothesize that this early erosion is soft fluff being moved or swept out of the channel bottoms due to currents. Since these channels were deep and farthest from the inflow, the velocity was very low, however, the fluff is moved very easily with low flows. By 3 September, both channels have filled between 0.6 and 0.75 m (2 and 2.5 feet) of sediment. This deposition is most likely from recutting sediment in shallower parts of these channels being moved down the channels. We most likely seeing the deposition from the erosion noted in more upstream survey lines.

6. Conclusions

We conclude that sediment delta recutting and movement in DCR can be monitored and potentially quantified using single beam sonar measurements. We were able to identify changes in the sediment surface showing both deposition and erosion that followed expected physical patterns. We found that the sediment moved from upstream to downstream in the submerged channels during the survey period and was adequately observed with sonar detection.

We found that a single beam sonar was a useful tool to use to quantify sediment mass movement. The survey was not designed to develop quantitative estimates of sediment volumes. Although this project did not develop a sediment budget, these methods can be followed for future studies for its development. The main difference would be the location and spacing of the survey lines and the timing of the field survey trips.

For sediment budgets, we suggest that cross-sections or survey lines be closer together to better characterize how each channel is connected to the next to better understand sediment movement downstream. Each cross section should be surveyed two times per survey; once in each direction. This provides some redundancy and also helps minimize measurement noise and errors. We did not use GPS differential corrections though we recommend this be done for quantitative work to more accurately overlay the survey lines. We also recommend that distances should be calculated in two dimensions, both along the line and offset from the line, as opposed to what we did which was distance from the beginning of the line.

This study shows that delta sediment recutting, suspension, and deposition can be monitored using sonar methods. While this sediment movement can have major impacts to reservoir water quality because it occurs in warm late summer during drawdown, the actual volumes of sediment are low and localized to submerged channels only a few feet in size. It was not clear at the onset that sonar would have the resolution and precision, especially a single beam sonar, to perform this monitoring. This study shows that such monitoring is possible and does not require a more expensive and complex multi-beam sonar, though this method is difficult to implement.

Author Contributions: Conceptualization, G.P.W.; methodology, G.P.W. and A.C.W.; formal analysis, G.P.W. and A.C.W.; resources, G.P.W.; data curation, A.C.W.; writing—original draft preparation, G.P.W.; writing—review and editing, G.P.W. and A.C.W.; visualization, A.C.W.

Funding: This research was funded by the Upper Colorado Region of the U.S. Bureau of Reclamation and the Provo River Watershed Council.

Acknowledgments: Jerry B. Miller provided comments and limnological information about DCR.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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