

# PARDEE RESERVOIR CAPACITY STUDY AND SEDIMENTATION ANALYSIS, 2014

Sea Floor Mapping Lab

Division of Science and Environmental Policy

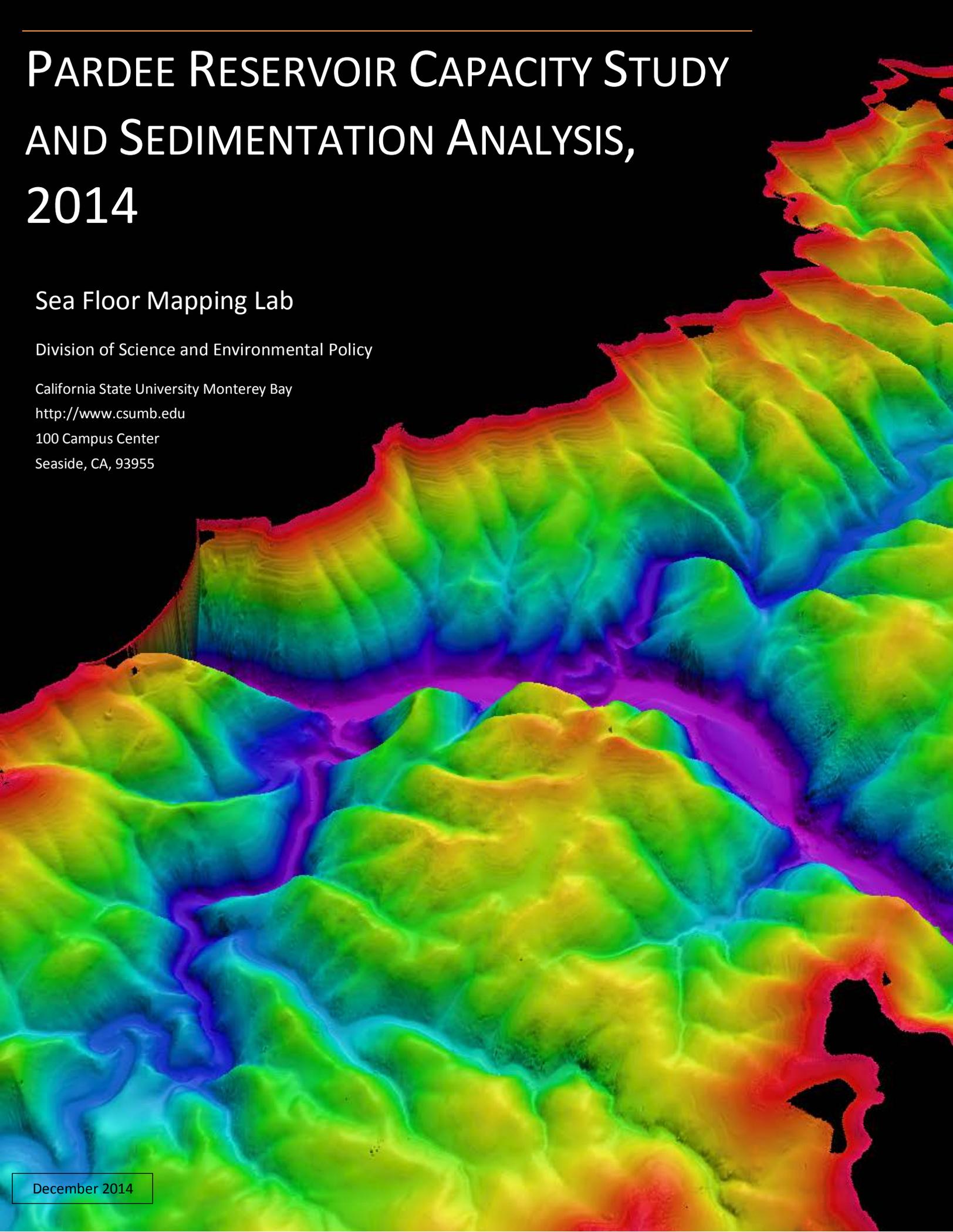
California State University Monterey Bay

<http://www.csumb.edu>

100 Campus Center

Seaside, CA, 93955

December 2014





## ACKNOWLEDGEMENTS

Thanks to the following people from East Bay Municipal Utility District who provided information or facilitated the survey work or research in some way: John Hurlburt, Rey Encarnacion, Russ Taylor, Kevin Fung, Jason Koenig, Christi Nelson, Steve Martin, Michael Shaddle, Kent Lambert, Chris Swan, Chuck Beckman, Greg Francek, and Pat Lydon and ACC support staff. Thanks to Sean Todaro of EBMUD for reviewing and editing of the draft and to David Hansen for assistance in researching the spillway datum. From CSUMB, thanks to the SFML ship's captain Bill Williamson for his nimble navigation of the narrow inlets of Pardee, Alex Snyder for software training and to my faculty advisor Fred Watson for helping me get the project off the ground. Special thanks go to Rikk Kvitek for logging a lot of extra miles in the Kelpfly and Pat Iampietro for answering every single question I asked.

This report may be cited as:

EBMUD. 2014. Prepared by John Urness, Pat Iampietro, and Rikk Kvitek. Seafloor Mapping Lab, CSU Monterey Bay. Pardee Reservoir Hydrographic and Lidar Topographic Survey and Sedimentation Analysis. East Bay Municipal Utility District. Oakland, CA.

## EXECUTIVE SUMMARY

In August of 2014, East Bay Municipal Utility District (EBMUD) awarded a contract to the Sea Floor Mapping Lab at California State University Monterey to conduct a combined hydrographic and topographic survey of Pardee Reservoir. The survey was performed in September and October of 2014 and generated a dataset of over 1.3 billion raw data points using LiDAR, multi-beam and swath sonar. The raw data were cleaned and the final output was used to create a digital elevation model (DEM) of reservoir bathymetry and topography. Statistical interpolation was used to fill small data gaps and any remaining gaps were back-filled using the existing 1995 bathymetric DEM in order to match extents and allow for comparison between the two surveys. The final DEM was used to generate a table of volumes and surface areas of the reservoir at a 0.01 foot elevation (local datum) resolution. At the spillway elevation of 567.65 feet local datum (567.25 feet NGVD 1929), the reservoir capacity was calculated to be 203,795 acre-feet. The updated volume indicates that the reservoir has lost 2.93% of its capacity since 1929, although the direct volume comparison is imprecise because of differing methodologies and lack of known topographic error in the 1929 survey. The relatively small volume loss since 1930 can be explained by the geology of the upland Mokelumne watershed and the existence of multiple impoundments on the North Fork of the Mokelumne River that act as sediment settling ponds.

The 2014 bathymetry was compared to the low-resolution bathymetric survey that was conducted in 1995 to examine recent change in volume and scour and deposition. The comparison showed an apparent reservoir volume increase of 2.94% volume since the 1995 survey; however, this increase was caused by non-existent surface features in the 1995 DEM that were artifacts of an interpolation-based DEM created from insufficient data. Similar problems were identified when scour and deposition were geospatially examined using GIS visualization: large amounts of sediment of the central reservoir body had apparently been scoured and deposition had occurred along most of the eastern arm of the reservoir.

Historically, EBMUD's approach to quantifying siltation rates was to perform leadline surveys across fixed transect locations. To compare the 1929 silt profiles to those of 1995 and 2014, "synthetic" profiles were created by extracting data from the 1995 and 2014 DEMs using historical transects. Synthetic profiles and all previous silt survey profiles were visually compared in Excel using data from EBMUD archives and a quantitative analysis was done using GIS software to calculate profile areas from 1929, 1995 and 2014. In the quantitative analysis, all but three of the eighteen transects showed increases in sedimentation since 1929, and those transects that showed scour were located at a sharp bend in the upstream shallow portion of the reservoir.

Future work could include deeper research into the error estimation of the volumetric methods that EBMUD used historically to improve comparison with previous bathymetry. Earlier techniques that were used to calculate volume may have underestimated reservoir capacity which would result in an apparent rate of sedimentation that was lower than the actual rate. Additional research using basin-scale erosion modeling and sediment transport modeling that consider climate change and fire scenarios would predict possible outcomes and inform long-term planning efforts that address threats to reservoir capacity.

# TABLE OF CONTENTS

<b>Acknowledgements.....</b>	<b>ii</b>
<b>Executive Summary.....</b>	<b>3</b>
<b>Table of Contents.....</b>	<b>4</b>
<b>List of Acronyms.....</b>	<b>6</b>
<b>Water Suppliers.....</b>	<b>6</b>
<b>List of Software .....</b>	<b>6</b>
<b>Introduction .....</b>	<b>7</b>
<b>Sea Floor Mapping Lab.....</b>	<b>7</b>
<b>Study Area .....</b>	<b>7</b>
<b>A Brief History of Pardee Silt Surveys, Capacity Tables and Bathymetric/Topographic Maps.....</b>	<b>8</b>
<b>Project Overview.....</b>	<b>9</b>
<b>Methods .....</b>	<b>10</b>
<b>Hydrographic and Topographic Survey Data Acquisition .....</b>	<b>10</b>
Hydrographic Survey: Sonar Data Acquisition .....	10
Topographic Survey: LiDAR Data Acquisition.....	13
Sonar Data Post Processing .....	13
LiDAR Data Post Processing .....	14
Sonar Data Cleaning.....	14
LiDAR Data Cleaning .....	15
Merging Hydrographic and Topographic Data Sets .....	16
<b>Quality Control and Patch Testing.....</b>	<b>16</b>
Sonar Patch Test.....	17
LiDAR Patch Test.....	17
<b>Establishing a Vertical Control and Spillway Elevation Datum.....</b>	<b>18</b>
<b>Vertical Accuracy Assessment and Vertical Map Error.....</b>	<b>18</b>
<b>Digital Elevation Model (DEM) Creation .....</b>	<b>20</b>
1995 DEM .....	20
2014 DEM .....	21
<b>Calculating Stage-volume and Stage-surface .....</b>	<b>23</b>
<b>Geospatial Distribution of Sediment Scour and Deposition Analysis.....</b>	<b>24</b>
<b>Visual and Quantitative Trend Analysis of Historical Silt Profiles .....</b>	<b>24</b>
<b>Results.....</b>	<b>25</b>
<b>Survey Data Acquisition.....</b>	<b>25</b>
<b>Final Topo-Bathymetry DEM.....</b>	<b>25</b>
<b>Elevation Surface-Volume Table.....</b>	<b>28</b>
<b>Volumetric Change.....</b>	<b>29</b>
<b>Geospatial Distribution of Scour and Deposition.....</b>	<b>29</b>
<b>Visual and Quantitative Analysis of Historical Sediment Profiles .....</b>	<b>31</b>
<b>Discussion.....</b>	<b>34</b>
Volumetric Change .....	34
Geospatial Distribution of Scour and Deposition .....	34
Visual and Quantitative Trend Analysis of Historical Silt Profiles .....	35
Summary.....	35

<b>Next Steps .....</b>	<b>35</b>
<b>References.....</b>	<b>36</b>
<b>Appendix .....</b>	<b>38</b>
<b>Table of Delivered Files.....</b>	<b>38</b>
<b>Table of GIS Data and Layers .....</b>	<b>39</b>
<b>Example of SVP Data for a Single Water Column Sample.....</b>	<b>40</b>
<b>ArcGIS 10.1 Model Builder Diagram for Stage-volume calculations .....</b>	<b>40</b>
<b>GPS Survey MB7 Benchmark, OPUS GPS Solution .....</b>	<b>41</b>
<b>DEM Creation Methods Exploration.....</b>	<b>46</b>
Procedure 1.....	47
Procedure 2.....	49
Procedure 3.....	50
<b>DEM Methods Results.....</b>	<b>51</b>
<b>1995 Survey Data Example .....</b>	<b>51</b>
<b>LiDAR Patch Test .....</b>	<b>52</b>
<b>ArcGIS Project: Hierarchy of Layer.....</b>	<b>58</b>
<b>Pardee Reservoir Spillway Elevation Datum .....</b>	<b>59</b>
Spillway Elevation Research.....	59
1937 Report .....	59
2006 Survey .....	60
2008 Survey .....	60
2014 CSUMB Survey .....	60
Conclusion.....	60
Attachment: 1977 D.A.Wilson Memo.....	61
Attachment: 2006 Survey Field book FB-4375.....	62
Attachment: "Pardee Reservoir" .....	63

## LIST OF ACRONYMS

AF: Acre-feet  
CORS: Continually Operating Reference Station  
CSUMB: California State University Monterey Bay  
DEM: Digital Elevation Model  
DTM: Digital Terrain Model (same as DEM)  
GAMS: GPS Azimuth Measurement System  
GCS: Geographical Coordinate System  
GPS: Global Positioning System  
IHO: International Hydrographic Organization  
IMU: Inertial Measurement Unit  
LiDAR: Light detection and ranging  
MGD: millions of gallons per day  
NGS: National Geodetic Survey  
NOAA: National Oceanic and Atmospheric Administration  
OPUS: Online Positioning User Service  
IAPPK: Inertially Aided Post Processed Kinematic  
RTK GPS: Real-time kinematic GPS  
SBET: Smoothed Best Estimate Trajectory  
SFML: Seafloor Mapping Lab  
TIN: Triangulated irregular network  
TPU: Total Propagated Uncertainty  
USACE: US Army Corps of Engineers  
USGS: US Geological Survey  
XYZ: data that is comprised of latitude, longitude, elevation

## WATER SUPPLIERS

CPUD: Calaveras Public Utility District  
CCWD: Calaveras County Water District  
AWA: Amador Water Agency  
EBMUD: East Bay Municipal Utility District  
JVID: Jackson Valley Irrigation District

## LIST OF SOFTWARE

ArcGIS 10.1 SP1, ESRI: GIS software used to generate final DEM and derivative products  
Corpscon 6.0.1, USACE: Software used to convert XYZ from one datum to another  
HIPS and SIPS Pro 8.1, CARIS: Software used to manage sonar survey and sounding data, create base maps and digital elevation models and edit sonar and LiDAR point data which can then be exported as XYZ data  
Fledermaus and DMagic 7.5.2, QPS: Software to manage and package sonar and LiDAR data and generate digital terrain models.  
POSPac MMS 5.3, Applanix: Software and hardware suite from Applanix that calculates collects high precision position and attitude data that is used for post-processing positional data that is then merged with sonar and LiDAR data prior to cleaning  
SwathProcessor, SEA, Inc.: Used for post-processing of swath sonar prior to cleaning in Caris HIPS and SIPS  
UltraEdit, IDM Computer Solutions: used for manipulating or viewing very large text files  
vDatum 3.3, NOAA: Used to convert the elevation and horizontal position from one datum to another

## INTRODUCTION

East Bay Municipal Utility District (EBMUD) owns and operates a network of aqueducts, reservoirs, and water treatment facilities that serves 1.3 million customers in the East San Francisco Bay Area. The primary water supply reservoir is Pardee Reservoir, which is fed by the Upper Mokelumne Watershed. As part of its reservoir management practice, EBMUD surveys Pardee Reservoir to gage sedimentation rates and recalculate volume. This is done to determine if erosion mitigation steps need to be taken in the upland watershed, and to provide information for the operation of the water supply system, as these are contingent upon reservoir volume (J. Hurlburt, personal communication, October 2014).

Rates of reservoir sedimentation depend on a variety of factors including reservoir size, geology, basin soil types, land-cover, land-use patterns and precipitation intensity and quantity. With increased precipitation variability predicted by climate models and potential for 100 year droughts as posited by Stine (1994), there is a more pressing need for accurate estimation of reservoir volumes and rates of sedimentation. Most climate models predict that California will experience warming over the next century with higher snowlines, greater winter stream flows, and lower summer flows. Snowmelt-driven watersheds, like the Upper Mokelumne Watershed, will experience a 50% reduction in late winter snowpack toward the end of this century (Miller et al. 2004). Using a downscaled atmosphere-ocean-ice-land Parallel Climate Model (PCM), Dettinger et al. (2004) conclude that stream flow timing will arrive a month earlier by 2100 and that reduced late flows will result in dryer conditions that will tax ecosystems and increase fire risk and severity. Predicted changes in precipitation and snowmelt timing are a concern because climate-change has been a significant driver of increased rates of erosion in past geologic periods (Peizhen et al. 2001).

## SEA FLOOR MAPPING LAB

California State University at Monterey Bay's (CSUMB) Sea Floor Mapping Lab (SFML) has worked on offshore seafloor mapping projects for the US Navy, USGS, PG&E, USACE, NOAA and others and led the California Seafloor Mapping Project to create a high resolution base map for state waters (Kvitek & Iampietro 2010). Previous hydrographic surveys of reservoirs include Loch Lomond and Los Padres in Santa Cruz and Monterey Counties, respectively.

## STUDY AREA

Pardee Reservoir is located 85 miles to the east-northeast of EBMUD's headquarters in Oakland, California (Figure 1). It is fed by the 544 square mile Upper Mokelumne Watershed which ranges in elevation from 10,400 feet (RMC Water and Environment 2007) near the crest of the Sierra Nevada down to 600 feet where it ends at Highway 49.

The geologic formations in the Pardee Reservoir study area include mafic volcanic rock, slate, peridotite and argillite (USGS 2005). The confluence of the North, Middle and South tributaries of Mokelumne River occurs 11 miles east of Pardee Reservoir. Up to 85% of the flow comes from the North Fork basin of the upper watershed (RMC Water and Environment 2007) which has several impoundments which are used for power generation and also act as barriers to natural flow and foster the settling of suspended sediment. Upper Mokelumne geology along the north fork is characterized primarily by granodiorite. The remaining flow is carried by the Middle and South Fork, both of which are free-flowing and characterized by a mix of granodiorite and argillite geologic formations (USGS 2005).

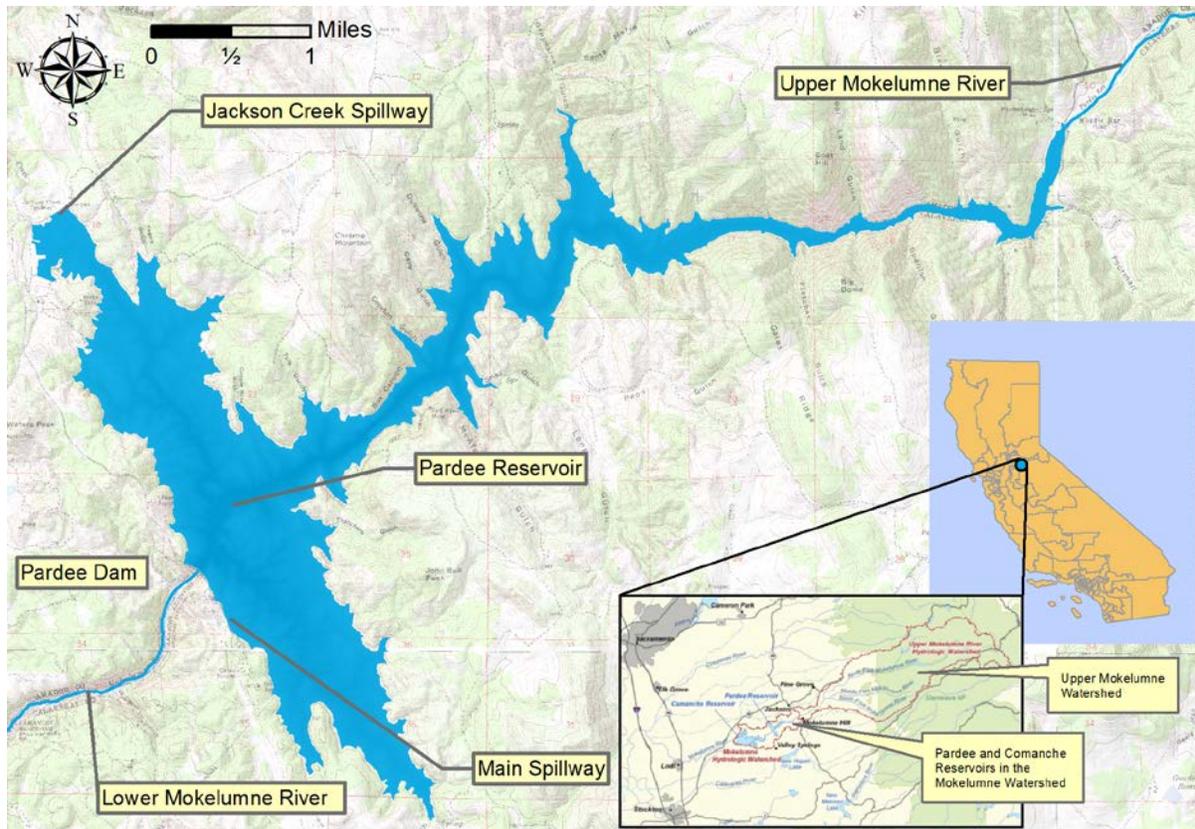
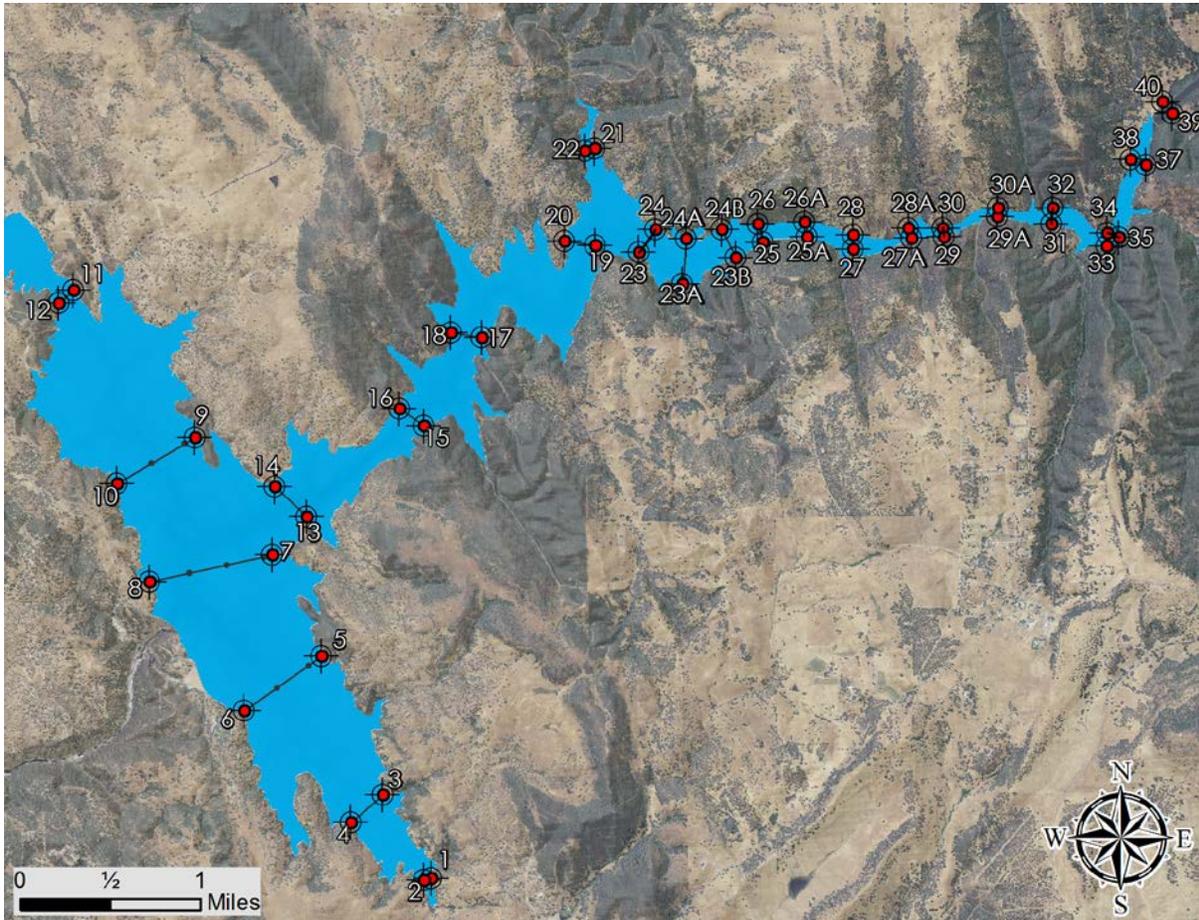


Figure 1. Pardee reservoir study area. EBMUD inset blow-up map shows reservoir in context of upper watershed and lower Comanche Reservoir. Data sources: USGS, EBMUD.

## A BRIEF HISTORY OF PARDEE SILT SURVEYS, CAPACITY TABLES AND BATHYMETRIC/TOPOGRAPHIC MAPS

Since construction of the Pardee Dam was completed in 1929, EBMUD has intermittently conducted leadline silt profile surveys using 25 transects between fixed monuments (Figure 2). Silt surveys were performed in 1929, 1938, 1943, and 1977 using different subsets of the transects and the data were aggregated in EBMUD field book FB-3647 (EBMUD 1978). Capacity tables that are known to exist are from 1930, 1976, and 1995 (EBMUD 1930; EBMUD 1976; EBMUD 2005). Bathymetry contour maps were found for 1929, 1951, 1960, 1977, and 1995. The contour maps from 1951 and 1960 also included surface-volume graphs (Longwell 1944; Kennedy 1951; DeCosta 1960) imprinted on the drawing itself and the contour maps from 1929 and 1977 had been converted into GIS layers. In 1995 EBMUD conducted a single beam sonar survey that was combined with a 1977 aerial survey to update elevation capacity (also known as stage surface volume) tables. The table currently in use was generated using data from the 1995 hydrographic survey, but no transect profile data from 1995 appears to have been extracted for comparison to previous silt profile studies.

The data acquisition methods and GIS techniques used to create the 1995 bathymetric map were not well documented. An EBMUD ranger who participated in the survey reported that the survey used a depth finder to measure depth (C. Swan, personal communication, November 2014), but no information was found on how sensor



**Figure 2. Pardee reservoir silt profile monuments and transect lines. There are a total of 24 transects that have been used historically to do leadline soundings for siltation measurements.**

attitude data were collected and applied. Position data was acquired using GPS and corrected using a Trimble 4000 base station, but its location was not documented (EBMUD *Date unknown*). Additionally, because of the comparatively low number of soundings generated in the single beam sonar survey, the digital elevation model (DEM) was created using a highly interpolated triangular irregular network (TIN) surface resulting in a less accurate assessment of capacity when compared to current multibeam methods. The apparent volumetric loss between 1930 and 1995 was 5.6% (EBMUD 1930; EBMUD 2005). This had been attributed to sediment deposition; however, because the map error is unknown, it is difficult to determine how much change is attributable to actual sedimentation and how much is because of error. Additionally, a hillshade visualization of the 1995 DEM shows unrealistic bottom features (Figure 15), indicating that the 1995 result is suspect. It should be noted that we were unable to establish the techniques used for data collection, contour map making or vertical error of the original or subsequent studies.

**PROJECT OVERVIEW**

The purpose of the Pardee Reservoir Capacity Study and Sedimentation Analysis project was to complete a hydrographic and topographic survey of the Pardee Reservoir, determine its current volume, and create an updated elevation-capacity table to give EBMUD a more accurate assessment of the reservoir’s capacity. The survey will serve as a baseline for future high-resolution studies that will be better able to detect change in



**Figure 3. Launching the 35' R/V *VenTresca* hydrographic survey vessel at Pardee.**

capacity caused by sediment deposition and will allow for rough comparisons of historical volumes. A secondary goal was to use previous bathymetric and leadline transect surveys to investigate the sedimentation trends at historical transects, geospatial distribution of sediment deposition and scour, and volume change since the 1995 hydrographic survey.

## METHODS

### HYDROGRAPHIC AND TOPOGRAPHIC SURVEY

#### DATA ACQUISITION

The 2014 survey utilized a variety of survey equipment and sensors to collect survey vessel position, attitude and trajectory data, sound velocity profiles, sonar soundings, and laser point data. The survey vessels

were equipped with a combination of the SWATHplus 468 kHz Interferometric bathymetric side scan sonar, a RESON 7125-SV2 dual-frequency (200 kHz and 400 kHz with 256 or 512 equidistant spaced beams respectively) multibeam sonar, a sideways-mounted Riegl FML-z420i LiDAR, an ANL SV+ sound velocimeter, the Applanix POS/MV 320 v4 and Trimble realtime-kinematic (RTK) GPS system. Hydrographic data was collected below the surface with sonar and LiDAR was used to collect topographic data above the waterline.

The sensors were mounted to two different survey vessels: for water deeper than 15', we utilized the R/V *VenTresca*, a 35' aluminum hull catamaran (Figure 3) and for shallow-water sonar and for the above-lake topographic survey, we used the R/V *Kelpfly*, a highly modified Jetski. (Figure 4). Both vessels are based at CSU Monterey Bay and operated by CSUMB's Sea Floor Mapping Lab (SFML) in Seaside, CA. The R/V *VenTresca* survey was conducted from September 18 to 21, 2014 and the R/V *Kelpfly* swath sonar work was conducted September 28 and October 12, 2014.

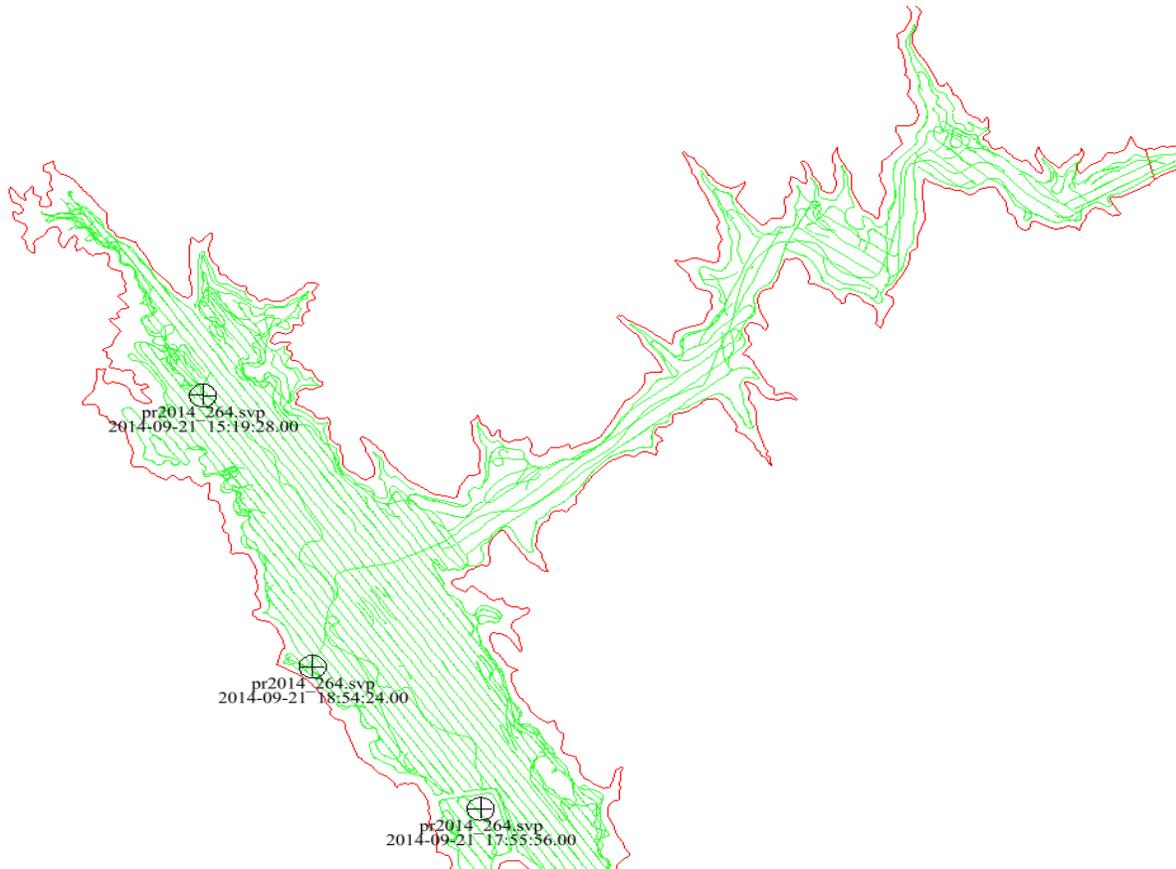
Survey tracklines were designed prior to beginning the work on Pardee Reservoir. The tracklines were designed to pass through the reservoir using the longest track possible and were spaced so that sonar data would have a 20-75% overlap (Figure 5) allowing for verification of vertical co-registration. In the shallower areas this resulted in large amounts of overlapping sonar data. Shallower areas in narrow inlets had to be cautiously navigated with data collection frequently started and stopped as the vessel was repositioned. The average speed over the course of the entire survey was under 2 nautical miles per hour.



**Figure 4. The R/V *KelpFly*. A highly modified Jetski designed for nearshore bathymetric survey of ocean areas where a non-jet boat would get its prop tangled in seaweed.**

#### HYDROGRAPHIC SURVEY: SONAR DATA ACQUISITION

Vessel position and attitude data were critical to the proper geolocation of sonar sounding points. As the survey vessel moved through the water, its position,



**Figure 5. Survey tracklines on Pardee Reservoir. Survey lines were designed to ensure sufficient multibeam sonar overlap in all depths. Over 200 km of sonar survey tracklines were run by the *VenTresca* and the *Kelpfly*. Icons in image are stamped with dates and times where sound velocity profiles were taken and represent a subset of all profiles that were taken.**

speed, attitude and trajectory were in constant flux. To account for this constant change, we used the POS/MV system to collect position and attitude information at 200 Hz on the *VenTresca* and 100 to be used in the post processing phase. Data for pitch, yaw and roll axes, heave, and GPS position were collected for later use, but also applied in realtime. The POS/MV's inertial motion measuring device, combined with differential GPS inputs to the GPS Azimuthal Measuring System (GAMS), calculates course heading accuracy to within  $\pm 0.02\%$ . Additionally the POS/MV system specifications were  $\pm 0.05^\circ$  for pitch and roll and  $\pm 0.05$  meters / 5% for heave. By accounting for the various types of motion POS/MV system can accurately place sonar soundings both vertically and on a horizontal plane (Figure 6). Vertical accuracy of the POS/MV system is around 10 cm (3.9 in) (McPherson et al. 2009).

Because the speed of sound through water varies with water density, sonar beams refract as they pass through density changes in the water column. As a result, the sonar beams do not travel in straight lines from the sonar transducers to the reservoir floor and back. This refraction can lead to significant errors in the sounding data unless corrected. Sound velocity profile casts are therefore taken throughout each survey day that are then used to model the structure of the water column which in turn is used to calculate the actual path of the sonar beams during post-processing. For the Pardee sonar surveys, AML SV+ sound velocity profilers were used aboard the *VenTresca* (Figure 7) and an YSI Castaway profiler was used aboard the *KelpFly*.

The RESON 7125 dual-frequency multibeam sonar was operated at both 200 kHz and 400 kHz during the survey. The lower frequency (200 kHz) sonar is more effective in deeper water and was used along survey track lines over the deepest part of the reservoir. The RESON 7125 uses 512 beams in its array when operated under 400 kHz and 256 sensors when used at 200 kHz. During the survey the RESON 7125 was generating between 4 and 30 pings per second for a total of 2,048 to 15,360 soundings per second when operating in the upper frequency. For comparison, the 1995 hydrographic survey collected a total of just 5310 sonar soundings (EBMUD 1995) over the course of 10 weeks (Appendix). The RESON 7125 can also be turned sideways to better capture vertical surfaces and structures (Figure 8).

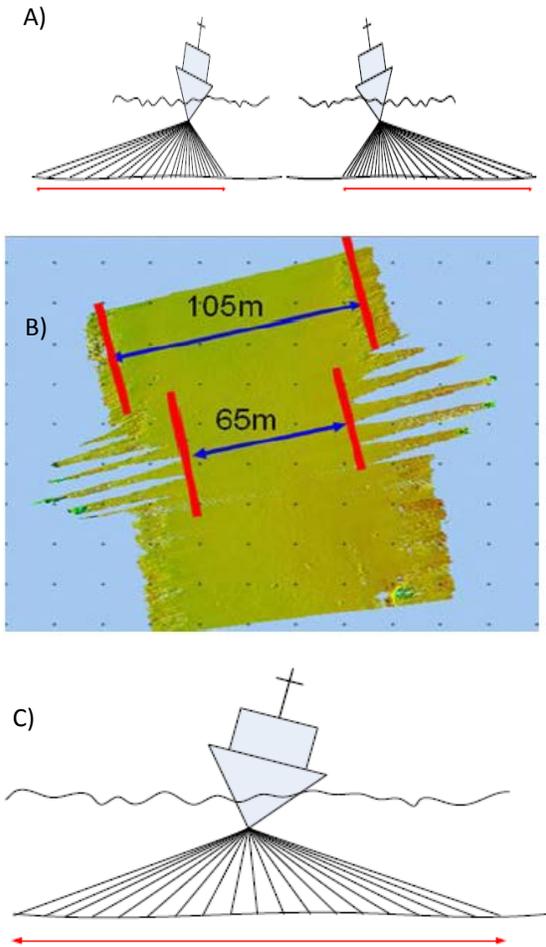


Figure 6. Example of sonar sounding displacement caused by movement around the roll axis. Vessel roll shown in A) depicts how the changing angle of the sonar could lead to incorrect sounding position data. Assuming a potential 105 meter effective swath-width in B), POS/MV will correctly geo-locate soundings regardless of movement around the roll axis, but without roll stabilization the swath would be effectively reduced to 65 meters. By applying roll stabilization to sonar data during survey C), motion around the ship's roll axis is applied in realtime (RESON 2010) enabling the larger 105 meter effective swath width. Images from RESON SeaBat 7125 Operator's Manual.

The SWATHplus 468 kHz Interferometric sonar system utilized "swath-sounding" to measure depth along a profile line from the transducer. The transducer is typically mounted perpendicular to the survey platform to allow sounding swath profiles to be generated as the vessel moves forward (SEA 2009). Interferometry compares the phase angle of the reflected sound from the seafloor as it is received by several vertically-separated transducer staves to calculate the direction from which the echo was reflected. This is in contrast to beam-forming sonar (e.g. the RESON 7125 multibeam) which use peak signal strength to determine the distance to the reservoir floor. The SWATHplus system has a ping rate that ranges from 2.5 Hz to 10.7 Hz. This was adjusted according to depth, as sound takes longer to return from the deeper reservoir floor (SEA 2009).



Figure 7. SV+ sound velocity profiler being retrieved.

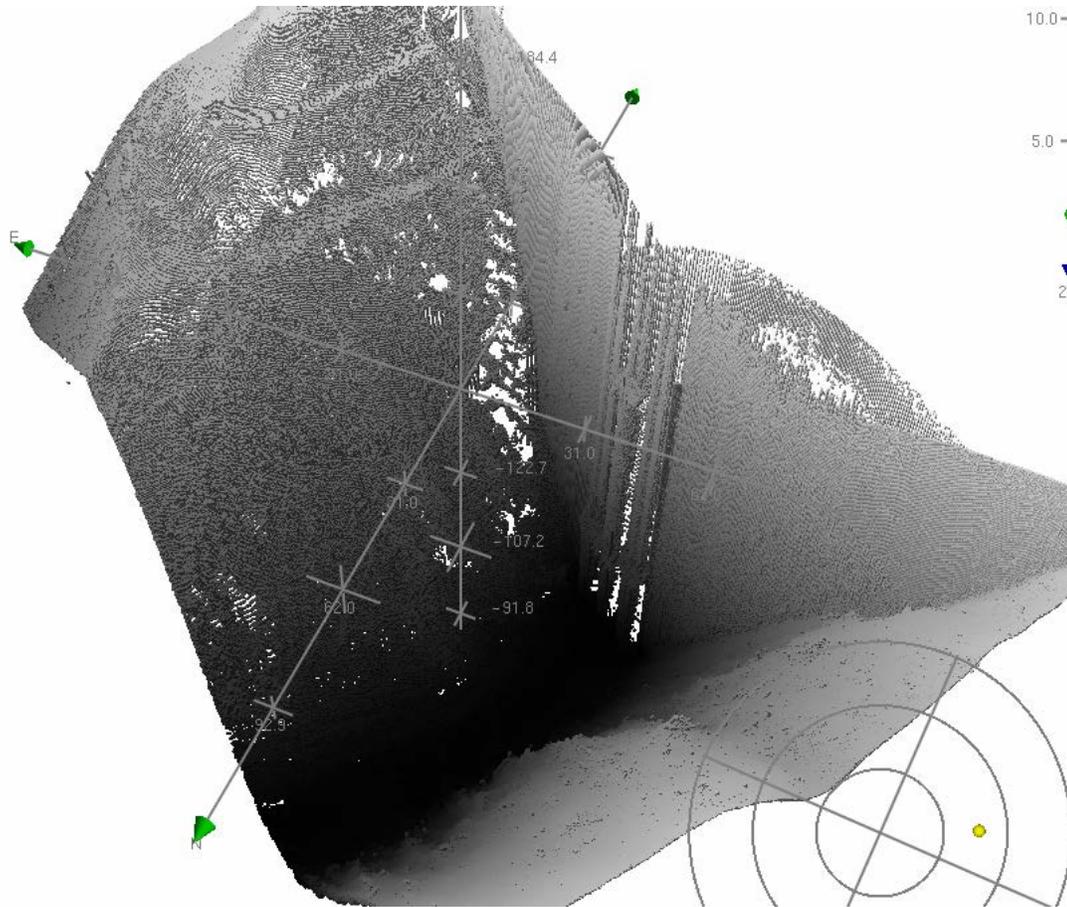


Figure 8. 3D Editor in Caris HIPS and SIPS. Looking downward into the deep trough next to Pardee Dam.

#### TOPOGRAPHIC SURVEY: LIDAR DATA ACQUISITION

The topographic survey was completed using the *R/V Kelpfly* mounted Riegl LMS-Z420i LiDAR terrestrial laser scanner and Applanix POS/MV Wavemaster. As with the sonar survey, the POS/MV system collects position, attitude, and trajectory information used in post-processing (McPherson et al. 2009). The Riegl system has a range of 1000 m, a measurement rate of 8,000 points per second, a precision of 0.8 mm and an accuracy of  $\pm 10$  mm. The vertical line scan range field of view is up to  $80^\circ$  (Riegl 2010). These and all other raw point data were corrected in post-processing.

#### SONAR DATA POST PROCESSING

To ensure vertical and horizontal accuracy, sonar data post-processing was required to correct for vessel motion and sound velocity changes in the water column. While the POS/MV system is used to correct sonar data in realtime, the POS/MV data was later reprocessed after the survey using Applanix POSpac Mobile Mapping Suite 5.3 software. The software used an Inertially Aided Post Processed Kinematic (IAPPK) technique that compiled positional data acquired at 200 Hz by the POS/MV system into smoothed best estimated trajectory (SBET) files. The SBET files included attitude and heave information which, along with SVP data, were applied in CARIS HIPS and SIPS Pro prior to manual cleaning. Area CORS network GPS stations were used to generate a virtual reference station (VRS) solution for the processing of the POS/MV data in POSpac to the SBET trajectory of the vessel position. Using CARIS HIPS and SIPS Pro, the SBET files and SVP data were then merged with the raw multibeam sonar in preparation for manual cleaning. In CARIS HIPS and SIPS the raw sonar data elevation values were converted from ellipsoid-based elevation to NAVD88 elevation using the 2012A geoid model. Using an analogous

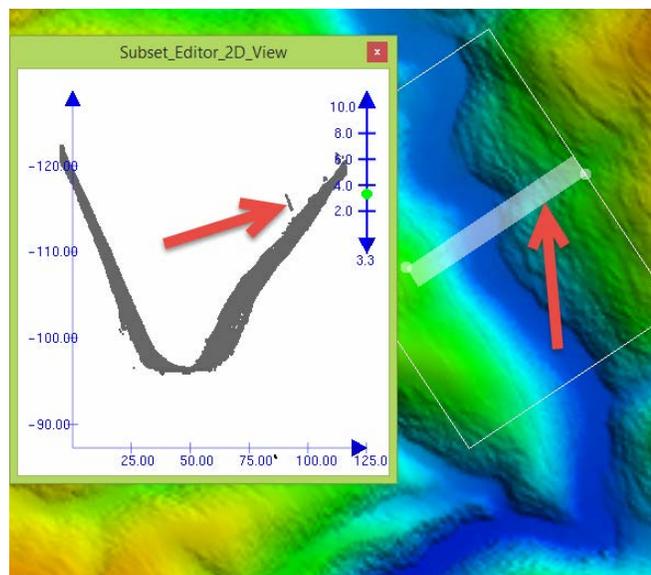
process, SWATHplus swath sonar data was merged with SBET and SVP data using SEA SwathProcessor software (v3.06.04.06) and subsequently added to the HIPS and SIPS project (McPherson et al. 2009) so that all sonar could be viewed and edited in a single project. When this process has been completed, all data were corrected for sound velocity changes in the water column, and position and attitude error.

### LiDAR DATA POST PROCESSING

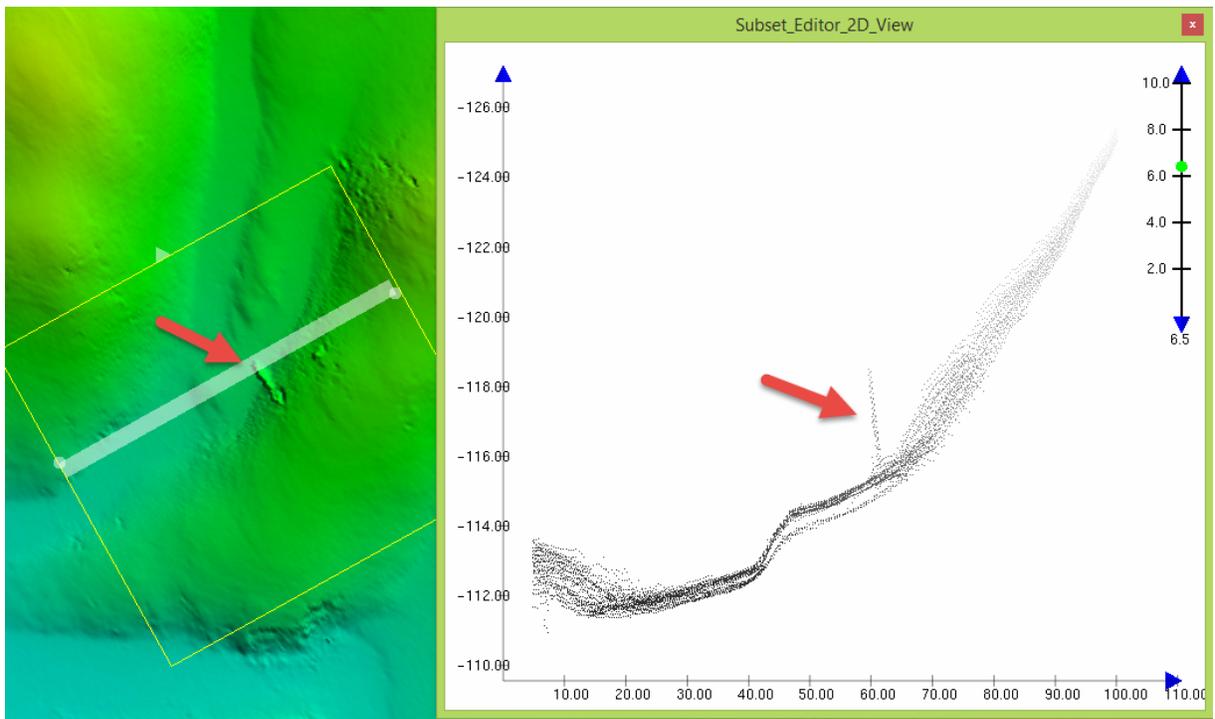
To ensure vertical and horizontal accuracy, LiDAR data post-processing was required to correct for vessel motion. Similarly to sonar data, POSPac was used to generate SBETs for position and trajectory that was then applied to the geometric center of the LiDAR scanner. Riegl RiWORLD 4.1.2 (Riegl 2011) was used to apply SBETs and configure and export XYZ data. Corpscon 6.0.1 (USACE 2004) software was used to take the ellipsoid-based elevation output from RiWORLD and convert it to NAVD88 vertical datum using the 12A GEOID model as the final step before cleaning in Fledermaus (Kvitek 2011). When this process was completed, all data were corrected for position and attitude error.

### SONAR DATA CLEANING

After post-processing was completed, the data were cleaned manually using CARIS HIPS and SIPS Pro 8.1 (CARIS 2014) to remove spurious soundings caused by fish, submerged trees or buildings, multiple returns (where sound bounces multiple times between the vessel and the lake floor) and other sonar artifacts. This step was required to ensure that the final digital elevation model was an accurate representation of bare lake floor elevation. The HIPS and SIPS Pro *Subset Editor* tool was used to load sections of the bathymetric data for review and cleaning. To act as a visual guide and to verify cleaning progress, a Bathymetry Associated with Statistical Error (BASE) surface was created using the Combined Uncertainty and Bathymetry Estimator (CUBE) algorithm applied to the data from swath and multibeam sonar at 2 meter resolution (Figure 9). The data set was initially reviewed and cleaned in its entirety using the *Subset Editor* with a 2 meter resolution BASE map as a visual guide. Within *Subset Editor*, a user-defined profile was adjusted to highlight swaths of data for cleaning.



**Figure 9. Subset Editor in Caris HIPS and SIPS Pro 8.1. Using a 2 meter resolution BASE surface (plan view in background) as a guide was sufficient for first round cleaning, but did not always expose spurious data. Bogus data that were not visible on the 2 meter BASE surface (arrow on right) were seen here in 2D Editor (arrow on the left at the same location) and subsequently removed. The 2D Editor window shows an elevation view of data from the shaded rectangle within the subset.**

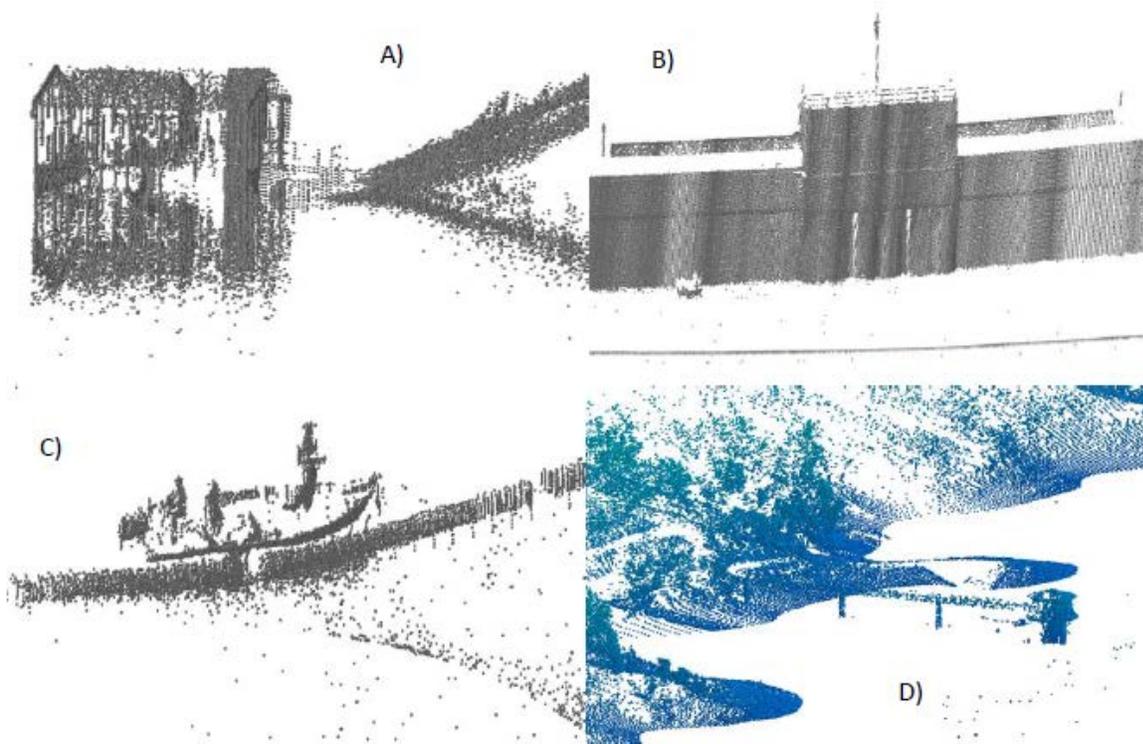


**Figure 10. CARIS HIPS and SIPS Subset Editor with a 2D Editor window. After two rounds of cleaning with a 2 meter BASE surface, subsequent rounds used a higher resolution 0.5 meter BASE surface (in background). The 2D editor (sub-window to right) was used to remove spurious data that did not align with the lake floor surface and resulted in an unnatural BASE surface feature (left arrow). Each subsequent, higher resolution BASE surface visual exposed spurious data that would affect surface export at that resolution. Creating and cleaning a BASE surface was performed to 0.5 meters because the final metric product was exported at that resolution.**

Initial quality control at this point was done by exporting the resulting 2 meter BASE surface into an XYZ format ASCII file, converting the XYZ file into a "PFM" project using QPS DMagic (Quality Positioning Services BV (QPS) 2014a) then gridding it into a digital terrain model (DTM). The DTM was opened with QPS Fledermaus (Quality Positioning Services BV (QPS) 2014b) and viewed as a fly-through 3D model in Fledermaus which was used to look for unexpected spikes and shapes in the reservoir floor. Then using HIPS and SIPS, a new BASE surface was generated at 0.5 meter resolution for a second round of cleaning with *Subset Editor* (Figure 10) to fix the issues discovered in Fledermaus. Finally, using the 0.5 meter resolution BASE map as a reference, the third round of subset cleaning was conducted. The cleaned data were then exported from the final 0.5 meter resolution BASE surface in ASCII format XYZ file for a total of 30,942,086 gridded points.

#### LIDAR DATA CLEANING

To correctly identify the bare earth topography of Pardee Reservoir's shoreline, LiDAR data were cleaned to remove spurious point return data including structures, vegetation, reflections, objects on water, and vessel wake. Similarly to sonar cleaning, this step was required to achieve an accurate representation of the topographical features in the final DEM. Post-processed Corpscon ASCII XYZ files were loaded into QPS DMagic, filtered to include all data between the waterline (552.16 feet- NAVD88 elevation, not local) and the highest LiDAR return on the spillway (570.243 feet NAVD88 elevation, not local) into a project PFM database using QPS DMagic. The LiDAR-only PFM was then imported into Fledermaus for point editing. LiDAR points of reflections, survey vessel wake or objects floating on the water, structures and vegetation (Figure 11) were removed resulting in bare-surface



**Figure 11. Examples of different LiDAR point data that were removed. Structures A), B), and D) were removed. LiDAR point mirroring A) was removed. R/V wake lines B) had to be removed along with objects on water surface C). Vegetation was removed to get a bare-earth surface D). Note the LiDAR point shadow cast by the small boat in B).**

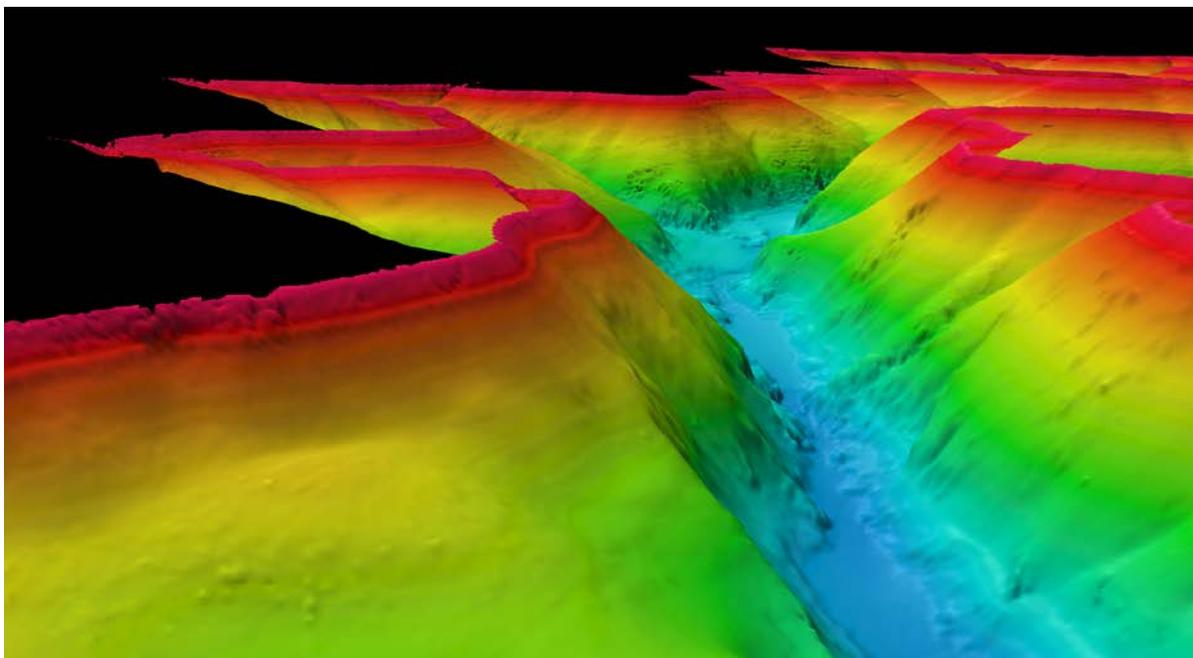
elevation points. The data cleaning process resulted in 10,440,884 XYZ bare-earth grid points when exported to an ASCII format XYZ file which was merged with cleaned sonar data in the next step.

#### MERGING HYDROGRAPHIC AND TOPOGRAPHIC DATA SETS

The two separate data sets were merged for final quality control/cleaning and to generate a DTM for final processing with GIS software. This step was required because the merged dataset exposed issues that were not visible when the data were cleaned separately. Additionally, the DTM export required that the hydrographic and topographic data be merged. To fuse the data, final XYZ exports of sonar and LiDAR data were combined into a DMagic PFM and then imported into Fledermaus for the final rounds of cleaning. The merged bathymetric/topographic data exhibited a ledge-like seam where the two data sets met at the waterline due to the wider scattering of the sonar soundings at the extreme limit of the swath range. This seam was trimmed away using the more accurate LiDAR data as a reference surface (Figure 12). Flyers and outlier data were also deleted using methods described previously. After the merged data were cleaned, “accepted” soundings data were then exported from Fledermaus in ASCII XYZ format. Exported XYZ data were added to a new DMagic PFM project, gridded into a DTM, and exported as a geotiff at a 0.5 meter resolution for additional processing using GIS software.

#### QUALITY CONTROL AND PATCH TESTING

Quality control was conducted to ensure that the collected data met IHO Hydrographic Standards – Special Order as outlined in the project contract. Quality control was a real-time process throughout the entire survey with ordered procedures to monitor and correct the incoming data, as described in detail in the Appendix. During the



**Figure 12. Data seam where LiDAR and sonar data are joined due to the wider scatter of sonar soundings at the extreme limits of the swath range. The ledge was removed and any resulting data gaps were filled by interpolation or backfilled with '95 data.**

mobilization and setup of the system in preparation for multibeam data acquisition many steps were taken to ensure the system is in proper calibration and working condition. The RESON 7125 multibeam echosounder (MBES) and SEA SWATHplus interferometric sonar transducers are installed on an over-the-side pole mount aboard the R/V *VenTresca*, requiring minimal mobilization effort.

#### SONAR PATCH TEST

Prior to conducting the survey, a standard “patch test” calibration survey was performed on the R/V *VenTresca* on August 26, 2014 (JD 238) at the City of Marina sewer outfall in Monterey Bay, CA. A patch test was required to quantify angular offsets between sensors which were then applied to survey data. A patch test survey was performed for the R/V *KelpFly* at the City of Pajaro sewer outfall on July 1, 2014 (JD 182). The results of patch test data analysis provided sensor alignment offsets for navigation latency and pitch, yaw, and roll of the MBES and SWATHplus relative to the vessel coordinate system, as well as verification of system operation and survey repeatability.

#### LIDAR PATCH TEST

A patch test was conducted for the LiDAR system to account for any angular offsets. The Riegl LS420i laser scanner mounted atop the *R/V Kelpfly* for the Pardee Reservoir shoreline scan was calibrated (bore-sighted) to the Applanix POS MV based on a patchtest conducted at the Pardee parking lot on October 12, 2014. For the patchtest, a Trimble NetR5 geodetic grade GPS receiver and antenna were setup on a tripod in the middle of the parking lot and used as the target object (Appendix, Figure 46). GPS data were logged for 2.5 hours and subsequently processed through the NGS OPUS online site for a static solution shown at the end of this document. This solution gave the precise location of the antenna and the elevation of the pavement directly beneath the antenna, which were used in the subsequent patchtest analysis. The result of this analysis was to produce angular offset corrections for pitch, yaw, and roll differences between the Applanix POS/MV and Riegl laser scanner (Appendix).

## ESTABLISHING A VERTICAL CONTROL AND SPILLWAY ELEVATION DATUM

To align the 2014 survey elevation with the local datum that EBMUD uses for its elevation staff plate and volume tables, a vertical control was established using benchmark MB7 on the Pardee Dam. The survey was conducted using a Trimble 5700 GPS, which served as the master geodetic control point following McPherson et al (2011). Existing local and NGVD 1929 elevations currently in use were compared to the resulting NOAA OPUS solution (Appendix) derived from a CORS network of GPS base stations and a datum shift from NAVD88 to local was calculated (Table 1).

**Table 1. GPS survey of MB7 was used to establish vertical control and determine datum shift between NAVD 88 elevations and Local Datum. The local datum is the official elevation used by EBMUD to determine elevation capacity.**

	Datum/GPS static survey		Datum shift
<b>Datum description</b>	MB7 Pardee Dam benchmark (Local Datum)	MB7 Pardee Dam benchmark (NAVD88)	Vertical shift required to convert from NAVD88 to Local Datum
<b>Source</b>	<i>EBMUD</i>	<i>CSUMB GPS Static Survey</i>	<i>NAVD88 - Local</i>
<b>Elevation (ft)</b>	<b>576.49 ft</b>	<b>578.501</b>	<b>-2.011 ft</b>

Separately from the shift from NAVD88 survey elevation to local datum, official volume was calculated using spillway elevation which has historically been reported in either local datum or NGVD 1929. The spillway elevation was determined to be 567.65 feet in reference to the local datum using documents from EBMUD archives and field book data from the 2006 survey (Hall 1937; Wilson 1977; EBMUD 2006) (Appendix, Figures 50-53). In 1959 and 1977 surveys the spillway elevation low point was surveyed at 567.25 feet using USGS benchmarks. The 0.40

**Table 1a. Comparison of elevations using local and NGVD 1929 datums.**

Benchmark or location	Elevation (feet) comparison by datum		
	Local datum	NGVD 1929 (1959, 1977 surveys)	Difference
<b>MB7</b>	576.49	576.075	0.415
<b>Spillway</b>	567.65	567.25 (1977 only)	0.40

vertical shift between NGVD 1929 spillway elevation and the local datum elevation reported by Wilson (1977) essentially matches the shift between the two datums at benchmark MB7 (Table 1a).

## VERTICAL ACCURACY ASSESSMENT AND VERTICAL MAP ERROR

Vertical error of the final DEM was assessed using two methods: independent *in situ* measurement of depth (elevation), and using modeled Total Propagated Uncertainty (TPU) in CARIS HIPS and SIPS Pro. The more conservative (greatest error) estimate was then used to model the potential effect of vertical error on reservoir volume calculations.

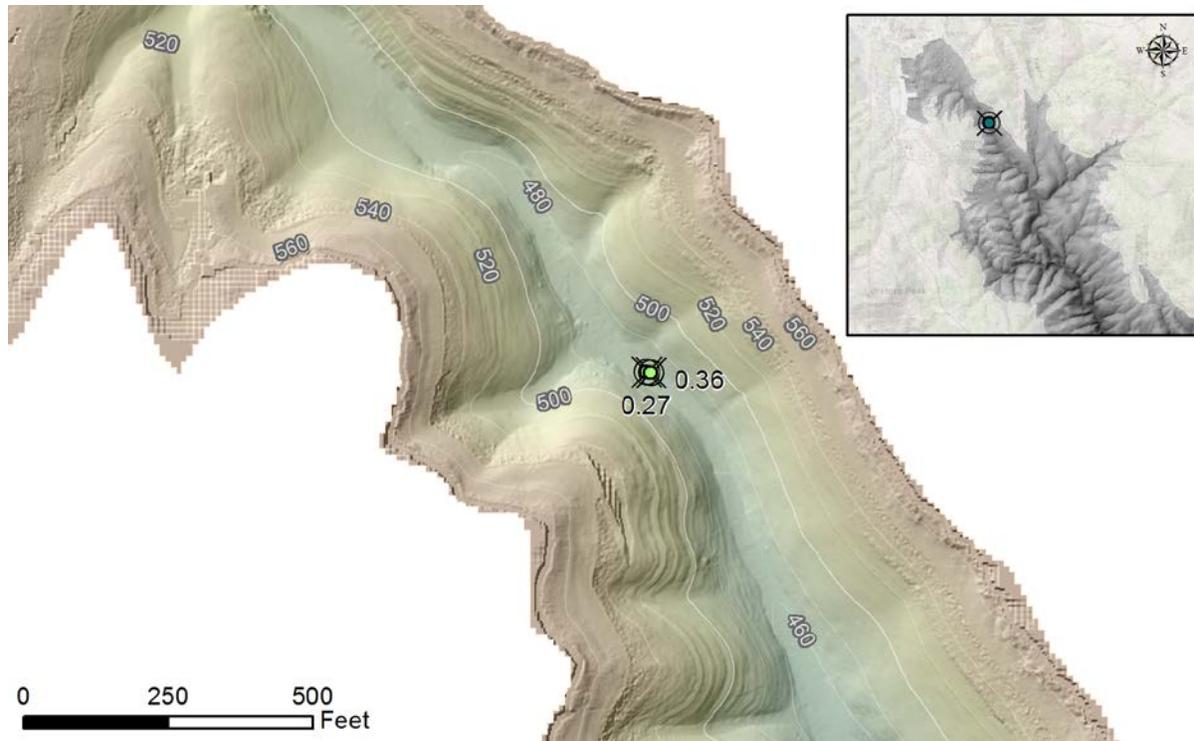
During the *Kelpfly* sonar survey, a limited number of *in situ* leadline soundings were taken to assess accuracy of sonar depth. Water depths were measured from the top of the *KelpFly* antenna arch and then were corrected for height above waterline (3.83 feet). In addition, depth below the waterline was measured concurrently using the Castaway CTD used for sound velocity profiling during the *KelpFly* survey. Leadline/Castaway sounding positions

**Table 2. Comparison of static survey and LiDAR points to assess accuracy. CSUMB GPS static survey point and LiDAR point were compared to assess LiDAR vertical offset from the control point at the Pardee Dam gatehouse.**

	GPS Static survey vs LiDAR point		Vertical difference
<b>Survey point description</b>	GPS Ortho height of antenna on West wall top near gatehouse (NAVD88)	GPS Ortho height of LiDAR point on West wall top near gatehouse (NAVD88)	GPS Ortho height compared to LiDAR point on West wall top near gatehouse (NAVD88)
<b>Elevation (ft)</b>	<b>584.05</b>	<b>584.19</b>	<b>0.14</b>

were recorded using a Trimble Juno 3B GPS and data were differentially corrected using the UNAVCO Oakdale p306 station listed in the Trimble Provider list. This station was also among the 3 selected by OPUS in processing the laser patch test target NetR5 data. Two test soundings locations were taken (Figure 13). The vertical offsets between the final DEM and the two test soundings were 0.27 feet (3.24 inches) and 0.36 feet (4.32 inches). Although an effort was made to keep the leadline completely vertical, some measurement error may have occurred due to vessel drift, and may have contributed to the observed differences between the DEM and leadline elevations. Because of the scarcity of leadline soundings taken and the casts and the fact that they were done on only one area, the error estimate generated from them, which was lower than the estimate from TPU analysis described below, was not used in final DEM and volume calculation error modeling.

LiDAR accuracy was assessed by using LiDAR point data on the dam near the gatehouse. A GPS survey was conducted from the top of the wall and a laser level tied the MB7 benchmark of the dam to the GPS antenna elevation (see Establishing Vertical Control). The highest LiDAR point return near the antenna on the gatehouse



**Figure 13. Leadline survey points. Castaway depths were affected by drift indicating a slightly deeper sounding than was sensed using sonar. The final DEM elevation at this location was 0.36 and 0.27 feet above the castaway depth.**

wall (Table 2) (Appendix, Figure 34) was 0.14 feet above the NGS OPUS solution value for the static occupation of that point on the wall. The difference between the 2014 CSUMB GPS static survey NGVD 1929 elevation and the EMBUD 1959 (and 1977) NGVD 1929 elevation was 0.017 feet (Appendix). The cumulative error is approximately +0.157 feet ( $\pm 1.9$  inches). The error result was lower than the TPU-based estimate.

Total Propagated Uncertainty (TPU) is a theoretical estimate of sounding uncertainty that attempts to model the combined contributions of all individual sources of uncertainty during the survey. These sources include the sonar itself, the position and attitude (roll, pitch, heave, and heading) sensors, sound velocity measurements, alignment and lever arms of the system sensor geometry, sensor timing, and other factors. Developed at the Center for Coastal and Ocean Mapping (CCOM) at the University of New Hampshire, the TPU algorithm provides uncertainty measures for every sonar sounding that are utilized by the CUBE (Combined Uncertainty Bathymetric Estimator) algorithm used to create surface models from the sounding point cloud, and can be used to model potential uncertainty in the surface models created. CARIS HIPS and SIPS Pro provides tools for TPU calculation and CUBE surface uncertainty assessment, and these were used to estimate potential error in the final DEM product for Pardee Reservoir. Each node in a CUBE surface is assigned a vertical uncertainty estimate based upon the TPU of the input soundings. The TPU algorithm models the theoretical *uncertainty (potential error)* for every sounding, based upon the values for parameters described above. By definition, none of these factors is considered to be perfect, or without uncertainty, so that TPU will never equal zero, even for soundings with perfect accuracy (*error* = 0). Because TPU can never be 0, the measure tends to overestimate actual error; however, error larger than the TPU estimate is possible.

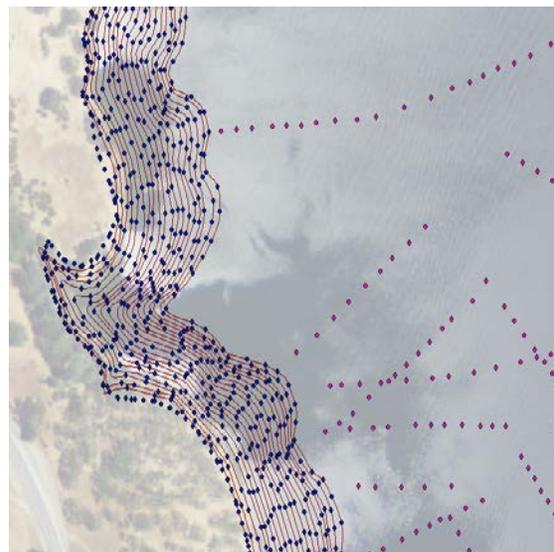
The mean uncertainty of the  $\sim 31$ M nodes in the 0.5m CUBE BASE surface (on which the final DEM was based) was 0.19 meters (0.623 feet). This value was used to define a 95% confidence interval (CI) for all DEM cell elevation values which established the minimum and maximum range of volumes based on  $\pm 0.623$  feet. To calculate the range in reservoir volume based on the DEM elevation CI, 0.623 feet were added ( $DEM_{E+}$ ) and subtracted ( $DEM_{E-}$ ) from the DEM and the resulting  $DEM_{E+}$  and  $DEM_{E-}$  volumes were calculated with the ArcGIS 3D Analyst Surface-volume tool.

## DIGITAL ELEVATION MODEL (DEM) CREATION

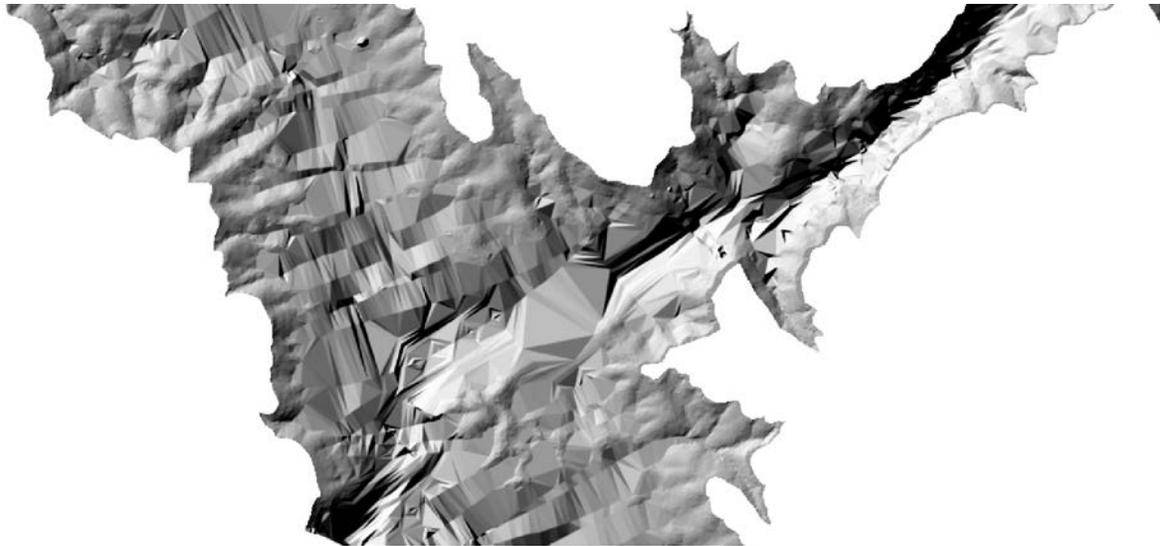
In order to compare 1995 and 2014 surveys it was necessary to understand the methods which were used in creating the 1995 bathymetric DEM. For the 2014 DEM several methods of fine-tuning were investigated and their concomitant volumes were calculated for comparison (Appendix). The procedure that utilized the least amount of smoothing and minimized data “backfilling” was chosen.

### 1995 DEM

The 1995 DEM was used to calculate volume and create the elevation capacity curve currently used by EBMUD reservoir operators. However, it is not well documented how it was created. Searching through EBMUD’s DOX system and inquiring with team members in water supply and the GIS group did not yield any report or document describing the specific methods of sonar or position data



**Figure 14. A sample of sonar sounding points and points extracted from 1977 contours that were used for creating the 1995 bathymetric DEM. Sonar data from 1995 are the more sparsely spaced red points. The denser data along contour lines are probably from the photogrammetry analysis of the 1977 aerial survey.**



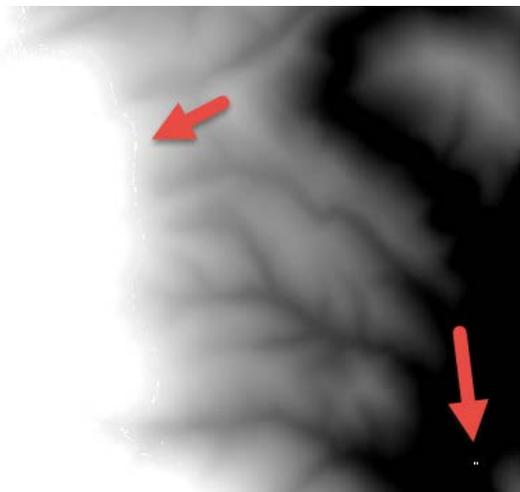
**Figure 15. 1995 bathymetric DEM. The final 1995 DEM was highly interpolated which resulted in geomorphically unlikely features, particularly in deeper water.**

acquisition or the GIS techniques used to generate the DEM. A sparsely detailed document provided at the end of the project noted that the aerial survey of 1977 used an NGVD 1929 datum, but that the 1995 sonar survey did not specify its vertical datum (EBMUD *Undated*). The document further states that field notes for the soundings can be found in Field Book 4114 which is not currently available in the EBMUD document management system. Anecdotally, the 1995 map used elevation data derived from photogrammetry analysis of 1977 aerial imagery taken during a very low reservoir elevation year (S. Wollmer, personal communication, September 14, 2014) and single beam sonar collected using a depth finder in 1995 (C. Swan, personal communication, November 2014). Sonar soundings were geospatially located using RTK-GPS using a shore-based reference station, but no information is stated on how the data were corrected for vessel attitude (EBMUD). The GIS files for the 1995 bathymetric map contained a source layer comprised of 76,012 points. Of these, only 5,301 were single beam sonar soundings; the remaining data consisted of points derived from intervals along contours that appear to have been created from the aerial survey (Figure 14).

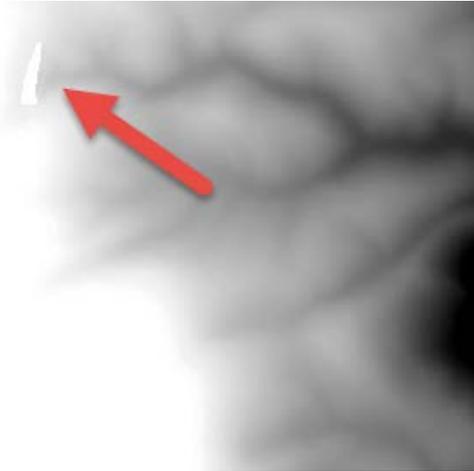
The resulting DEM showed a geometry that was geomorphically unnatural and highly interpolated. This was exposed when visualizing the 1995 DEM with a hillshade algorithm which showed the reservoir bed surface to be angular (Figure 15). The odd hillshade “geomorphology” indicates that the point data was converted into a TIN prior to being exported to a geotiff raster.

### 2014 DEM

The initial 2014 DEM was exported from QPS DMagic at a 0.5 meter resolution as a DTM geotiff format file after cleaning of spurious data was completed using a combination of CARIS HIPS and SIPS and Fledermaus as described above. Once the initial DEM was exported, all other processing and



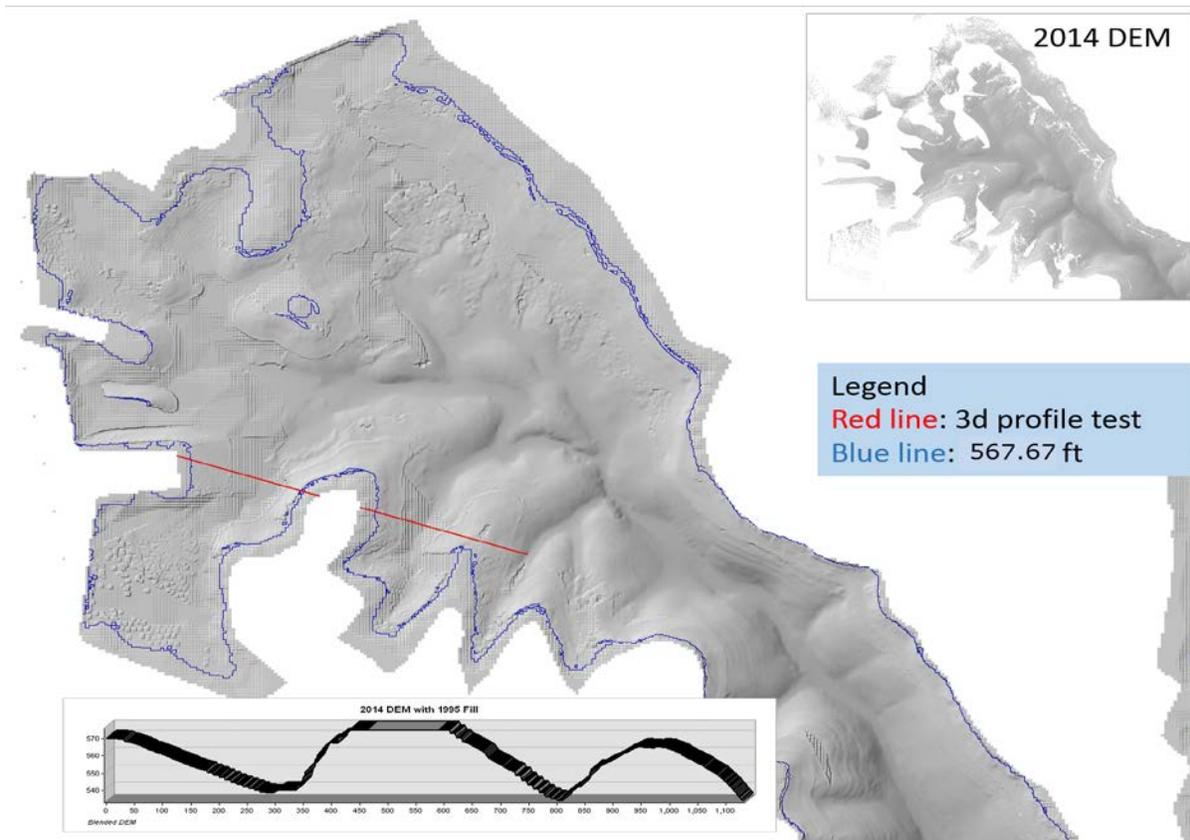
**Figure 16. Data gaps in DEM. Many very small gaps were a result of LiDAR/sonar seam cleaning. A very small number of gaps overall were caused by cleaning.**



**Figure 17.** After *FocalStatistics* tool was applied using a conditional statement, only larger data gaps remained. The final DEM used 1995 data to “backfill: the larger gaps that could not be easily filled using interpolation.

analysis of the DEM was done with ArcGIS 10.1 (ESRI 2012).

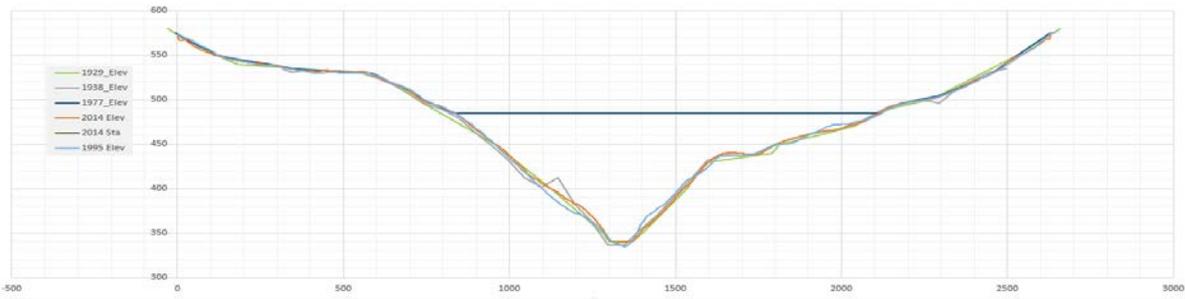
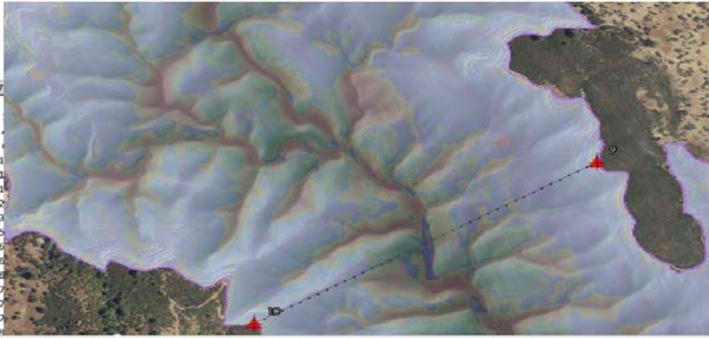
All processing work up to this point was done in NAD83 (2011) UTM 10N and NAVD88 vertical datum coordinates. This DEM file (DEM 1) served as the initial DEM from which all other derivative DEM products were created. To change to EBMUD’s coordinate system, DEM 1 was re-projected from NAD83 (2011) UTM10N to NAD83 California State Plane III FIPS 0403 (CSP3) as a new DEM (DEM 2). During the re-projection process, the data were resampled from 0.5 meter to 2 foot resolution using a cubic convolution algorithm. The vertical elevation values were then converted from meters to feet by multiplying the raster by 3.28084 feet using ArcGIS Spatial Analyst extension *Raster Calculator* tool. This process resulted in a DEM (DEM 3) with a horizontal resolution of 2 feet projected in NAD 83 CSP3 with vertical units also in feet in the NAVD88 vertical datum. After converting elevation values from meters to feet in the DEM, 2.011 feet were subtracted from the DEM to convert from NAVD88 to the Pardee local datum using



**Figure 18.** ArcGIS 3D Analysis profiles of the 1995/2014 data seam were examined to check for vertical offsets. In this example, the upper-right inset image shows the 2014 DEM before backfilling holes with 1995 data. The 3D graph in the bottom-left shows that the two data-sets align well. Note the stair-stepping of 1995 profile due to its lower resolution

Historical Transect Data X10-X9  
 EBMUD/CSUMB Pardee Reservoir Survey and Sediment Study  
 John Urness  
 12/4/2014

FID	Transect	1929_Sta	1929_Elev	1938_Sta	1938_Elev	1943_Sta	1943_Elev	1977_Sta	1977_Elev	1995_Sta	1995_Elev	2014_Sta	2014_Elev
0	X10-X9	-30	580	318	534.3								
1	X10-X9	10	570	346	530.9								
2	X10-X9	115	550	396	532.9								
3	X10-X9	180	540	446	522.7								
4	X10-X9	550	530	496	530.2								
5	X10-X9	635	520	546	531.6								
6	X10-X9	690	510	596	524.8								
7	X10-X9	720	500	646	516.8								
8	X10-X9	955	450	696	506.9								
9	X10-X9	1125	400	746	494.5								
10	X10-X9	1280	350	796	489.8								
11	X10-X9	1300	340	846	479.4								
12	X10-X9	1370	340	896	462.7								
13	X10-X9	1400	350	946	448.3								
14	X10-X9	1535	400	996	432.7								
15	X10-X9	1570	420	1046	412.5								
16	X10-X9	1600	430	1096	401.5								



**Figure 19. Example of visual comparison using sediment profile X10-X9. New data from 2014 was extracted using GIS for comparison with historical data. Additionally, 1995 data had not been previously extracted so this was done as well and added to the comparison.**

*Raster Calculator* tool to create a new DEM (DEM 4). This subtraction number was based on a vertical control point established by a CSUMB GPS static survey of benchmark MB7 on the Pardee Dam (Table 1). To create a NGVD 1929 DEM, we then subtracted 0.415 feet from the local datum DEM which is the difference between the official EBMUD NGVD 1929 and local elevations at MB7 (EBMUD 2014).

After projecting the data and converting to the desired units, DEM 4 was interpolated to fill small data gaps and remaining shoreline data gaps were filled with data from 1995. Gaps in the DEM dataset (Figure 16) were caused by seam cleaning or missing data and required additional work on the DEM for it to be comparable to the 1995 bathymetric survey. Interpolation can solve the problem of missing data, but in a geometric shape like a valley or reservoir, average elevation data were artificially increased because there are more points at higher elevations than at lower elevations. This results in an interpolated reservoir bottom with a higher elevation, and therefore a smaller reservoir volume. This would occur if the dataset as a whole was iteratively interpolated to fill to the 1995 extent. To avoid this problem, small data gaps were filled using *Raster Calculator* which conditionally interpolated only the null cell values using Spatial Analyst *FocalStatistics* and *Con* tools with a mean of 10 neighboring cells in a square (Figure 17) (see Appendix for code example). Then the remaining holes were filled with data from 1995 bathymetry itself. Several other procedures were examined and corresponding volumes were calculated, but were thought to be less accurate (Appendix, Table 9). To see how well the 1995 elevation data aligned vertically with the new DEM, we examined multiple profiles using ArcGIS 3D Analyst (Figure 18).

**CALCULATING STAGE-VOLUME AND STAGE-SURFACE**

Using the final DEM, stage volume and surface were calculated using ArcGIS 10.1 3D Analyst Tools *Surface Volume* tool. To calculate volume, the *Surface-Volume* tool creates a TIN surface by connecting the centers of all pixels prior to calculating volume between the reference plane (the stage elevation) and the TIN (ESRI 2012). ArcGIS Model Builder was used to iteratively calculate surface and volume between the elevations of 260 feet and

585 feet at increments of 0.01 foot. The resulting stage-volume table was used to determine official reservoir volume using the published spillway elevation of 567.65.

## GEOSPATIAL DISTRIBUTION OF SEDIMENT SCOUR AND DEPOSITION ANALYSIS

Because a digitized map of bathymetry does not exist for 1929 or subsequent years except 1995, the study was limited to geospatially quantifying scour and deposition between 1995 and 2014. Quantifying change between 1995 and 2014 is dependent on the quality of the data available so the results of the analysis are likely to be skewed because the 1995 bathymetry had known issues that were likely to result in an overestimation of sediment scour. ArcGIS Spatial Analyst *Raster Calculator* was used to subtract the two rasters in order to expose areas of deposition or scouring. Even though vertical error of the 2014 map was 0.623 feet based on a 95%CI, this value was not used for comparison because 1995 DEM error, while unknown, was assumed to be higher. For this analysis, error was arbitrarily assigned at  $\pm 3$  feet so that only change in elevation greater than 3 feet would be quantified. Because much of the shallow water data came from photogrammetry analysis that had a  $\pm 1.5$  foot margin of error, a difference of 3 feet is a conservative error envelope for that part of the bathymetry.

## VISUAL AND QUANTITATIVE TREND ANALYSIS OF HISTORICAL SILT PROFILES

Using handwritten data from the EDMUD Construction Division archives, leadline surveys of historical transects from 1929, 1938 and 1977 were entered into Excel and visually compared. The horizontal datum was NAD 1927 and the vertical datum is assumed to be the local Pardee datum which is 0.415 foot higher than NGVD 1929. Profiles were then superimposed on each other in order to assess change over time (Figure 19). ArcGIS 3D Analyst was used to extract lake-floor elevations along the historical transects. Because no 1995 data were found in the leadline survey workbooks, the same procedure was followed with this data as well. It was not known at the time of the study what method was used historically to compare the profiles of previous silt studies so ArcGIS was used to calculate the area between the lake floor elevation profile and a horizontal reference plane to assess change (Figure 20).

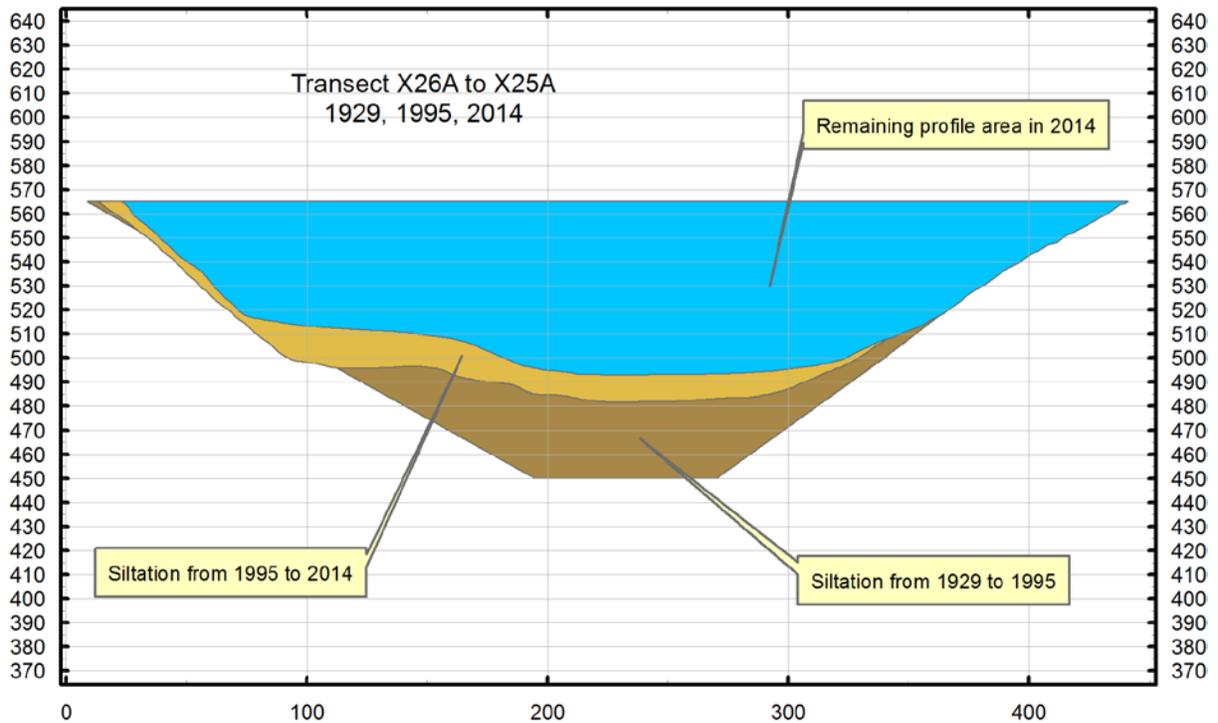


Figure 20. Silt profile comparison using 1929 data and data extracted from 1995 and 2014 DEMs along the same transect using ArcGIS. Elevation of 1929 and 2014 are local datum and 1995 data is assumed to be in the local datum. Sedimentation was analyzed using EBMUD’s system of silt-survey transects showing an increasing amount of sediment deposition in this example (transect X26A-X25A).

## RESULTS

### SURVEY DATA ACQUISITION

The sonar survey acquired 997,331,770 sonar returns over 518 survey vessel track lines. The LiDAR topographic survey gathered a total of 38,641,756 point returns. From the final merged and cleaned dataset, a gridded DTM of 40,571,865 points was exported.

### FINAL TOPO-BATHYMETRY DEM

From the final clean data we generated a 2 foot resolution DEM which included both bathymetry and topography of the Pardee reservoir (Figure 21-22). Contour files were created at 10, 20 and 100 foot intervals. Geospatial metadata was generated to FGDC standards (FGDC 2014) using the survey results and were integrated into the DEM layers and other selected layers (Table 8) within the delivered ArcGIS map package.

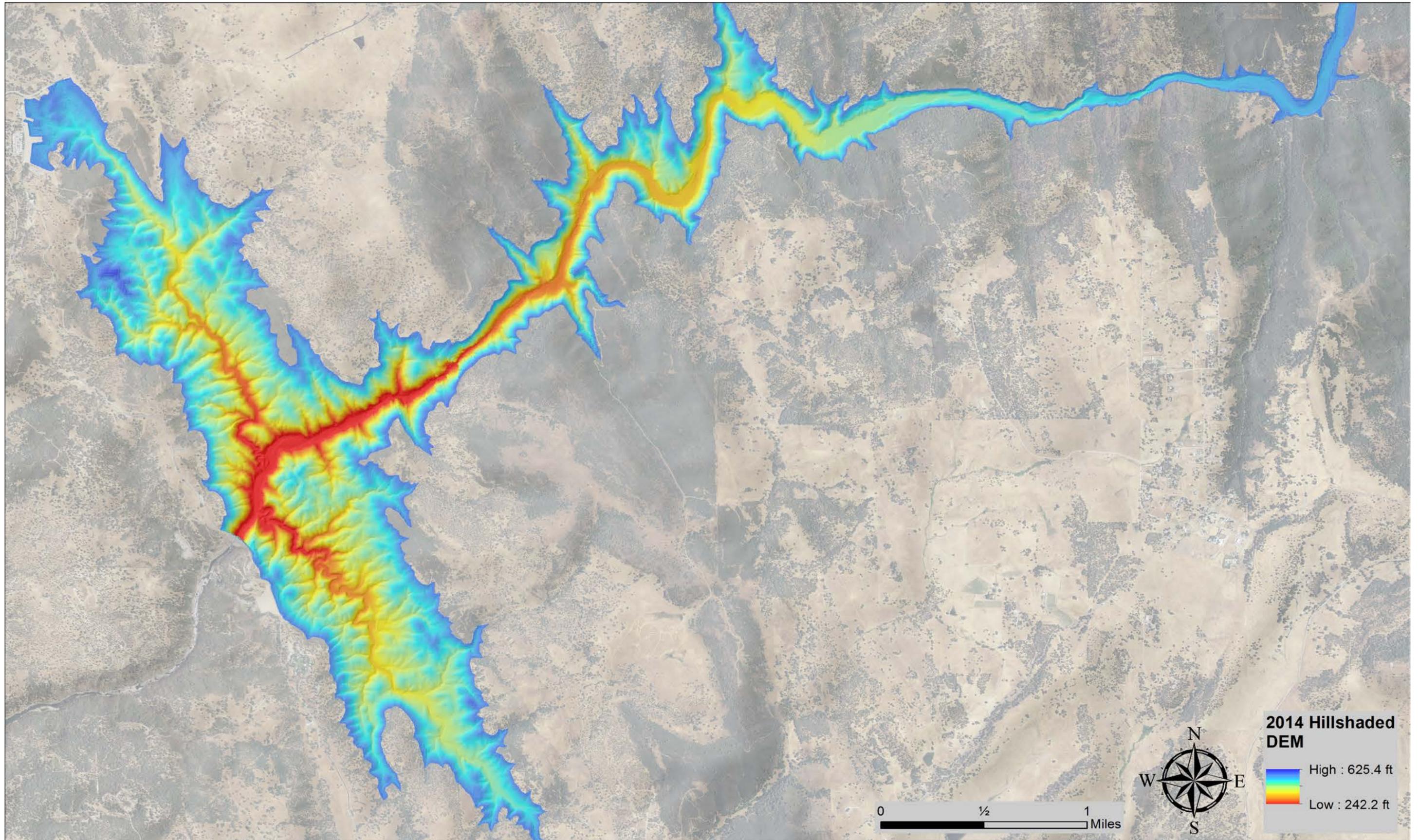


Figure 21. 2014 2ft horizontal resolution hill-shaded digital elevation model of Pardee Reservoir. Elevations in local datum. NAIP imagery from USDA, additional data from USGS.

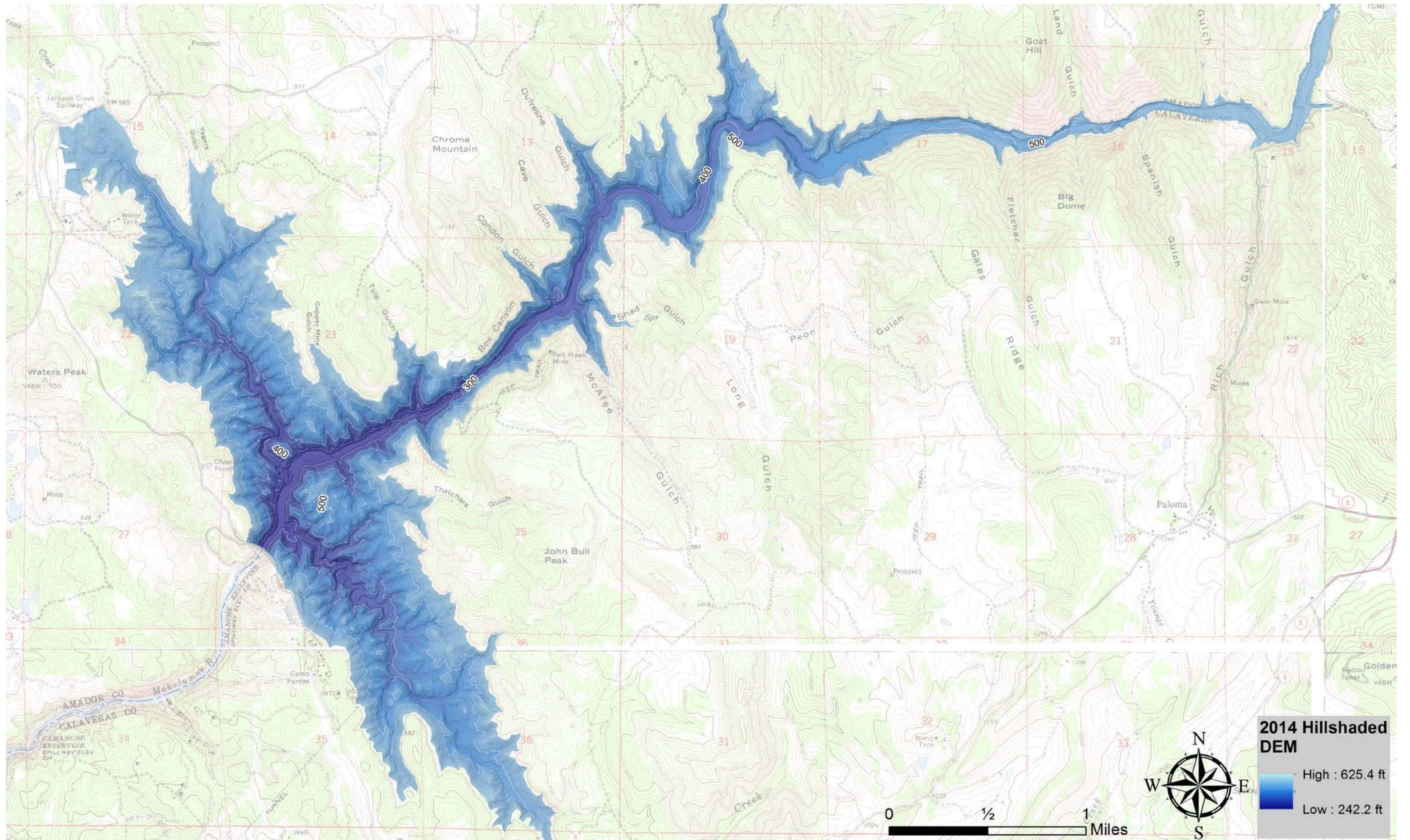


Figure 22. 2014 Pardee Reservoir bathymetry with 100 foot elevation contours with USGS topographic contour maps for additional context. Hill-shading algorithm was applied to emphasize relief. Additional data from USGS.

## ELEVATION SURFACE-VOLUME TABLE

Table 3. Example section of 2014 reservoir elevation surface and capacity table. Elevations are based on local vertical datum. Surface is in acres and volume is in acre-feet. An additional file listed in the table of delivered files contains the complete table using 0.01 foot intervals. The final table spans 260- 585' elevations.

Elevation (Local datum)	Surface area (acres)	Volume (AF)	Elevation (Local datum)	Surface area (acres)	Volume (AF)	Elevation (Local datum)	Surface area (acres)	Volume (AF)
567.70	2,263.40	203,907.84	567.42	2,245.88	203,276.32	567.14	2,231.62	202,649.58
567.69	2,262.77	203,885.19	567.41	2,245.30	203,253.85	567.13	2,231.19	202,627.27
567.68	2,262.14	203,862.56	567.40	2,244.73	203,231.40	567.12	2,230.77	202,604.96
567.67	2,261.47	203,839.93	567.39	2,244.17	203,208.96	567.11	2,230.34	202,582.66
567.66	2,260.83	203,817.31	567.38	2,243.61	203,186.52	567.10	2,229.90	202,560.35
<b>567.65</b>	2,260.13	<b>203,794.60</b>	567.37	2,243.04	203,164.08	567.09	2,229.49	202,538.06
567.64	2,259.50	203,771.99	567.36	2,242.49	203,141.65	567.08	2,229.07	202,515.77
567.63	2,258.84	203,749.39	567.35	2,241.94	203,119.23	567.07	2,228.66	202,493.48
567.62	2,258.21	203,726.79	567.34	2,241.38	203,096.81	567.06	2,228.26	202,471.20
567.61	2,257.58	203,704.21	567.33	2,240.85	203,074.40	567.05	2,227.87	202,448.92
567.60	2,256.93	203,681.62	567.32	2,240.32	203,052.00	567.04	2,227.47	202,426.64
567.59	2,256.30	203,659.05	567.31	2,239.80	203,029.60	567.03	2,227.08	202,404.37
567.58	2,255.68	203,636.49	567.30	2,239.26	203,007.20	567.02	2,226.70	202,382.11
567.57	2,255.01	203,613.92	567.29	2,238.75	202,984.82	567.01	2,226.30	202,359.84
567.56	2,254.38	203,591.37	567.28	2,238.24	202,962.43	567.00	2,225.93	202,337.59
567.55	2,253.76	203,568.83	567.27	2,237.73	202,940.05	566.99	2,225.56	202,315.33
567.54	2,253.13	203,546.29	567.26	2,237.23	202,917.68	566.98	2,225.18	202,293.08
567.53	2,252.52	203,523.76	567.25	2,236.74	202,895.31	566.97	2,224.82	202,270.83
567.52	2,251.90	203,501.23	567.24	2,236.24	202,872.95	566.96	2,224.47	202,248.59
567.51	2,251.29	203,478.71	567.23	2,235.76	202,850.59	566.95	2,224.09	202,226.34
567.50	2,250.65	203,456.19	567.22	2,235.28	202,828.24	566.94	2,223.74	202,204.11
567.49	2,250.04	203,433.69	567.21	2,234.81	202,805.89	566.93	2,223.38	202,181.87
567.48	2,249.43	203,411.19	567.20	2,234.34	202,783.55	566.92	2,223.04	202,159.64
567.47	2,248.80	203,388.69	567.19	2,233.88	202,761.21	566.91	2,222.69	202,137.42
567.46	2,248.21	203,366.20	567.18	2,233.42	202,738.87	566.90	2,222.35	202,115.19
567.45	2,247.63	203,343.72	567.17	2,232.96	202,716.54	566.89	2,222.01	202,092.97
567.44	2,247.03	203,321.24	567.16	2,232.52	202,694.22	566.88	2,221.67	202,070.75
567.43	2,246.45	203,298.78	567.15	2,232.07	202,671.90	566.87	2,221.34	202,048.54

## VOLUMETRIC CHANGE

Pardee volume at 567.65 feet (local datum) was 203,795 (+1,412 of -1,390) AF (Table 3). Using a 567.65' as a reference elevation, the reservoir lost 6,156 AF of its capacity since 1930 (Table 4). This represents an average loss of 73 ( $\pm 17$ ) AF capacity per year from 118,000 ( $\pm 27,000$ ) cubic yards of transported sediment. A graph of reservoir capacity tables showed a very gradual downward trend over time (Figure 23).

## GEOSPATIAL DISTRIBUTION OF SCOUR AND DEPOSITION

Results of raster subtraction are shown delineating the apparent distribution of scour and deposition (Figure 24) assuming a  $\pm 3$  feet error. Total apparent change was estimated at 4,094,640 cubic yards of sediment deposition and 12,877,626 cubic yards of scour (Table 5) since 1995. Scour and deposition were not calculated between the years of 1929 and 2014 because no DEM existed for the original survey, but sediment deposition displaced an estimated 6,156 AF of reservoir volume since 1929. The difference between the unnatural geomorphology seen in the central part of the reservoir in the 1995 DEM and the same area in the 2014 DEM, resulted in apparent large-scale scouring and an apparent 5,846 AF *increase* in volume. This result confirmed our suspicion that the earlier bathymetry was not accurate, at least in deeper parts of the reservoir. For example, in deeper water the apparent "scour" of over 30 feet of sediment in the center of the reservoir (Figure 24) and in other places is unlikely and indicates that the sediment never existed in the first place.

**Table 4. Volume by year and using the local datum. Pardee lost 2.93% of its capacity between 1929 and 2014. Reference elevation for comparison was spillway elevation.**

Survey	Elevation 567.65 (Local Datum)	Notes
1930	209,950	Interpolated from 193 table
1976	209,946	EBMUD updated table
1995	197,950	1995 has suspect data
<b>2014</b>	<b>203,795</b>	<b>CSUMB final table. Error is <math>\pm 0.69\%</math> (at spillway)</b>

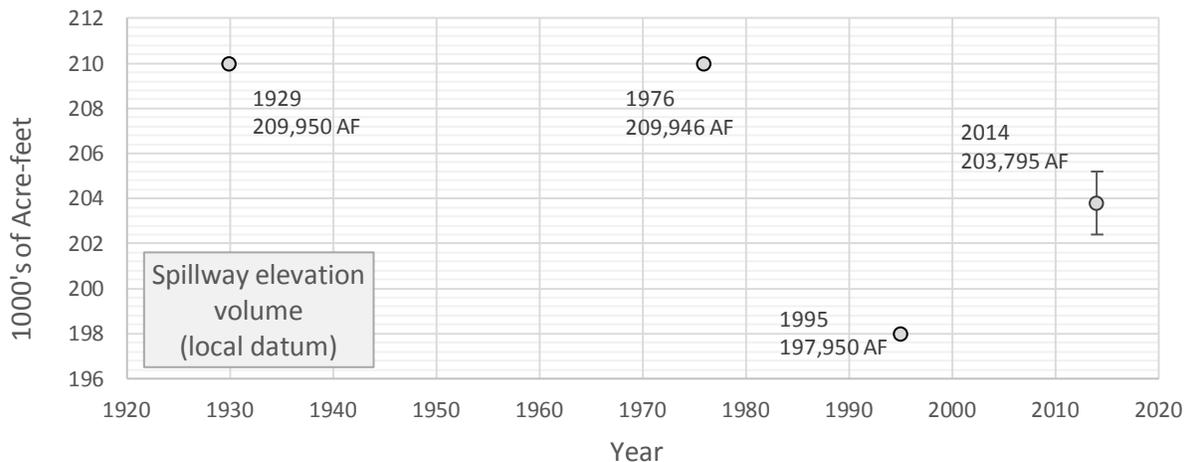


Figure 23. Volume graph showing decline since 1930. Currently there is not enough data to fit a sedimentation rate model, but an average rate of sedimentation may be adequate for planning purposes.

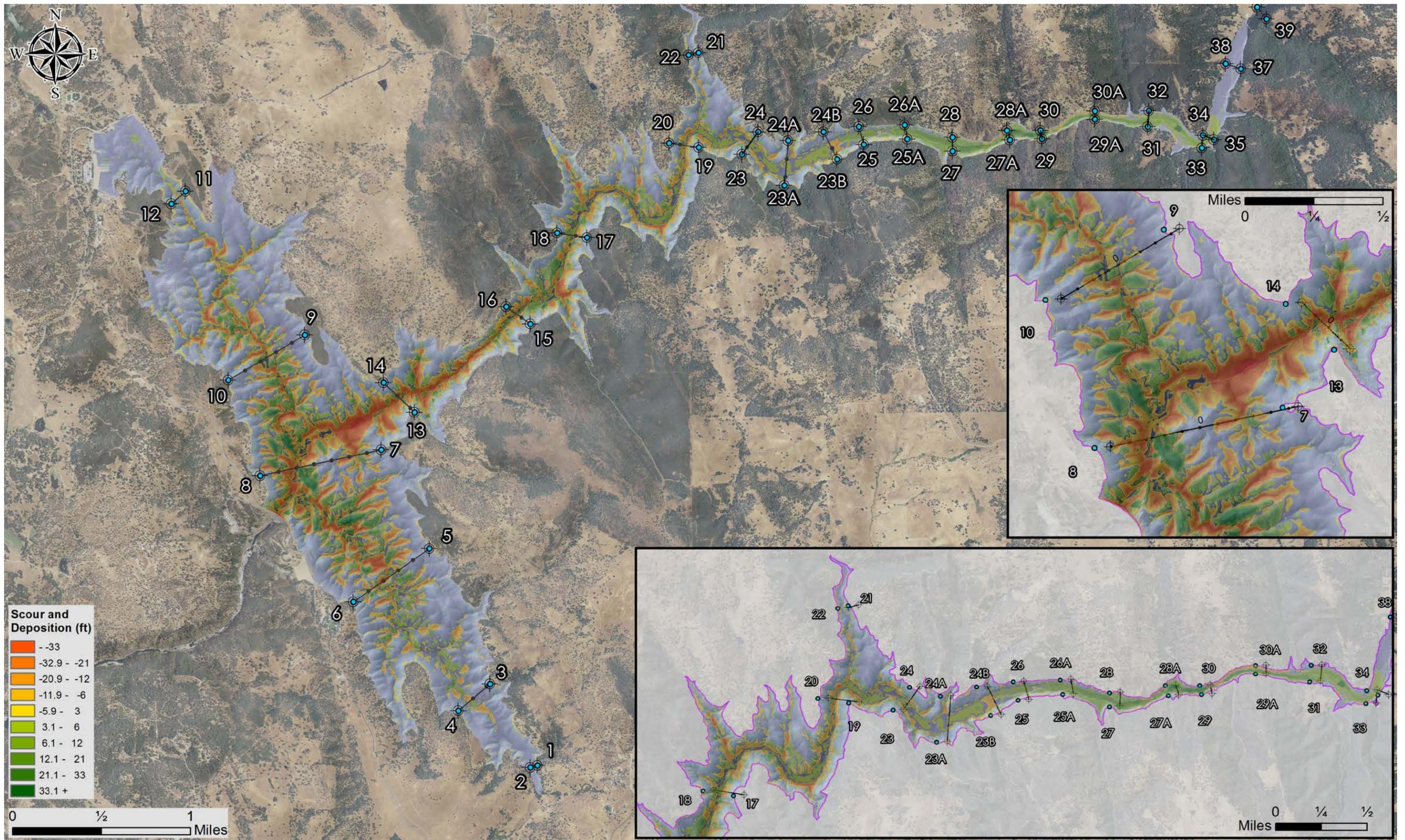


Figure 24. Apparent sediment scour and deposition map. Dark red indicates areas where apparent sediment scour has occurred and green areas show where apparent sediment deposition has occurred since 1995. Upper-right inset map shows zoomed in view of main body of reservoir; lower inset shows eastern arm of reservoir.

**Table 5. Apparent scour and deposition of sediment in cubic yards and loss of volume in acre-feet (AF) since 1995. Because of variable accuracy of 1995 bathymetry, these numbers should be viewed skeptically. Apparent scour and apparent deposition totals assume  $\pm 3$  feet error and were calculated using the local vertical elevation datum.**

Source data	Apparent scour since 1995 (cubic yards) (with $\pm 3$ error)	Apparent deposition since 1995 (cubic-yards) (with $\pm 3$ error)
1995 and 2014 DEMs	12,877,626	4,094,640

### VISUAL AND QUANTITATIVE ANALYSIS OF HISTORICAL SEDIMENT PROFILES

The results of the visual sediment profile comparison of 1929, 1938, 1977, 1995 and 2014 using Excel are extensive and are available in an ancillary Excel file listed in the Appendix (Table 7). Sediment profile quantitative analysis results for 1929, 1995 and 2014 sediment profiles showed that sedimentation had happened across all but three of the transects since 1929 (Figure 25). Two of the three transects (X34-X33, X34-X35) that showed evidence of scour were located at a sharp, narrow bend in the upper eastern arm of the reservoir where flow velocity would be relatively high. The 1995 data generally matched the overall trend, but in some cases overestimated or underestimated the degree of change when compared to the overall trend between 1929 and 2014. The largest reduction of profile area from 1929 to the present survey was 45.63%, and six of the profiles in the upper arm had profile reductions of over 20% (Table 6). As with other parts of this study, neither the 1929 nor 1995 silt profile data had an estimated error so this analysis did not include best or worst estimates of profile area loss/gain.

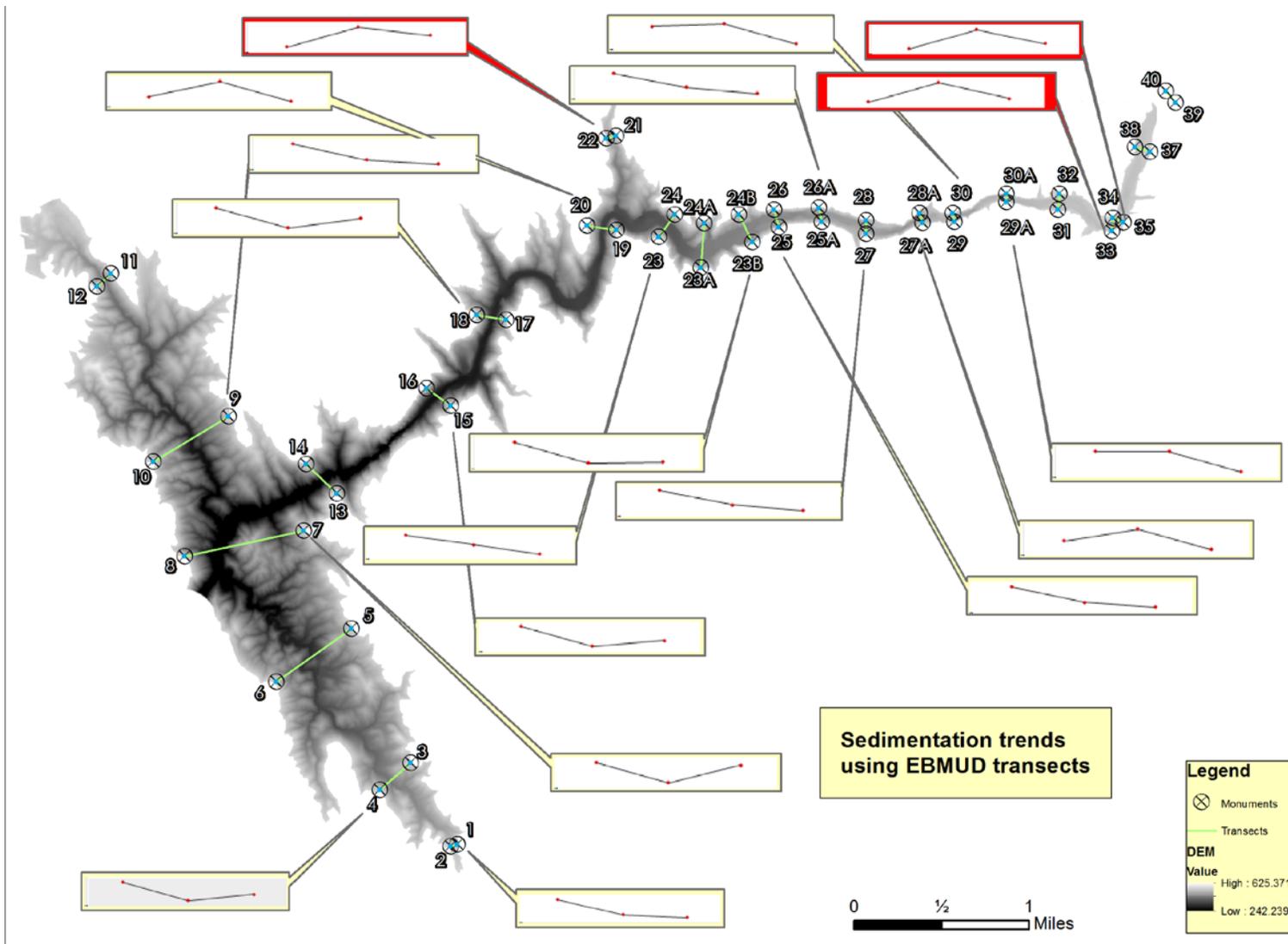


Figure 25. Silt-survey profile area trends along survey transects using 1929, 1995 and 2014 data. When sedimentation increased the reservoir floor elevation below a transect, the area of the cross-section was reduced which was represented by a downward trend on the graph. The overall trend from 1929 to 2014 showed a reduction in profile area in all but three transects which were depicted with red background.

Table 6. Silt profile area 2D analysis. A 570 or 565 foot datum based on the Pardee local datum was used to calculate the 2D area between the water surface datum and survey elevations at points along the transect. A positive percentage indicates scouring (increase in volume) and a negative percentage indicates deposition (loss of volume). As profile area decreases, the line trends downward indicating volume loss.

Transect ID	Horizontal reference plane	Silt profile area (ft <sup>2</sup> )			Change (%)			Trend
		1929	1995	2014	1929- 1995	1995-2014	1929-2014	
X2-X1	565'	2,956	2,471	2,361	-16.41%	-4.45%	<b>-20.13%</b>	
X4-X3	565'	58,700	57,865	58,167	-1.42%	0.52%	<b>-0.91%</b>	
X8-X7	570'	510,925	478,590	506,169	-6.33%	5.76%	<b>-0.93%</b>	
X10-X9	570'	250,167	247,614	246,807	-1.02%	-0.33%	<b>-1.34%</b>	
X16-X15	565'	111,281	105,648	107,389	-5.06%	1.65%	<b>-3.50%</b>	
X18-X17	565'	101,731	96,360	98,913	-5.28%	2.65%	<b>-2.77%</b>	
X20-X19	565'	72,600	74,449	72,001	2.55%	-3.29%	<b>-0.83%</b>	
X22-X21	565'	7,162	8,101	7,717	13.11%	-4.74%	<b>7.75%</b>	
X24-X23	565'	71,700	68,083	64,429	-5.04%	-5.37%	<b>-10.14%</b>	
X24B-X23B	565'	74,744	57,270	58,646	-23.38%	2.40%	<b>-21.54%</b>	
X26-X25	565'	40,744	33,894	31,496	-16.81%	-7.07%	<b>-22.70%</b>	
X26A-X25A	565'	29,028	23,706	20,995	-18.33%	-11.44%	<b>-27.67%</b>	
X28-X27	565'	24,612	20,180	18,211	-18.01%	-9.76%	<b>-26.01%</b>	
X28A-X27A	565'	10,256	11,362	9,441	10.78%	-16.91%	<b>-7.95%</b>	
X30-X29	565'	9,450	10,130	5,138	7.20%	-49.28%	<b>-45.63%</b>	
X30A-X29A	565'	6,656	6,622	4,837	-0.51%	-26.96%	<b>-27.33%</b>	
X34-X33	565'	4,631	6,154	4,944	32.89%	-19.66%	<b>6.76%</b>	
X34-X35	565'	4,125	5,740	4,592	39.15%	-20.00%	<b>11.32%</b>	

## DISCUSSION

### VOLUMETRIC CHANGE

The results of this study show that reservoir capacity at spillway elevation (567.65 feet local datum) is 203,795 AF, +1,412 or -1,390 AF using a 95% confidence interval. The volume loss result is equivalent to a sediment deposition rate of 118,000 ( $\pm 27,000$ ) cubic yards per year since 1930. Our greatest *in situ* vertical error sample for either sonar or LiDAR was 0.36 feet, which was a little over half the 0.623 feet used for the 95%CI calculation. The comparison to previous capacity tables showed a loss of 6,156 AF or 2.93% capacity since 1930 (Table 4) at a 567.65 foot elevation. The 2.93% capacity loss since 1929 is significantly less than the nearly 6% loss indicated by the 1995 survey. While much of this difference between the change from 1929 to 1995 and the change from 1929 to 2014 is attributable to improvements in sonar technology since 1995, less is known about the accuracy of the original volume calculations of the 1929 survey and no error estimation was found for that study. Accuracy of the 1929 topography is unknown because before photogrammetry was widely adopted by the USGS in the 1940's, contour lines were hand-drawn in the office by surveyors and error was a function of how many known points were established (USGS *Date unknown*, J. Hurlburt, personal communication, December 1, 2014 and January 27, 2015). It is possible that if the original survey were redone that it would result in either a smaller or larger estimated initial volume. If this were the case, then the rate of sedimentation could be significantly different than the 118,000 cubic yards per year calculated in this study.

### GEOSPATIAL DISTRIBUTION OF SCOUR AND DEPOSITION

The results of 1995-2014 sediment scour and deposition analysis identified areas where these *apparent* changes occurred (Figure 24). The study calculated more scour (12,877,626 cubic yards) than deposition (4,094,640 cubic yards) (Table 5). These results were implausible since reservoirs are receiving bodies for sediment and typically will not show an increase in volume unless dredged. Consequently, when analyzing change overall and change in specific geospatial extents of sediment and scour since 1995, caution must be used when drawing conclusions from these results. The  $\pm 1.5$  foot error specification of the 1977 photogrammetry analysis (EBMUD, *Date unknown*) and the higher density of 1977 data in shallow-water areas (Figure 26), may have led to a more precise interpolation, and therefore a more accurate DEM surface in shallow water. One implication of this accuracy and data density difference between 1977 and 1995 data is that change that was detected in shallower areas may be real and quantifiable with a higher degree of confidence; however testing this may have limited value.

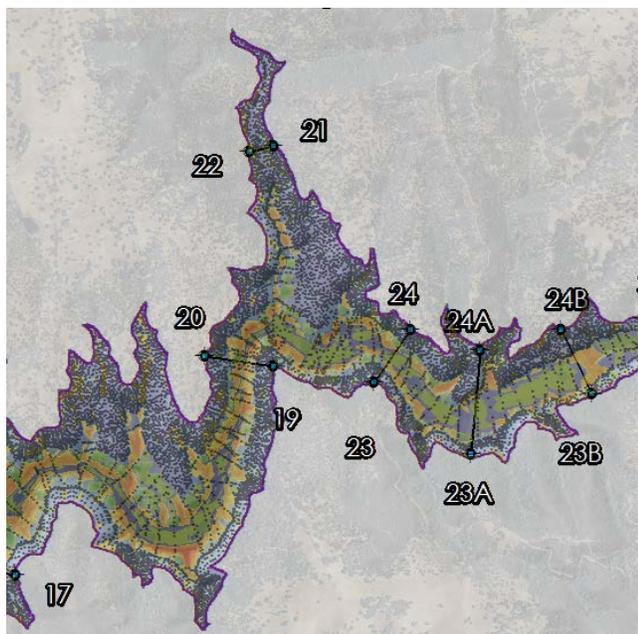


Figure 26. Zoomed view of section of eastern arm of Pardee. Image shows apparent scour (red) and apparent deposition (green) with historical silt-profile transects and point data used to make 1995 DEM. Note the density of shallow water data (grey dots). When compared to hydrographic data density of the main body of Pardee, the relatively high amount of sonar points (linear sets of dots that cross channel) in the channel area could have resulted in a more accurate data for that section of the 1995 DEM.

## VISUAL AND QUANTITATIVE TREND ANALYSIS OF HISTORICAL SILT PROFILES

The results of the quantitative silt-profile analysis show that, since 1929, the maximum loss of profile area from sedimentation was 46% and the maximum increase in area due to scour was 11% at the surveyed profiles. By quantitatively comparing the original 1929 profile elevations to 1995 and 2014 data, we were able to determine that all but three of the 18 transects that were examined showed deposition trends. Even when using the relatively imprecise initial profile survey data from 1929 and some questions about 1995 accuracy, the silt profile analysis showed a general trend of sedimentation that, in some cases, indicate dramatic volume loss in smaller profile areas over time. Reduced profile areas were seen in almost all transects, but were biggest, in terms of percentage loss, in the narrower parts of the reservoir in the eastern arm. Noting that six transects in the reservoir's eastern arm showed higher rates of profile reduction, we can infer that, over the long term, this part of the reservoir will fill in first.

## SUMMARY

The loss of capacity was expected and confirms that Pardee Reservoir is filling up with sediment over time. Except in the upper arm where some scour occurred, deposition has been fairly intense over most of the eastern arm extent and may have been exacerbated by a forest fire in 1995. While the sedimentation rate since 1929 may be manageable in the short and medium-term, higher fire risk predicted by climate change may lead to more fires, higher intensity fires, or both, exacerbating watershed erosion issues (Jeton et al. 1996; Vicuna et al. 2007). In addition to changing fire regimes, by the end of the century, climate models predict changing timing in flows in the Sierras (e.g. from the upper Mokelumne watershed) along with higher snow-lines and the more variable and more intense precipitation in the form of rain, all of which will have some effect on erosion in the upland Mokelumne watershed. Moving forward with the 2014 DEM as a baseline, future surveys will be able to more accurately quantify the rates and distribution of sediment scour and deposition. Because the error in the 2014 DEM is small, finer scale changes will be detectable in future high-resolution surveys.

## NEXT STEPS

Because older survey techniques may have underestimated the original 1929 volume, more capacity may have been lost than is indicated by this study. To address this issue, a retrospective survey could be done using the original survey contour maps of Pardee Reservoir. Investigation into older methods of volume calculation could shed light on if or how error was calculated allowing for a more comprehensive determination of best and worst-case estimates of sedimentation rates. Beyond that, future projects should be considered that do basin-scale modeling of erosion and sediment transport. A more in-depth modeling study of sediment transport would require field-collected sediment data and a properly designed, long-term study. Both erosion and sediment modeling could help forecast the impacts of climate change and fire scenarios. Because the problems related to sedimentation unfold over long time periods, EBMUD might also consider the installation of a suspended sediment monitor in the reservoir inlet in its long-term planning.



## REFERENCES

- CARIS. 2014. CARIS HIPS and SIPS Professional.
- DeCosta JD. 1960. Index Map Pardee Reservoir Topography [dh-4592-40-1].
- Dettinger MD, Cayan DR, Meyer MK, Jeton AE. 2004. Simulated Hydrologic Responses To Climate Variations And Change In The Merced, Carson, And American River Basins, Sierra Nevada, California, 1900-2099. *Clim Change*.:283–317.
- EBMUD. 1977 and 1995 Surveys.doc. :1.
- EBMUD. 1930. Capacity Table for Pardee Reservoir. :1–43.
- EBMUD. 1976. Pardee Reservoir Area Capacity Table.
- EBMUD. 1978. Fieldbook FB-3469.
- EBMUD. 1995. GIS “GPS2.asc” Layer.
- EBMUD. 2005. Pardee Reservoir Elevation Capacity Table. :1–5.
- EBMUD. 2006. Fieldbook FB-4375. :9.
- EBMUD. 2014. Pardee Reservoir Near Valley Springs, CA Station Description. Oakland, CA.
- ESRI. 2012. ArcMAP 10.1 [Internet]. Available from: <http://www.esri.com/>
- FGDC. 2014. Geospatial Metadata Standards — Federal Geographic Data Committee [Internet]. [cited 2015 Jan 5]. Available from: <http://www.fgdc.gov/metadata/geospatial-metadata-standards#csdgm>
- Hall S. 1937. Pardee Reservoir: Data on Elevations at Spillways and Outlets. Also, Water Surface Area and Capacity. :5.
- Jeton BAE, Dettinger MD, Smith JL. 1996. Potential Effects of Climate Change on Streamflow, Eastern and Western Slopes of the Sierra Nevada, California and Nevada. US Geol Surv Water-Resources Investig Rep.
- Kennedy RC. 1951. Index Map Pardee Reservoir Topography [dh4503-431].

Kvitek R. 2011. Mobile Laser Scanner Processing Guide for CSMP data (UTM NAD83 NAVD88) Using POSPAC, RiWorld, UltraEdit, Corpscon, DMagic, & Fledermaus Area Based Cleaning to create final XYZ topographic data. :1–43.

Kvitek RG, Iampietro PJ. 2010. California's seafloor mapping project. In: Breman J, editor. Ocean Globe. Redlands, CA: ESRI Press Academic; p. 75–85.

Longwell JS. 1944. Pardee Reservoir Topography Key Map Showing Location Sheets [0320r-1.pdf].

McPherson KR, Freeman LA, Flint LE. 2009. Analysis of Methods to Determine Storage Capacity of, and Sedimentation in, Loch Lomond Reservoir, Santa Cruz County, California, 2009. [place unknown].

Miller NL, Bashford KE, Strem E. 2004. Potential Impacts Of Climate Change On California Hydrology. 95821:771–784.

Peizhen Z, Molnar P, Downs WR. 2001. Increased sedimentation rates and grain sizes 2 ± 4 Myr ago due to the influence of climate change on erosion rates. *Nature*. 410:891–897.

Quality Positioning Services BV (QPS). 2014a. DMagic [Internet]. Available from: <http://www.qps.nl>

Quality Positioning Services BV (QPS). 2014b. Fledermaus [Internet]. Available from: <http://www.qps.nl>

RESON. 2010. SeaBat 7125 SV2 High-Resolution Multibeam Sonar System OPERATOR'S MANUAL. :1–192.

Riegl. 2011. RiWORLD [Internet]. Available from: [www.riegl.com](http://www.riegl.com)

Riegle. 2010. Long Range & High Accuracy 3D Terrestrial Laser Scanner: LMS-Z420i Data Sheet [Internet]. :4. Available from: [http://www.riegl.com/uploads/tx\\_pxpriegldownloads/10\\_DataSheet\\_Z420i\\_03-05-2010.pdf](http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_Z420i_03-05-2010.pdf)

RMC Water and Environment. 2007. Upper Mokelumne River Watershed Assessment and Planning Project. Valley Springs, CA.

SEA. 2009. SWATHplus Getting Started. :1–106.

Stine S. 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature*. 369:546–547.

USACE. 2004. Corpscon [Internet]. Available from: <http://www.agc.army.mil/Media/FactSheets/FactSheetArticleView/tabid/11913/Article/480938/corpscon.aspx>

USGS. A 125 Year History of Topographic Mapping and GIS in the U.S. Geological Survey 1884-2009, Part 1 1884-1980 [Internet]. [cited 2014 Feb 10]. Available from: <http://nationalmap.gov/ustopo/125history.html>

USGS. 2005. State geologic maps [Internet]. Available from: [http://pubs.usgs.gov/of/2005/1305/data/CAgeol\\_dd.zip](http://pubs.usgs.gov/of/2005/1305/data/CAgeol_dd.zip)

Vicuna S, Maurer EP, Joyce B, Dracup J a., Purkey D. 2007. The Sensitivity of California Water Resources to Climate Change Scenarios. *J Am Water Resour Assoc* [Internet]. 43:482–498. Available from: <http://doi.wiley.com/10.1111/j.1752-1688.2007.00038.x>

Wilson DA. 1977. Pardee Reservoir Water Surface Datum. EBMUD Arch.:1.

## APPENDIX

### TABLE OF DELIVERED FILES

Additional files were delivered as part of the project including cleaned source data that were used to generate the DTM.

**Table 7. Table of files delivered as part of project.**

Filename	File Type	Contents	Units	Notes
2014_Pardee_Reservoir_Survey_and_Sedimentation_analysis.pdf	Acrobat	Hydrographic and topographic survey		Final report
2014_Pardee_Reservoir_Stage-SurfaceVolume.xlsx	Excel	2d surface (ft <sup>2</sup> ), volume (acre-feet)	ft <sup>2</sup> and acre-feet	Includes tabs for elevation surface and volume curves
XYZ_Combined_SonarC3_LiDARF2C1_CC5_Accepted.csv	csv	XYZ table in ASCII format	meters	Combined sonar and LiDAR data that has been cleaned. This was the data used to generate the DTM. NAD83, NAVD88 datums. UTM10N
EBMUD_Pardee_Historical_SiltSurvey_Data.xlsx	Excel	Profile analysis from 1929 to 2014	feet and ft <sup>2</sup>	Vertical is assumed to be local datum. XZ data was the source data for quantitative profile analysis in GIS
2014Pardee_BathymetricSurvey.mpk	Map package	ArcGIS DEM data and associated layers	meters and feet	Various coordinate systems and vertical datums. Final EBMUD data in California State Plane 3, NAD83.
Pardee Reservoir Spillway Research.pdf	Acrobat	Analysis and attachments of EBMUD source documents		Report explains how the vertical datum was decided for the spillway
Pardee_VolumeLoss_Trends_567.65Elevation.xlsx	Excel	tables and graphs	AF	Graph and tables of showing volumes from 1929, 1976, 1995 and 2014 tables using an arbitrary 570' elevation (local datum) as well as 567.65' spillway elevation

## TABLE OF GIS DATA AND LAYERS

**Table 8. List of GIS map package contents. Layer ID 10 represents the final DEM on which volumes were calculated.**

LyrID	Layer name (in order found in MPK). Dataframe 1.			Resolution	Datum (Horizontal/Vertical)		Units	Notes
	Type	Purpose	Datum					
1	Pardee_Silt_Survey_Monuments_NAD83_CSP3Anno	polygon	labeling	NA	NAD83 CSP3 FIPS0403/ local datum	NA	Anno used for flexible geolocated labeling	
2	Pardee_Silt_Survey_Monuments_NAD83_CSP3	point	analysis	NA	NAD83 CSP3 FIPS0403/ local datum	feet	Data from EBMUD FB for monuments was in NAD 1927 so file was reprojected	
3	Pardee_Silt_Survey_Transects	line	analysis	NA	NAD83 CSP3 FIPS0403/ local datum	feet	Used to extract 2D XZ profile data from 1995 and 2014 DEMs for comparison to 1929	
4	2014_pardee_100ft_contours	line	visualization	NA	NAD83 CSP3 FIPS0403/ local datum	feet	FGDC metadata included	
5	2014_pardee_20ft_contours	line	visualization	NA	NAD83 CSP3 FIPS0403/ local datum	feet	FGDC metadata included	
6	2014_pardee_10ft_contours	line	visualization	NA	NAD83 CSP3 FIPS0403/ local datum	feet	FGDC metadata included	
7	2014_DEM_INT_Subtract_1995_RS_DEM_INT.tif	raster	analysis	2 feet	NAD83 CSP3 FIPS0403/ local datum	feet	Analysis of scour and deposition by looking at difference between two DEMs	
8	2014_Pardee_SLOPE.tif	raster	visualization		NAD83 CSP3 FIPS0403/ local datum	feet	Calculation of each cell's slope	
9	2014_Pardee_Hillshade315A_45E.tif	raster	visualization		NAD83 CSP3 FIPS0403/ local datum	feet	Hillshade created with sun angle at 45 degrees and azimuth at 315 degrees.	
<b>10</b>	<b>2014_PardeeReservoir_DEM</b>	<b>raster</b>	<b>DEM</b>	<b>2 feet</b>	NAD83 CSP3 FIPS0403/ local datum	<b>feet</b>	<b>Final DEM which includes data from layer 15 and 16. FGDC metadata included</b>	
11	2014_PardeeReservoir_DEM_NGVD1929	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ NGVD 1929	feet	Adjusted from final local datum DEM (layer 10) by -0.415 ft	
11a	2014_PardeeReservoir_DEM_NAVD1988.tif	raster	DEM	2 ft	NAD83 CSP3 FIPS0403/ NAVD 1988	feet	Adjusted from final local datum DEM (layer 10) by +2.011 ft	
12	2014_Pardee_DEM_2ft_NAD83_CSP3_LocalVDatum.tif	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ local datum	feet	DEM based on layer 13, NAVD88 elevation in feet converted to local vertical datum. FGDC metadata	
13	2014_Pardee_DEM_2ft_NAD83_CSP3_NAVD88_ft.tif	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ NAVD88	feet	DEM based on layer 14, vertical units converted to feet. FGDC metadata	
14	2014_Pardee_DEM_2ft_NAD83_CSP3_NAVD88_m.tif	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ NAVD88	feet/ meters	Reprojected DEM from layer 19 into EBMUD official horizontal datum. Vertical/horizontal units differ. FGDC metadata	
15	2014_Pardee_DEM_2ft_NAD83_CSP3_LocalVDatum_ft_CONFS_SM10x10.tif	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ local datum	feet	Based on layer 12. Small data gaps filled with conditional interpolation. FGDC metadata included	
16	pard_bath_RS2x2.tif	raster	DEM	2 feet	NAD83 CSP3 FIPS0403/ Unkown vertical datum	feet	Resolution increased via resampling; created using layer 17	
17	pard_bath	ASC	DEM	10 feet	NAD83 CSP3 FIPS0403/ Unkown vertical datum	feet	Vertical datum assumed to be local. EBMUD official DEM from 1995	
18	USGS Topo (various)	raster	visualization	24k	NAD83	meters	USGS topographic raster data	
19	2014_Pardee_DEM_0.5m_NAD83UTM10_NAVD88.tif	raster	DEM	0.5 meter	NAD83UTM10N/NAVD88	meters	DEM1 output from Fledermaus. This is the initial DEM. FGDC metadata	
LyrID	Layer name (in order found in MPK). Dataframe 2			Resolution	Datum (Horizontal/Vertical)		Units	Notes
	Type	Purpose	Datum					
1-170	Silt survey profiles	polylines and points	sediment profile analysis	NA	XZ data not on a datum	feet	<u>Remove GCS from dataframe to use.</u> All surveys where data from 1929, 1995 and 2014 were present	

## EXAMPLE OF SVP DATA FOR A SINGLE WATER COLUMN SAMPLE

Example of profile output (Figure 27) demonstrates that as the water gets colder, sound moves slower.

Date	Time	Depth (m)	SV (m/s)	Temperat	Battery (V)
9/21/2014	56:37.4	0.13	1494.568	23.878	12.23
9/21/2014	56:37.3	0.29	1494.446	23.866	12.25
9/21/2014	56:37.1	0.45	1494.477	23.848	12.23
9/21/2014	56:36.9	0.61	1494.529	23.828	12.25
9/21/2014	56:36.6	0.74	1494.543	23.802	12.23
9/21/2014	56:36.4	0.99	1494.515	23.792	12.25
9/21/2014	56:36.2	1.21	1494.477	23.761	12.23
9/21/2014	56:36.0	1.37	1494.517	23.742	12.25
9/21/2014	56:35.8	1.53	1494.473	23.722	12.23
9/21/2014	56:35.7	1.59	1494.432	23.699	12.25
9/21/2014	56:35.8	1.72	1494.433	23.716	12.23
9/21/2014	56:35.5	1.95	1494.305	23.665	12.23
9/21/2014	56:35.3	2.11	1494.169	23.619	12.25
9/21/2014	56:35.1	2.27	1494.139	23.577	12.2
9/21/2014	56:34.9	2.43	1494.13	23.553	12.23
9/21/2014	56:34.8	2.5	1494.253	23.53	12.25
9/21/2014	56:34.9	2.63	1494.069	23.545	12.25
9/21/2014	56:34.7	2.69	1494.007	23.507	12.2
9/21/2014	56:34.4	2.84	1494.205	23.449	12.25
9/21/2014	56:34.3	2.91	1494.237	23.43	12.23
9/21/2014	56:34.2	3.07	1494.22	23.4	12.23
9/21/2014	56:34.4	3.1	1494.178	23.44	12.25
9/21/2014	56:33.9	3.32	1494.044	23.296	12.23
9/21/2014	56:33.8	3.42	1494.03	23.251	12.2
9/21/2014	56:33.8	3.61	1494.082	23.266	12.23
9/21/2014	56:33.6	3.68	1493.972	23.188	12.25
9/21/2014	56:33.3	3.84	1493.594	23.042	12.25

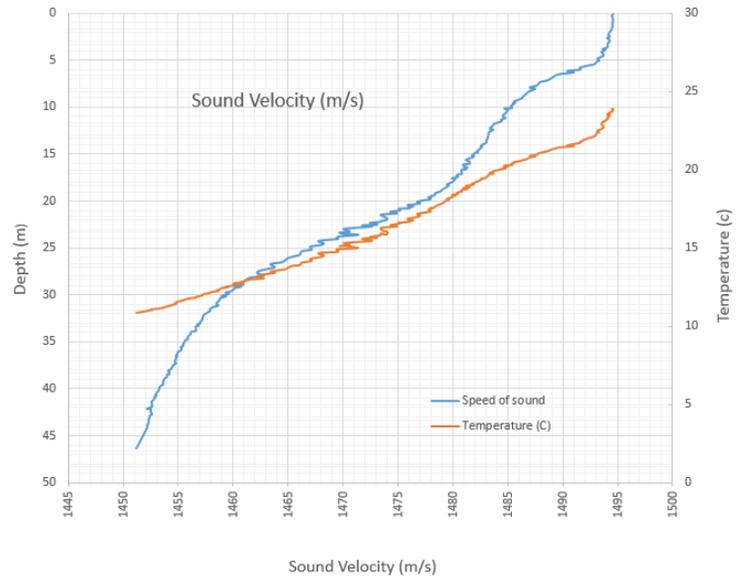


Figure 27. SVP sample profile.

## ARCGIS 10.1 MODEL BUILDER DIAGRAM FOR STAGE-VOLUME CALCULATIONS

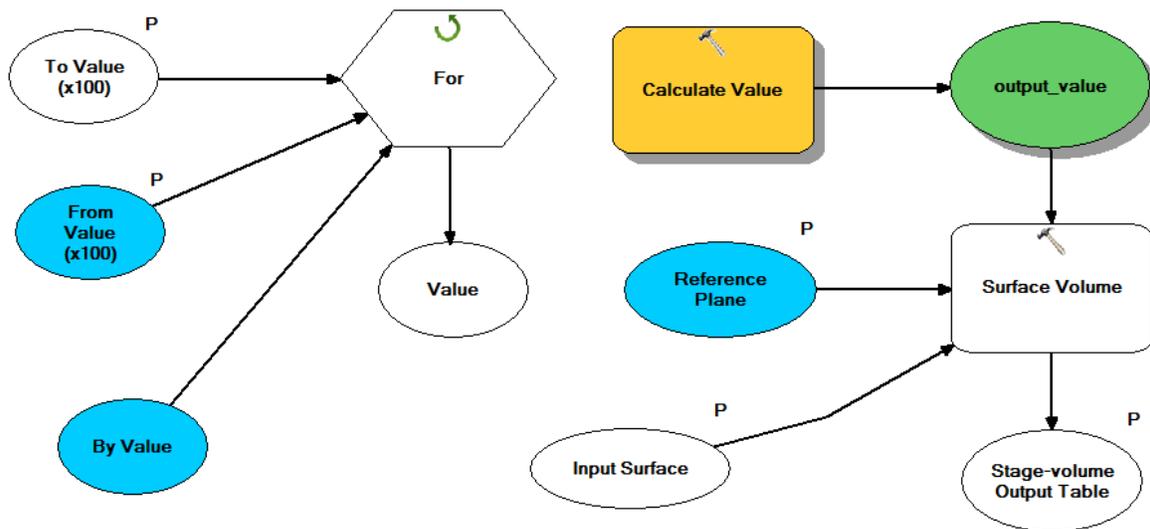


Figure 28. ArcGIS ModelBuilder layout view of 3D Analyst surface volume model.

GPS SURVEY MB7 BENCHMARK, OPUS GPS SOLUTION



Figure 29. Looking NW at GPS antenna in place on top of east dam wall near MB7 and south of the gate house.



Figure 30. Looking SE at GPS antenna in place on top of east dam wall near MB7 and south of the gate house.



Figure 31. Benchmark MB7 aka D2. Interestingly, it has the same elevation spray painted next to it (576.09) that we obtained based on the OPUS solution for the east dam wall occupation shown below minus the 5.554 feet elevation of the wall above the benchmark measured via laser level.

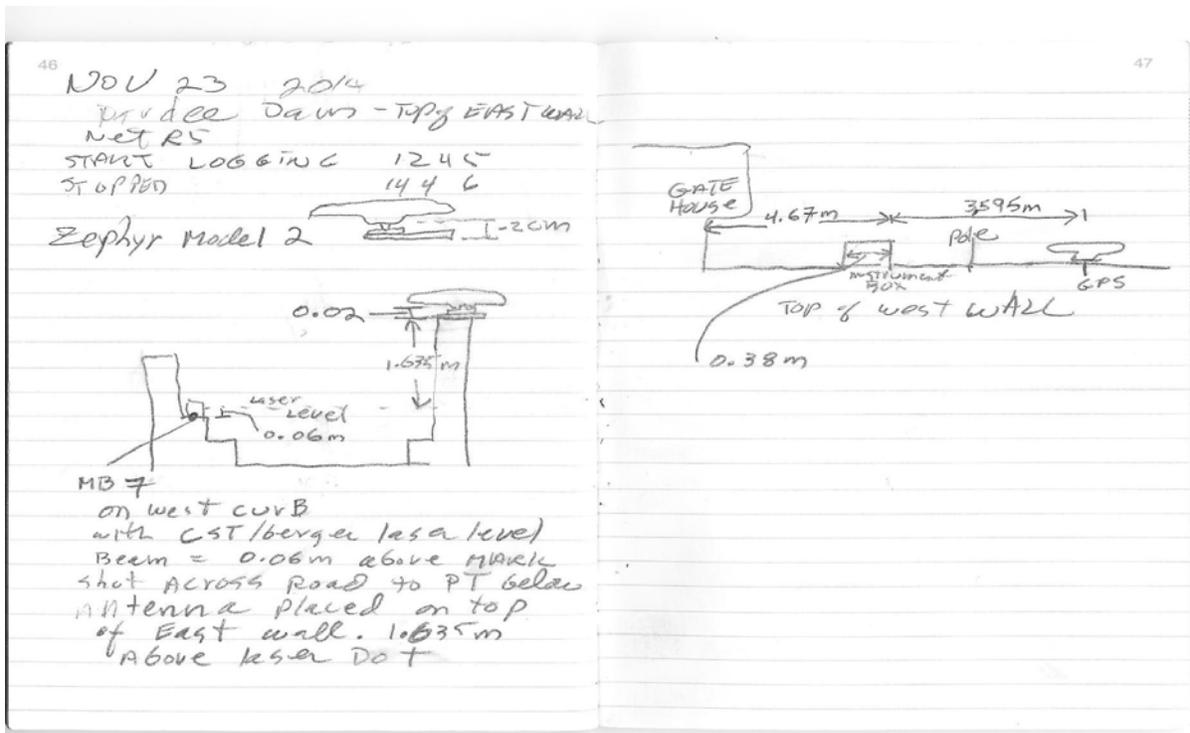


Figure 32. Rikk Kvitek's field notes from the second MB7 vertical control survey.

MB7 Survey OPUS solution Antenna placed on top of East dam wall 8m south of the gate house.

FILE: 4819K55871201411232043.14o OP1416850540841

2005 NOTE: The IGS precise and IGS rapid orbits were not available  
 2005 at processing time. The IGS ultra-rapid orbit was/will be used to  
 2005 process the data.  
 2005

NGS OPUS SOLUTION REPORT  
 =====

All computed coordinate accuracies are listed as peak-to-peak values.  
 For additional information: <http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy>

USER: rkvitek@csumb.edu DATE: November 24, 2014  
 RINEX FILE: 4819327u.14o TIME: 17:36:27 UTC  
 SOFTWARE: page5 1209.04 master91.pl 022814 START: 2014/11/23 20:43:00  
 EPHEMERIS: igu18200.eph [ultra-rapid] STOP: 2014/11/23 22:46:00  
 NAV FILE: brdc3270.14n OBS USED: 4293  
 / 4590 : 94%  
 ANT NAME: TRM55971.00 NONE # FIXED AMB: 31  
 / 33 : 94%  
 ARP HEIGHT: 0.02 OVERALL RMS: 0.010(m)  
 REF FRAME: NAD\_83(2011)(EPOCH:2010.0000) IGS08 (EPOCH:2014.8956)

X:	-2571608.424(m)	0.022(m)	-2571609.305(m)	0.022(m)
Y:	-4305369.120(m)	0.021(m)	-4305367.806(m)	0.021(m)
Z:	3927997.890(m)	0.024(m)	3927997.856(m)	0.024(m)
LAT:	38 15 26.11763	0.003(m)	38 15 26.13035	0.003(m)
E LON:	239 9 0.05635	0.013(m)	239 8 59.99753	0.013(m)
W LON:	120 50 59.94365	0.013(m)	120 51 0.00247	0.013(m)
EL HGT:	148.268(m)	0.036(m)	147.716(m)	0.036(m)
ORTHO HGT:	178.020(m)	0.064(m)	[NAVD88 (Computed using GEOID12A)]	

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 10)	SPC (0403 CA 3)
Northing (Y) [meters]	4236544.625	695083.674
Easting (X) [meters]	688114.707	1969368.756
Convergence [degrees]	1.33166566	-0.21427163
Point Scale	1.00003583	0.99996813
Combined Factor	1.00001257	0.99994487

US NATIONAL GRID DESIGNATOR: 10SFH8811436544(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
DN7366	P306 WILDCATCRKCN2006 CORS ARP	N374742.588	W1203839.998	54373.8
DH8725	SACR SACRAMENTO COOP CORS ARP	N383917.971	W1212115.193	62341.5
DN7372	P310 ALDERRIDGECN2006 CORS ARP	N384408.171	W1202003.561	69622.4

NEAREST NGS PUBLISHED CONTROL POINT

JS4023	CAMP PARDEE WATER TANK	N381448.123	W1205035.305	1318.4
--------	------------------------	-------------	--------------	--------

This position and the above vector components were computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.

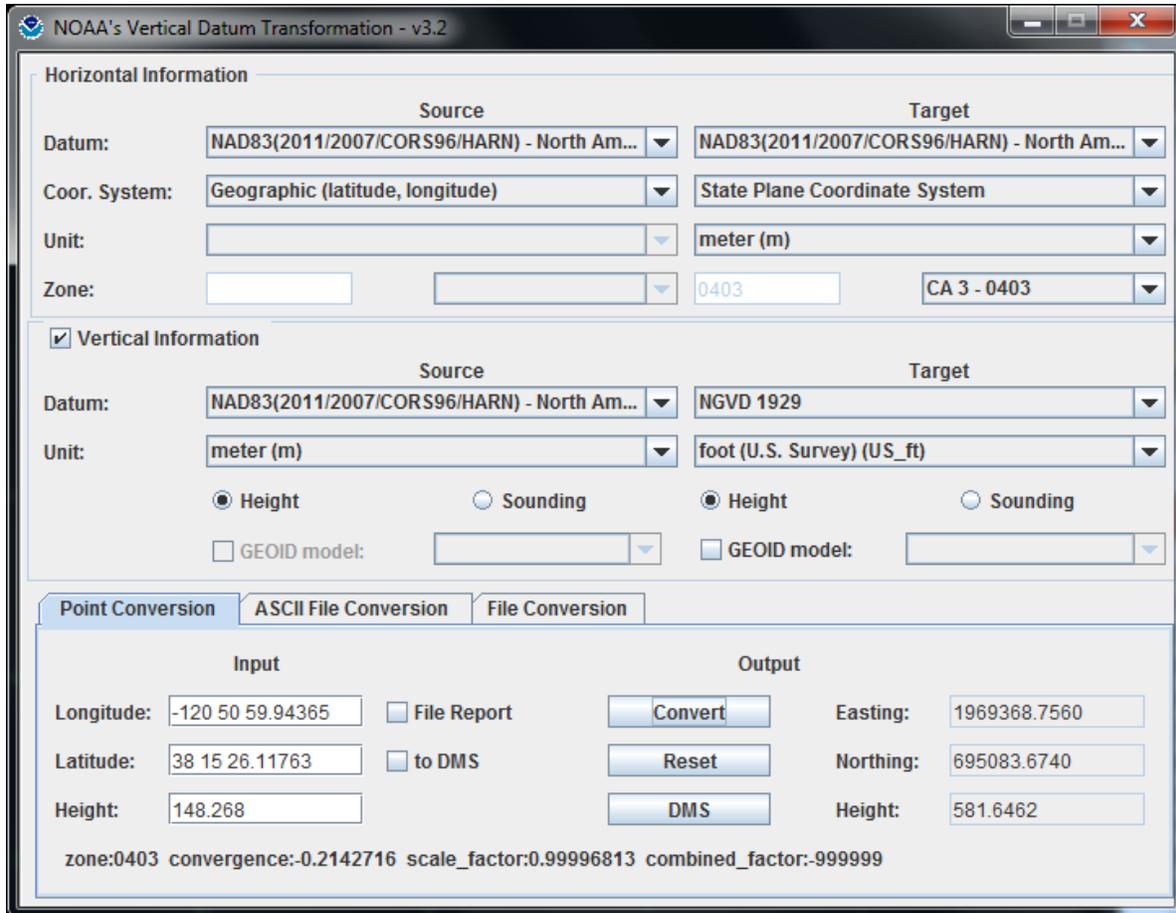


Figure 33. vDatum conversion of OPUS NAD83 Ellipsoid Height in meters for the top of the east dam wall to NGVD1929 height in Feet.

Vertical height of wall at antenna position above the MB7 (D2) benchmark measured using laser level:

1.693 m 5.554 ft

NGVD1929 Height of MB7 based on OPUS solution minus the 5.554 ft measured antenna height above mark:

576.092 ft

Height of MB7 reported by EBMUD 5/6/08 surveyors:

576.075 ft

DIFFERENCE: 0.017 FT

$576.092 - 576.075 \text{ ft} = 0.017 \text{ foot}$



**Figure 34. NW view of east dam wall with antenna in place 8 meter south of the gate house.**

#### East Wall Elevation

OPUS NGVD88 geoid12A elevation of the wall top:

ORTHO HGT:            178.020(m)    0.064(m) [NAVD88 (Computed using GEOID12A)]

Laser scanner point cloud elevation of the top edge of east wall at same location:

178.06 m

#### CONCLUSION:

There is no need to adjust the SFML survey data vertically once they are converted to NGVD1929 because they are no more than 0.15 ft (0.04 m) above the MB7 benchmark vertical control. This difference is within the error envelope of the data.

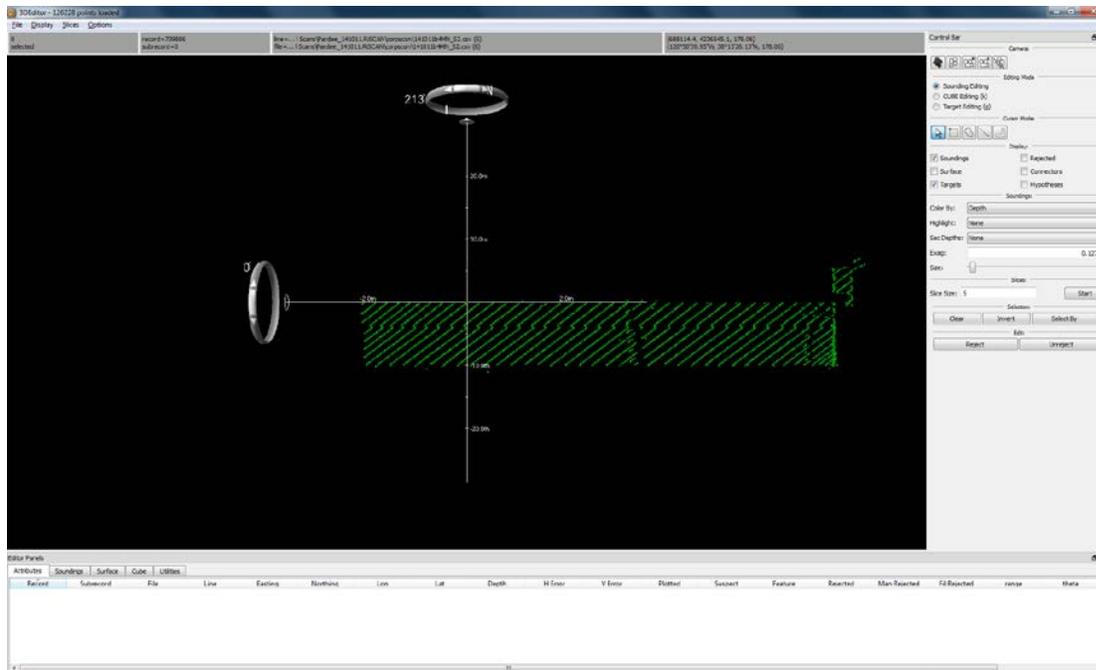


Figure 35. Laser scanner point cloud of the top edge of east wall at antenna location showing highest point elevation value of 178.06 meter (NAD83 ellipsoid height). The pole and instrument box shown in the photo above can also be seen in the point cloud. Given that the vertical spacing between consecutive points is on the order of 10-13 cm, close inspection of all top points along the wall edge for several meters on either side of the antenna location, show none higher than 178.06 meter and all are between 177.92 – 178.06 m. It is therefore highly likely that the top edge is at 178.06 m, which is only 4 cm above the OPUS solution for the wall edge.

## DEM CREATION METHODS EXPLORATION

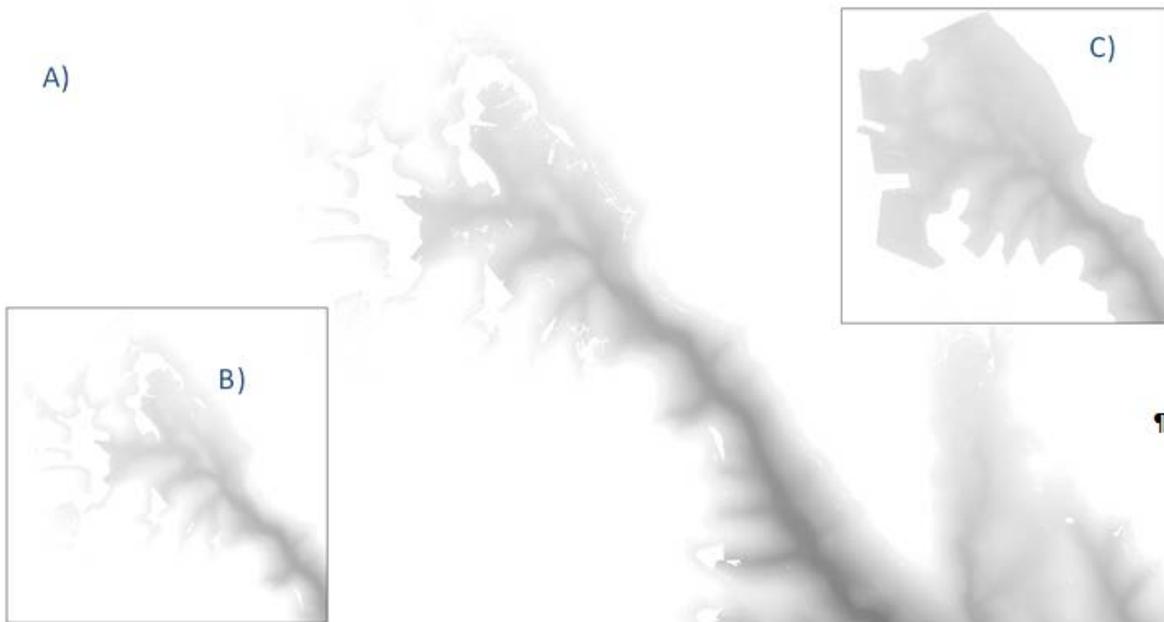
The 2014 root DTM was exported from QPS DMagic 7.4.1d as a geotiff format raster file after cleaning of spurious data was completed using a combination of CARIS HIPS and SIPS 8.1 and Fledermaus 7.4.1d (CARIS 2014; Quality Positioning Services BV (QPS) 2014a; Quality Positioning Services BV (QPS) 2014b). In more detail, sonar C3 (cleaning iteration 3) XYZ export from 0.5 meter BASE surface export and Lidar C1 (cleaning iteration 1) XYZ from LiDAR-only F2 PFM1 was used to merge the data into a second PFM project. The pre-cleaned data now merged, the second PFM was imported into Fledermaus and edited to attenuate the data seam and flyers/outliers using methods described above. After the merged data was cleaned, “Accepted” soundings data were then exported from Fledermaus in ASCII XYZ format. Exported XYZ data was added to DMagic SonarLidarSeam project, gridded into a DTM, and exported as a geotiff for additional processing in ArcGIS.

Data processing up to this point was done in the WGS84 geographical coordinate system (GCS) using UTM Zone 10N and the NAVD88 vertical datum. The initial “raw” 2014 DTM was then modified in ArcGIS to convert to EBMUD’s required geographical coordinate system and projection, smooth bathymetry. We then transformed the DEM GCS to California State Plane III FIPS 0403 and from meters to feet. Additionally, after converting elevation values from meters to feet in the DEM, we subtracted 2.011 ft to the DEM to convert from NAVD88 to Pardee Local Datum using ArcGIS Spatial Analyst Raster Calculator tool. This number was based on a vertical control point established by a CSUMB GPS static survey of MB7. Multiple methods were researched, but Procedure 1 was the most effective at filling gaps in data while avoiding changing the existing 2014 data and thereby generated the most accurate result.

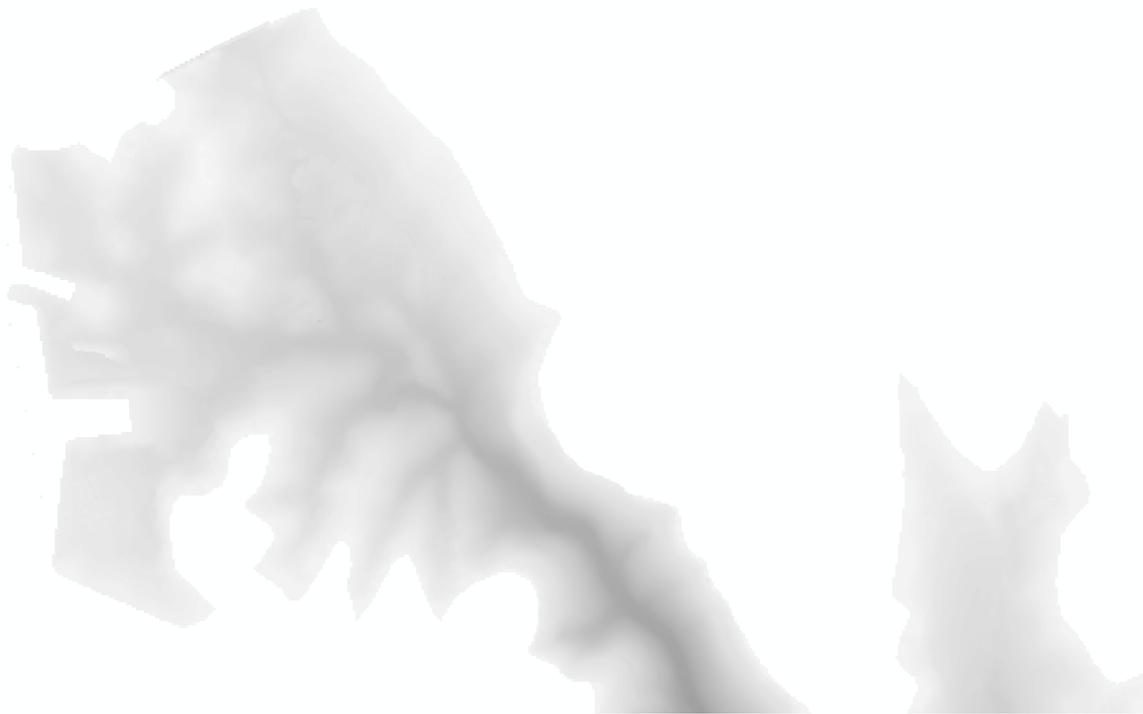
## PROCEDURE 1

This was the final procedure that was used in our analysis. Because of holes in the DEM dataset (Figure 36A) that were caused by seam cleaning or missing data, additional processing was required in order for it to be comparable to the 1994 bathymetric survey. Small gaps were filled by conditionally interpolating the raster using Spatial Analyst *FocalStatistics* with a mean of 10 neighboring cells in a square (Figure 36B). After small gaps were filled, the remaining large gaps were backfilled with 1995 data which achieved the goal of minimal interpolation (Figure 37). Several other procedures were examined and corresponding volume calculations were made from a single reference surface for comparison (Table 9). Code for focal statistics was a variation of the following line using *Raster Algebra*:

```
Con(IsNull("raster"),  
FocalStatistics("raster",NbrRectangle(10,10),"MEAN"),"raster")
```



**Figure 36. Procedure 1. Step 1 was to apply conditionally apply Spatial Analyst FocalStatistics smoothing to small gaps in the 2014 DEM. Small holes were assigned values by interpolating data from the next 10x10 neighboring cells and replacing the void with the mean resulting value. Step 2 was to fill the remaining gaps with 1995 DEM data.**



**Figure 37. Final blended DEM using combination of ArcGIS conditionally applied FocalStatistics with 1995 bathymetry back-filling the remaining voids.**

## PROCEDURE 2

Conditionally iterate *FocalStatistics* tool on successive rasters dataset to fill to the NULL value cells using specified nearest neighbors. This was repeated successively until the 2014 extent reached that of the 1995 extent. A partial



Figure 38. Procedure 2. ArcGIS Con tool used with Raster Algebra using a *FocalStatistics* mean from a square of 3x3 neighboring cells in A), 20x20 in B) and 20x20 on B) as an input generating C) and so forth until filling out to the equivalent 1995 extent.

sequence is shown in Figure 38.

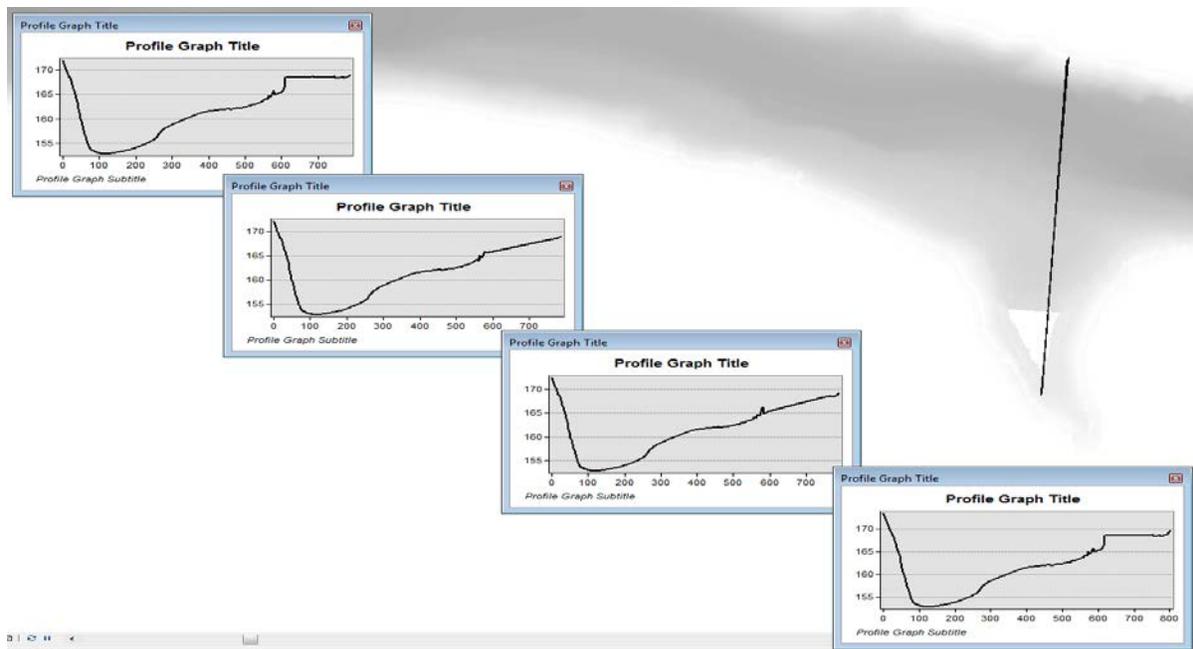
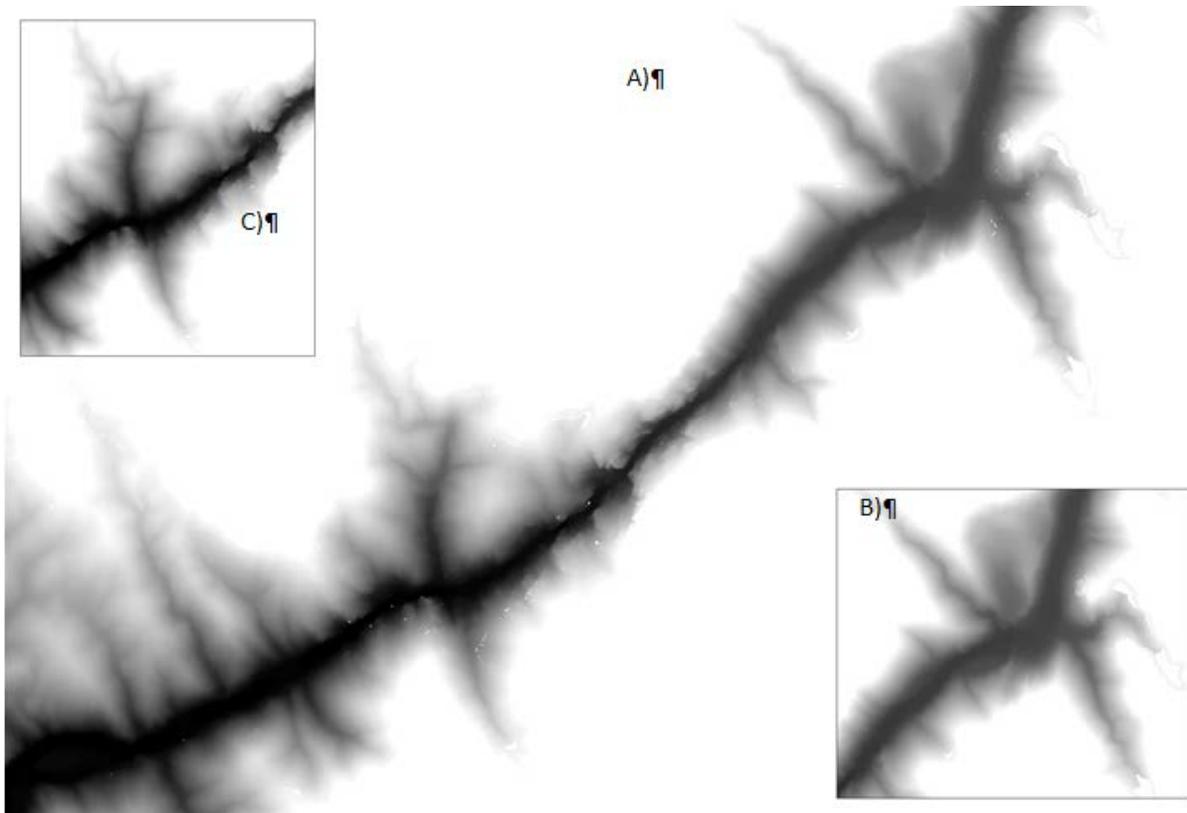


Figure 39. Procedure 2. From top left to bottom right, 3D profiles start off using initial DEM, the *FocalStatistics* tool mean of 3x3 cells, 20x20, and then 20x20 on top of the preceding 20x20. The main DEM raster background image shown is from the latter. Note that the ledge reappears in the last iteration. By the time the hole is completely filled, a similar ledge exists.

### PROCEDURE 3

Similar to Procedure 2, but rather than conditional application of *FocalStatistics* tool, Procedure 3 is iteratively applied to the complete dataset until all data holes are filled to the 1995 extent (Figure 40). Two problems resulted using this approach. Similarly to Procedure 2, the edges were distorted (Figure 39), but more importantly the overall average elevation of cells increased resulting in an artificially lower volume.

The resulting DEM had surface-volume calculations run to see results (Appendix Table 9).



**Figure 40. Procedure 3. Small data holes in the initial DEM A) were successively filled B) using the output of successive *FocalStatistics* interpolations which were iterated until reaching the 1995 bathymetric DEM extent.**

## DEM METHODS RESULTS

Table 9. Various degrees of smoothing on all or part of the DEM were tried as a way of interpolating data gaps. Best results minimized interpolation and used 1995 DEM data for backfilling large data gaps. Some elevation in table are in meters. The DEM elevation used for comparison was 567.75' and was done prior to-finalizing DEM so comparison here is useful relative to each other only.

Dataset	Plane Height	Area 2D (ft <sup>2</sup> )	Area 3D (ft <sup>2</sup> )	Volume (ft <sup>3</sup> )	Volume AF	Notes
..urvey\1995Bathymetry\pard_bath	567.75	96,820,891	103,801,262	8,630,804,081	198,136	1995 bathymetry
..2ft_LocalDatum_CC5_95Blend.tif	567.75	97,409,630	107,864,780	8,888,280,449	204,047	2014 DEM with 1995 backfill
..calVDatum_FS_MS5x5_95Blend.tif	567.75	97,899,544	106,177,540	8,887,251,823	204,023	2014 DEM smoothed with 1995 backfill
..m_CC5FS_CONFS5x5x7_95Blend.tif	567.75	100,099,809	108,525,385	8,885,096,546	203,974	DEM smoothed, then iteratively interpolated around null values only, then backfilled with 1995 data
...5m_CC4_FS_MS5x5x4_50x50x3.tif	173.05	9,639,696	10,085,889	8,680,892,351	199,286	Iteratively smoothed with focal statistics

## 1995 SURVEY DATA EXAMPLE

Field1	Field2	Field3	Field4
5001	649780	1896620	477
5002	649764	1896608	479
5003	648927	1897194	468
5004	648902	1897169	456
5005	648886	1897156	455
5006	648871	1897137	452
5007	648855	1897117	464
5008	648839	1897099	468
5009	648813	1897076	476
5010	648751	1897105	469
5011	648770	1897094	458
5012	648804	1897073	468
5013	648252	1897199	473
5014	648287	1897446	476
5015	648318	1897470	462

Figure 41. Attribute table showing details of the 1995 hydrographic survey. File naming implies survey took 10 weeks. It is unknown if changing water elevations were accounted for or which vertical datum was used as a reference.

## LIDAR PATCH TEST

*KelpFly* Laser Patchtest Results for Pardee Reservoir Survey – October 12, 2014

Rikk Kvittek

The Riegl LS420i laser scanner mounted atop the *RV Kelpfly* for the Pardee Reservoir shoreline scan, was calibrated (bore-sighted) to the Applanix POS MV based on a patchtest conducted at the Pardee parking lot on October 12, 2014. For the patchtest, a Trimble NetR5 geodetic grade GPS receiver and antenna were setup on a tripod in the middle of the parking lot and used as the target object (Figures 42 and 43). GPS data was logged for 2.5 hours and subsequently processed through the NGS OPUS online site for a static solution shown at the end of this document. This solution gave the precise location of the antenna and the elevation of the pavement directly beneath the antenna, which were used in the subsequent patchtest analysis to calculate angular offset corrections for Yaw, Roll and Pitch differences between the Applanix POS MV and Riegl laser scanner.

During the patchtest, the *KelpFly* was then driven past the target at distances of 50m in two directions for 6 passes acquiring laser and POS MV data. The uncorrected views of the tripod and pavement surface from all passes are shown in Figure 44 illustrating both vertical and horizontal offsets of the target in the point-cloud. These offsets were measured and used to calculate the angular corrections needed to bring the points from passes run in opposite directions into registration, and to bring the elevation of the pavement surface seen in the uncorrected point cloud into alignment with the elevation determined from the GPS data. Figure 45 shows the point cloud after applying the calculated angles, with the tripod and pavement surface points in correct registration.



Figure 42. GNSS antenna and receiver set up as patchtest target during static GPS occupation of the target location.



Figure 43. Patch test lines were run at a distance of 50 meter on either side of a GPS tripod in the parking lot of Pardee recreational area.

Patch test analysis completed 141026

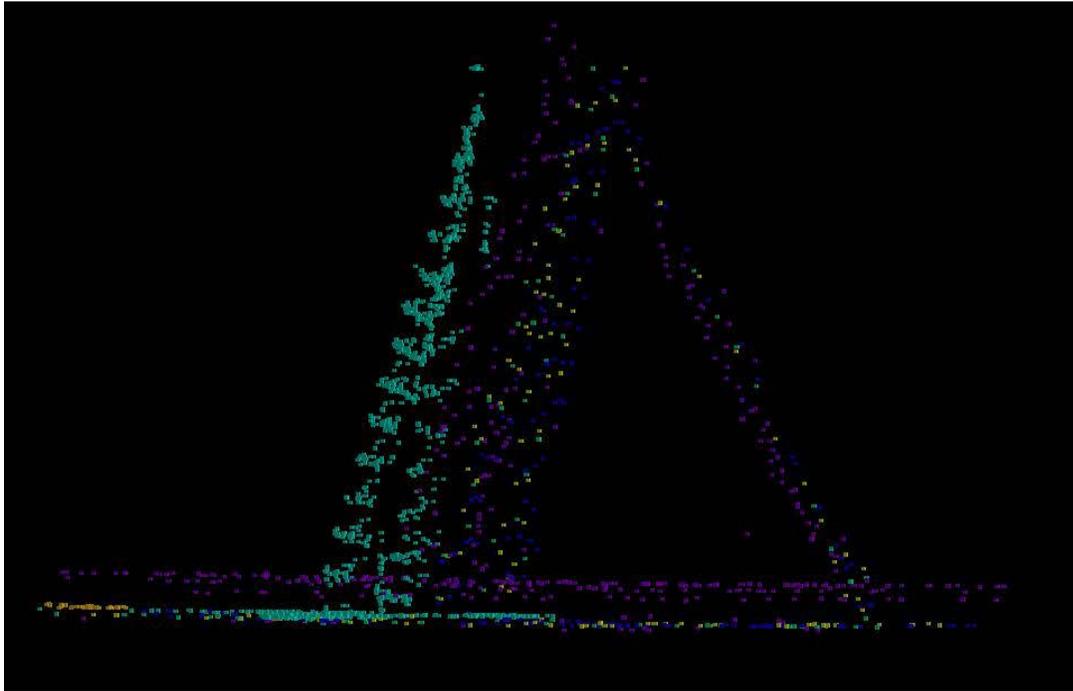


Figure 44. Side view of tripod and pavement surface in uncorrected point cloud seen in Fledermaus 3D editor.

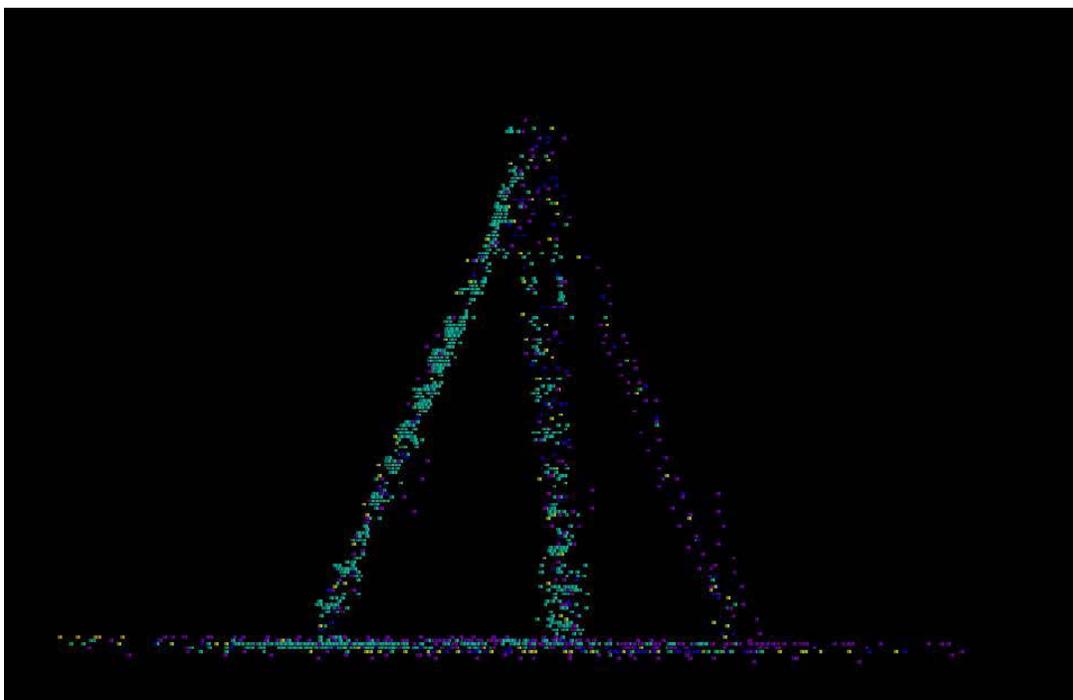


Figure 45. Side view of tripod and pavement surface in correct point cloud seen in Fledermaus 3D editor after applying the calculated Roll and Pitch values required to align the scans shot in opposite directions.



**Figure 46. Laser scanner mounted on *KelpFly* facing starboard as during Pardee survey.**

These corrections, which brought the position of the aligned point cloud points to within 1 cm of the GPS results both horizontally and vertically, were used to process all the laser shoreline data collected with the *KelpFly*. Independent assessment of the laser data accuracy was confirmed by comparing the elevation of the top edge of the east wall running along the dam roadway with another GPS static occupation of that same location. The vertical results from the two independent measurements of the wall height were within 1cm of each other.

Patch Test Results for Starboard Side Only – use these values in RiWorld

	Roll	Pitch	Yaw
Strb	-0.179	0	0.169

Note: This patchtest was for the starboard (90 degree) view only because there were no scans to the port side during the Pardee survey. Previously there have been different Yaw values for Port and Starboard facing scans which must be run through RiWorld separately (see screen grabs below):

Matrix SOCS->IMU values:

-1	0	0	0
0	1	0	0
0	0	-1	0
0	0	0	1

Note: these matrix values to be used in RiWorld are different from the scanner mount used on the *VenTresca* and *Van*.

On *KelpFly* mount, the Scanner base and IMU both face the bow of the vessel.

Note: x,y,z axis of the scanner and IMU frames have opposite signs (i.e. point in opposite directions)

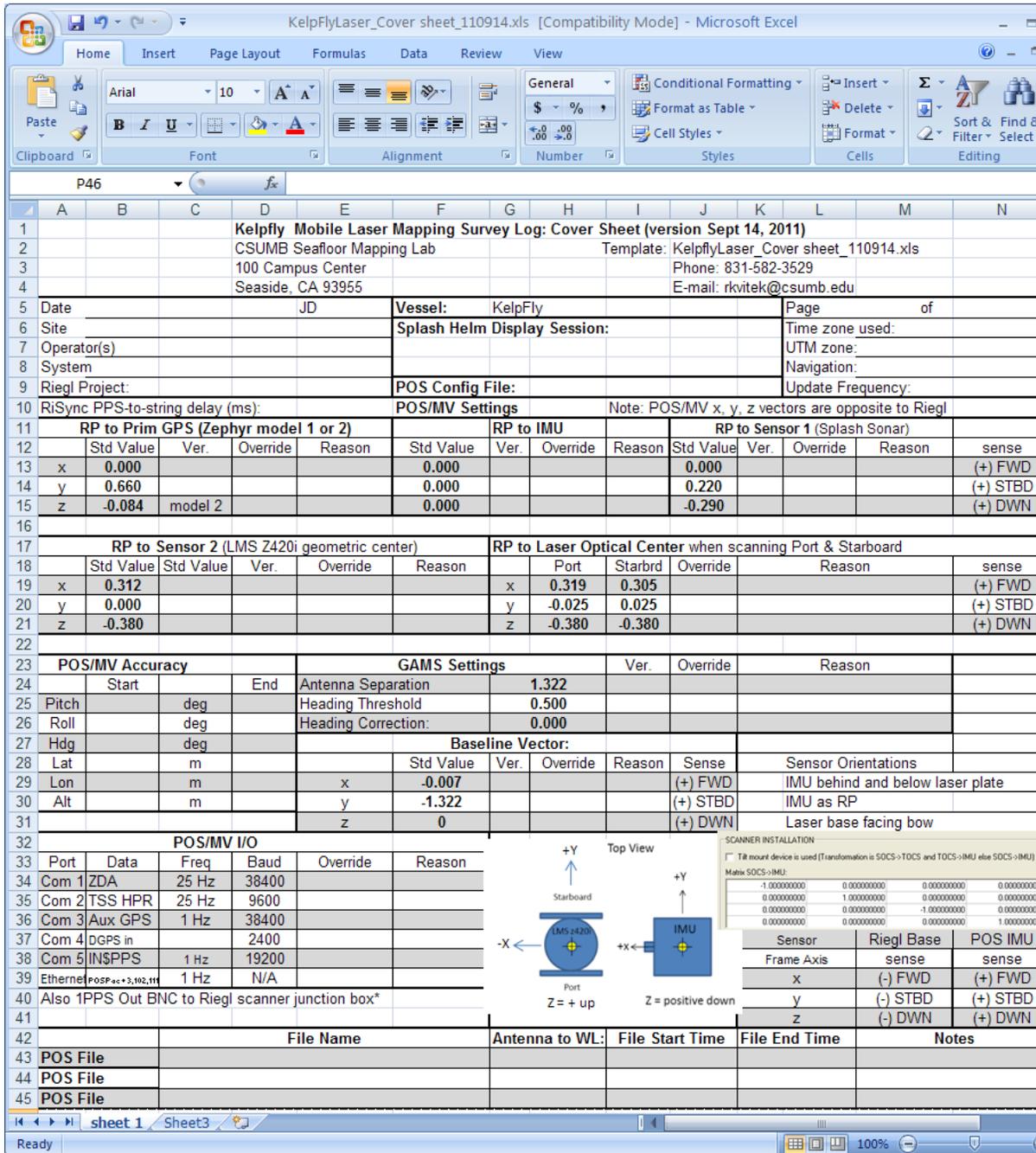


Figure 47. Lever arms from IMU to Geometric Center of the Riegl LMS z420i were used as per Survey Coversheet shown here.

OPUS solution for GNSS occupation of patch test target tripod.

FILE: 58712710.14o OP1414349072628

NGS OPUS SOLUTION REPORT

=====

All computed coordinate accuracies are listed as peak-to-peak values.  
 For additional information: <http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy>

USER: rkvitek@csumb.edu DATE: October 26, 2014  
 RINEX FILE: 58712710.14o TIME: 18:45:21 UTC

SOFTWARE: page5 1209.04 master91.pl 022814 START: 2014/09/28 14:33:00  
 EPHEMERIS: igs18120.eph [precise] STOP: 2014/09/28 17:06:00  
 NAV FILE: brdc2710.14n OBS USED: 5822 / 6250 :  
 93%  
 ANT NAME: TRM55971.00 NONE # FIXED AMB: 38 / 39 :  
 97%  
 ARP HEIGHT: 1.170 OVERALL RMS: 0.013(m)

REF FRAME: NAD\_83(2011)(EPOCH:2010.0000) IGS08 (EPOCH:2014.7415)

X:	-2572079.221(m)	0.007(m)	-2572080.099(m)	0.007(m)
Y:	-4302882.936(m)	0.010(m)	-4302881.624(m)	0.010(m)
Z:	3930393.374(m)	0.013(m)	3930393.341(m)	0.013(m)

LAT:	38 17 5.12966	0.007(m)	38 17 5.14240	0.007(m)
E LON:	239 7 50.96924	0.003(m)	239 7 50.91053	0.003(m)
W LON:	120 52 9.03076	0.003(m)	120 52 9.08947	0.003(m)
EL HGT:	146.033(m)	0.014(m)	145.482(m)	0.014(m)
ORTHO HGT:	175.763(m)	0.033(m)	[NAVD88 (Computed using GEOID12A)]	

	UTM COORDINATES	STATE PLANE COORDINATES
	UTM (Zone 10)	SPC (0402 CA 2)
Northing (Y) [meters]	4239557.953	569228.465
Easting (X) [meters]	686365.088	2098936.405
Convergence [degrees]	1.32057542	0.71294922
Point Scale	1.00002776	1.00001137
Combined Factor	1.00000485	0.99998846

US NATIONAL GRID DESIGNATOR: 10SFH8636539557(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
DM7533 P140	SLATEMTN_CN2006 CORS ARP	N384945.232	W1204135.446	62369.5
DN7372 P310	ALDERRIDGECN2006 CORS ARP	N384408.171	W1202003.561	68446.6
DN7366 P306	WILDCATCRKCN2006 CORS ARP	N374742.588	W1203839.998	57814.6

NEAREST NGS PUBLISHED CONTROL POINT

JS0391	M 3 USGS	N381740.	W1205448.	4006.1
--------	----------	----------	-----------	--------

This position and the above vector components were computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.

## ARCGIS PROJECT: HIERARCHY OF LAYER

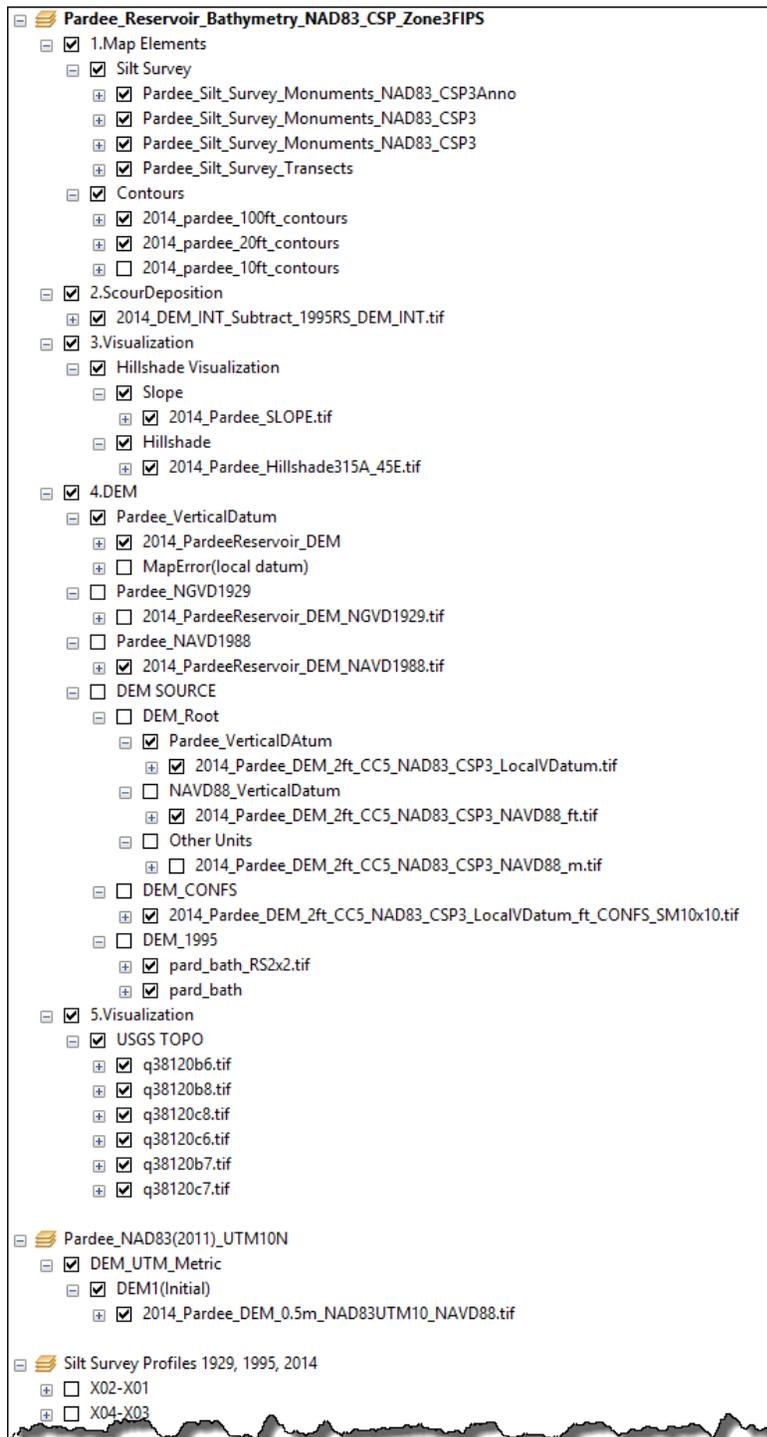


Figure 48. Hierarchy of GIS layers in ArcGIS MPK file.

## PARDEE RESERVOIR SPILLWAY ELEVATION DATUM

In the process of calculating the stage-volume of the reservoir, it was necessary to determine which vertical datum(s) would be used. For operational purposes there is an established legacy of using the Pardee local datum as the vertical reference for determining reservoir volume at a given water elevation. For the official reservoir capacity, spillway elevation is used. However, the spillway elevation published in the EBMUD station description (EBMUD 2014) does not explicitly define the reference datum for that elevation. This study confirmed that the official spillway elevation of 567.65 feet is correct and that the spillway elevation is based on the local datum.



Figure 49. MB7 Benchmark on Pardee Dam was originally known as D2

## SPILLWAY ELEVATION RESEARCH

Internal EBMUD documents show that the spillway was originally surveyed in the local datum and subsequently surveyed in the USGS NGVD 1929 datum and corrected to the local datum.

## 1937 REPORT

In an internal EBMUD report (Figures 52 and 53) on Pardee, the mean spillway elevation is noted as 567.66 feet and the “lowest portion of the spillway crest” as 567.65 feet, but it does not specifically note to which datum these elevations are tied (Hall 1937). Hall notes that reservoir capacity was calculated based on a survey from 1930 which was also used to create a capacity table published in 1931 (1937). Historically EBMUD capacity tables have always used the local datum so an inference could be made that both spillway volume and capacity tables because NGVD 1929 had probably not been adopted by 1930. Strengthening this inference, a discrepancy shows up when surveying a proposed aerator installation in Walnut Creek whereby 0.42 feet must be added to convert to Pardee local datum in reference to outlet tower inlet elevation. If water surface using local datum and outlet structures are using Pardee local datum, then it can be inferred that the spillway also used this datum at this early date.

Table 10. Comparison of survey results.

Station elevations	Survey Year						2014 CSUMB		Notes
	1937	1959	1977	5/25/2006	10/17/2006	2008	Static GPS		
MB7(D2) NGVD 1929	576.075	576.075	576.090	576.074	576.144	576.092		All coincide pretty well, 576.075' is a accepted elevation	
MB7(D2) NAVD88						578.501		NAVD 88	
Spillway published elevation (local datum)	567.66	567.65	567.65					With adjustment of 0.40 feet, the spillway 567.65 (local datum)	
Staff plate at 1" mark (USGS)			568.25						
Spillway elevation USGS datum (low point)	567.25	567.25							
Spillway bay 15		567.28						Datum for survey in 2006 was base on USGS. Data from 1977	
Spillway bay 16		567.34		567.292				D.A. Wilson memo essentially matches 2006.	
Spillway bay 17		567.34		567.321					
Spillway bay 18		567.37		567.371					
Spillway bay 19		567.25							

### *1977 MEMO AND FB-3469*

In a 1977 memo from D.A. Wilson (Figure 50), the Pardee superintendent details survey results that show the elevation of lowest point on the spillway to be 567.25 “when equated to corrected USGS BM ‘BM10’” (Wilson 1977) (Table 10). USGS benchmarks would have used NGVD 1929 at that time. In the 1977 memo, the vertical offset from the published number is negative 0.40 feet. A similar offset is found at the dam. Benchmark MB7 (D2) is stamped with the elevation 576.49 (Figure 49), but was surveyed at 576.075 (NGVD 1929) in 1959 and 1977. 1977 survey details are found in EBMUD field-book FB-3469 (1978). The elevation of 576.49 at MB7(D2) is referred to as the local datum or the “as-built” datum. The surveyed NGVD 1929-to-local datum shift of 0.415 feet at MB7(D2) is essentially the same as the 0.40 foot offset noted by Wilson in 1977.

### 2006 SURVEY

The October 2006 survey results were nearly identical to the 1977 survey. EBMUD Field-book FB-4375 (Figure 51) shot points from BM1 (NGVD elevation) to spillway bays 17, 18 and 19, elevations matched 1977 results to within 0.05 ft. The 2006 survey was less extensive and did not measure three stations for each bay as did the 1977 survey. The notes in the field-book appear to have measured at the pylons rather than between pylons. While the 2006 survey did not measure the 567.25 foot spillway low-point that was measured in 1977 in bay 19, the other measurements coincide closely (Table 10).

### 2008 Survey

The 2008 EBMUD survey result showed that MB7(D2) was at an elevation of 576.144 (NGVD 1929) which was approximately 0.07 foot different from the surveys from 1959, 1977 and 2006. Because NGVD 1929 was no longer supported by 2008, this survey has limited value and was not adopted for official use.

### 2014 CSUMB Survey

The 2014 Seafloor Mapping lab static survey result for MB7(D2) was 576.092 feet (NGVD 1929), which is 0.017 feet higher than the 1959 (and 1977) EBMUD survey result of 576.075 feet (NGVD 1929). The Seafloor Mapping lab static survey result of 576.092 feet (NGVD 1929) is equivalent to 578.501 when converted to NAVD88. Note that the data for the 2014 study were collected using the NAVD88 datum.

### CONCLUSION

The NGVD 1929 elevation of the spillway low-point is 567.25. When the 0.415 difference between local and NGVD 1929 elevations (using MB7) is added, the local-datum corrected elevation is 567.67 feet (when rounded from 567.665 feet). However, Hall’s memo is thought to be definitive and a shift of 0.40 was applied to the low-point elevation of 567.25 NGVD making the official elevation 567.65 feet, local datum. It is possible that at one point, official capacity was based on NGVD 1929, but this research shows that that volume would then have been based on an elevation between 0.40, 0.415, or 0.42 feet less (different offsets are found throughout the documentation) than the published elevation which is either 567.65 or 567.67 feet. If the lower elevation (567.25 feet) has never appeared as a published elevation then one can conclude that the official elevation has always been based on the local datum.

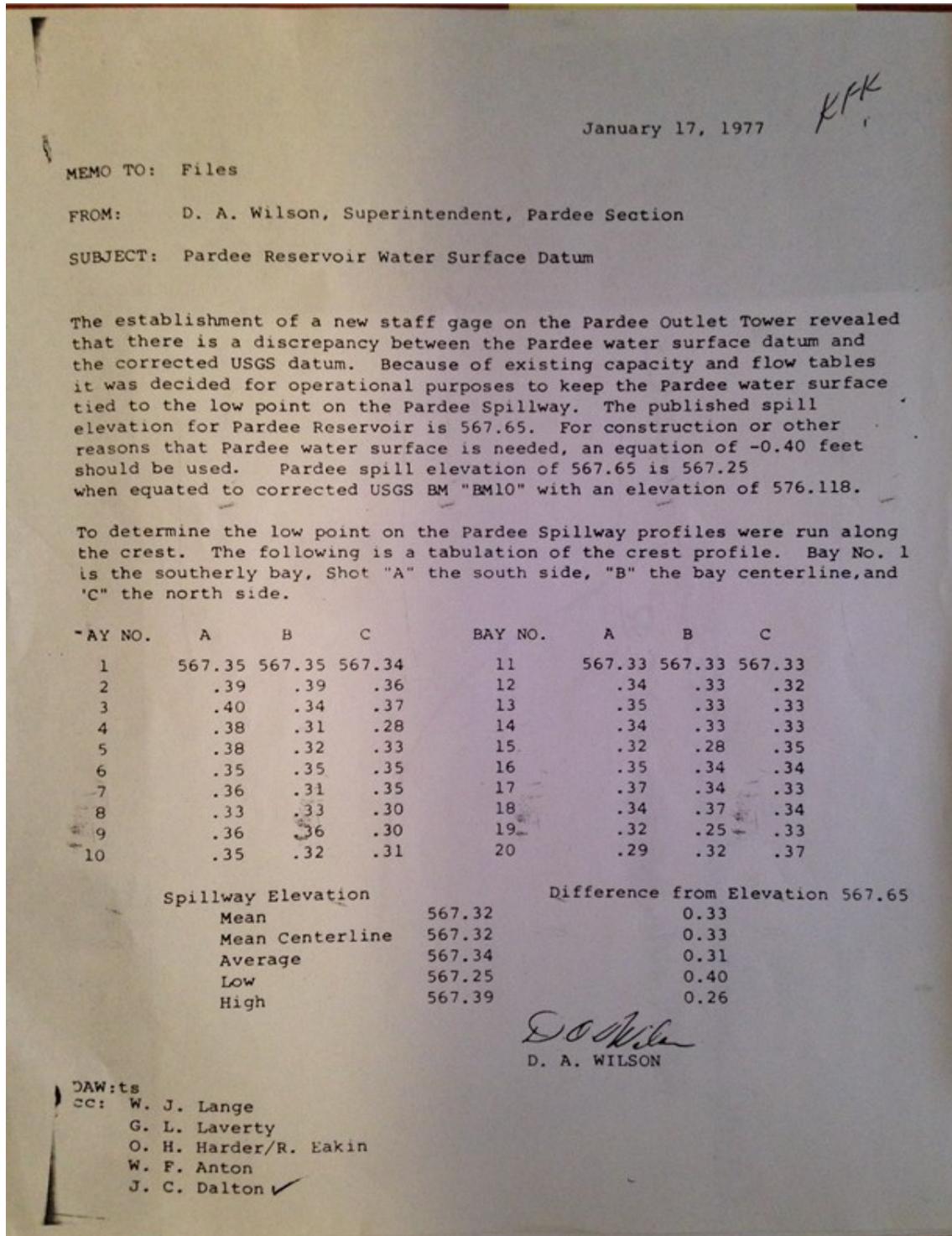


Figure 50. 1977 memo from outlining survey results.

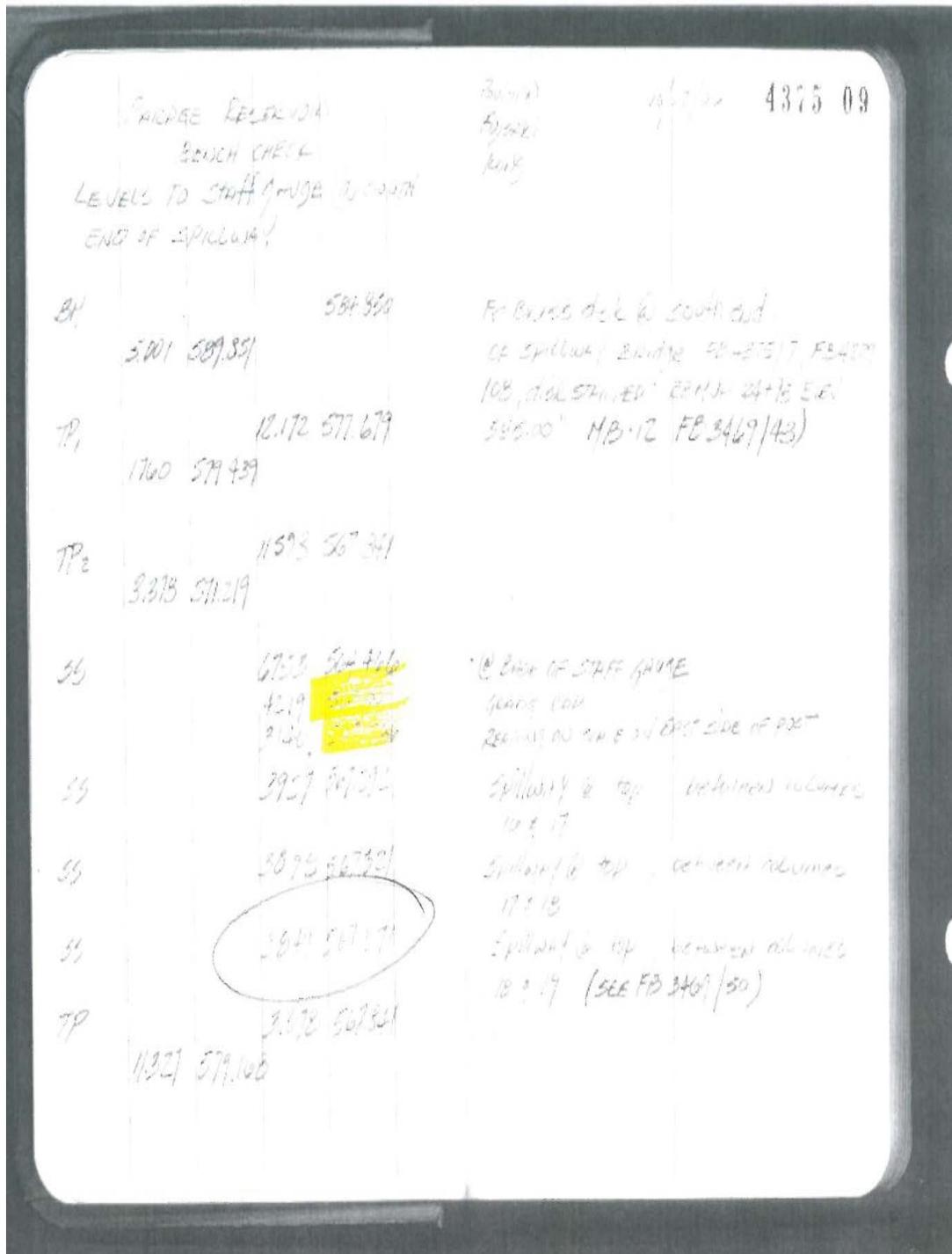


Figure 51. Page 9 of FB-4375 shows four survey shots in-between bays 16/17, 17/18, 18/19 and an underdetermined location. The scan reproduction was poor, but was transcribed into Table 10.

ATTACHMENT: "PARDEE RESERVOIR"

PARDEE RESERVOIR

Pardee Reservoir is located on the Mokelumne River, about four miles north of Valley Springs. Construction started July 5, 1927, and by March 9, 1929, work had advanced to such a stage that storage in the reservoir was started. On June 19, 1929, diversion of water thru the aqueduct was begun, although the dam was not fully completed until a month or two later. The reservoir was completely filled and water flowed over the spillway on May 4, 1930.

There are two spillways from the reservoir, the South Spillway and the Jackson Creek Spillway. The latter was constructed under the terms of the Permit of the State Division of Water Resources and will allow water to be diverted into Dry Creek if a reservoir is constructed on that stream at some future date. Also in the near future it is planned to build a flood control tunnel near the Pardee Dam, which would have the inlet crest about 20 feet lower than the South Spillway, but would be provided with gates so that the reservoir level could be raised to the crest of the South Spillway after the period of flood runoff had passed.

The elevations at Camp Pardee were determined from a closed line of levels run from a U.S.G.S. Bench Mark located 0.5 mi. east and 3 miles south of Clements, described as an iron post stamped "B 1907 - 192.12" elevation 192.308. This Bench Mark was checked by E. E. Harris of the U.S.G.S. in 1932 on Standard Datum and found to be elevation 192.400 ft., or 0.092 ft. higher than the original levels. Harris destroyed the iron post and set a standard tablet in the top of a concrete post and stamped "1932 - H 17", elevation of which, to Standard Datum or U.S.G.S. 1929 General Adjustment, is 188.743 ft. Several bench marks have been set near the dam and spillway at Camp Pardee, and these are probably 0.10 ft. low on Standard Datum, since they were based on the old bench mark elevations of the U.S.G.S.

The water elevations at the reservoir are referred to a measuring point established at the top of the gate shaft well on the upstream face of the dam. The elevation of this point is 575.0 ft. Measurements are made to water level of the reservoir with a steel tape and the reservoir elevation obtained by subtraction. A water stage recorder located in a metal house situated at the south end of the gate house is set according to reservoir elevations obtained from depth to water readings described above. There is also a staff gage fastened to the west side of the outlet tower. The gage is set to read elevations above mean sea level. The water stage recorder at the dam is used for the official daily readings of reservoir water level.

The crest of the South Spillway according to plans (see DH 884-4 and DH 885-4) was to have been at elevation 567.5 ft., but actually the mean elevation is 567.66 ft. An erroneous elevation of 567.75 ft. has been used in some District reports. The spillway is of the ogee weir type and consists of 20 bays each 40 ft. in width, separated by piers. The center bays are at elevation 567.65 ft., but the end bays rise to elevation 567.69 ft. These elevations were obtained by Mr. E. L. Macdonald after the structure was completed.

At Jackson Creek the spillway is of the siphon type with sixteen openings, each having a throat area of 60 square feet and a crest elevation of 564.0 ft. The siphon vents have been arranged in pairs symmetrical to the center line with the top of vent for the lowest pair at elevation 564.0 ft., and the vent for each succeeding pair increasing in elevation by 0.25 ft., to a maximum of 565.75 ft. The openings to these siphons are to be covered with gates so that discharge will occur only at such times as it is desired. At present no water can be discharged through this spillway as the gates have not been installed and the openings are sealed with wooden bulkheads. The elevation of vents was taken from the plans as no check has been made of the true elevation since construction (Drawing DH 883-12).

The river discharge can also be controlled through four Lerner-Johnson valves in the dam. Two valves have 72 inch pipes with 60 inch nozzles; and two have 42 inch pipes with 30 inch nozzles. The center line of the pipes at the upstream face of the dam is at elevation 260.0 ft., and at the downstream face the center line of valves is at elevation 257.55 ft. (Drawings ME 1318-9, ME 1347-9, ME 1348-9 and ME 1407-9). A total flow of 4,568 second feet can be released through these four valves at full reservoir elevation.

The inlet to the turbines at the base of the dam is 115 feet above the valves. The bottom sill of the trash rack covering these openings is at elevation 375.0 feet (see Drawing ME 1337-9). The draft tube outlets are 5 ft., high with the bottom at elevation 230.0 ft. The normal water level in the river when the power house is in operation is 240.0 feet elevation. The maximum discharge from the power plant with both turbines running, varies from 600 to 700 second feet, depending on the reservoir level. The maximum turbine discharge occurs when the reservoir level is 540.0 ft. elevation.

The net storage capacity is that available between the spillway lip and the point on the aqueduct line controlling the lowest outflow. The bottom of the lowest 3 ft. diameter pipe in the outlet tower is at elevation 393.50 ft. (see Drawing DH 1350-6). However, the bottom of the notches in the weir crest of the Walnut Creek aerator is at a higher elevation and would control gravity flow. The elevation of these notches as shown on the plans (see Drawing DH 621-2) is elevation 396.84 ft.; but due to a discrepancy in the levels between Pardee Reservoir and Walnut Creek aerator, 0.42 ft. must be added to reduce the elevation to Pardee datum. The correct elevation on Pardee datum would be 397.26 ft. This correction was determined from the difference between original bench mark elevations and Standard Datum elevations and is not based on levels to the Walnut Creek aerator, and assumes that the aeration weir was constructed exactly as shown on the plans.

The reservoir capacity has been computed from a survey made by Mr. M. M. Bolton (see Drawing N 93) and completed in 1930. The computations were made by Mr. R. S. Jones and Mr. Ham C. Johnson, from which the capacity table dated 3-18-1931 was compiled. Two previous tables printed in the District's Annual Reports are obsolete. One shown on page 34 of "Report of Additional Water Supply of East Bay Municipal Utility District" was taken from the Old Keiffer survey made in 1924. The other shown on page 42 of the "Annual Report of the Calendar Year 1925" was based on a revision of the Keiffer survey following new levels run in 1925.

Figure 53.