

Evaluating Chirp Technology for Measuring Reservoir Sedimentation Thickness and Stratigraphy

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historical data are lacking, however-leading to great uncertainty over how to manage infrastructure. Even if bathymetric surveys								
have been pe	erformed (often t	they have not) to	o estimate storage ca	pacity, little ma	y be kn	own about the sediment characteristics.		
In August 20	020, USACE and	Reclamation jo	intly used a shallow	acoustic chirp s	ystem to	o map the stratigraphy and pre-impoundment		
surface of tw	70 reservoirs in C	Colorado. Both r	eservoirs are rich wi	th complement	ary data	regarding the distribution of sediments and		
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that the map	that the mapped sub-bottom surface elevations (from the chirp system) were consistent with known pre-impoundment surfaces prior							
to dam const	truction. Approx	imate volumes o	of accumulated sedir	nent were calcu	lated ba	ased on the mapping effort, and observations		
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Executive Summary

Reservoirs are designed to meet a variety of needs, including water supply, flood mitigation, hydropower, and recreation. Through the Bureau of Reclamation (Reclamation) and U.S. Army Corps of Engineers (USACE), the Federal Government owns and operates over 3,000 dams, many of which are among the largest in the country. Dams also result in the mostly unintended consequence of trapping sediment in the impounded reservoir, disrupting the natural continuity of sediment movement through the riverine system. Reservoir sedimentation reduces storage capacity and water supply reliability while impacting infrastructure. The rate of reservoir sedimentation varies in space (geography) and time (events)—creating great uncertainty in the useful lifespan of water infrastructure projects. Uncertainty in the type and amount of sediment in reservoirs leads to further challenges in creating sediment management plans. Many of the Federal dams have aged beyond the latter half of their design lifespans without having received sufficient study and monitoring to establish sediment management plans. Even if bathymetric surveys have been performed (often they have not) to estimate storage capacity, little may be known about the sediment characteristics.

In this pilot study, a joint Reclamation-USACE team demonstrated the feasibility of using chirp acoustic technology for characterizing deposited sediments. Chirp systems (termed for the audible "chirp" sound that they produce) use high-powered acoustic pulses over a range of relatively low frequencies to penetrate up to tens of meters into sediments for remote characterization of stratigraphy. Variation in sediment density due to compositional nonuniformities cause unique reflections of the transmitted acoustic signal, which can then be interpreted to generate maps of stratigraphy. The information garnered is more robust and cost-effective than what can be collected through traditional methods alone, such as sediment core sampling.

Prior to this study, this technique had not been thoroughly tested in reservoirs for geomorphic assessment. In August 2020, USACE and Reclamation jointly used a shallow acoustic chirp system to map the stratigraphy and pre-impoundment surface of two reservoirs in Colorado: Cherry Creek near Denver, Colorado, and Shadow Mountain Lake near Grand Lake, Colorado. Both reservoirs are rich with complementary data regarding the distribution of sediments and pre-impoundment surface, which provides for convenient assessment of chirp system capabilities. Qualitative comparisons suggest that the mapped sub-bottom surface elevations (from the chirp system) were consistent with known pre-impoundment surfaces prior to dam construction. Approximate volumes of accumulated sediment were calculated based on the mapping effort, and observations of the reflective surface indicated a gently sloping alluvial plane cut by numerous shallow fluvial channels. Overall, the results were useful in demonstrating the capability of the shallow acoustic technique in imaging pre-impoundment surfaces and assessing geomorphic conditions.

Results

Further data analysis was completed over the winter of 2020-2021. The reflection surfaces were digitized and exported as x,y,z data, where z is the distance of the reflection surface below the lake bed. The overall surfaces were compared to existing pre-impoundment topography, as well as sediment cores collected to quantify sediment accumulation, and lakebed elevation changes as mapped by single-beam and multibeam bathymetry.

Overall conclusions are that although the two reservoirs studied are not perfectly representative of all USACE and Reclamation reservoirs in either geology or geomorphology, the results are useful as a first-order suitability assessment of the chirp sub-bottom imaging technique to re-create the pre-impoundment reservoir surface.

Results and discussion from the study were presented at the 2021 USSD Annual Meeting (held virtually). A conference proceedings short paper was published by the joint USACE-Reclamation team and is attached as Appendix A (Wadman et al. 2021).

Next Steps

The scoping study was useful in demonstrating the capability of the shallow acoustic technique in imaging pre-impoundment surfaces and assessing geomorphic conditions. We anticipate active adoption of the technique, complimented by focused research, among governmental agencies:

- The results from the joint Reclamation-USACE effort garnered the attention of scientists working for the Reclamation Dam Safety Office (DSO). Application of the shallow acoustic chirp system is now being scoped for inclusion within a seismic hazard study. The concept of the study (anticipated in FY 2022) is to use the same approach to detect potential subsurface faults in the vicinity of a dam. Complicating the issues at hand is the presence of a glacial moraine pre-dating the dam, which may contain the signatures of seismic disturbance. Shallow acoustic chirp technology may provide the key to understanding sub-surface layers and reveal information that more commonly-applied high-resolution bathymetric mapping, while complementary, cannot ascertain.
- During the joint Reclamation-USACE scoping study, an EdgeTech CSS-2000 chirp system was used for subsurface mapping. This large and powerful system (designed primarily for oceanographic applications) had sufficient power to penetrate tens of meters into coarse-grained sediment deposited along the reservoir floor. Chirp systems transmit high-powered acoustic pulses over a broad range of low frequencies (relative to commonly-applied bathymetric mapping systems). Several companies manufacture a variety of systems advertised as having sub-bottom profiling capabilities; however, these systems remain fairly untested, especially in shallow water reservoir applications. Many of these systems are not true chirp systems, limiting their ability to both penetrate deeply (i.e., tens of meters) into the reservoir stratigraphy while also resolving fine-scale (i.e., inches) layers. Therefore, a primary uncertainty that remains is how the realization of results from mapping studies may depend on the various sub-bottom profiling systems used and their inherent characteristics. To

address this uncertainty, further study has been proposed (FY 2022 Reclamation Science & Technology Program Conducting Proposal) using a broad array of instrumentation at a study site featuring a breadth of prior sediment examination.

- The Sedimentation and River Hydraulics Group, based at the Denver Technical Service Center, is the primary provider of reservoir sedimentation and bathymetric surveying services to Reclamation-owned and operated facilities throughout the Western states. As such, the group stands in a strong position to adopt the sub-bottom profiling technology within a suite of services offered and to implement within workflow processes in meeting the increased need for reservoir sedimentation studies. The group owns and routinely operates multiple boats, global positioning system (GPS) equipment, high-resolution multibeam bathymetric surveying systems, and sediment coring samplers, which will facilitate a streamlined inclusion of sub-bottom profiling system(s).
- Since 2014, a Collaborative Research Team composed of members from the U.S. Army Engineer Research and Development Center (ERDC) and the Reclamation Research and Development Office (RDO) has supported mission responsibilities with increased effectiveness and cost efficiency. The Team is aimed with developing and fostering intergovernmental research and development to produce and infuse solutions for common agency challenges involving water resources infrastructure and environmental stewardship. Collaborative research concerning the application of sub-bottom profiling technology to address reservoir sedimentation fits squarely within the area of focus identified by the Team Charter. The Collaborative Research Team hosts an Annual Meeting where topics of mutual interest are discussed. The study trajectory and results will be highlighted as an example of interagency collaboration. Proceedings from the meetings facilitate the application of results by building mutual awareness among governmental organizations and promoting further inter-agency outreach.

Appendix A

Evaluating the Use of Chirp Seismic Reflection to Discern the Elevation of Pre-Construction Reservoir Surfaces

Wadman, H.M., J.E. McNinch, P.M. Boyd, K. Collins, and D. Dombroski, 2021. Evaluating the Use of Chirp Seismic Reflection to Discern the Elevation of Pre-Construction Reservoir Surfaces. USSD Virtual Annual Conference, May 10 – May 21, 2021.

EVALUATING THE USE OF CHIRP SEISMIC REFLECTION TO DISCERN THE ELEVATION OF PRE-CONSTRUCTION RESERVOIR SURFACES

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INTRODUCTION

Federal agencies have recently begun to consider the applications of chirp data for reservoirs, of which there are nearly 800 managed between the U.S. Army Corps of Engineers (USACE) and the Bureau of Reclamation (Reclamation). In cases where original reservoir surveys were not conducted at closure, the pre-impoundment bed topography is considered lost, buried by the continual deposition of sediments delivered to the reservoir from the watershed. To support modern sustainability initiatives, a history of the reservoir must first be developed. Currently, the only practical ways to determine pre-impoundment elevations include deep coring through the deposited sediments, and/or ground penetrating radar. These methods are neither fast nor cost effective, and ground-penetrating radar is further limited in that it will only reliably map the subaerial portion of the reservoir, missing the subaqueous sedimentation entirely. In this study, we examine the effectiveness of shallow acoustic reflective sub-bottom (chirp) technology to quantitatively recreate pre-impoundment elevations over large spatial regions.

METHODS AND ANALYSIS

The use of shallow acoustic reflection (chirp) sub-bottom data to gain insight on stratigraphy, sediment budgets, and subsurface hazards has greatly increased in the Federal government in the past 10 years. Chirp systems utilize a range of low-frequency acoustic pulses to map the elevation and spatial extent of underlying stratigraphy in a wide range of aqueous environments. Similar to multibeam and sidescan sonar systems, a chirp sub-bottom system generates an acoustic pulse. This acoustic pulse, referred to as a "chirp" for the audible sound that it produces, is composed of a range of frequencies, some of which penetrate the seafloor (or lakebed, riverbed, etc.). Contacts between changes in sediment density (e.g. changes in the composition of the underlying sediment stratigraphy) cause the signal to reflect back to the chirp receivers, generating improved three-dimensional maps of underlying stratigraphy relative to borehole collection alone (Figure 1-A).

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Figure 1: (A) Examples of acoustic data including bathymetry, sidescan sonar, and chirp sub-bottom stratigraphy. (B) EdgeTech CSS-2000 chirp towfish mounted on a 16 ft catamaran for ease of towing

Until recently, chirp sub-bottom imaging has not been sufficiently tested in reservoirs to show value as a geomorphic assessment tool. In August of 2020, USACE and Reclamation conducted a joint effort to determine the feasibility of using shallow acoustic chirp systems to map the stratigraphy and pre-impoundment surface of two reservoirs: Cherry Creek Reservoir, just south of Denver, CO, and Shadow Mountain Reservoir, in Grand County, CO. Data were collected using an EdgeTech CSS-2000 towfish mounted on a 16-ft catamaran. The CSS-2000 was chosen because this large (> 900 lbs), ocean-application towfish, unlike smaller and more easily mobile chirp towfish, has sufficient power to penetrate 10's of meters of coarse-grained sediment. To allow towing by small vessels, the CSS-2000 is mounted in a custom-built sled, secured on a catamaran for easy launch, towing, and retrieval (Figure 1-B). We will present results detailing the ability of sub-bottom imaging to map the pre-impoundment topography and improve estimates of sedimentation rates and available reservoir capacity.

FINDINGS AND CONCLUSIONS

The goal of the sub-bottom mapping effort was to assess the feasibility of using chirp technology to image pre-impoundment reservoir surfaces. The two reservoirs selected for study both have various pre-impoundment data and post-impoundment bathymetric surveys, which can be compared with the chirp-derived data to assess the method's efficacy. At Cherry Creek Reservoir, chirp sub-bottom profiles were collected along seven of the primary range lines (Figure 2-A) in order to provide relevant comparison data. The stratigraphy at Cherry Creek Reservoir is shown in Figures 2-B and 2-C, where panel B provides an un-interpreted sub-bottom image, and panel C shows interpretations. A distinct surface was mapped in the entire reservoir (Figure 3), and a 3D example of this surface as digitized on adjacent sub-bottom profile lines, ranging from 2-4 ft below the modern bathymetry, is shown in Figure 3-A. Qualitative comparisons suggest that the elevation of this surface is spatially-consistent with the pre-impoundment surface mapped prior to the construction of Cherry Creek Dam. The spatially varying elevation of this pre-impoundment surface was mapped throughout the spatial extent of Cherry Creek Reservoir, and the quantitative volume of sediment accumulated since impoundment as

derived by this method versus that derived from limited core data, plus potential error, was estimated.



Figure 2: (A) Map view of Cherry Creek Reservoir, with approximate sub-bottom track lines plotted in white. The location of the cross-sections in (B) and (C) are noted by the red A-A' line on plot (A). (B) Example of un-interpreted and (C) interpreted sub-bottom profiles.



Figure 3: Three-dimensional view of the pre-impoundment surface as imaged in intersection and adjacent sub-bottom profile lines. General position of the sub-bottom lines profiled in Panel-B are shown via a yellow box on Panel-A; The lakebed is digitized in red in Panel B. The pre-impoundment surface is represented by the dark black line below the lakebed in Panel B. Note the elevation variation in this line, and how at times multiple reflection surfaces (likely old fluvial fill from pre-impoundment geomorphology) are apparent between the pre-impoundment surface and the lakebed. At Shadow Mountain Reservoir, only limited pre-impoundment data were available, so profile lines were collected in a pattern to optimize efficiency of mapping the preimpoundment topography in the short survey window (Figure 4-A). The stratigraphy at Shadow Mountain is shown in Figures 4-B and 4-C, where panel B provides an uninterpreted sub-bottom image, and panel C shows interpretations. Similar to Cherry Creek, a distinct, spatially-consistent surface was mapped in the entire reservoir. The presence of glacial moraines in this high mountain valley, and the overall general topography of the region, suggest that the pre-impoundment topography of what is now Shadow Mountain Reservoir was an alluvial deposit formed from melting glacier outflow. Qualitative observations during the field data collection effort indicated that the reflection surface mapped throughout Shadow Mountain Lake was consistent in character with a gently sloping alluvial plane cut by numerous shallow fluvial channels, and this assumption can easily be confirmed using visuals from three-dimensional maps of intersecting sub-bottom lines shown in Figure 5.



Figure 4: (A) Map view of Shadow Mountain Lake reservoir, with sub-bottom track lines plotted in white. The location of the cross-sections in (B) and (C) are noted by the red A-A' line on plot (A). The glacial moraine is noted by the yellow arrow and text. (B) Example of un-interpreted and (C) interpreted sub-bottom profiles.



Figure 5: Three-dimensional view of the pre-impoundment surface as imaged in intersection and adjacent sub-bottom profile lines. General position of the sub-bottom lines profiled in Panel-B are shown via yellow boxes on Panel-A; The lakebed is digitized in black in Panel B. The pre-impoundment surface is represented by the light blue digitized line below the lakebed in Panel B. Note the relatively consistent elevation of this line below the lakebed, as the sub-bottom lines presented do not include relict fluvial channels from pre-impoundment geomorphology.

Further data analysis was completed over the winter of 2020-2021. The reflection surfaces were digitized and exported as x,y,z data, where z is the distance of the reflection surface below the lake bed. The overall surfaces were compared to existing pre-impoundment topography, as well as sediment cores collected to quantify sediment accumulation, and lakebed elevation changes as mapped by single-beam and multibeam bathymetry. Although the two reservoirs studied are not perfectly representative of all USACE and Reclamation reservoirs in either geology or geomorphology, the results are useful as a first-order suitability assessment of the chirp sub-bottom imaging technique to re-create the pre-impoundment reservoir surface.

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