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STUDYING ANTHROPOCENE SEDIMENTATION BEHIND A 19TH CENTURY DAM IN WESTERN CONNECTICUT

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INTRODUCTION

18th to early 20th century dams are a common occurrence in New England. Constructed from a range of materials – early on with compacted earth and rock, and later with stone and brick masonry and concrete – these river impoundments served a variety of functions from powering mills to cooling the iron products in smelting furnaces. Over time, the reservoirs behind these dams have become infilled with a sedimentary and geochemical archive of the contributing watershed that preserves landscape changes such as land clearing and forest regrowth, historic flood events, and heavy metal contamination such as mercury from upstream industries. With dam removal becoming more common, the possibility of remobilizing this contaminated sediment is a growing concern in the region.

Southern New England experienced drastic landscape changes from the 17th to early 20th century. The region began to be populated by settlers in the 17th century, which initiated deforestation and the draining of ponds for agriculture, pasture and settlement throughout the region. In northwest Connecticut, deforestation was also associated with charcoal production to support local iron mining and processing. Anthropogenic activity also produced many dams along riverways to power or divert water to various industries. After the boom in widespread agriculture and iron mining, the past 100 years have seen the reforestation of the land, with forest cover nearly doubling since New England's initial clearing (Foster 2008).

Our study reconstructs and analyzes sedimentation behind the Hollenbeck dam in Canaan Connecticut, which was used to cool the products of the Buena Vista iron furnace from ~1847-1893. We assess the volume, sedimentology and geochemistry of 19th-20th century sediment preserved at this site (Figure 1). We extracted three vibracore cores behind the Hollenbeck dam, and collected 30 probe-depth measurements in the river and floodplain locations. Cs-137 dating is used to constrain the age of post-dam sediment in the upper portions of the cores. Core samples were also analyzed for Hg levels and grain size. Field data, combined with a 2010 1m LIDAR

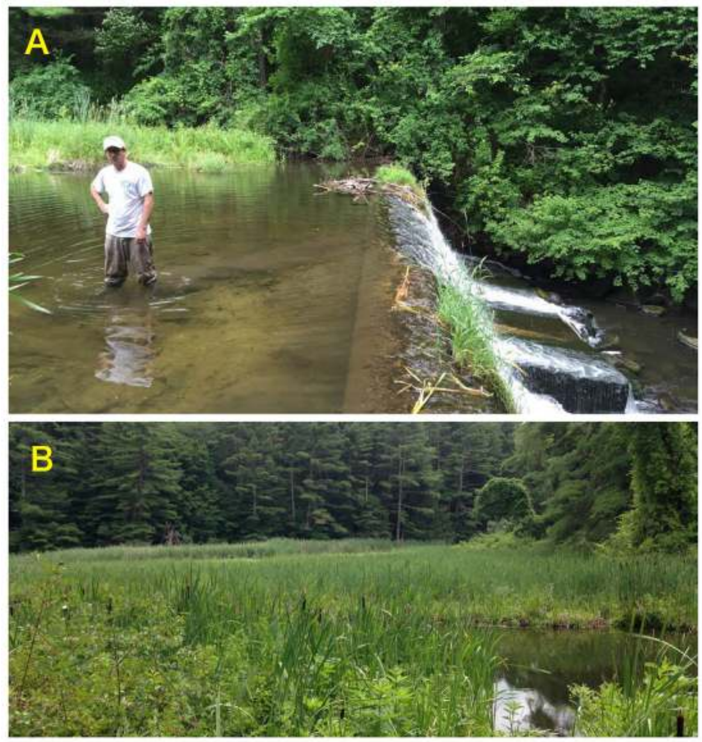

Figure 1. Photographs taken during July 2015 from behind the Hollenbeck Dam. (A) shows infilling right up behind the dam; (B) depicts the marsh environment that has developed upstream.

DEM and air photos from 1934-present, are used to analyze the extent of the upstream reservoir. Overall, the goal of this project is to use the cores, sediment depths, LiDAR and sediment chemistry data to correlate reservoir fill stratigraphy and reconstruct the Hollenbeck Dam's history of infilling associated with anthropocenic activities and land-use change.

STUDY AREA

The Hollenbeck Dam is located along the Hollenbeck River in Canaan, Connecticut between Route 63 and the Housatonic State Forest. It has a contributing watershed area of 27.83 km^2, measures 4.8 meters high, and extends about 16 meters from end to end. The Hollenbeck River is a tributary of the Housatonic River, which flows from the south to southeast in western Connecticut, ultimately discharging in the Long Island Sound in Stratford, Connecticut. Historically, the hatting industry in Danbury, Connecticut, has left a strong Mercury imprint on the Housatonic River, in which high Hg levels are seen in sediment beyond the point where the Still River enters the main channel (Lerman-Sinkoff, 2014). Relict charcoal hearths and abandoned stonewalls characterize the upland hillslopes of the Hollenbeck watershed. The Buena Vista iron furnace depended on water supplied by the Hollenbeck dam, redirecting ponded water through several stone tunnels. Prior to filling with sediment (Figure 2), aerial photographs indicate that the low-energy and marshy wetland environment that exists today was once a distinct channel surrounded by trees.

The Hollenbeck watershed is underlain with bedrock of marble, schist and quartzite composition from the Early Paleozoic age. Several episodes of glaciation have affected the area during the late Pleistocene, the most recent of which ended approximately 21,000 years ago (Stone et al., 2005; Foster et al., 2008). The colonial period began in the 1620's as English settlers began to inhabit Massachusetts, Rhode Island, and Connecticut, modifying the landscape into pasture space and small towns and developing an agrarian economy. Throughout the 1700's population growth and economic activity saw an increase in cleared land, transportation and trade, associated with the construction of more roads, railroads and canals. By the mid 19th century, the forest cover reached a low of 25% across the region (Foster et al., 2008), and even less in some towns. During the Industrial Revolution, the use of steam power fueled the rapid growth of factories throughout the northeast, bringing an end to widespread agricultural and pastoral activity, thus allowing the forest to regrow. As the shift to the modern era began in the 1920's, the factories of southern New England's industrial revolution were abandoned, but the many dams that supplied the water to run them remained. The reservoir sediment ponded behind these dams preserves the sedimentalogical and chemical signature of fluvial process since their original placement up to when they filled. Since its construction in the 19th century, the Hollenbeck dam has witnessed the last century and a half of this story, containing much of this history in its various layers of sediment. In addition to upstream landscape and land use change, the watershed also experienced large floods in 1936, 1938, 1995 and 2011 (Hurricane Irene).

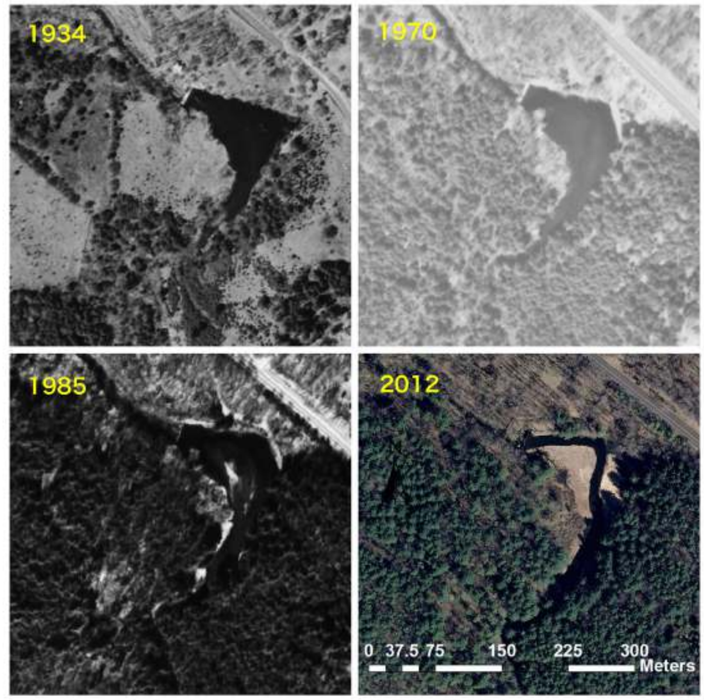

Figure 2. Aerial photography showing the Hollenbeck Pond and Dam from the years 1934, 1970, 1985 and 2015. Images display the narrowing of the channel, sediment infilling the reservoir and encroachment of vegetation. (Data Sources: Connecticut Environmental Conditions Online; University of Connecticut Libraries Online; nd and Dam)

METHODS

Field

Field observations and data collection were conducted during July 2015. Three sediment cores, HPSC1, HPSC2 and HPSC3 were extracted with a vibracorer from three separate locations behind the Hollenbeck dam (Figure 3). HPSC1, HPSC2 and HPSC3 recovered 237 cm, 203 cm and 390 cm of compacted sediment. At each core location, GPS coordinates were taken using a Garmin GPS Receiver. The total length of each core was dependent on core tube length and how far the sediment enabled us to penetrate. HPSC2 and HPSC3 were cored to the depth of refusal, where it is assumed the core tube came in contact with large cobbles; HPSC2 was a 10 ft core tube and we did not reach the depth of refusal. In addition to the cores, thirty probe-depth measurements were collected from river and floodplain locations behind the dam. At each point, we took a GPS point and measured depths of sand layers, which are hypothesized to reflect historic floods.

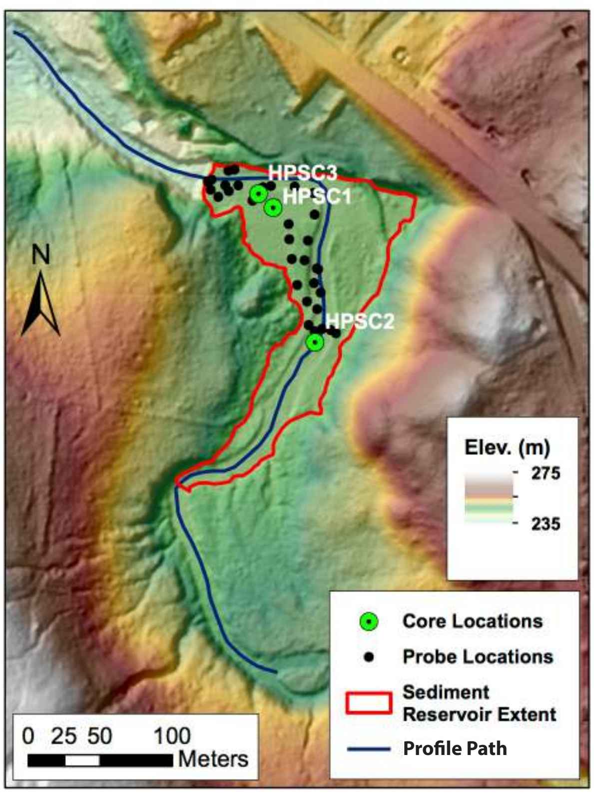

Figure 3. 1m LIDAR DEM draped over hillshade of the Hollenbeck dam site, noting core locations, sediment probe sites, reservoir extent and profile line.

Laboratory

The cores were split and sampled over the summer at the University of Connecticut, and Loss On Ignition (LOI) was measured at Mount Holyoke College. Approximately 10g of sediment every 5-10 cm was subsampled and dried in an oven at 100C for 1 hour, weighed, dried at 100 C for 10 hours, then baked in a muffle furnace at 550C for 4 hours and weighed for final LOI. Grain size analysis on all the samples took place at the University of Connecticut, using a CamSizer XT. Prior to grain size analysis, samples were sieved with a 63 micron sieve to determine weight % <63 µm. Grains >63 µm are summarized according to the 50th and 95th percentile size. Carbon-14 AMS dating of wood from the bottom of core HPSC3 at 390 cm was performed at the Woods Hole Oceanographic Institute, and the calendar ages were calibrated using the calibration curve *CalPal2007_HULU* (http://www.calpal-online.de/). Mercury and Cesium-137 analysis was performed on HPSC3. Mercury levels were measured at Amherst College lab facilities, using a Teledyne Leeman Labs Hydra-C to provide Hg data at a 5-10 cm sample interval of the core. Hg results were then normalized for LOI. A Canberra GL2020R Low Energy Germanium Detector Gamma counter spectrometer was used to sample the Cesium-137 activity of HPSC3 at depths 38, 52, 76, 100 and 140 cm (compacted sediment depths).

GIS Analysis

ArcGIS and ArcScene were used to map GPS locations, analyze historical aerial photos and model sediment depths. Historical aerial photography was obtained from Connecticut Environmental Conditions Online and University of Connecticut Libraries' Map and Geographic Information Center from the years 1934, 1951, 1965, 1970, 1985, 1990, 1995, 2004, 2012 and 2015 (e.g., Figure 2). The GPS locations were uploaded and visualized on a map in ArcGIS, and the depth information of sand layers was added to each corresponding point. An IDW Interpolation was used to create an 1850's (pre-dam) surface based on core information, and a mid-1900's surface based on probed sand layers <2 meters in depth and ages from HPSC3. The volume of sedimentation was calculated from the 1850 and mid-1900s surface. The longitudinal profile of the Hollenbeck River through the dam was generated based on a 1m LiDAR DEM.

RESULTS

Figure 4 highlights both the current elevation of the Hollenbeck River and the inferred 1850 (pre-dam) profile from sediment core depths and geometry. All depths mentioned are compacted downcore depths unless noted.

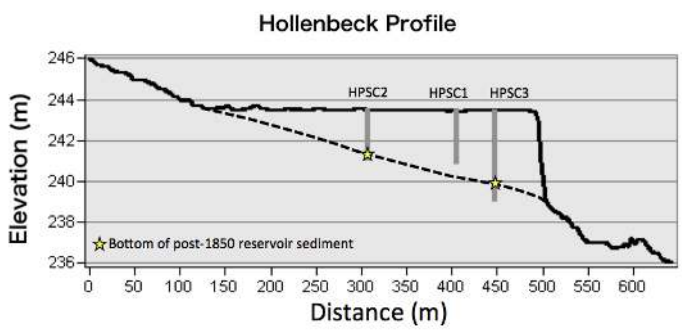

Figure 4. Longitudinal profiles of the modern and inferred (pre-dam) Hollenbeck river

Core Descriptions

HPSC1 had a penetration depth of 287 cm and compaction ratio of 1.2, resulting in 237 cm of recovered sediment. It was divided into 21 discernible layers. The majority of the core contains a mixture of silt and sand. Organic material occurs in most layers. There appear to be several transitions between a low-energy, marsh-like environment and fluvial environment at 143 cm (transition to lower energy indicative by the presence of more organics and a siltier material), 51 cm (fine sand becomes interbedded with silt, possibly a transition to fluvial) and back to a marsh-like environment at 31.5 cm (inferred from higher organic material and siltier sediment). There are also many storm and flood events seen in the core—notably distinct sand layers at 138 cm, 113.5 cm and 55 cm.

HPSC2 had a penetration depth of 263 cm and compaction ratio of 1.3, resulting in 203 cm of recovered sediment. It was divided into 18 distinctive layers, and displays a gradual transition from a low-energy, organic rich environment at the top to a high-energy, river environment as one moves downcore, indicated by increasing grain size, decreased layering and decreased organics. The upper half contains very large (some reaching 6 cm) pieces of wood and other organic debris scattered throughout. The lower 80 cm also displays a color contrast from the top half. The color transitions from a dark, organic-color to a lighter, yellow-tan, oxidized color.

HPSC3 is the longest core, with a penetration depth of 488 cm and compaction ratio of 1.3, resulting in 390 cm of recovered sediment. Its grain size is fairly consistent throughout the core, ranging from fine to very fine dark-colored sand, with the exception of two major sandy layers between 110-131 cm and 160-172 cm, which showed a dominance of coarse sand (Figure 5). These layers, we can assume, correlate to the first sandy layer from the probe depth measurements. While the probe depths varied across Hollenbeck, the ones extracted in close proximity to the core all fall around 150 cm. Many layers contained roots of thin to moderate thickness and small woody debris.

LOI

Loss on Ignition provides a measurement of organic content in sediment, which is indicative of the depositional environment and is a useful tool for correlating stratigraphy between separate cores. A higher LOI is interpreted as a quieter depositional setting, which allows organisms to settle in the aquatic environment. The results of HPSC1 indicate two major LOI spikes, 40.5% in the organic horizon at 1 cm deep and 80.6% at 105 cm. There is a minor spike to 21% at 53 cm downcore. The rest of the LOI values fall between 1.5% and 16.3%. HPSC2 produced the least organic content of all the cores. It displays increasing LOI after 110 cm, which then varies throughout the subsequent layers. This is expected, as HPSC2 was taken upstream, thus it is closer to the delta front in the early phase of filling around 1850-1900. LOI appears to decrease to almost its pre-1950 levels (as determined by the cesium content) at 68 cm, and spikes again at 24 cm, where it achieves its maximum LOI of 11.0%. Its O-horizon shows an LOI of just 6.4%. In HPSC3, the values are more consistent with HPSC1. Its O-horizon has an LOI of 19.7%, then varies downcore, with increased variation between

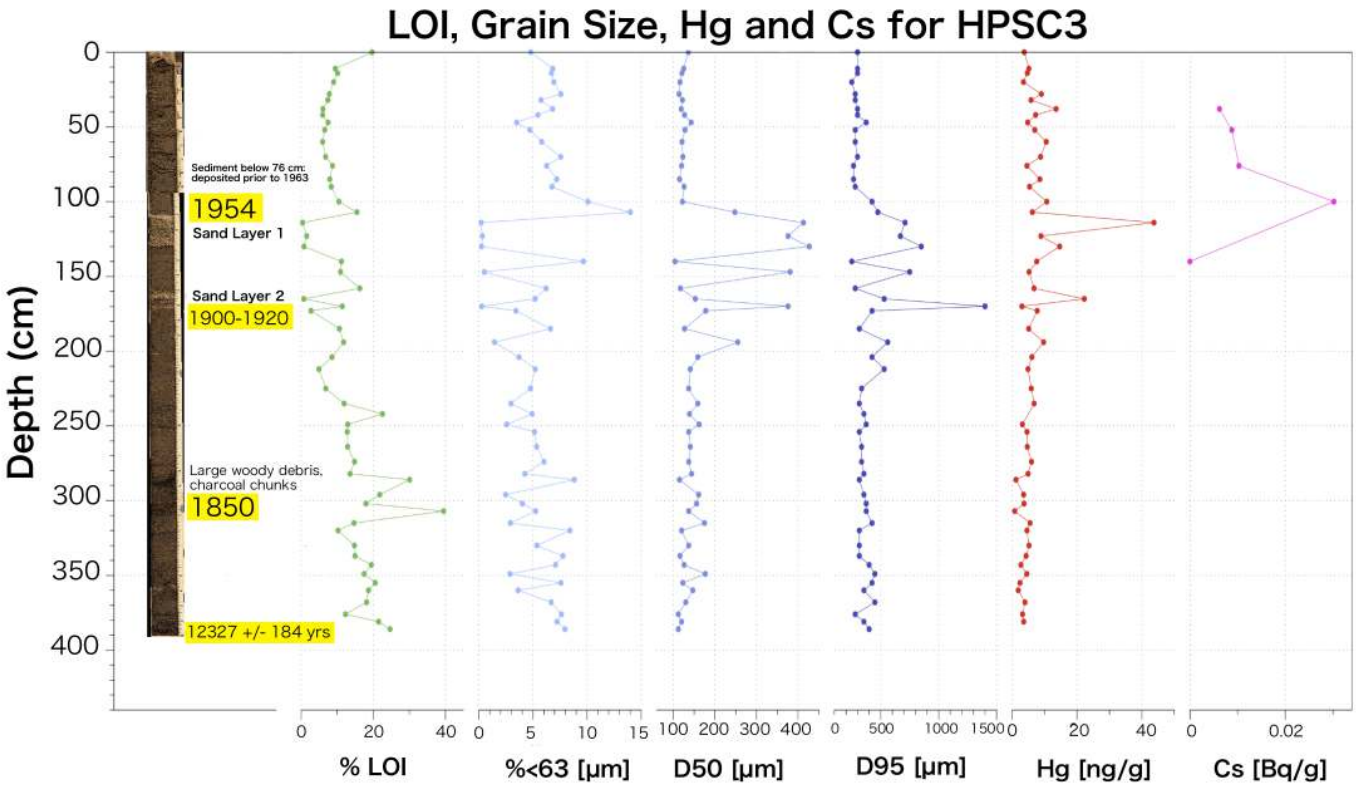

Figure 5. Summary core data for HPSC3: core photo; age constraints; LOI%; %<63µm; 50th and 95th percentile (cm) from grain sizes analysis, Hg concentrations normalized by LOI, and 137-Cesium results.

100-190 cm compacted and 280-320 cm compacted (Figure 5).

Grain Size

Grain size is a useful tool in determining the energy of a depositional environment. A larger grain size is indicative of a higher energy environment (a river, flood or storm event, etc.) while smaller grain sizes indicate a lower energy depositional environment, such as a marsh or pond. In HPSC1, the grain size is quite variable. It ranges from a median size class of medium to very fine, and this variation persists throughout the core. The bottom of HPSC2, from 182 cm to 202 cm, shows an average grain size, which approaches very coarse sand. The majority of the core that follows is fine to very fine sand, with another spike around 70 cm that displays medium sand. HPSC3 shows a similar trend, where the average grain size through the core is consistently fine to very fine sand. However, between 210-110 cm there is a sudden variation in median grain size, which seems to alternate between very fine sand to medium sand (Figure 5).

Aerial Photography

Historic photographs from the years 1934, 1970, 1985 and 2015 document the evolution of Hollenbeck (Figure 2). In the 1930's it appeared as a still pond with relatively little marsh in the surrounding area, but by the 1970's, the size of the body of water decreased as vegetation began to encroach on its outer edges. By 1985, the river passing through the body of water had increased in width and the site began to take on the appearance of an active stream channel. Currently, Hollenbeck Pond is surrounded by wetland areas and it has the appearance of a riverbend.

Chemical Analysis and Age Model for HPSC3

Only the bottom layer of HPSC3 was run for C-14, producing a calendar age of 12,327 years with an error of +/- 184 years. Large woody debris and chunks of charcoal are found at ~300 depth in HPSC3 – we infer this to be the 1850, pre-dam level in the core (Figure 5).

Cesium-137 is a fission product with an intermediate half-life of about 30.17 years. This radioisotope can be found in small quantities in the environment as a legacy of the nuclear weapons testing which occurred in the US between the 1954 and 1963, making it a useful tool in determining recent sedimentation rates. In HPSC3, only five depths (38, 52, 76, 100 and 140 cm downcore) were sampled for Cs. The results clearly display a Cesium peak at 100 cm downcore, followed by its gradual decrease (Figure 5). At 140cm, Cesium is not present, implying that 1954 lies somewhere between 100 cm and 140 cm downcore, and that the 1963 peak in nuclear testing occurred around the 100cm core depth.

While mercury is a naturally-occurring element in concentrations around 1-20 parts per trillion (Randall, 2013), high concentrations of it in the environment are the result of anthropogenic activities, such as mining, coal-fired power and most notably, it is a byproduct of New England's felt hat industry in the late 1800's—early 1900's. It is released into the air by these activities where it is deposited into local bodies of water. It is used as a marker for time periods of known mercury-producing anthropogenic activities. HPSC3 was tested for Hg content and showed a general increase from background values beginning at ~200 cm downcore and two spikes (147 ng/g at 165 cm depth, and 250.6 ng/g at 114 cm depth) (Figure 5). The beginning of Hg contamination in this region occurred in the 1900-1920 timeframe (Woodruff et al., 2013, Varekamp et al., 2003), thus Hg analysis implies that ~200 cm in HPSC3 marks the 1900-1920 timeframe. All the sediment deposited below 200 cm would have occurred after between dam construction. These results are consistent with the constraining ages provided by the Cesium dating, with the 1954-1963 timeframe occurring between 100 and 140 cm, and the aerial photos, which show the HPSC3 core location with reservoir space continuing to accumulate sediment from 1934 until ~2000.

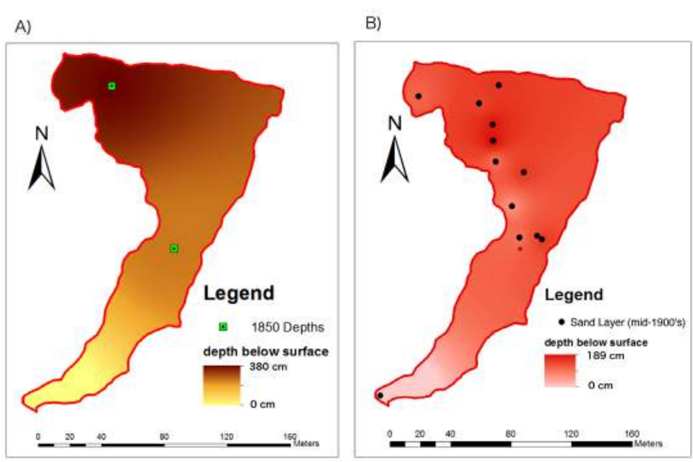

Figure 6. Interpolation results. (A) Interpolation of the 1850 surface based on inferred depths at HPSC2 and HPSC3 depths. (B) Interpolation of a mid-1900's surface based on probed sand layers <2 meters in depth and ages from chemical analyses of Hg and Cs in HPSC3

GIS Sediment Volumes

Figure 6A shows the interpolation results of the two 1850 core depths, and figure 6B shows the mid-1900's interpolation of sediment probe data. Mapping and then interpolating sand layers at all of the 36 probe location measurements at Hollenbeck would, in theory, provide us with a series of maps that estimate surface elevations for hypothesized flood layers. However, gaps in the sedimentary record exist. Therefore, we focus on sites where we clearly measured a sand layer at depths similar to ones we observe in HPSC1 and HPSC3, usually the first sand layer measured. Using the interpolations from each layer (Figure 6), we estimate that the total reservoir space (filled from 1850 onward) is 39,234 m^3 and volume filled from the mid 1900's onward is 20,537 m^3.

DISCUSSION AND CONCLUSION

The 1850's depositional surface can be estimated using two depths from HPSC2 and HPSC3. In HPSC3, the first appearance of charcoal (a key marker for the Anthropocene) occurs at 380 cm uncompacted. In HPSC2, the 1850's is demarcated by a gravel bed at the bottom of the core at 261 cm uncompacted. This bed is followed by finer sediment throughout the rest of the core, therefore it is a likely marker for 1850, when the dam was constructed. The interpolated surface using those two depths (Figure 6A) displays that the reservoir was deepest near the dam and got shallower upstream, as expected.

HPSC3 displays two distinct sand layers above the 1850's layer, one of which can be accurately used to put a timeframe to the probe depths we received. The deepest sand layer appears at 210-220 cm uncompacted (160-170 compacted, Figure 5), exactly where Hg sharply increases. We interpret this to mean that this sand layer was deposited in the early twentieth century, when the hat industry released large concentrations of mercury into the environment. The shallow sand layer occurs between 173-145 cm uncompacted (110-130 cm compacted, Figure 5), just before the Cesium peak, which occurs at 100cm (compacted). From this, it can be inferred that this sand layer was deposited in the mid 1900's. By projecting the chemically implied time markers from HPSC3 to other sediment probe sites where there is a sand layer 100-200 cm below the surface, we construct an approximate 1950's depositional surface behind the dam (Figure 6B). Comparing these interpolations with the aerial photographs from 1934 and 1970 (Figure 2), one can see how the north-west area becomes shallowed due to infilling, as vegetation begins to encroach on the edges of the site. There were also two major floods in the area between the 1900-1950's period, one in 1938 and one in 1955, which could possibly be attributed to the appearance of these large sand layers.

Overall, volumes of implied sediment filling since the 1850 surface and since the mid 1900's surface (39,234 m^3 and 20,537 m^3, respectively) allow us to determine rates of sedimentation for the Hollenbeck River. Using the years ~1850 and ~1950 for each layer, there was an estimated 18,696 m^3 of sediment filling over that 100 year period, for a yearly sedimentation rate at the site of 186.96 m^3/year and inferred sediment yield of 6.7 m^3/km^2/year for the Hollenbeck River. Since ~1950, sedimentation rate at the site has been 409.2 m^3/year and sediment yield for the Hollenbeck River has been of 14.7 m^3/km^2/year. This indicates that sedimentation has more than doubled in the past 50 years.

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