Maintaining Sediment Prevention through the Repair of Floodwater-Retarding Structures in McCulloch County

TSSWCB Project 01-21

Final Report

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Funding provided through a Clean Water Act §319(h) Nonpoint Source Grant from the Texas State Soil and Water Conservation Board and the U.S. Environmental Protection Agency

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List of Acronyms and Abbreviations

ARS	USDA Agricultural Research Service
ATV	all-terrain vehicle
BC	Brady Creek
C/A	Reservoir floodwater capacity divided by watershed area
DC	Deep Creek
DGPS	differential global positioning system
FRS	floodwater retarding structure
GPS	global positioning system
GC/ECD	Capillary gas chromatography/electron capture detection
KeV	thousands of electron volts
KHz	thousands of cycles per second
km	kilometer
LSSR	Lower San Saba River
m	meter
mton	metric tons, equivalent to 1000 kg
mi.	mile
NRCS	USDA Natural Resources Conservation Service
RMS	root-mean-squared error
RTK	Real time kinematic
SCS	Soil conservation Service
SWCD	soil and water conservation district
SWL	Southwest Laterals
USLE	Universal Soil Loss Equation
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
μCi	1×10^{-6} Curies (microCurie) radioactivity

Executive Summary

Starting in the early 1950s, the U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS; formerly Soil Conservation Service (SCS)) built 30 floodwater-retarding structures (FRS) in McCulloch County, Texas. McCulloch County is in the Edwards Plateau physiographic province of Texas. The primary function of these reservoirs is to slow the movement of runoff from storms in the uplands and thereby reduce flooding and erosion downstream. Since the 1950s, over 11,300 such structures have been built in 47 states. Half of those in McCulloch County have since reached the age of 50 yr. In this project, 29 of the FRSs in McCulloch County were inspected and repaired as needed, to bring the mechanical components back into safe operational condition. In addition, sediment surveys were conducted on four of the reservoirs to determine the status of their sediment pools and assess their impact on NPS pollution downstream, in terms of the amount and quality of the sediment they contain and their remaining sediment retention capacity. No sediment was removed as part of the FRS repairs.

The inspections of the FRSs involved visual inspection of external mechanical components of the primary spillways and inspection of internal and underground components of the spillways using a remotely operated camera. Of the 29 FRS inspected, 15 required repairs to their principle spillways, grade work around the dam embankments and other maintenance. Sediment surveys were conducted on FRSs Deep Creek Site 3 (DC 3), Deep Creek Site 8 (DC 8), Brady Creek Site 1 (BC 1), and Brady Creek Site 39 (BC 39). The surveys were conducted using a combination of sub-bottom acoustic profiling to map water depth and sediment thickness in submerged areas of the reservoirs and real time kinematic Global Positioning System (RTK GPS) surveying of the land surface elevation in the dry portions of the reservoirs. The results indicate that the rate of sediment fill has been lower than expected and that the sediment pools have exceeded their design capacities. The status of the sediment pools range from DC 3, which is 38.9% full after 55 yr, to BC 1, which is 7.3% full after 51 yr. Therefore, the sediment pools are not in immediate need of dredging or other operations to regain sediment pool volume. Based on the survey results, it is estimated that the 14 FRSs upstream of Brady Reservoir have collectively prevented 1,406,560 mton of sediment from reaching Brady Reservoir, which is the primary water supply for the City of Brady, TX. Included in this diverted sediment, is 17,230 mton of organic Carbon, 3.52 mton of Arsenic, 13.36 mton of Chromium, and 9.14 mton of Lead. Evidence from prior surveys of DC 3, ^{137}Cs dating of sediment cores, and variation in sediment volumes with FRS impoundment dates, all suggest that most of the sediment in the FRSs of McCulloch County was deposited during droughts in the 1950s and early 1960s. The volume loss rate at its peak in the 1950s was 170 times higher than the average rate during the relatively drought-free period since the mid 1960s. Brady Reservoir was impounded in 1963, after the peak period of sedimentation. Hence, the water quality benefit of the FRSs that have been experienced to date are relatively modest compared to potential benefits, if or when, as is more likely, the climate of the Edwards Plateau returns to the normal pattern of periodic droughts. When periodic droughts return to the Edwards Plateau region the water quality benefit of the FRSs will be important, as the sediment pools fill over 30 to 45 years with periodic droughts.

Introduction

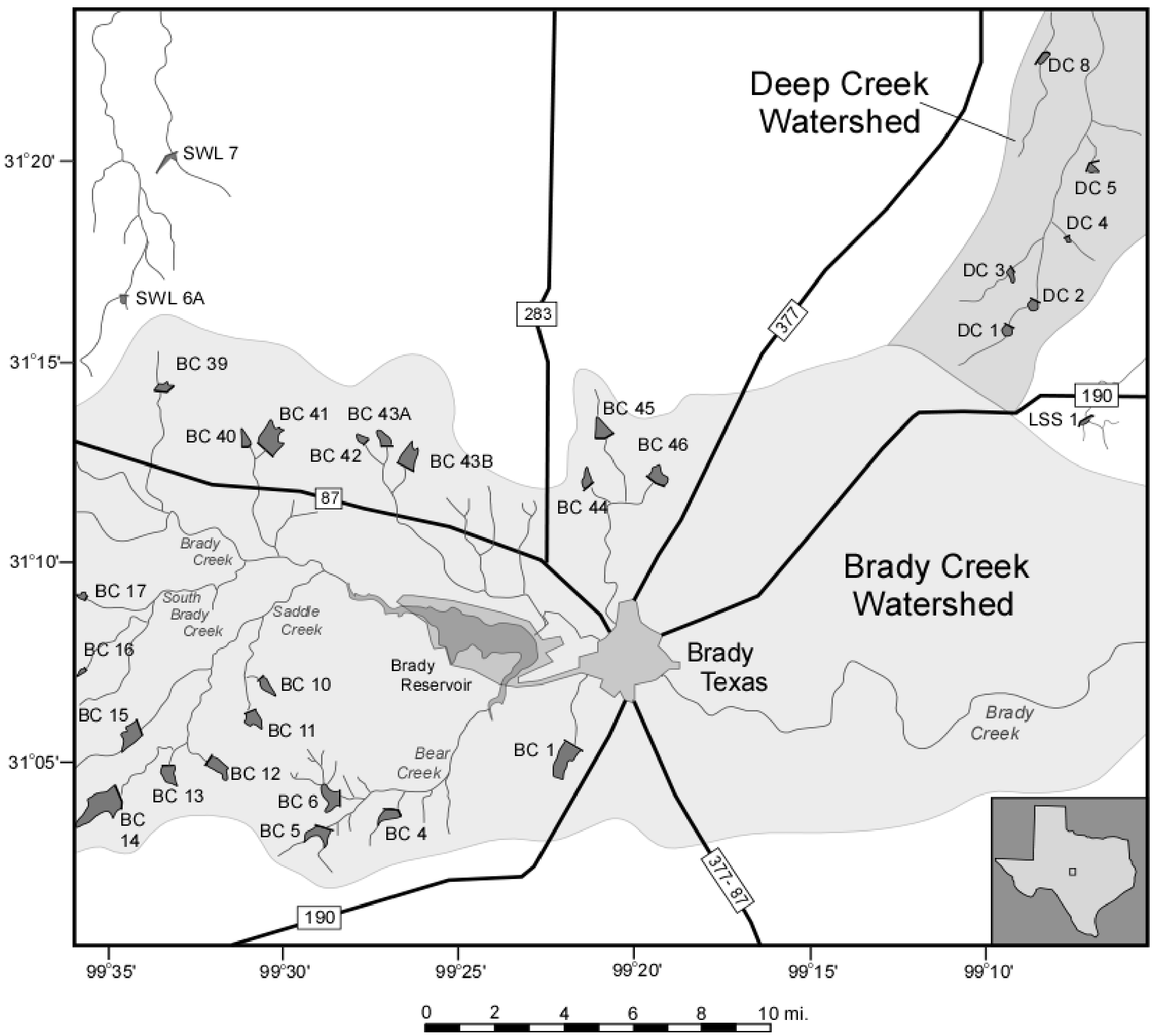
This report describes the repair and sediment surveys of floodwater retarding reservoirs (FRS) in the Middle Colorado watershed on Texas' Edwards Plateau. The U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS; formerly Soil Conservation Service (SCS)) has assisted local sponsors build more than 11,300 FRSs in 2000 watershed projects in forty-seven states since 1948. Between 1952 and 1987, thirty of these FRS were built in the Brady Creek (BC, 21), Deep Creek (DC, 6), the Lower San Saba River (LSSR, 1), and the Southwest Laterals (SWL, 2) sub-watersheds of the Middle Colorado River in McCulloch County, Texas (Figure 1). Those built in the 1950s were among the first NRCS FRSs built in the country. These FRSs have served well in preventing flooding and reducing nonpoint source pollution by trapping sediment and associated adsorbed contaminants from the uplands (cropland and rangeland) of these watersheds. By slowing storm flows, they also have reduced channel and bank erosion in streams below the structures. The 21 FRSs within the Brady Creek watershed are of particular importance because they are upstream of the City of Brady, population 5200, which was historically prone to flooding. Fourteen FRS are upstream of Brady Reservoir, which is the principle water supply of the City of Brady. The trapping of sediment and associated contaminants by these structures has prolonged the useful life of Brady Reservoir and improved its water quality.

After 50 years, many of the FRSs in McCulloch County needed significant repairs so they could continue to safely fulfill their flood control and sediment trapping functions. As FRS age, critical components of their principle spillways may deteriorate and be subject to failure, and their sediment pools eventually fill with trapped sediment. Some of the early FRSs, including those built in McCulloch County, were constructed with concrete principal spillways attached to corrugated metal tailpipes. These metal tailpipes corrode over time, and if left unrepaired, could lead to dam slope erosion and possibly failure. Other spillway problems, such as cracks in the spillway pipe or failure of seals could also lead to internal erosion of the dam and eventual failure. A structural failure would result in the release of built-up sediment directly into the watershed. Over time, the sediment pool may fill with trapped sediment. While this does not affect the flood control function of the FRS, the structure will no longer trap sediment carried in floodwaters. Sediment, and any attached pollutants, will then flow through the spillway(s) along with the floodwater and eventually be deposited in downstream channels and reservoirs causing nonpoint source pollution.

Prior to this project, periodic inspections of the FRSs in McCulloch County revealed that many of the principle spillways were in need of immediate repair. The only information on the status of the sediment pools was from a series of surveys conducted by the SCS of DC 3 in 1953, 1960, 1965, and 1971. These surveys indicated an overall rate of volume loss of 1.9%/yr between the impoundment of the reservoir in 1952 and the last survey in 1971. At this rate, the normal pool of DC 3 would have been completely filled with sediment by 2005. However, the series of surveys indicated that the rate of fill was not constant in time. There had been an initially high loss rate of 16.8%/yr in the first year, but the rate diminished considerably after that, averaging only 0.2%/yr between the 1965 and 1971 surveys.

The goals of this project were to inspect and repair failing spillway components of the FRS in McCulloch County and to conduct sediment surveys of selected reservoirs to assess the sediment retention impact of the FRS on abating NPS pollution in the watershed. This included determining the amount and rate of sedimentation that had occurred. Also, in order to assess the impact of these FRSs on water quality, chemical analyses of trapped sediment were performed to screen for common contaminants. The presence of significant levels of contaminants within the trapped sediment would greatly influence the relative costs and consequences to downstream water quality of the future repair, rehabilitation, or breach options.

Figure 1 USDA-NRCS FRS of McCulloch County, Texas.



There are 30 FRS in McCulloch Country. Brady Reservoir serves as both a FRS and as the principle water supply for the city of Brady, Texas. Watershed statistics for the remaining 29 FRS are given in Table 1.

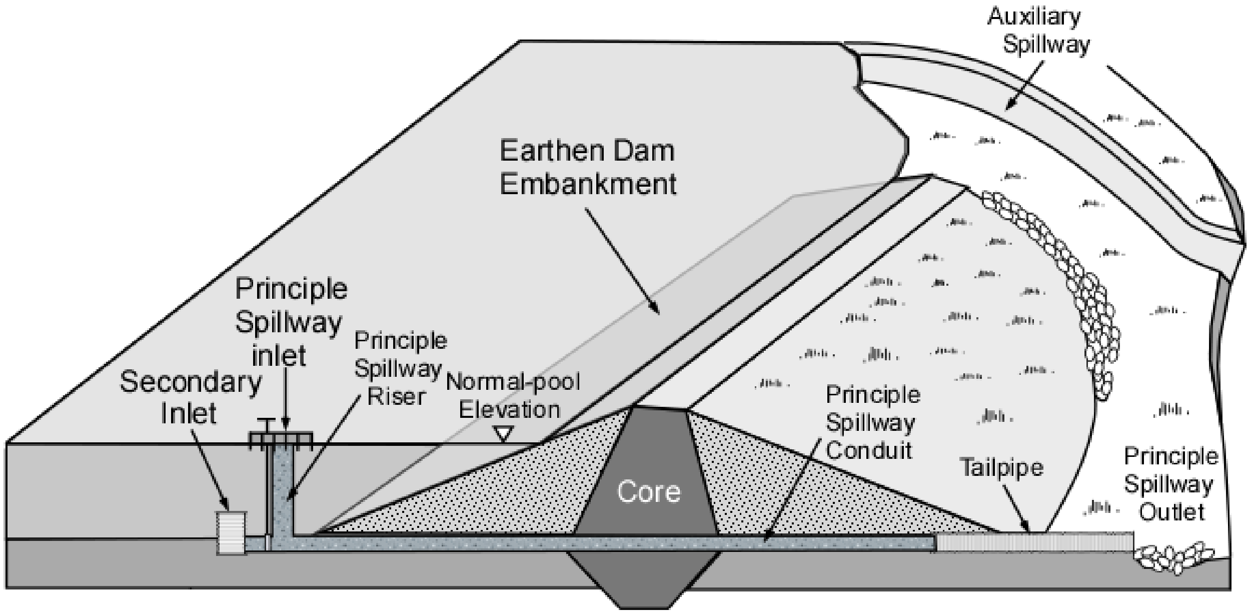
Background

In response to widespread flooding in the United States during the 1930's and 1940's, the U.S. Congress authorized the USDA-NRCS to assist local communities in addressing flood control problems in small watersheds. The strategy was to build small FRS on upland tributaries of flood-prone streams. This effort resulted in the construction of nearly 11,000 FRS throughout the United States since 1948 (Caldwell, 1999). Because FRS were built on small streams in the upper reaches of watersheds, the upstream drainage areas are relatively small, ranging from 1 to 20 km^2. The dams for these reservoirs typically consist of an earthen embankment 6 to 20-m high with a principal spillway consisting of a riser and conduit made of concrete 0.3 to 1.8 m in diameter (Figure 2). There is also an auxiliary spillway at a higher elevation for the safe conveyance of floodwater around the dam when runoff exceeds the flood storage capacity. The auxiliary spillway is designed to prevent the dam from overtopping. The volume between the principal spillway elevation and the auxiliary spillway elevation is the flood storage pool. The volume below the principal spillway is the sediment storage or, if the FRS was designed to include water supply, the sediment plus normal storage. In time the normal pool will become completely full of sediment. Under normal conditions FRS are nearly empty, ranging from small lakes, filled to the principal spillway level, to small ponds with most of the area of the reservoir dry. The normal pool areas typically range from 5 to 50 hectares.

During flood events, the FRS fill with water over a period of hours and then discharge slowly over several days. This reduces the peak discharge and lessens downstream flooding. During this process, 80 to 95% of the sediment suspended in the floodwater drops out in the reservoir and is permanently retained (Dendy, et al., 1984). Because most of the nutrients, metals, and agrichemicals transported by water are adsorbed onto the sediments, the sediment trapping mechanism also captures a high percentage of the contaminant load carried by the floodwater. Hence, a secondary affect of FRS is improved downstream water quality.

In normal operation, FRSs operate unattended but require regular maintenance such as debris removal, embankment mowing, brush removal, and fence maintenance and repair. However, over time, the sediment pool can fill with sediment to the principal spillway level. Once this happens, the reservoir no longer traps the sediment which is then carried through the principal spillway with the flood water to be deposited downstream. For this reason, in the 1950's through the 1970's sediment surveys were periodically conducted on selected FRS to assess their rate of fill and the operational safety of the dams. In these surveys, water covered areas were commonly surveyed by pulling small boats along cables stretched across the reservoirs and measuring the water depth at regular intervals by polling or with a lead line (Blanton 1982). Exposed portions of the reservoir bottom were surveyed using conventional optical transit and rod methods. These surveys were labor intensive, typically requiring weeks or months of fieldwork to accomplish. During the 1970's the practice of routinely surveying USDA-NRCS FRS was stopped, due to budgetary considerations.

Figure 2 Elements of FRS.



Schematic diagram of a typical USDA-NRCS FRS.

Since the 1970s, the equipment and methods used to survey water reservoirs have changed markedly. Geographic location is determined using differential Global Positioning System (DGPS) navigation, while water depth and sediment thickness are simultaneously measured using acoustical profiling instruments (Sullivan, 1995; Dunbar et al., 1999, 2001). These improvements in instrumentation are applicable to surveys of large water-supply reservoirs, but the instrumentation is normally too large and heavy to be used on the small boats used to survey FRS. FRS normally do not have prepared boat access and require shallow-draft boats in the 12 to 14 ft range that can be carried or towed overland to the shore (Figure 3). Recently, a smaller and lighter profiling instrument with an integrated DGPS navigation system was developed specifically for FRS surveys (Dunbar and Allen, 2004). This system makes it possible to survey FRS with higher spatial sample density and in less time than traditional methods. Surveys of FRS that required weeks or months of field time in the 1950's and 1960's can now be completed in a single day.

Figure 3 FRS surveying equipment.

a. b.

(a) Launching survey boat down portable roller ramps at BC 39. (b) FRS survey system.

Methods

Principle spillway inspection and repair

The principle spillway is a critical part of FRSs, and failure could result in breach of the dam with catastrophic consequences. Although the components of the principle spillway vary, many have an inlet consisting of a vertical riser made of concrete or steel pipe (Figure 2). The top of the principle spillway riser is covered by a grate to prevent debris from entering the outlet works and topped by a steel and wood or concrete platform (Figure 4 a). There is also a valve that opens a secondary inlet near the base of the riser, which is used to drain the reservoir for maintenance (Figure 4 b). A perforated steel cap on the drain inlet, called the minnow bucket, prevents debris from entering the secondary inlet while it is open (Figure 4 c). The riser attaches to a sub-horizontal conduit that passes through the dam to the downstream side (Figure 4 d). In some of the early designs, the section of pipe that passes through the dam is made of concrete and is attached to a tailpipe made of corrugated steel pipe. The attachment point between the two sections is buried 6 to 10 m into the downstream side of the dam embankment.

Inspection of the principle spillway is conducted in two phases. First, the operational status of the spillway platform, top grate, and the secondary drain value can all be inspected from the platform. The grating is subject to corrosion and damage from debris. The valve that opens the secondary inlet is subject to corrosion and breakage. Second, the condition of the riser, through-dam conduit, and tailpipe are inspected using a remotely operated video camera. The camera is waterproof and mounted on a small remotely controlled, wheeled vehicle. The camera vehicle is attached to an umbilical cable that provides power and control to the vehicle, and real-time video feed from the vehicle to the operator on the surface. The remote control camera is used to inspect the interior parts of the spillway for corrosion, cracks, and collapse.

Selecting FRS for surveys

In the early days of the USDA-NRCS Watershed Program, it was standard practice to monitor the volume loss due to sedimentation in FRSs by repeating sediment surveys every 5 to 10 years (Dendy, 1968). Since most of the factors that control sedimentation rates are similar across local watersheds, it was customary to select one or two representative FRSs to survey in each watershed. The overall volume loss rate of FRSs within the watershed was estimated based on the results for the representative reservoirs. The same approach is used in this project. The goal was to select FRSs for surveys that likely reflect the typical state of sedimentation of other FRSs in the watershed.

Figure 4 Inspecting principle spillway components.

(a) Inspecting secondary inlet valve controller. b) Inspecting the operation of the valve to secondary inlet to the principle spillway. (c) Inspecting the Minnow Bucket, which prevents debris from entering the secondary inlet to the principle spillway. (d) Inspecting the joint between the principle spillway conduit (concrete) and the principle spillway tailpipe (corrugated iron pipe). See elements of FRSs in Figure 2.

Factors that influence the long-term rate of reservoir sedimentation can be divided into a group of factors that are time invariant aspects of the contributing watershed and two other factors that can change significantly over the service life of the reservoir (Dendy, 1974). The main time invariant factors are the soil erodability, landscape slope, watershed area, and reservoir trap efficiency. By definition, highly erodable soils promote erosion, as does increased land surface slope. Watershed area is a factor in reservoir sedimentation, because not all the sediment eroded from the landscape reaches the FRS. Sediment is delivered more efficiently in small watersheds than in large watersheds (Greiner, 1982). The trap efficiency of a FRS in a given storm event is a function of the ratio of the floodwater storage capacity of the structure and the volume of the runoff. Over the long term and within a given watershed, FRS trap efficiency is a function of the ratio of the floodwater storage capacity and the contributing watershed area (Dendy, 1974). Hence, sedimentation in a FRS per unit watershed area depends on four main time invariant factors. These are: (1) soil type, (2) average slope, (3) watershed area, and (4) the ratio of the floodwater capacity of the FRS to the contributing watershed area. Table 1 lists these properties for the FRSs in McCulloch County. The preference is to pick reservoirs for surveys for which these factors are near the overall averages for all the FRSs in the County.

The two main factors controlling reservoirs sedimentation that change over time are land use and climate. Within the same soil type and slope, land use influences the amount of sediment produced per unit area or sediment yield. Forestland normally has the lowest sediment yield and cropland the highest, with pastureland, rangeland, and brushland tending to fall between these two extremes (Greiner, 1982). Urban areas are a special case, in which the process of urbanization commonly results in a pulse of high sediment yield, followed by lower yields when the process is complete (Wolman, 1967). In general, the conversion from natural landscapes to agricultural and urban landscapes can result in an overall increase in sediment yield by a factor of 150 or more (Verstraeten and Prosser, 2008).

Table 1 Properties of FRS of McCulloch County, Texas.

Reservoir	Longitude (deg)	Latitude (deg)	Date Impounded	USLE K*	Relief Ratio	Primary Land Use	Watershed Area (km^2)	C/A (m)
BC 1	-99.3650	31.0917	1956	0.32	0.013	Range-Brush	18.21	0.253
BC 4	-99.4450	31.0667	1957	0.32	0.009	Range-Brush	9.30	0.231
BC 5	-99.4783	31.0567	1958	0.32	0.010	Range-Brush	10.52	0.196
BC 6	-99.4717	31.0783	1958	0.32	0.009	Range-Brush	11.63	0.216
BC 10	-99.5117	31.1183	1957	0.32	0.011	Range-Brush	3.63	0.208
BC 11	-99.5167	31.1033	1958	0.32	0.009	Range-Brush	6.89	0.133
BC 12	-99.5367	31.0833	1959	0.32	0.009	Range-Brush	6.68	0.238
BC 13	-99.5533	31.0733	1958	0.32	0.009	Range-Brush	8.91	0.252
BC 14	-99.5800	31.0717	1956	0.32	0.006	Range-Brush	29.84	0.320
BC 15	-99.577	31.0967	1959	0.32	0.008	Range-Brush	11.84	0.209
BC 16	-99.6067	31.1233	1959	0.32	0.009	Range-	9.66	0.201

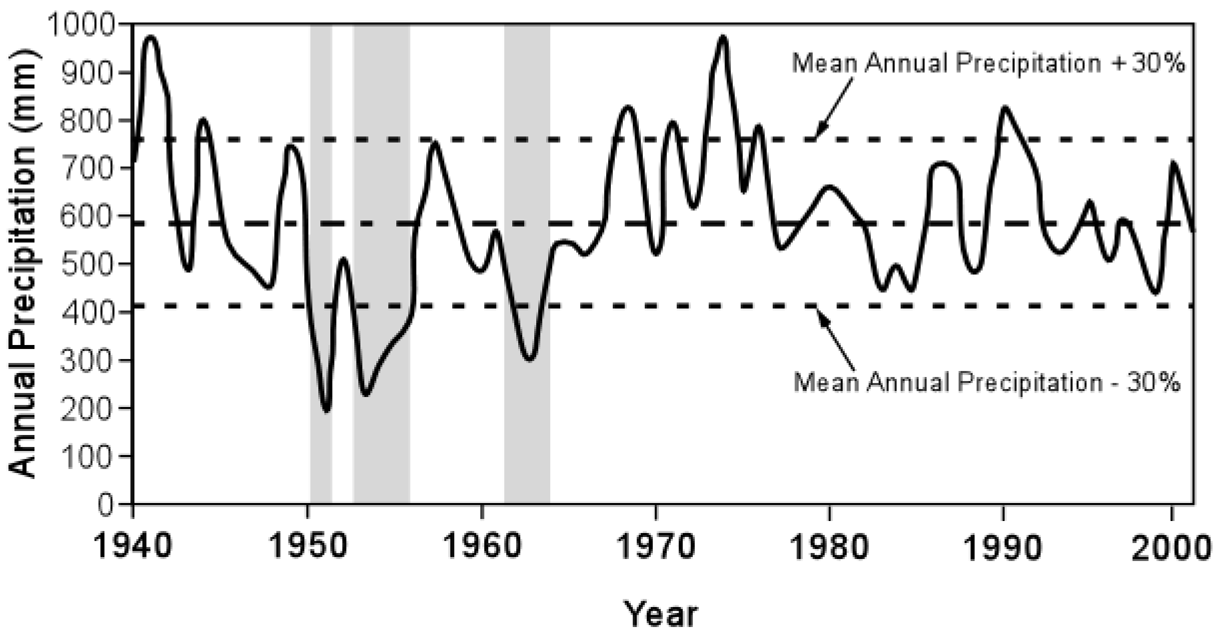
Reservoir	Longitude (deg)	Latitude (deg)	Date Impounded	USLE K*	Relief Ratio	Primary Land Use	Watershed Area (km^2)	C/A (m)
						Brush		
BC 17	-99.5967	31.1467	1962	0.32	0.004	Range-Brush	74.60	0.223
BC 39	-99.5600	31.2367	1955	0.32	0.009	Range-Brush	11.94	0.211
BC 40	-99.5267	31.2150	1955	0.32	0.011	Range-Brush	3.88	0.213
BC 41	-99.5100	31.2150	1958	0.32	0.008	Range-Brush	23.26	0.198
BC 43A	-99.4533	31.2150	1960	0.32	0.006	Agricultural	7.72	0.196
BC 43B	-99.4417	31.2083	1960	0.32	0.011	Range-Brush	15.96	0.206
BC 44	-99.3550	31.2000	1955	0.32	0.007	Agricultural	5.83	0.340
BC 45	-99.3483	31.2217	1956	0.32	0.006	Agricultural	8.55	0.285
BC 46	-99.3233	31.2017	1956	0.32	0.011	Improved Grass	7.62	0.343
DC 1	-99.1567	31.2683	1952	0.32	0.010	Range-Brush	23.08	0.244
DC 2	-99.1400	31.2783	1952	0.32	0.014	Agricultural	2.46	0.263
DC 3	-99.1683	31.2833	1952	0.17	0.016	Range-Brush	8.50	0.282
DC 4	-99.1300	31.2950	1952	0.32	0.015	Range-Brush	3.26	0.200
DC 5	-99.1200	31.3350	1952	0.32	0.011	Range-Brush	12.33	0.243
DC 8	-99.1400	31.3850	1952	0.24	0.011	Range-Brush	14.01	0.191
LSS 1	-99.1200	31.2283	1959	0.32	0.012	Range-Brush	7.12	0.148
SWL 6A	-99.5847	31.2797	1987	0.32	0.013	Agricultural	20.88	0.117
SWL 7	-99.5583	31.3367	1982	0.32	0.007	Improved Grass	9.58	0.206
Averages				**0.31**	**0.010**	**Range-Brush**	**13.37**	**0.226**

Entries for surveyed reservoirs are shaded. C/A is the ratio of the reservoir floodwater storage capacity (m^3) to the watershed area (m^2). Properties of Brady Reservoir are not included. Brady Reservoirs is owned and maintained by the City of Brady, Texas.

Land use in the project area is predominantly rangeland and brush, with only minor amounts of cropland (2%), and has not changed significantly over time. While an important consideration in many sedimentation studies, land-use change is not an important factor in this project. To be representative of the project area, the preference is to select FRSs with rangeland and brush-land watersheds. The dominant land use within the watersheds of the FRSs of McCulloch County are listed in Table 1. Table 1 does not include Brady Creek Reservoir.

In contrast to land-use change, short-term climate change is normally always a factor in reservoir sedimentation, in that climate is seldom constant over spans of 50 to 100 years. The most important climate factor influencing sediment yield in Texas is drought. The period from 1950 to 1956, during which many of the FRSs in McCulloch County were built, includes the most severe drought on record in the Edwards Plateau (Bradley and Malstaff, 2004). Drought influences erosion by reducing vegetative cover and soil moisture, making the soil more vulnerable to erosion by the intense rains that may occur during and immediately following droughts (Nearing et al., 2005). Two droughts occurred within the period from 1950 to 1956 in the Edwards Plateau. The long-term average annual rainfall for the project area is 580 mm/yr. In the rainfall record from the City of Menard, Texas, 54 km southwest of the City of Brady, there was a short-lived drought during 1950, in which the rainfall dropped to 190 mm/yr, followed by a recovery to near normal levels during 1951 (Figure 5). During 1952, rainfall dropped back down to 200 mm/yr and remained below normal through the end of 1955 in what is now referred to as the “drought of record” for the Edwards Plateau (Bradley and Malstaff, 2004). The 1950s droughts were followed by one less severe drought from 1961 to 1963. Since then local rainfall levels have remained near normal levels or above. To account for possible variations in sedimentation rates through the 1950s droughts, the year of impoundment is considered in selecting FRSs for surveys. The preference is to survey reservoirs impounded at different times within and just after the drought period. The years in which FRSs in McCulloch County were impounded are given in Table 1.

Figure 5 Precipitation record for the project area.



Annual precipitation recorded for the City of Menard located 54 km (33 mi.) southwest of Brady, Texas. Periods of drought, defined at annual precipitation rates 30% below normal, are indicated with grey shading. This figure is modified from Bradley and Malstaff, 2004).

In addition to physical factors, there are programmatic and technical factors that are considered in the final FRS selection. For the purposes of this project, the preference was to survey FRSs that have reached the design life of the sediment pool (50 years). It was also preferable to select the oldest FRSs, because they provide the longest record of sedimentation. Similarly, sediments deposited in 1954 ± 2 yr can be identified in cores using the ^{137}Cs method. Hence, FRSs that were impounded from 1952 to 1956 are preferred, because the onset of sedimentation coincides with the onset of ^{137}Cs deposition. Finally, the preference is to re-survey FRSs in the region that were previously surveyed by USDA-NRCS. This provides comparability between the new surveys and past surveys and makes it possible to assess the change in sedimentation rates over time.

Sediment surveys

Modern sediment surveys of water supply reservoirs are conducted by traversing the reservoir along parallel profiles in a vessel equipped with an acoustic fathometer and a DGPS positioning system (USACE, 1989; 2001). The data are used to map the bathymetry of the reservoir and to compute the water storage capacity at the normal pool elevation. The volume of post-impoundment sediment is then inferred indirectly from the apparent change in water capacity between the time of impoundment or a previous survey and the current survey. This approach relies on the reservoir being filled nearly to the normal-pool elevation and having an accurate previous survey. These conditions are seldom met for FRSs. In McCulloch County, FRSs range from being completely dry most of the time, to being completely full most of the time. In the former case, in which the water level is significantly below the normal pool elevation, normal reservoir survey methods must be augmented with land surveying as necessary to achieve complete data coverage.

Lake surveying

In the water-covered portions of FRSs, the survey method is similar to the standard method used for surveys of large water-supply reservoirs, except that the profiles are spaced 10 to 15 m apart verses 100 m or more apart. The survey is done using a shallow-water boat equipped with a lightweight, five-frequency sub-bottom acoustic profiling system with signal frequencies of 12, 25, 50, 100 and 200 kHz and a lightweight underwater vibracoring system. The high-frequency acoustic signals are used to map water depth, from which the remaining reservoir storage capacity is computed. Where possible, the low frequency signals are used to map the sediment thickness, from which the sediment volume is computed (Dunbar et al., 1999). Full-waveform digital recordings of the acoustic profiles are made during the survey so that the water bottom and base of sediment can be manually traced on the redisplayed data during post-survey processing. This is normally not done in standard bathymetric surveys, but is particularly important in shallow or highly vegetated reservoirs. Under these conditions, conventional fathometers commonly miss-identify multiple reflections within the water column and reflections from vegetation as direct reflections from the water bottom. This can result in significant error in the water depth measurements.

During post-survey data processing, the round-trip travel time of acoustic signals from the transducer array to the bottom and base of sediment are measured. The travel times are converted to depth by multiplying by one-half the speed of sound in water. The speed of sound in the reservoir water is determined from an empirical relationship relating the speed of sound and the temperature and salinity of the water (Del Grosso, 1974). Water temperature and electrical conductivity are measured on a vertical profile through the water column at the deepest point in the reservoir, using a temperature/conductivity meter. Conductivity is then related to salinity using a second empirical relationship (Poisson, 1982). Because water in FRSs tends to be shallow and well stirred by winds, the variation in the speed of sound in the water due to changes in temperature and salinity tends to be 1% or less. The accuracy of the water depth measurements are verified by measuring the two-way travel times to a flat aluminum plate temporarily positioned at a known depth below the acoustic transducer array in deep water. The survey water depth measurements are relative to the water surface. To convert these measurements to water depth relative to the spillway elevation, the elevation difference between the water surface and the spillway is also measured on each day of the survey. The difference is added to the acoustically determined water depth.

In addition to the water depth measurements, the thickness of the sediment fill can also be measured with the low-frequency acoustic signals. This makes it possible to determine the sediment volume directly, without reference to prior surveys. Acoustically determined sediment thickness measurements are adjusted for the difference in the speed of sound in sediment by collecting co-located sediment cores in a few locations and comparing the sediment thickness measured in the cores with the two-way acoustic signal travel time through the sediment layer.

Two sets of acoustic profiles are collected during the surveys. One set crosses the narrow axis of the reservoir orthogonal to the long axis of the reservoir and a smaller set trends parallel to the long axis. During post-survey processing, the water bottom and base of sediment are independently traced on profile both sets. Then a special feature of the interpretation software computes the vertical miss-tie at the crossing points. The root-mean-square (RMS) miss-tie at profiling crossing points is used as an estimate of survey uncertainty. The RMS mist-ties for the water bottom is multiplied by the normal pool area to compute an estimate of the uncertainty in the water volume. The sum of the RMS miss-ties for the water bottom and base of sediment is multiplied by the normal pool area to compute an estimate of the uncertainty in the sediment volume. In cases in which the change in normal pool volume between two surveys is used to estimate the sediment volume and no error estimate is available for the initial survey, the combined uncertainty of the two surveys is assumed to be twice that of the present survey.

Acoustic measurement of the sediment thickness depends on the acoustic signal making a two-way transit through the sediment column. This works best in cases in which the sediment has high water content (30-80%) and is not too thick (0 to 3 m). In situations in which the sediment contains biogenic gas, the gassy sediment absorbs the acoustic signal and prevent the signal from reaching the base of sediment, even if the sediment layer is relatively thin. In these cases, the sediment volume is determined from the change in water volume from either the as-built reservoir volume or the volume determined in a prior survey.

Land surveying

For FRSs that are only partly full of water, land-based surveying operations are required to survey the complete normal-pool area. In the land-based surveying, the difference in elevation of the exposed reservoir bottom relative to the principle spillway elevation is measured using real-time kinematic (RTK) GPS. In RTK GPS, measurements of the carrier phase of the GPS signal are used to correct the GPS positions in real time to an accuracy of 1-2 cm horizontally and 2-3 cm vertically (USACE, 2001, Chapter 16). Two RTK units are deployed and linked by radio. One unit is left at a fixed reference location and the other station is mounted on a mobile survey vehicle. For moving over the dry FRS bottom efficiently, the mobile RTK GPS unit is mounted on an all terrain vehicle (ATV), with the antenna held at a fixed height above the ground surface. As the ATV is driven along profiles across the dry reservoir bottom, the RTK GPS system measures and records the geographic position and elevation difference between the mobile and fixed station. The precision of the RTK GPS system is determined by measuring the position of a fixed station before and after each survey. In post-survey analysis, the RTK GPS data are combined with the water-based measurements and used to map the reservoir depth and compute the remaining reservoir storage capacity below the normal pool elevation.

RTK GPS measures the land surface elevation, but provides no means of mapping the thickness of sediment that may have been deposited in areas of the FRS that are dry during the survey. If a significant volume of sediment occurs in the exposed area, the sediment volume will be underestimated by the direct measurement approach. To test for this possibility, the sum of the current water storage capacity and the sediment volume are compared to the reported as-built water storage capacity. If the sum is significantly less than the as-built volume, missing sediment is suspected. To further test for sediment deposits on land, cores are collected from the dry reservoir bottom to check for deposits with sediment texture rather than soil textures.

Surface modeling and volumetric calculations

The water storage and sediment volumes within the normal pool of FRS are determined by generating surface models of the water depth and sediment thickness and then integrating those values over the area of the normal pool. Triangulated irregular network (TIN) surfaces are used to represent the complex shapes of FRS. First, a flat triangular surface is generated within the area to be mapped. Then the surface is deformed to pass through the acoustically determined water depth and sediment thickness points in a least-squares sense, while remaining as smooth as possible. Volumes are calculated by summing the volumes associated with each triangular facet.

The rate of sediment yield from contributing watershed is determined from the dry mass of sediment deposited per year in FRS. This effectively factors out differences in the degree of sediment compaction between reservoirs and within the same reservoir over time. The dry mass of sediment is computed by multiplying the volume of trapped sediment by the average dry bulk density of the sediment, which is the mass of dry sediment per unit volume of wet sediment. The volume of sediment is measured directly from acoustically mapped sediment thickness or inferred from the apparent change in storage volume from the as-built volume or the volume reported in a prior survey. Experience from surveys of over 30 FRS indicates that the as-built volumes reported in the NID (National Inventory of Dams, 2007) and USDA-NRCS records match the sum of water and sediment volume from modern surveys within 1 to 2% in many cases (Dunbar and Allen, 2006). In other examples, the discrepancy is 50% or more, with the modern water storage capacity in some cases exceeding the recorded as-built volumes. In these instances, the reported normal-pool volume is thought to reflect the volume relative to the natural landscape prior to construction of the dam and does not include the volume of borrow material extracted from the normal-pool area to build the dam. In these cases, the only recourse is to rely on the acoustically measured sediment volume.

Sediment and soil coring

Sediment core samples are collected as part of the sediment survey to estimate the average dry bulk density of the sediment and to provide samples for ^{137}Cs dating and chemical analyses. Sediment texture and degree of compaction tend to vary along the axis of reservoirs, with the sediment in backwater regions being coarser and more compacted than sediment in the deeper regions near the dam (Dendy, 1982). Following the strategy described by Van Metre et al. (2003), three core sites are selected in each FRS surveyed to sample sediment variability. One site is in the deepest water near the dam, one site is in an intermediate position along the axis of the reservoir and one site is in the backwater region. Two cores are collected at each site to provide one set of samples for visual inspection and analysis of physical properties and another set for chemical analyses.

Where there is sufficient water depth to float the survey boat, sediment cores are collected using a submersible vibracoring system. Vibracoring is a standard method for obtaining cores of unconsolidated sediment with little or no bypass of sediment around the core tube (Lanesky et al., 1979; Smith, 1984). For FRSs, with access limited to small boats, the light weight of the vibracoring equipment makes it the only practical option for collecting cores that penetrate the entire sediment column and into the pre-impoundment material. The vibracoring system is sufficiently lightweight (40 kg) that it can be deployed from a 14 ft Jon boat fitted with an A-frame and hand-operated winch. The device runs on 24-volt DC current supplied by two 12-volt trolling motor batteries connected in series. The vibrator is connected to the top of an aluminum or stainless steel core tube, with 1.5 mm wall thickness and 76 mm diameter. The vibration causes the sediment to liquefy in a region a few millimeters thick near the core tube wall, allowing the tube to slide into the sediment with little drag. This device collects cores up to 3 m in length in soft sediment.

To the extent possible, cores are collected in the water-covered parts of the FRS. Nutrients and other contaminants in exposed and dried sediment are subject to vertical migration with meteoric water and uptake by plants. Hence, sediments in the parts of reservoirs that are dry most of the year are not ideal recorders of trapped contaminants. Where necessary, coring the exposed reservoir bottom requires a different approach. Here, a vibracoring system based on a pneumatic fencepost driver is used. Because the sediments are dry and compacted, more power is required to drive the core tube into the sediment. The pneumatic driver essentially hammers the tube into the ground. The land coring system consists of a gasoline-powered air compressor, driver head, and a trailer-mounted tripod with a hand winch for extracting the tubes. The system is towed to the coring site. For consistency, the same thin-walled aluminum or stainless steel core tubes are used for both water and land coring operations.

Core analysis

Physical properties

The two cores collected at each site are used for different analyses. Cores collected in aluminum core tubes are cut open lengthwise for visual inspection to identify the depth to the pre-impoundment surface based on delineated stratigraphic and sedimentological properties. After visual inspection and interpretation, these cores are sub-sampled in 5 cm increments for water content analysis, penetration resistance measurements, and ^{137}Cs dating. The water content by mass of the sediment is determined from the core samples by weighing sub-samples wet, drying the samples for 24 hours at 106 °C, and then weighing the samples again after they are dry. The water content is then given by the fractional change in the mass of the sediment sample from its wet to dry states

$$wc = \frac{m_{wet} - m_{dry}}{m_{wet}}, \quad (1)$$

where m_{wet} is the mass of the sediment sample in its field condition and m_{dry} is the mass of the same sample after drying (ASTM Standard Method D2216-92, as defined in ASTM Standards Volume 04.08 – Construction, Soil, and Rock).

The dry mass of sediment in each FRS is determined by multiplying the total volume of wet sediment times the dry bulk density of the sediment (mass of dry solids divided by the volume of the wet sediment). The dry bulk density of the sediment is computed from the water continent using the relation (Van Metre et al., 2003)

$$\rho_{db} = \frac{\rho_w \rho_s \left(1 - wc\right)}{\rho_s (wc) + \rho_w (1 - wc)}, \quad (2)$$

where ρ_{db} is the dry bulk density, ρ_w is the density of water, wc is the water content by mass, and ρ_s is the average density of the sediment solids.

The density of the solids fraction of the sediment is computed from the density of the primary components, mineral sediment grains and organic carbon (Avnimelech et al., 2001). The sediment mineral grains are a mixture of quartz, which has a density of 2.65 g/cm^3, and clay, which ranges in density from 2.6 to 2.7 g/cm^3. Hence, an average mineral grain density of 2.65 g/cm^3 is assumed. Organic particles are assumed to have a density of 1.25 g/cm^3. The average solids density is then given by

$$\rho_s = 2.65(1 - OC) + 1.25OC, \quad (3)$$

where *OC* is the organic carbon weight fraction produced by the analytical method listed in Table 2.

To compute an estimate of the average dry bulk density for the sediment in a FRS, the average dry bulk density is determined for the post-impoundment interval within each core. Then the average of densities of the cores weighted by the length of the post-impoundment interval in the cores is computed.

^{137}*Cs Analysis*

The dried sediment samples from the aluminum core tubes are also used for ^{137}Cs analysis. ^{137}Cs analysis is a standard method for identifying age lines in sediment cores in lakes and water reservoirs that correspond to changes in fallout rates of atmospheric ^{137}Cs (Ritchie et al., 1986; Ritchie, 1998; Van Metre et al. 2003; 2004). ^{137}Cs is a component of radioactive fallout from atmospheric nuclear tests in the 1950s and 1960s, which has a half-life of 30.2 yr. Significant fallout of radioactive ^{137}Cs began in North America in 1954 ± 2 yr and reached a peak in 1964 ± 2 yr (Ritchie et al., 1986). ^{137}Cs is primarily carried by the clay texture fraction of sediment. Hence, the core from each FRS that appears to be the most clay-rich and to contain the most complete depositional record is selected for dating. This is normally the core from the deepest part of the reservoir. ^{137}Cs analyses are performed on each 5 cm sub-sample of the selected core. The concentration of ^{137}Cs is determined by placing 25 g of powered and sieved sediment in a 50x9 mm Petri dish and placing the dish in a lead-shielded chamber containing a Germanium gamma ray detector. The gamma rays emitted by the sample that fall within a Gaussian window about 661.65 KeV are then counted for 80,000 s (22.2 hr). The reservoirs surveyed were all impounded between 1952 and 1956. Hence, the presence of detectable concentrations of ^{137}Cs in sub-samples of the cores indicates post-impoundment deposition, and identification of the 1964 peak in ^{137}Cs in the cores makes it possible to compare sedimentation rates from the date of impoundment to 1964 and from 1964 to present.

Table 2 Sediment chemical analysis performance specifications.

Analyte	Units	Method	Reporting limits	Recovery at Reporting Limits	PRECISION (RPD of LCS/LCSD)	BIAS (% Rec. LCS/LCSD mean)
Total Organic Carbon	mg/L	EPA 415.1	2.0 (AWRL)	75-125	80-120	80-120
Total Nitrogen	mg/L	EPA 353.2	0.01	75-125	80-120	80-120
Total Phosphorus	mg/L	EPA 365.3	0.01	75-125	80-120	80-120
NH_3-N	mg/L	EPA 350.1	0.02	75-125	80-120	80-120
NO_2-N+NO_3-N	mg/L	EPA 350.1	0.02	75-125	80-120	80-120

Analyte	Units	Method	Reporting limits	Recovery at Reporting Limits	PRECISION (RPD of LCS/LCSD)	BIAS (% Rec. LCS/LCSD mean)
Metals	mg/L	EPA 1620	0.0002-5	75-125	80-120	80-120
Pesticides	ng/g	EPA 612	0.5	75-125	80-120	80-120

References for Table 2:

1. USEPA, *Methods for Chemical Analysis of Water and Wastes*, EPA-600-4-79-020.
2. American Public Health Association, American Water Works Association, and Water Environment Federation, *Standard Methods for the Examination of Water and Wastewater*, 21st Edition, 2005.
3. TCEQ, *SWQM Procedures Volume 1: Physical and Chemical Monitoring Methods for Water, Sediment and Tissue* (December 2003).
4. American Society for Testing and Materials (ASTM) Annual Book of Standards, Vol. 11.02.

Sediment contaminant analysis

The cores collected in stainless steel tubes at each core site are used to establish the quality of the trapped sediment. Sediment quality is of interest for two reasons. First, it is a measure of the amount of contamination that has been removed from surface water over the life of the FRS and thereby was not transported into downstream water bodies, including water supply reservoirs. Second, it is a measure of how much contamination could potentially be remobilized and added to surface water if the FRS were removed or the sediment dredged. The sediment in the cores is extruded in 5 cm sub-samples and frozen for preservation. Average concentrations of contaminants are determined by forming a composite sample from the core sub-samples. The composite samples are analyzed to determine concentrations of total organic carbon, common nutrients (total nitrogen, total phosphorus, NH3-N, NO2-N, and NO3-N), a suite of trace metals, and a suite of common pesticides. Contaminant analytes and the methods used to measure their concentrations are listed in Table 2. These analyses determine the mass of each analyte per gram of dry sediment sample. The mass concentrations are used to estimate the total mass of each contaminant species trapped within the reservoirs that would have potentially remained in the surface water or adjacent floodplain, if the reservoirs were not present.

Assessing the overall impact of FRSs in McCulloch County

Brady Reservoir was impounded in 1963, with an initial water storage capacity of 37,012,500 m^3. The 1,329 km^2 watershed of Brady Reservoir includes the watersheds of 14 of the 29 FRSs in McCulloch County. The other 15 FRSs are on tributary streams of the Colorado River, which is the main tributary of the Highland Lakes of the Lower Colorado River.

The 14 FRSs within the Brady Reservoir watershed have a combined watershed area of 223 km^2. All 14 reservoirs were completed prior to the construction of Brady Reservoir in 1963. Their combined watershed area represents 16.8% of the watershed of Brady Reservoir. Assuming an average trap efficiency of 80%, this would mean that the 14 FRSs have trapped approximately 13% of the sediment and adsorbed contaminants coming from the watershed of Brady Reservoir and prevented them from reaching the reservoir. The actual amounts of sediment and adsorbed contaminants that have not reached Brady Reservoir because of the action of the FRSs is estimated by using the results of the FRS sediment surveys. An effective sediment yield per unit area of supplying watershed is computed by dividing the mass of sediment trapped in surveyed reservoirs during a time interval by the area of the supplying watershed and the length of the time interval. This value is then multiplied by the total of the watershed areas of upstream FRSs, an in-stream sediment delivery ratio, and the age of the Brady Reservoir. The delivery ratio accounts for the fact that not all of the sediment generated in a watershed reaches a given outlet point. The assumption is made that the sediment deposited in FRSs had been transported overland and into small streams before it was trapped. Therefore, the in-stream delivery ratio suggested by Greiner (1982) for streams of Texas is used

$$D = 0.695\left(2.713\right)^{-0.0000406A}, \quad (4)$$

where D is the in-stream delivery ratio and A is the watershed area in km^2.

By Equation 4, the delivery ratio for the Brady Reservoir watershed is 0.659. The age of Brady Reservoir at the time of the surveys was 44 yr. Hence, the mass of sediment not present in Brady Reservoir as a result of the 14 upstream FRSs is given by

$$M = 38,536Y_e, \quad (5)$$

Where M is the mass of sediment in mton and Y_e is the effective sediment yield in mton/km^2/yr for the watershed.

Once the mass of sediment prevented from reaching Brady Reservoir is known, the mass of adsorbed contaminant species is estimated by multiplying their mass concentration in the trapped sediments times the mass that would have reach Brady Reservoir. Representative concentrations for the Brady Reservoir watershed as a whole are estimated by computing average concentrations from the individual reservoirs, weighted by the watershed areas of the surveyed reservoirs.

Results

Principle spillway inspection and repair

Of the 29 FRSs that were inspected, 15 required repairs and maintenance at a total cost of $277,865, in 2007 dollars. Of those that required repairs, 14 were 50 yrs old or older at the time of the inspection. The repairs performed were to the principal spillway and dam embankment. These included replacing corroded and collapsing tailpipe sections on 11 of the FRSs (Figure 6 a), repairing and replacing secondary inlet values on 12 of the FRSs and a minnow bucket and line on one FRS (Figure 6 b), and repairing the through-dam spillway conduit on 3 FRSs by inserting plastic slip liners (Figure 6 c). In addition to mechanical repairs of the principle spillway, grading work was performed on dam embankments of 6 FRSs, and other maintenance activities were required on 11 of the FRSs. No sediment was removed as part of the FRS repairs. Brady Reservoir is operated by the City of Brady and was not included in this project.

Reservoirs selected for surveys

Of the 30 FRSs in McCulloch County, only DC 3 had been surveyed before. DC 3 was surveyed four times after impoundment between 1953 and 1971. These surveys provide the best constraint on the change in sedimentation rates over time in the project area. Hence, DC 3 was chosen as one of the FRSs to survey. The 8.50 km^2 watershed area of DC 3 is less than the overall average of 13.37 km^2. Hence, DC 8, with a watershed area of 14.01 km^2 was chosen as the second FRS in the Deep Creek watershed to bracket the average. Similarly, BC 1 with a relief ratio of 0.013 and a watershed area of 18.21 km^2 and BC 39 with a relief ratio of 0.009 and 11.94 km^2, were chosen from the Brady Creek watershed to bracket the average relief ratio of 0.01 and the average watershed area. The watersheds of the four selected reservoirs are a combination of rangeland and brush land, which is characteristic of most of the Brady Creek and Deep Creek watersheds. Both DC 3 and DC 8 were impounded in 1952 and were in place throughout the drought of record. BC 39 was impounded in 1955, in the last year of the drought. BC 1 was impounded in 1956, in the year after the drought had broken in the project area. Therefore, this selection provides a range of impoundment dates during and after the drought of record.

Sediment surveys

Normal-pool capacity and sediment volumes

The sediment surveys of McCulloch County FRSs DC 3, DC 8, BC 1, and BC 39, were conducted in the winter to take advantage of the relatively high water levels in the reservoirs during that part of the year and required one field day for each survey. Although DC 3, DC 8 and BC 39 were filled to near their normal pool levels, most of the normal pool area of BC 1 was exposed and dry. For DC 3 and DC 8 essentially all of the normal pool area was underwater and was therefore surveyed by acoustic profiling (Figures 7 and 8). The land surveying RTK GPS system was used only to survey the perimeters of the normal pools. The lower lake level of BC 1 required combined acoustic profiling and RTK GPS surveying to survey the water covered and exposed portions of the normal-pool areas (Figure 9). For BC 39, most of the normal pool area was water covered, but an extensive land survey was conducted to establish the normal-pool outline (Figure 10).

Figure 6 Repairs to FRSs.

a.

b.

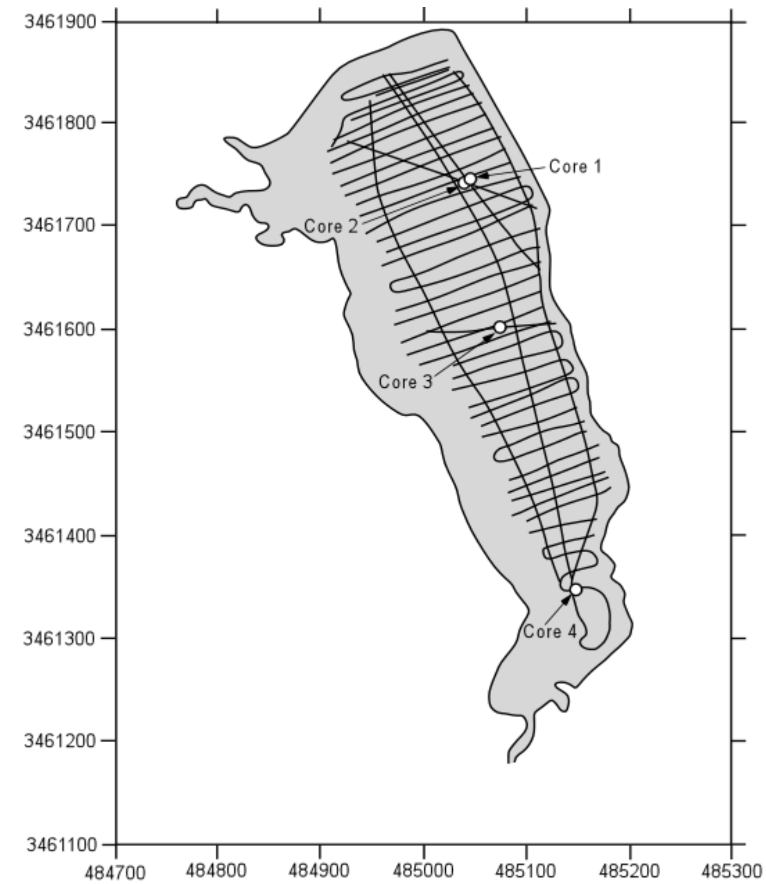
c.

(a) Replacing a tailpipe. (b) Replacing the valve and minnow bucket to the secondary inlet to the principle spillway.
(c) Inserting a slipline into a collapsing tailpipe.

Acoustic profiles from DC 3 and DC 8 show the water bottom clearly throughout, but do not show the base of sediment throughout. Comparison with the sediment cores indicates that the base of sediment coincides with the base of 25 kHz acoustic returns in intermediate water depths, but is below the maximum penetration of the acoustic signals in the deep water near the dams (Figures 11 and 12). High intensity scatter from near the top of the sediment column in the deep water in these two FRS suggests the presence of biogenic gas, which absorbs the signal. In contrast, acoustic profiles from BC 1 and BC 39 show the water bottom and the base of sediment clearly throughout (Figures 13 and 14). Aquatic vegetation is more prevalent in BC 1 and BC 39 than in DC 3 and DC 8. In the acoustic data, vegetation appears as narrow, vertical strips of acoustic returns that extend up into the water column from the water bottom on the 200 kHz records (Figures 13 a and 14 a). The underlying, true water bottom is a relatively smooth surface with a dark grey appearance on the acoustic records. The sediment layer in BC 1 and BC 39 is generally thinner than in DC 3 and DC 8 and apparently lacks biogenic gas. Comparison with cores shows that the base of sediment in BC 1 and BC 39 coincides with the bottom of the low frequency acoustic returns, which appear in shades of purple and blue on the acoustic records (Figures 13 b and 14 b).

The different acoustic response of the sediments in the FRS of the Deep Creek and Brady Creek watersheds necessitates different approaches to estimating the volume of trapped sediment. Because the base of sediment could not be traced acoustically over the entirety of the Deep Creek reservoirs, only the water depth was mapped for DC 3 and DC 8 (Figures 15 and B4-16). The base of sediment could be traced acoustically in the Brady Creek reservoirs. Hence, both the water depth and the sediment thickness were mapped in BC 1 and BC 39 (Figures 17 to 20). The sediment volume for BC 1 only includes contributions from the water-covered area of BC 1, which makes up just 30% of the surface area of the normal pool. Exposures of limestone float blocks from the surrounding valley slopes in the dry portions of the normal pool, as well as observed soil textures in two cores from the dry portion, indicate there has been little sediment accumulation in the dry portion of the normal pool. Because some sediment was likely deposited within the dry portion of the normal pool, the sediment volume estimate for BC 1 should be considered a minimum value.

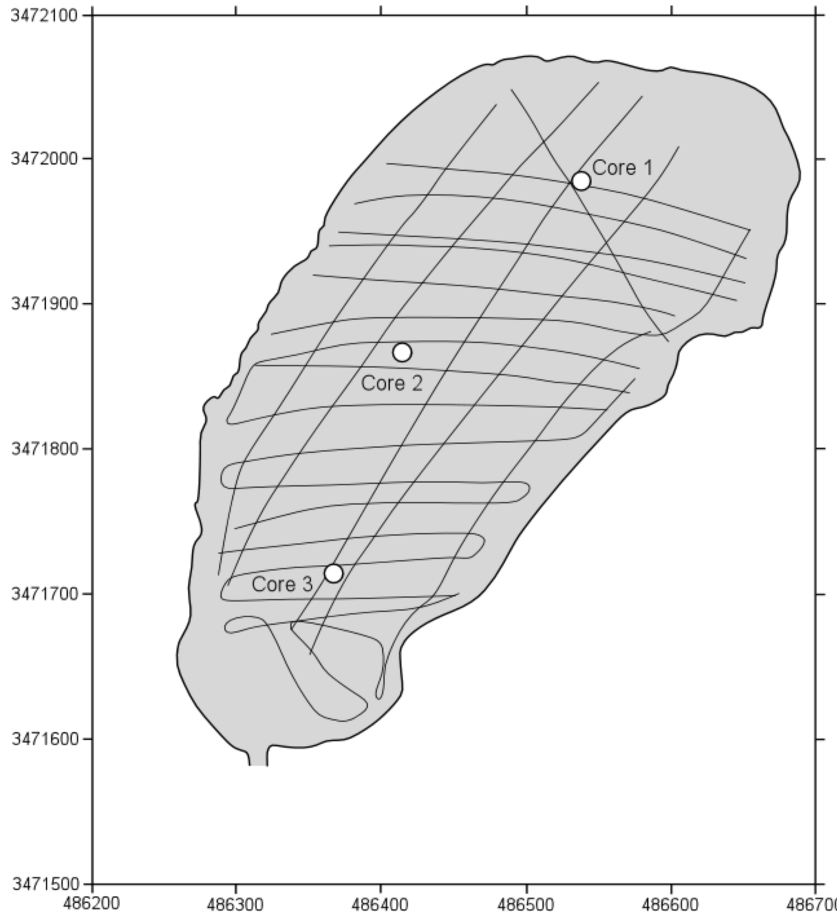
Figure 7 Profile and core location map for the survey of FRS DC 3.



Underwater region of normal pool is shaded in grey. Black curves mark recorded profile tracks. White circles indicate core locations. Geographic coordinates are in UTM Zone 14, North, meters.

The original volumes of BC 1 and BC 39 were computed by adding the current water and sediment volumes (Table 3). The as-built volumes recorded in the NID for BC 1 and BC 29 are 231,945 m^3 (188 acre-ft) and 46,882 m^3 (38 acre-ft), respectively. These volumes are less than the normal-pool volume measured in this project by 23 and 35%, respectively. This suggests that the normal-pool volumes recorded in the NID reflect the volume of the normal-pool area prior to reservoir construction and do not include the volume of material removed from the normal-pool area to construct the dams. For this reason, the sediment volumes for BC 1 and BC 39 were computed from the sediment thickness maps for the reservoirs (Figures 18 and 20).

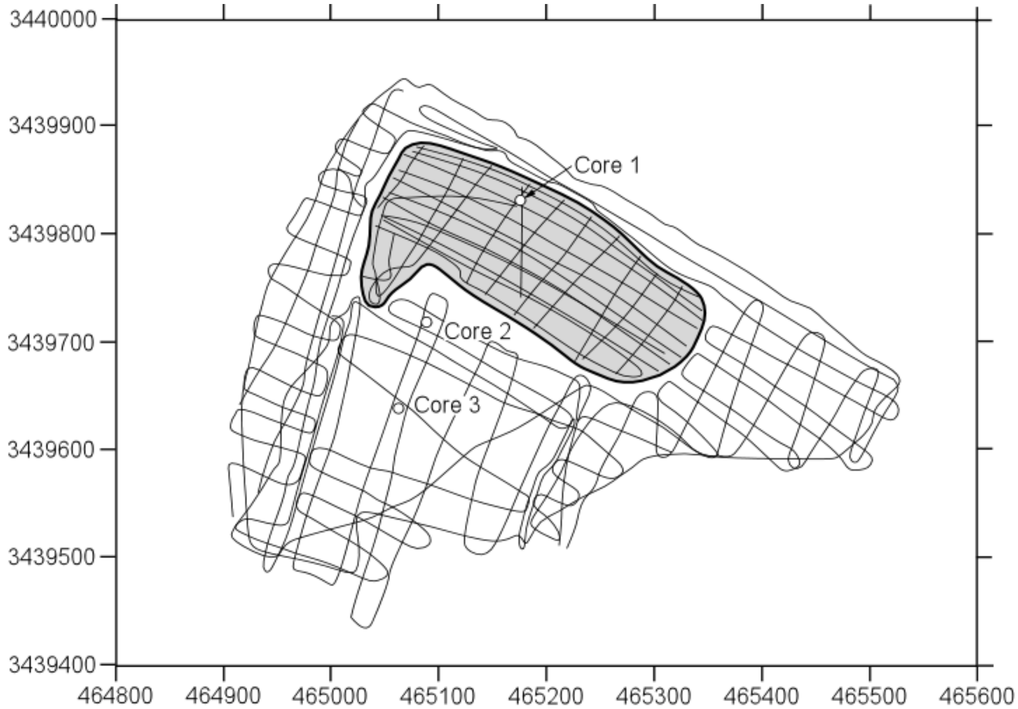
Figure 8 Profile and core location map for the survey of FRS DC 8.



Underwater region of normal pool is shaded in grey. Black curves mark recorded profile tracks. White circles indicate core locations. Geographic coordinates are in UTM Zone 14, North, meters.

The volume loss rates reported in Table 3 reflect the average loss rate over the life of the reservoirs. Prior surveys of DC 3 in 1953, 1960, 1965, and 1971 provide a record of how the loss rate for DC 3 changed over time (Figure 21). DC 3 underwent an initial rapid rate of volume loss, which progressively decreased over the first 19 yr after impoundment from an initial rate of 37,148 m^3/yr between 1952 and 1953, to 395 m^3/yr between 1960 and 1965. After 1965, the loss rate stabilized to the point that over the last 36 yr the average rate has been 217 m^3/yr.

Figure 9 Profile and core location map for the survey of FRS BC 1.



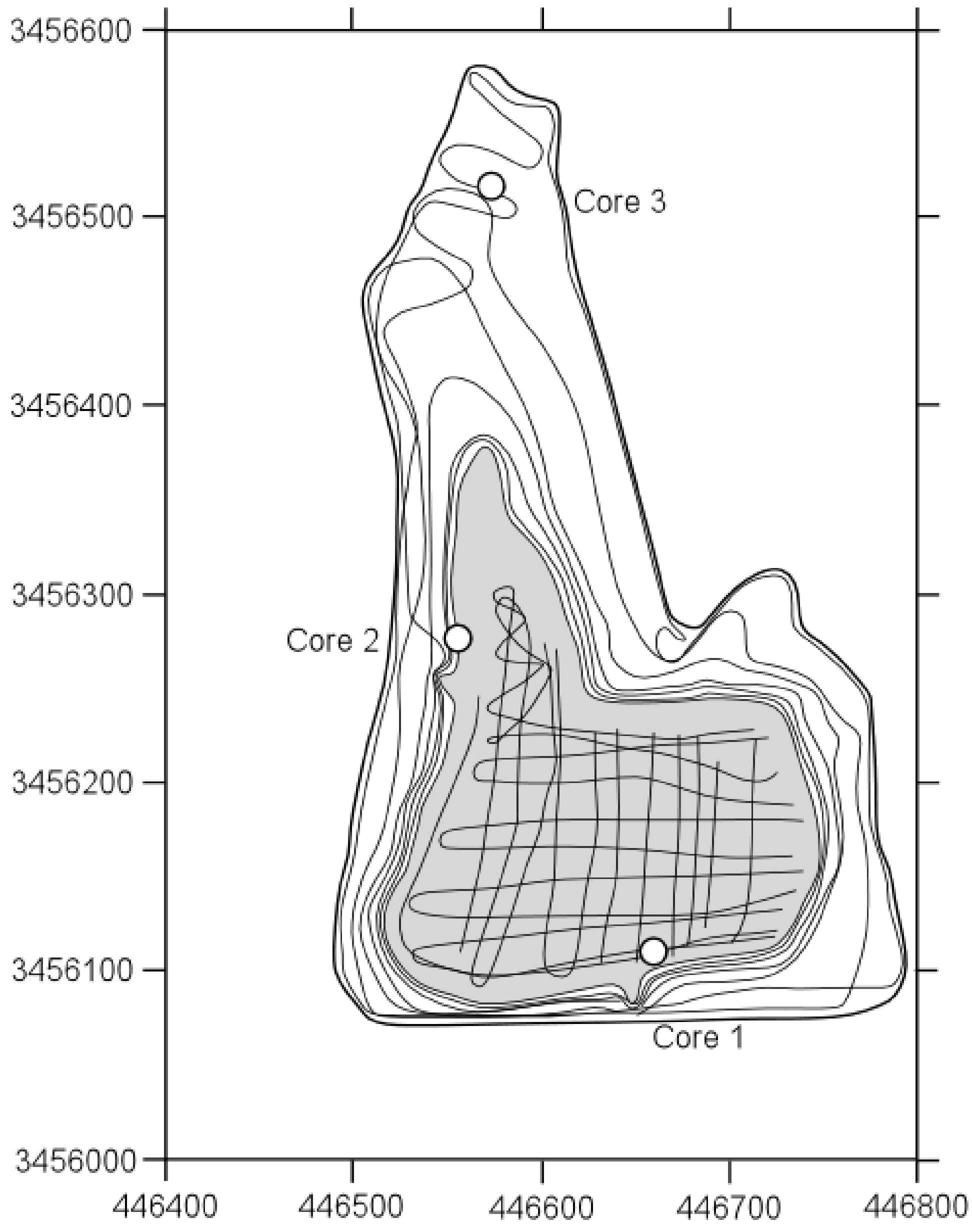
Underwater region of normal pool is shaded in grey. Black curves mark recorded profile tracks. White circles indicate core locations. Geographic coordinates are in UTM Zone 14, North, meters.

Erosion rates within different watersheds and at different times within the same watershed are compared using the effective sediment yield, which is the dry mass of accumulated sediment per unit area of the contributing watershed per year (Table 4). This parameter is a better indicator of erosion rates than volume loss rate, because it factors out differences in sediment compaction between reservoirs as well as differences in watershed area. In terms of the overall average, the two Deep Creek reservoirs record almost a factor of 10 greater effective sediment yield. However, the effective sediment yield recorded in DC 3 between 1971 and 2007 is comparable to the overall effective sediment yield values for the two Brady Creek reservoirs.

Sediment core analysis

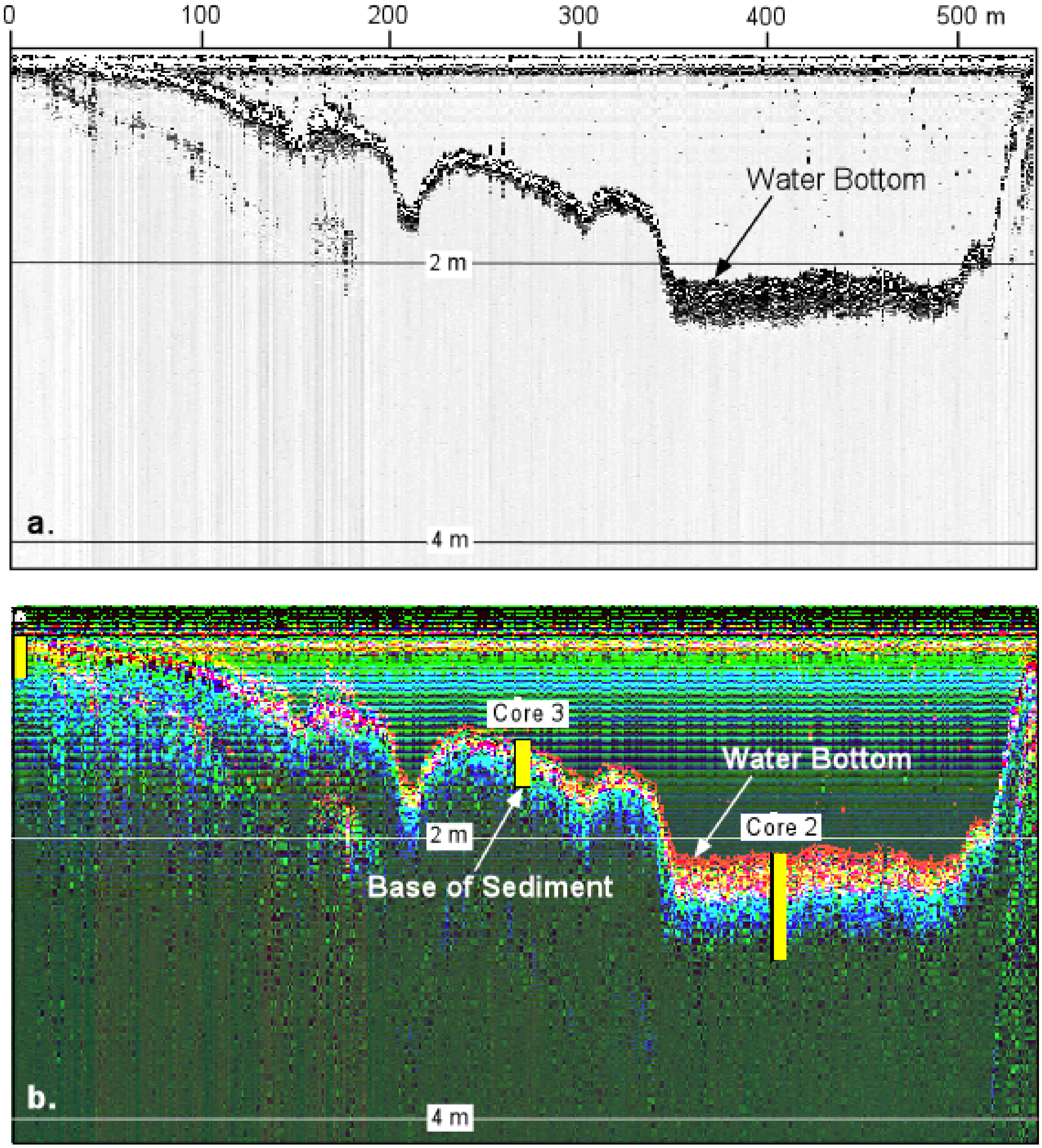
At least three cores were collected in each FRS at points distributed over both submerged and exposed parts of the normal-pool area (Figures 7 to 10). The cores provide a means of verifying and calibrating acoustically determined sediment thickness, provide point measures of sedimentation rates through ^{137}Cs analysis for comparison with volume loss rates, and provide samples to test for chemical contaminants. In DC 3, all but 15 cm of Core 1 was lost during retrieval. Hence, a second core, DC 3 Core 2, was collected at a slightly offset location in the deepest water near the dam (Figure 7). Vibracoring works best in high-water content, fine-grained sediment or wet sand. Coring in the McCulloch County FRSs was hampered by the highly compacted, clay-rich sediment. With the exception of the 148-cm-long DC 8 Core 3, none of the cores showed clear signs of penetration into the pre-impoundment material. Cores collected in shallow water in DC 3 and DC 8 and all of the cores from BC 1 and BC 39 were short (15 to 35 cm), and likely did not reach the pre-impoundment surface. All the cores were sub-sampled in 5-cm increments and water content and penetration resistance were measured on each sub-sample. In addition, ^{137}Cs analysis was run on the three longest cores, DC 3 Core 2, DC 8 Core 3, and BC 1 Core 1 (Figures 22 to 24).

Figure 10 Profile and core location map for the survey of FRS BC 39.



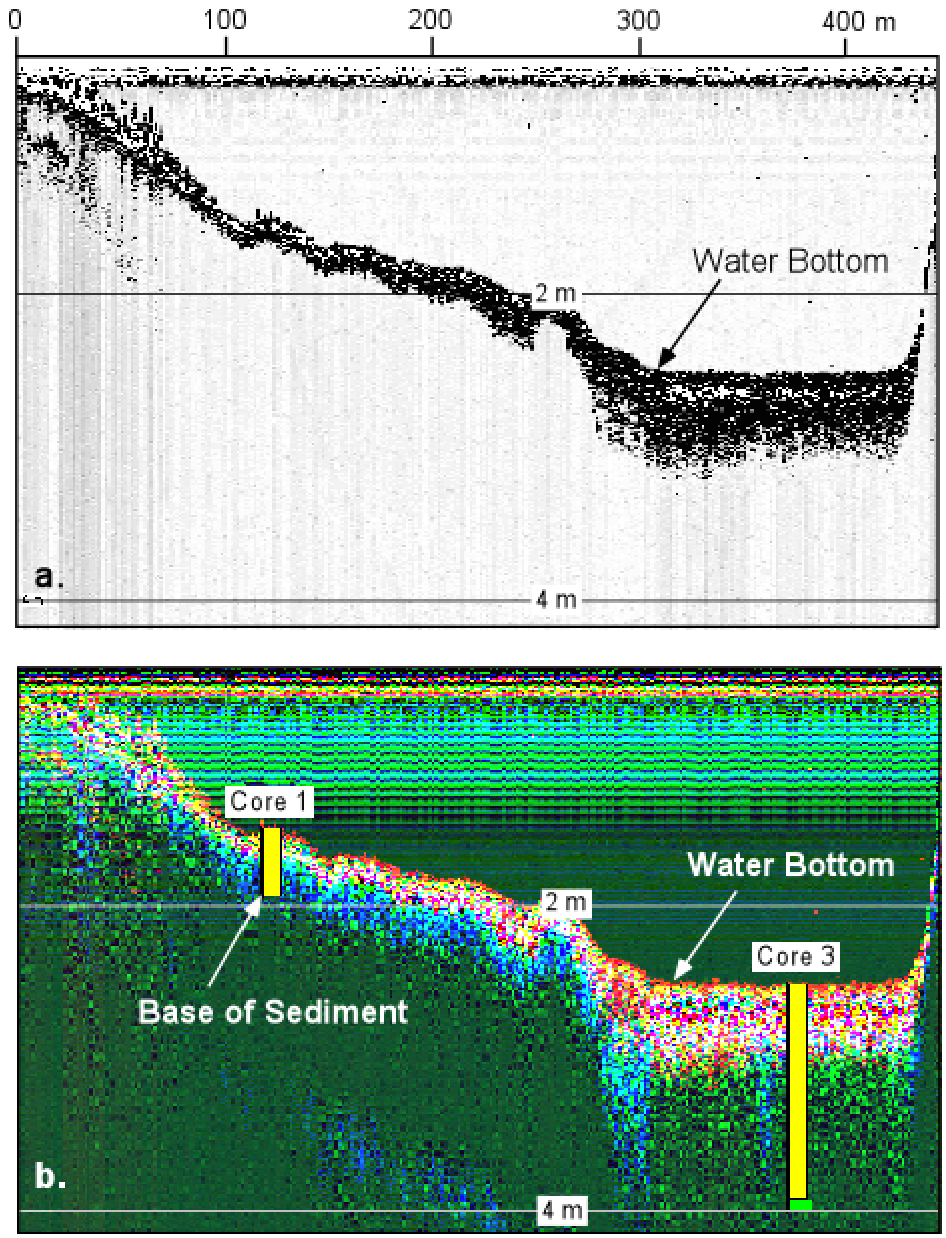
Underwater region of normal pool is shaded in grey. Black curves mark recorded profile tracks. White circles indicate core locations. Geographic coordinates are in UTM Zone 14, North, meters.

Figure 11 Axial acoustic profile from DC 3.



(a) 200 kHz profile used to measure water depth. (b) Multi-frequency composite profile. The red intensity is set from the 200 kHz signal, the green intensity is set with the 50 kHz signal, and the blue intensity is set from the 25 kHz signal. The yellow bars indicate the length of co-located sediment cores.

Figure 12 Axial acoustic profile from DC 8.



(a) 200 kHz profile used to measure water depth. (b) Multi-frequency composite profile. The red intensity is set from the 200 kHz signal, the green intensity is set with the 50 kHz signal, and the blue intensity is set from the 25 kHz signal. The yellow bars indicate the length of co-located sediment cores. Green bar at base of core diagram indicates pre-impoundment material.

DC 3 Core 2 provides the longest (77 cm) and most complete record of sedimentation in DC 3 (Figure 22). The water content of the sediment by weight varies from 52% to 38% over the length of the core and averages 42.7%. The mechanical stiffness of the sediment, measured by penetration resistance, reaches a maximum in the 15 to 20 cm sub-sample and decreased both upward and downward in the core from that point. This is indicative of a buried desiccation surface produced by a period of sub-aerial exposure and drying, which accounts for the relatively low overall water content of the core. The sediment in the bottom-most sub-sample of the core contains measurable ^{137}Cs, which indicates that the pre-impoundment material was not sampled (Figure 22 b). Rather than a distinct peak in ^{137}Cs concentration associated with the 1964±2 yr peak in ^{137}Cs deposition, DC 3 Core 2 shows a blunted peak. This is likely an artifact of the 5 cm sample interval, which is relatively large compared to the core length. It is assumed that in this case, that the interval of highest ^{137}Cs concentration was split between two samples. The apparent peak near the depth of 45 cm suggests 1.04 cm/yr of deposition of after 1964. Because the core interval of post-impoundment sediment between 1952 and 1964 may be incomplete, only a minimum deposition rate can be established from the core data. The ^{137}Cs peak at 45 cm depth in the 77 cm long core indicates a minimum of 3.2 cm/yr prior to 1964. Accumulation rates are converted to dry-mass deposition rates by dividing the volume within the different core segments by the dry bulk density of the segment. The dry-mass deposition rate between 1964 and 2007 was 0.93 g/cm^2/yr. Between 1952 and 1964 the rate was a minimum of 2.6 g/cm^2/yr.

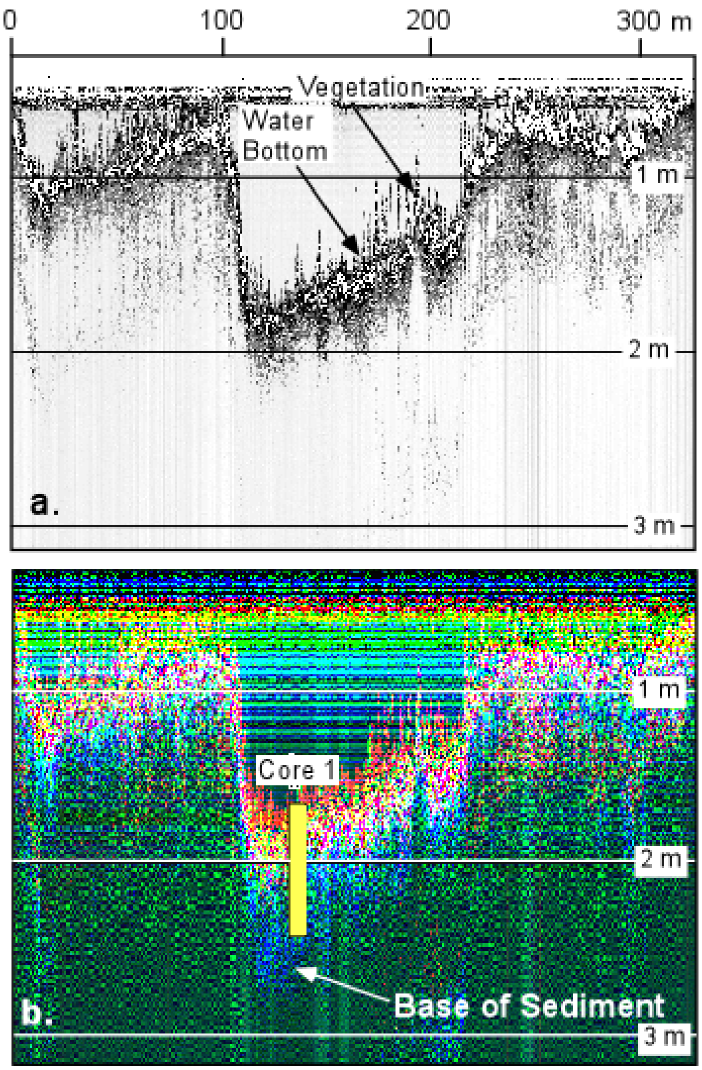
Table 3 Sediment survey results.

Reservoir	DC 3	DC 8	BC 1	BC 39
As-built normal-pool volume (m^3)	183,700	332,500	327,000	87,800
2007 normal-pool volume (m^3)	134,850 ±5,868	207,590 ±2,930	289,520 ±2,464	72,600 ±690
Sediment volume (m^3)	48,580 ±11,736	124,910 ±5,860	37,480 ±6,430	15,200 ±2,250
Volume loss (%)	26.6	37.6	11.5	17.3
Volume loss rate (m^3/yr)	905	2,271	713	292
Volume loss per year (%/yr)	0.49	0.68	0.22	0.33

The as-built volumes for DC 3 and DC 8 are from the NID. The as-built volumes for BC 1 and BC 39 were estimated by adding the acoustically-determined sediment volume to the remaining water volume in the normal pool, determined in the 2007surveys.

DC 8 Core 3 consists of 143 cm of variably compacted silty-clay sediment over a pre-impoundment surface of highly compacted clay soil with angular lithic fragments up to 4 cm in diameter (Figure 23). The water content curve shows a gradual decrease with depth from a high of 67% near the water bottom to 50% at a depth of 110 cm in the core. The sharp decrease in water content between 110 and 115 cm and then recovery to higher water content below, again suggests a buried desiccation surface. The ^{137}Cs analysis records the onset of ^{137}Cs deposition (1954 ± 2 yr) in the 135-140 cm sub-sample and the peak in ^{137}Cs deposition (1964 ± 2 yr) in the 80-85 cm sub-sample. This indicates that from impoundment in 1952 to the peak of ^{137}Cs deposition in 1964 ± 2 yr, the deposition rate was 5.0 cm/yr. From the ^{137}Cs peak to the time of the survey in 2007, the deposition rate was 1.9 cm/yr. The corresponding dry-mass deposition rate between 1952 and 1964 was 3.4 g/cm^2/yr and the rate from 1964 to 2007 was 1.0 g/cm^2/yr. Hence, the ^{137}Cs results, like volume loss rates for DC 3, indicate substantially higher deposition rates prior to 1964 than after 1964.

Figure 13 Longitudinal acoustic profile from BC 1.

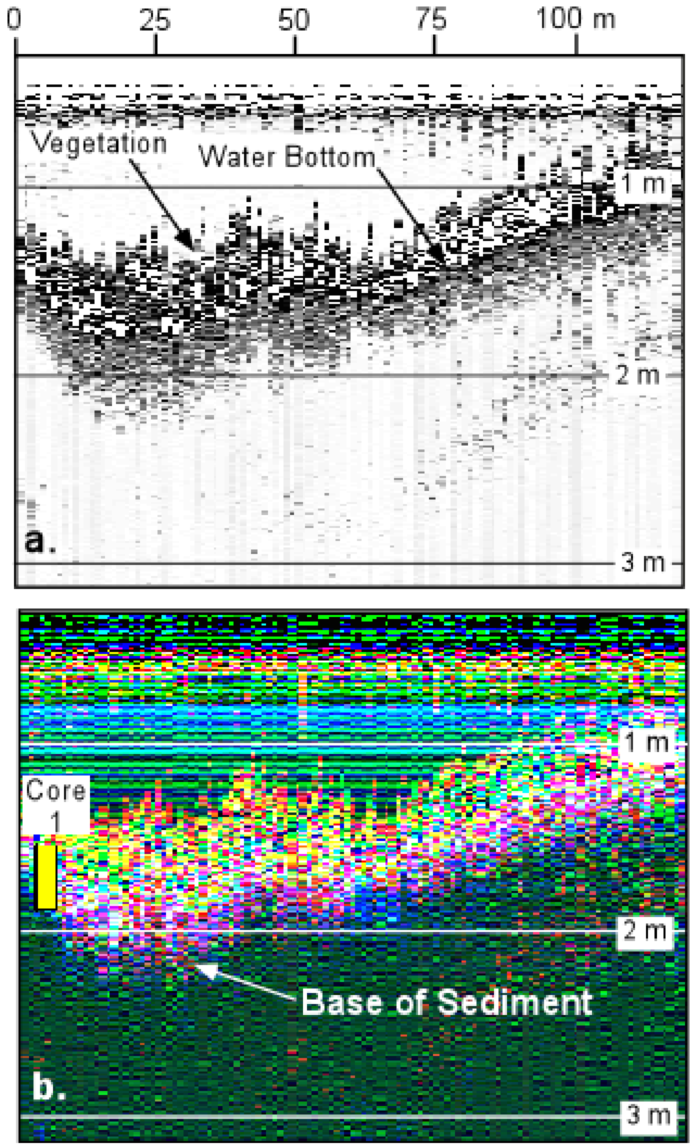


(a) 200 kHz profile used to measure water depth. (b) Multi-frequency composite profile. The red intensity is set from the 200 kHz signal, the green intensity is set with the 50 kHz signal, and the blue intensity is set from the 25 kHz signal. The yellow bar indicates the length of co-located sediment core.

BC 1 Core 1 is 75 cm long and is composed of silty-clay sediment (Figure 24). The most recent deposits in the upper-most 10 cm have high water content (48 to 60%) and have probably never been sub-aerially exposed. The underlying interval from 10 to 75 cm in depth has an average water content of 40% and has likely been repeatedly exposed and dried. Rather than a well-defined peak as seen in DC 8 Core 3 (Figure 23), the ^{137}Cs concentration in BC 1 Core 1 shows a gradual increase with depth to a maximum in 30 to 35 cm sub-sample and then an equally gradual decline below that depth. This is likely the result of vertical movement of ^{137}Cs during prolonged periods of sub-aerially exposure. Hence, no age interpretation of the ^{137}Cs profile is possible. There was also no evidence of pre-impoundment material found at the base of BC 1

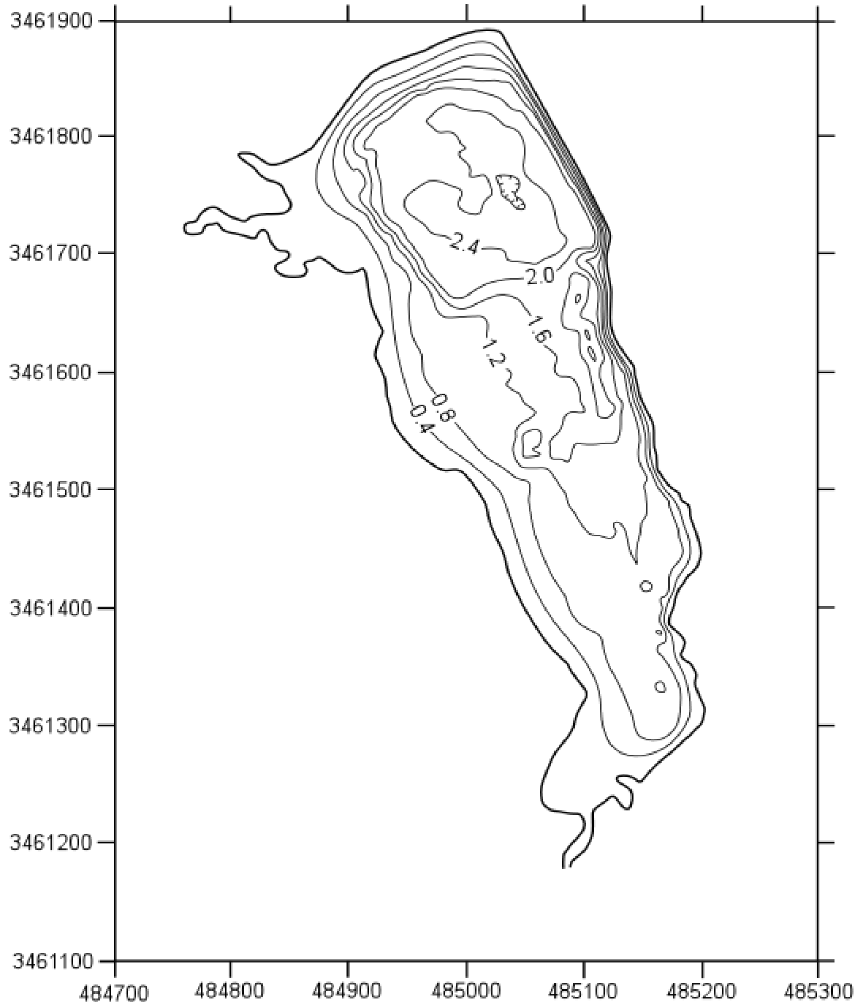
Core 1. Therefore, only a minimum overall deposition rate of 1.47 cm/yr can be established for the period from impoundment in 1956 to 2007. The cores collected in BC 39 were all short (14 to 20 cm) and did not span a sufficient portion of the likely sediment column to use ^{137}Cs analysis to draw conclusions about the deposition rates. The lack of penetration had more to do with the high degree of compaction of the sediment than the lack of sediment in the reservoir.

Figure 14 Axial acoustic profile from BC 39.



(a) 200 kHz profile used to measure water depth. (b) Multi-frequency composite profile. The red intensity is set from the 200 kHz signal, the green intensity is set with the 50 kHz signal, and the blue intensity is set from the 25 kHz signal. The yellow bar indicates the length of co-located sediment core.

Figure 15 Normal-pool depth map for DC 3.



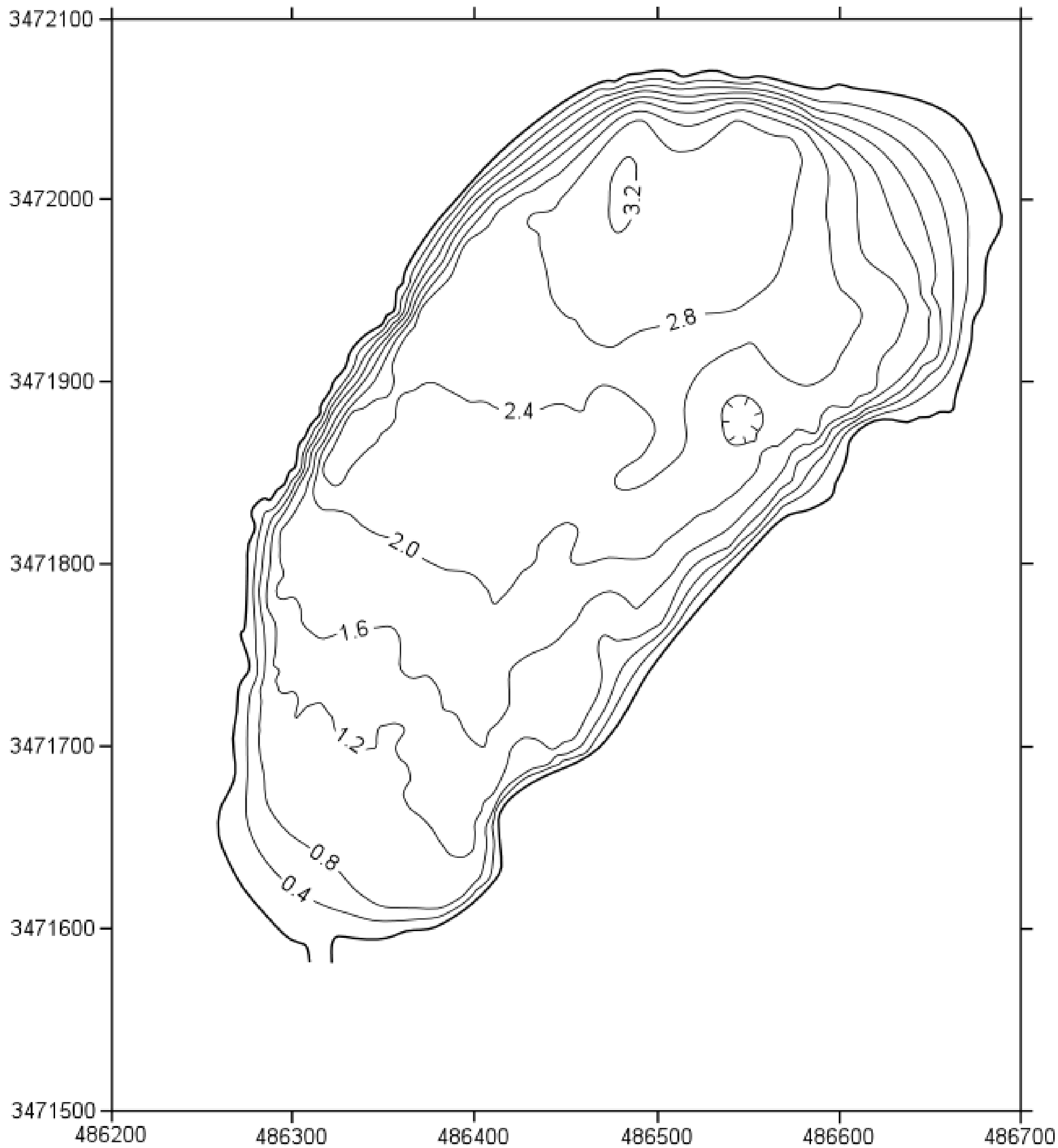
Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

Table 4 Effective sediment yield for watersheds of McCulloch County FRSs.

Reservoir	Period	Effective sediment yield (mton/km^2/yr)
DC 3	1952-1953	4,785
	1953-1960	568
	1960-1965	228
	1965-1971	51
	1971-2007	28
	1952-2007	201
DC 8	1952-2007	124
BC 1	1956-2007	23
BC 39	1955-2007	32

The effective sediment yield is computed by dividing the dry sediment mass trapped in the reservoir by the watershed area, and the accumulation period.

Figure 16 Normal-pool depth map for DC 8.



Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

In addition to ^{137}Cs analysis of core samples, composite samples were made of cores collected in stainless steel tubes. These composite samples were analyzed for organic carbon, nutrients, and suites of common metals and pesticides. The results are reported in Table 5 as core-length-weighted averages for each reservoir. For the metal suite, no concentration is within 10% of the screening level. For the pesticides, no concentration is within 1% of the associated screening level. The core-length-weighted average concentrations are used to estimate the total mass of the analytes in each reservoir (Table 6).

Table 5 Concentration of contaminants in reservoir sediment.

Analyte	Units	Screening Levels	DC 3	DC 8	BC 1	BC 39
Total Organic Carbon	%	NA	1.340	1.073	0.43	2.02
Dry bulk density	kg/m^3	NA	1,095	764.1	899.5	1,317
Nutrients						
Phosphate	µg/g	NA	0.276	0.266	0.196	0.298
Nitrate/Nitrite	µg/g	NA	0.462	0.332	0.174	2.09
Total Nitrogen	µg/g	NA	10.12	13.16	NP	NP
Total Phosphorus	µg/g	NA	1.278	396.1	NP	NP
Metals						
Aluminum	mg/g	NA	21.7	17.4	16.0	13.5
Antimony	mg/g	25	0	0	0	0
Arsenic	mg/g	33	0.002	0.002	0.002	0.003
Barium	µg/g	NA	146	98	131	125
Berylium	µg/g	NA	5	5	6	6
Boron	µg/g	NA	3	7	5	4
Cadmium	mg/g	4.98	0	0	0	0
Chromium	mg/g	111	0.019	0.016	0.010	0.009
Cobalt	µg/g	NA	9	7	5	5
Copper	mg/g	149	0.007	0.007	0.004	0.004
Iron	mg/g	40,000	7.1	5.9	3.2	3.2
Lead	mg/g	128	0.014	0.010	0.007	0.006
Magnesium	µg/g	NA	4,663	5157	4961	4056
Manganese	mg/g	1,100	0.298	0.273	0.302	0.255
Mercury	µg/g	1.06	0.020	0.025	0.018	0.010
Molybdenum	µg/g	NA	0	0	0	0
Nickel	mg/g	48.6	0.022	0.020	0.012	0.014
Selenium	µg/g	NA	0	0	0	0
Silver	mg/g	2.2	0	0	0	0
Thalium	µg/g	NA	0	0	0	0
Tin	µg/g	NA	0	0	0	0
Vanadium	µg/g	NA	18	17	14	19
Zinc	mg/g	459	0.036	0.034	0.024	0.025
Organic Contaminants						
Hexachlorobenzene	ng/g	240	0.02	0.04	0.01	0.08
Total Chlordane	ng/g	17.6	0.08	0.09	0.10	0.07
Heptachlor Epoxide	ng/g	16	ND	ND	0.01	ND
Aldrin	ng/g	80	0.03	0.03	0.07	0.04
Dieldrin	ng/g	61.8	ND	ND	1.09	ND
Endrin	ng/g	207	0.05	0.03	0.11	0.02
Mirex	ng/g	1300	ND	ND	ND	ND

Analyte	Units	Screening Levels	DC 3	DC 8	BC 1	BC 39
Total DDTs	ng/g	572	2.45	1.52	1.25	0.88
Total PCBs	ng/g	676	3.74	3.27	5.76	3.55

Fields labeled with NP indicate analysis not performed. Fields labeled ND indicate the analyte was not detected.

Influence of FRSs on downstream water quality

From the effective sediment yield results (Table 4), it is apparent the there have been dramatic changes in sediment yield over time in the project area. The best-constrained yield information is for DC 3. Therefore, an estimate of the effective sediment yield for the period after the impoundment of Brady Reservoir in 1963 is made by interpolating between the 1960 and 1965 survey results from DC 3. This produces an estimated volume loss 15,580 m^3, between 1963 and 2007. The associated average effective sediment yield for the period from 1963 to 2007 is 36.5 $mton/km^2/yr$. From Equation 5, this indicates the FRSs upstream of Brady Reservoir have prevented 1,406,560 mton of dry sediment from reaching Brady Reservoir. Estimated contaminant concentrations for sediments derived from the Brady Creek watershed are computed by taking the average of concentrations found in samples from BC 1 and BC 39. The associated masses of sequestered contaminants are given in Table 7.

Table 6 Estimated total mass of contaminants contained in surveyed reservoirs.

Analyte	Units	DC 3	DC 8	BC 1	BC 39
Dry sediment mass	mton	53,195	95,440	33,713	20,020
Total Organic Carbon	mton	717.4	1,024	145.7	404
Nutrients					
Phosphate	kg	14.7	25.4	6.60	6.0
Nitrate/Nitrite	kg	24.6	31.7	5.86	41.8
Total Phosphorus	kg	538.3	1,260	NP	NP
Total Nitrogen	kg	67.8	37.8	NP	NP
Selected Metals					
Arsenic	kg	106.4	190.9	67.4	60.1
Chromium	kg	1,010	1,527	337.1	180.2
Lead	kg	744.7	954.4	236.0	120.1
Mercury	kg	1.06	2.39	0.607	0.200
Organic Contaminants					
Hexachlorobenzene	g	1.07	3.82	0.337	1.60
Total Chlordane	g	4.25	8.59	3.369	1.40
Heptachlor Epoxide	g	ND	ND	0.367	ND
Aldrin	g	1.60	2.86	2.37	0.800
Dieldrin	g	ND	ND	36.8	ND
Endrin	g	2.66	2.86	3.71	0.400
Mirex	g	ND	ND	ND	ND
Total DDTs	g	130.5	145	42.1	17.6
Total PCBs	g	199.0	312	194	71.1

Discussion

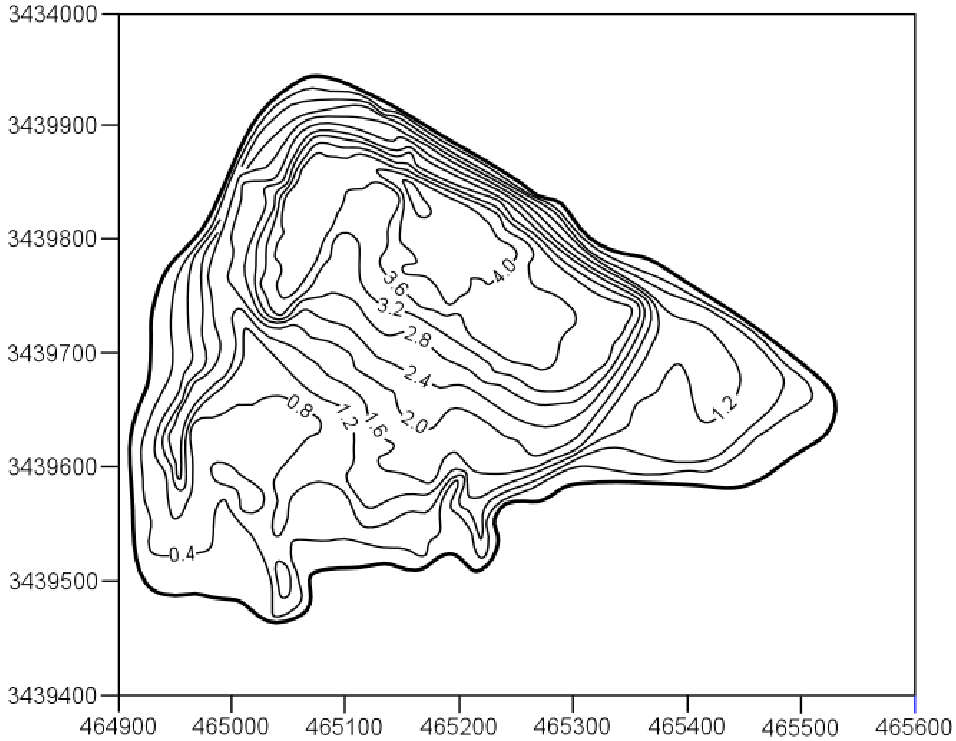
The NID lists 526 FRSs built by the USDA-NRCS throughout the U.S. that reached the age 50 year or older in 2008. Most of these reservoirs have not been surveyed for 35 years. By 2018, the number of NRCS FRSs in the U.S. that will have exceeded their evaluated life will reach 2,740. Most of the aging FRS in this project required some level of principal spillway repair.

Table 7 Contaminants prevented from reaching Brady Reservoir by upstream FRSs.

Analyte	Units	Mass
Dry sediment mass	mton	1,406,560
Total Organic Carbon	mton	17,230
Nutrients		
Phosphate	mton	0.347
Nitrate/Nitrite	mton	1.59
Metals		
Arsenic	mton	3.52
Chromium	mton	13.36
Lead	mton	9.14
Mercury	kg	19.7
Organic Contaminants		
Hexachlorobenzene	g	63.3
Total Chlordane	g	120
Heptachlor Epoxide	g	7.03
Aldrin	g	77.3
Dieldrin	g	767
Endrin	g	91.4
Mirex	g	ND
Total DDTs	kg	1.50
Total PCBs	kg	6.55

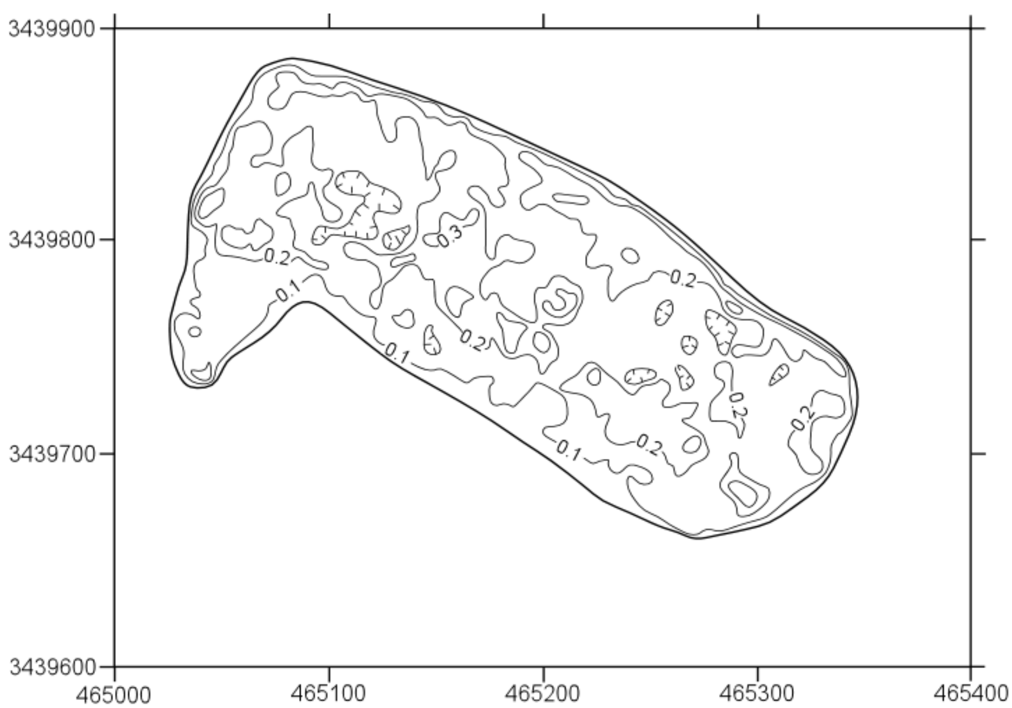
The status of the sediment pools of FRSs in McCulloch County presents a more optimistic picture. Of the four FRSs surveyed, DC 3 and DC 8 are the oldest and contain the most sediment. DC 3 is only 38.9% full and DC 8 is only 37.6% full, after 55 years of impoundment (Table 3). At their average rate of fill, both structures have another 140 yr of sediment retention capacity remaining. Chemical analyses of the sediment indicate that all samples fell well below the screening levels of common contaminants. Baring any change in this condition, sediment quality will not be a problem for future sediment removal projects. The FRSs upstream of Brady Reservoir have produced a measurable reduction in the amount of sediment and adsorbed contaminants reaching Brady Reservoir (Table 7). However, the benefit is less than the typical case for two reasons. First, the amount of sediment trapped in the FRSs is less than expected, which is believed to be the result of lower than expect average sediment yield. Second, only 16.8% of the watershed of Brady Reservoir is controlled by FRSs. Throughout the U.S., the watersheds of FRSs and other small impoundments represent 21% of the land surface area and are estimated to trap 25% of the total sheet and rill erosion (Renwick et al., 2005). Hence, in the dry landscape of McCulloch County, with its lower density of small reservoirs, FRSs have a smaller influence on water quality.

Figure 17 Normal-pool depth map for BC 1.



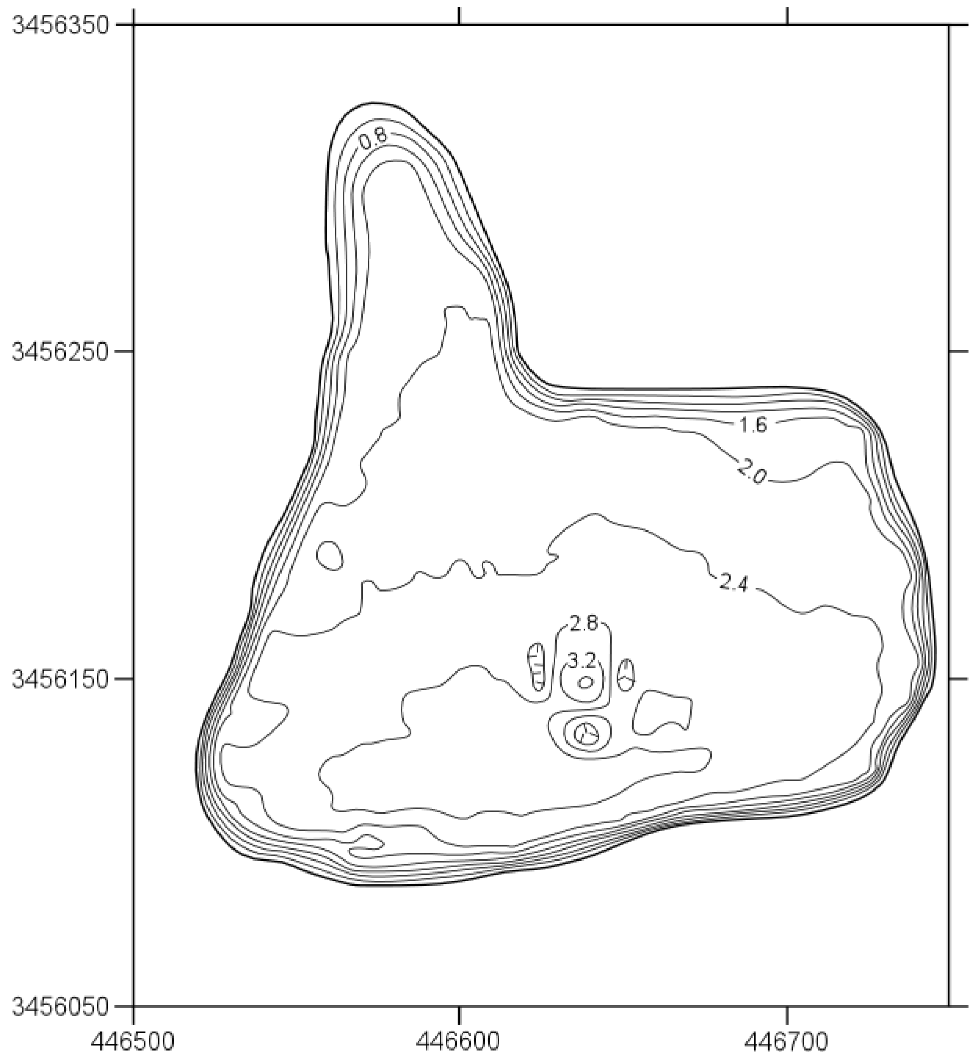
Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

Figure 18 Sediment thickness map for BC 1.



Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

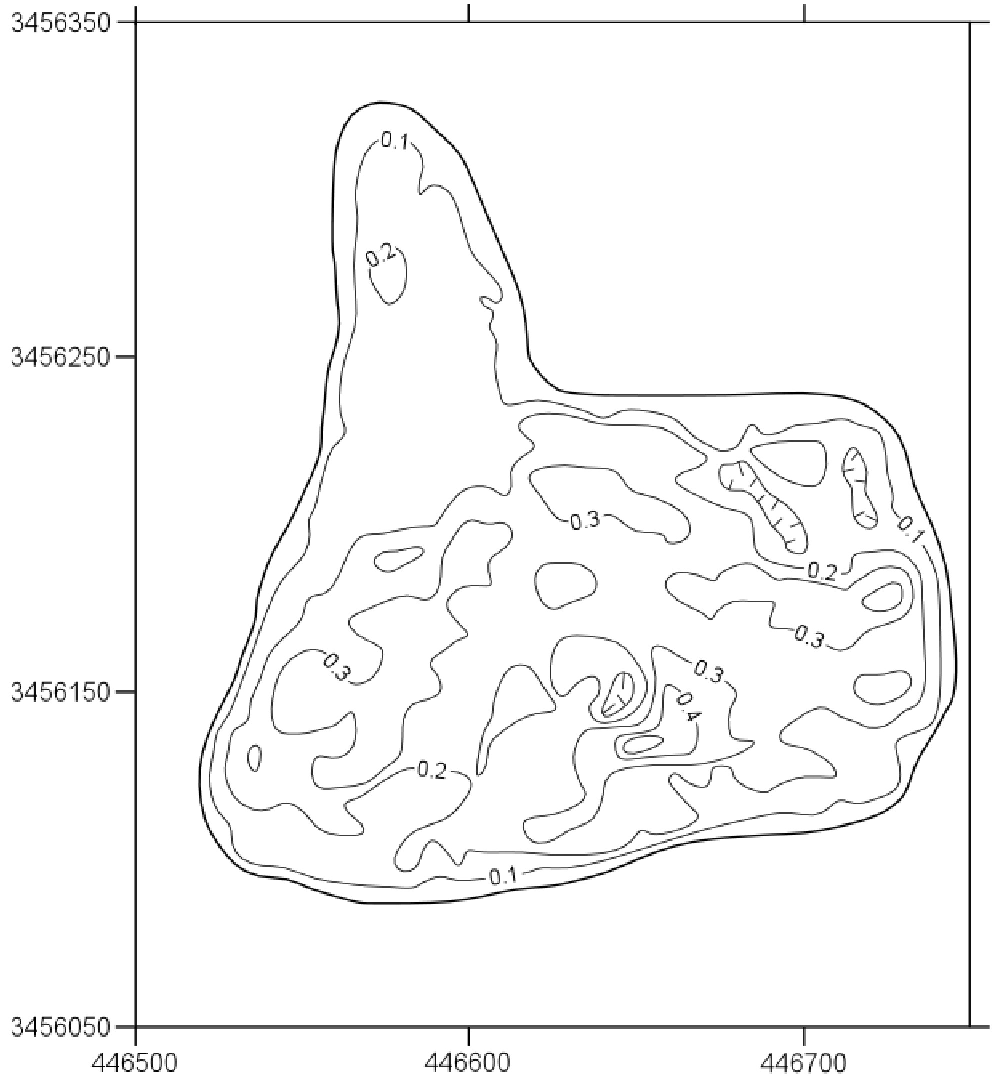
Figure 19 Normal pool depth map for BC 39.



Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

As a cautionary note, there is evidence that the past long-term sediment retention performance of the FRSs of McCulloch County may not be indicative of their future performance. The time history of sedimentation provided by DC 3 indicates that the reason the FRSs of McCulloch County have performed better than expected in terms of sediment retention life, is that the sedimentation rates have decreased dramatically since the 1950s (Figure 21). If the initial volume loss rate of 37,148 m^3/yr, experienced over the first year of impoundment of DC 3 had continued unabated, the initial 220,840 m^3 of the normal pool would have been filled with sediment in less than 6 yr. Instead, the deposition rate decreased dramatically between 1953 and 1971, and averaged only 217 m^3/yr between 1971 and 2007. This represents a drop in the volume loss rate by a factor of 170. If this new lower volume loss rate were to continue unchanged into the future, the remaining normal pool volume of DC 3 (134,840 m^3) would last another 600 yr. Hence, the remaining sediment retention life could be as short as 6 yr or as long as 600 yr, depending on local conditions that control sedimentation rates.

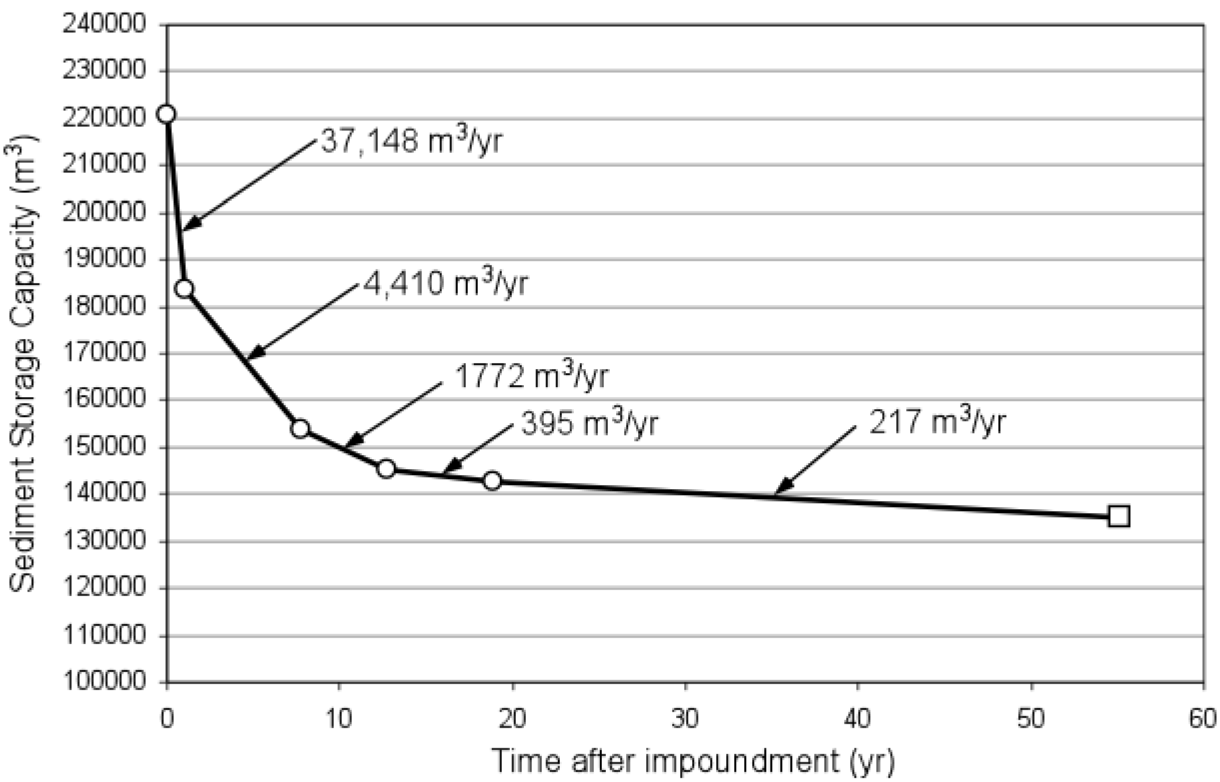
Figure 20 Sediment thickness map for BC 39.



Contours are in meters. Geographic coordinates are UTM Zone 14, meters.

Land use has not changed significantly since the 1950s in the project area. Hence, short-term climate change is the likely cause of the decreased sedimentation rate since the 1950s. From 1891 to 1959 the Edwards Plateau of Texas, on which the project area is located, experienced 9 droughts lasting 2 or more years (Lowry, 1959). Drought conditions, defined as a reduction in annual rainfall by 30% or more from the long-term average, prevailed 40% of the time during that period with an average recurrence interval of 8 yr. The last drought in this period, which locally occurred from 1952 through 1955, was the most severe on record in the region. Locally, the period after the 1950s to 2007 was marked by one less severe drought from 1962 to 1964, followed by 40 yr of near normal or above normal rainfall (Figure 5). DC 3 and DC 8 were impounded in the first year of the 1950s drought and have the highest overall effective sediment yield of FRSs surveyed in this study (Table 4). BC 39 was impounded in the last year of the 1950s drought in 1955 and has an intermediate effective sediment yield. BC 1 was impounded in 1956, the year after the 1950s drought ended, and has the lowest effective sediment yield of the reservoirs surveyed. Even though the four-year drought of the 1950s represents less than 10% of the age of the reservoirs, the timing of impoundment within this drought period seems to be the dominant factor controlling how much overall sediment they contain after more than 50 yr of impoundment. The fact that the less severe drought of the 1960s did not reverse the trend of diminishing volume loss rate in DC 3, suggests that not all droughts produce dramatic increases in sedimentation rate (Nearing et al., 2005).

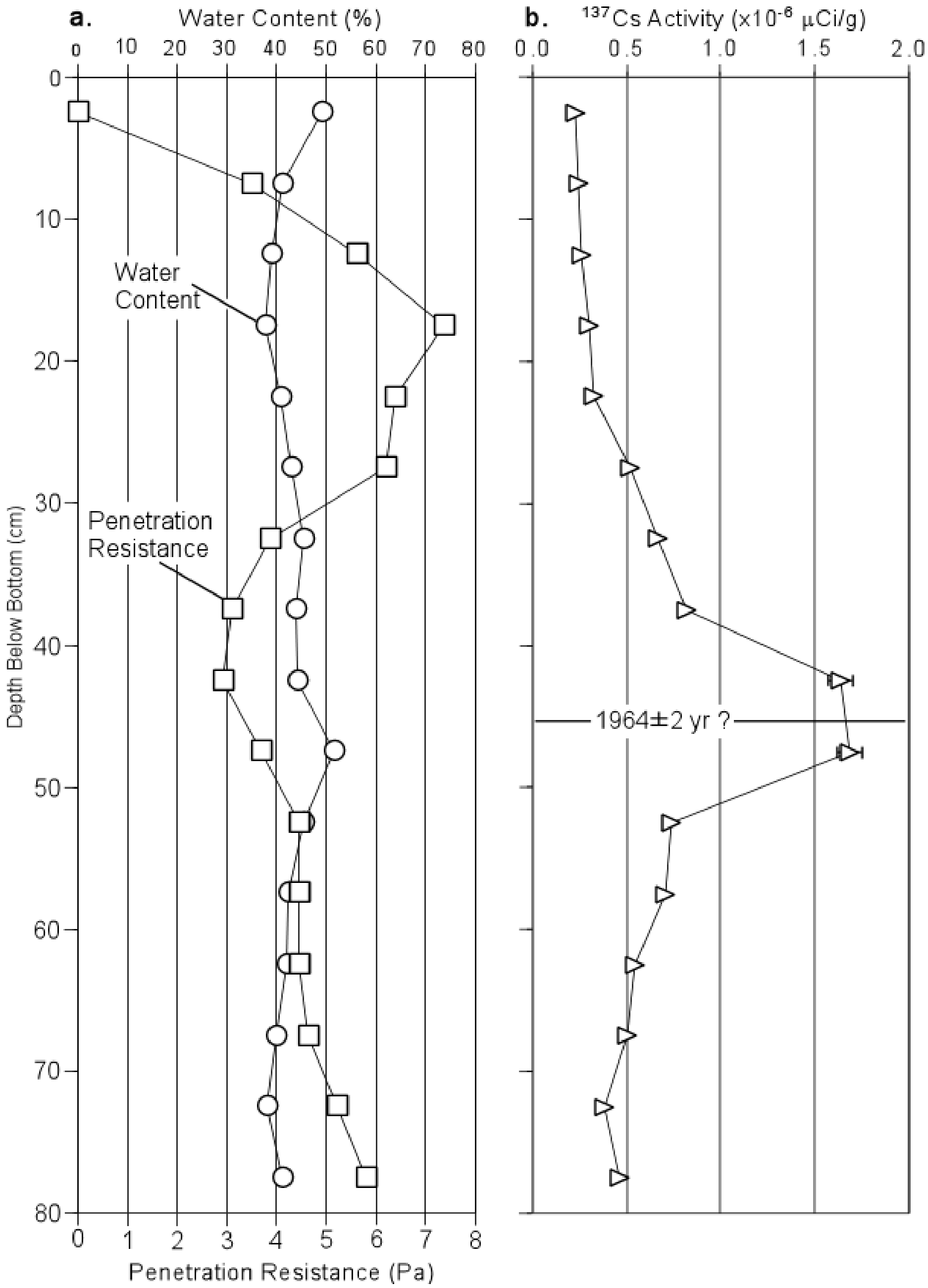
Figure 21 Normal-pool storage capacity versus time for DC 3 in 1952.



Normal-pool volumes from prior surveys are marked with circles. The square marks the results of the survey from this study. The average volume loss rate between successive surveys are indicated in cubic meters per yr.

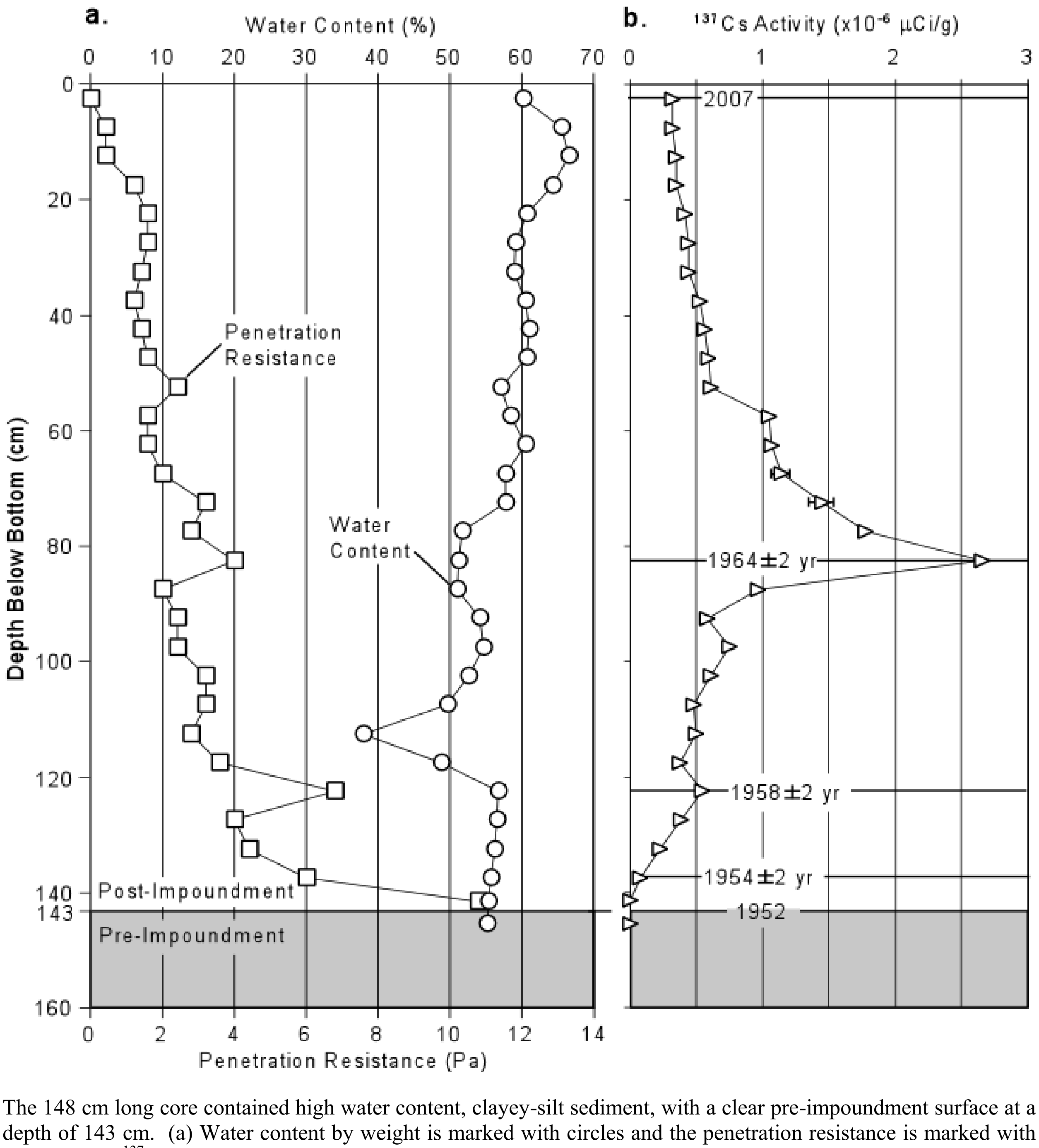
Drought by itself does not result in increased sedimentation. Drought influences sedimentation primarily by reducing vegetative cover and soil cohesion (Schumm, 1977). This makes the landscape more vulnerable to erosion by the few rains that do occur during the drought and rains following the drought period. For stable landscapes, sediment yield is maximum for regions that receive an average annual precipitation of 280 mm and is less by a factor of 2 in regions that receive 150 mm or less and in regions that receive 640 mm or more precipitation (Schumm, 1977, Fig. 2-5). In regions that receive less than 280 mm of precipitation, erosion is limited by the amount of water available to move the sediment. In regions that receive more than 640 mm of precipitation, erosion is limited by increased vegetative cover. These contrasts apply to comparisons between regions with different average precipitation, in which the vegetation has had sufficient time to adapt to the local conditions. The affect produced by drought is potentially much more dramatic, because vegetation that could survive under the drier conditions does not have time to become established. However, if the drought is short-lived or rainfalls of insufficient intensity do not occur within or shortly after the drought, a large increase in erosion does not occur.

Figure 22 Analysis of DC 3, Core 2.



The 77 cm long core contained compacted clayey-silt sediment. No evidence for pre-impoundment material was found. (a) Water content by weight is marked with circles and the penetration resistance is marked with squares. (b) ^{137}Cs concentration. Error bars indicating the 95% confidence intervals are show for the two largest concentration errors. The 95% confidence intervals are smaller than the triangle symbols for all other measurements.

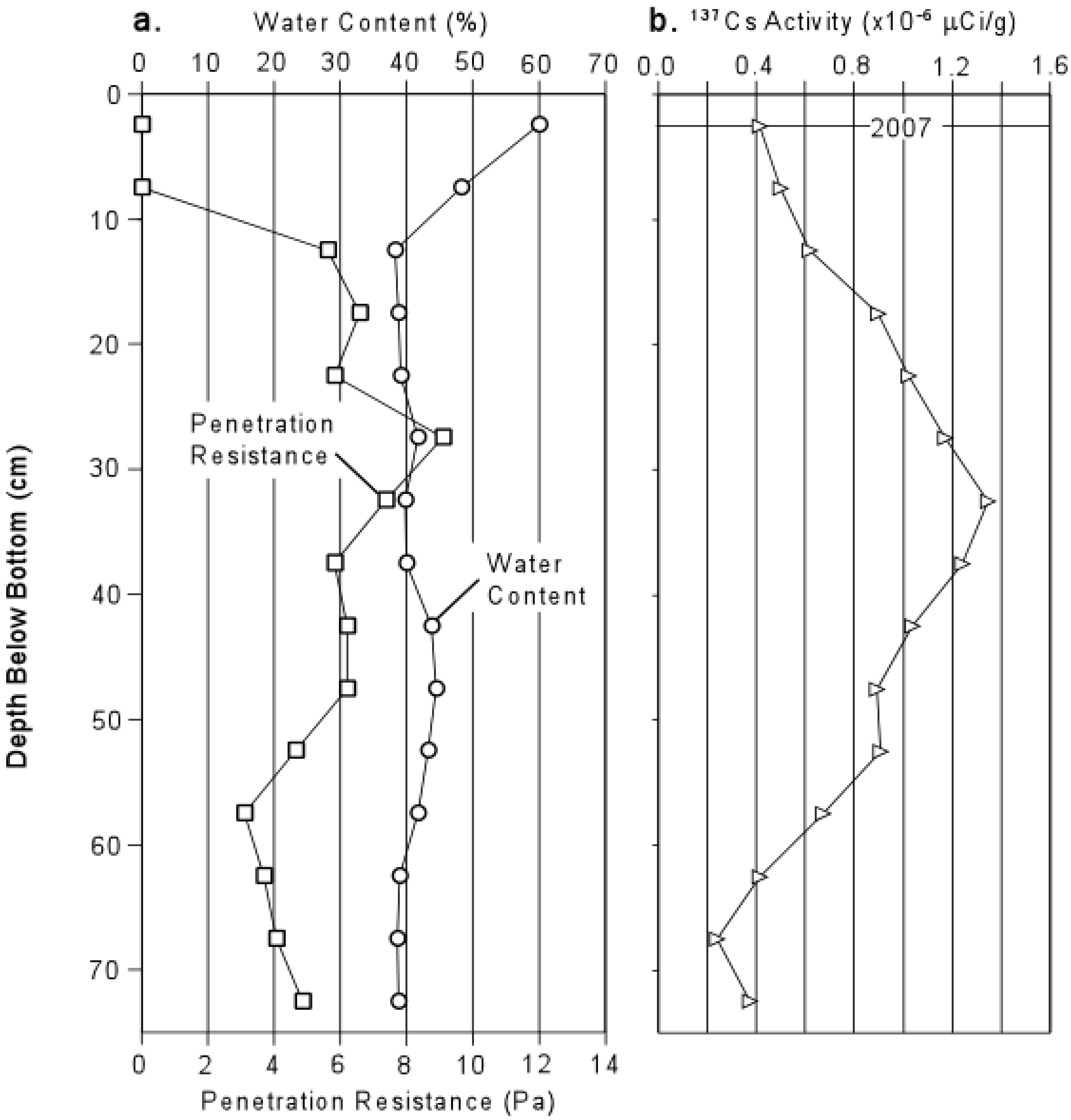
Figure 23 Analysis of DC 8, Core 3.



The 148 cm long core contained high water content, clayey-silt sediment, with a clear pre-impoundment surface at a depth of 143 cm. (a) Water content by weight is marked with circles and the penetration resistance is marked with squares. (b) ^{137}Cs concentration. Error bars indicating the 95% confidence intervals are show for the two largest concentration errors. The 95% confidence intervals are smaller than the triangle symbols for all other measurements.

The results of this project indicate that the standard approach of estimating the remaining life of the sediment pool will not work for the FRSs in McCulloch County. The standard approach is to extrapolate the average rate of volume loss between the last two surveys into the future. In the case of DC 3, 35.4% of the initial volume of the sediment pool was lost in the first 19 yr after its impoundment, due to two droughts and their aftermath. In the following 36 yr, only an addition 3.5% was lost. The standard approach would suggest 628 yr of remaining sediment retention life. However, the last 36 yr have been the wettest and most drought-free period in the region for over 100 yr. When this pattern changes, two more droughts like the one experienced in the 1950s will fill DC 3 to the top of the principle outlet works. Three more will fill every FRS in the region.

Figure 24 Analysis of BC 1, Core1.



The 75 cm long core contained compacted clayey-silt sediment. No evidence for pre-impoundment material was found. (a) Water content by weight is marked with circles and the penetration resistance is marked with squares. (b) ^{137}Cs concentration. The 95% confidence intervals are smaller than the triangle symbols for all measurements.

The recurrence interval of severe drought in the Edwards Plateau of Texas is likely to be the limiting factor on the remaining sediment retention life of the FRS in McCulloch County. Drought recurrence in turn, is largely controlled by the El Niño-Southern Oscillation phenomenon (ENSO) and the associated El Niño\La Niño precipitation patterns (e.g. Viles and Goudie, 2003). La Niño conditions are associated with droughts in the U.S. Gulf of Mexico Coast and the southwest U.S. (Cayan et al., 1999). The ENSO pattern since 1970s has differed significantly from the ENSO pattern from the 1900s to 1970s, in that El Niño conditions occurred more often and were more intense. However, a particularly strong La Niño that began in 1998 and persisted through 2001 may mark the change back to a more normal El Niño/La Niño pattern (Viles and Goudie, 2003; Kousky and Bell, 2000). If that is the case, the sedimentation rates in the McCulloch County FRS would be expected to resume more normal rates after the 35 year hiatus. Their original sediment capacity was expected to last 50 yr under normal conditions. This would mean that the Deep Creek FRS could expect an additional 30 to 35 yr of sediment retention life, whereas the Brady Creek FRS could expect another 40 to 45 yr.

Conclusions

In this project some of the first of over 11,000 FRSs built in the U.S. were inspected, repaired, and surveyed. The results indicate that nearly all of those that had reached the age of 50 yr were in need of immediate repairs. Repairs were made to the various mechanical components of the principle spillways. Grading work was needed on and adjacent to the earthen dams and additional maintenance activities were required around the dams. The repairs made to return the FRSs to safe operational status required approximately $18,500 per FSR (2007 dollars).

Four of the 30 FRSs in the McCulloch County project area were surveyed to determine the remaining sediment retention volume and the volume of sediment they currently contain. The reservoirs surveyed were selected to be representative of those throughout the study area in terms of sedimentation. From this sampling, it can be concluded that the FRSs in McCulloch have 60% or more of their initial sediment pool remaining and are not in immediate need of dredging or other work to increase sediment retention capacity. Chemical analyses performed on sediment samples indicate that the concentrations of common agricultural contaminants are well below screening levels. Hence, baring change in this status, sediment quality will not be a problem for future projects that involve sediment removal.

Evidence from past surveys of DC 3, ^{137}Cs dating of core samples collected in DC 3 and DC 8, and survey results for FRS impoundment at different times in the 1950s, all suggest that sedimentation rates in the FRSs of McCulloch County have changed by two orders of magnitude or more since the early 1950s. The fact that the project area experienced the most severe drought on record in the 1950s, suggests that drought occurrence is the main controlling factor in the rate of fill of the McCulloch Country FRSs. At volume loss rates that have occurred over the last 36 years, which have been relatively drought free, the sediment retention capacity of the FRSs of McCulloch County would last another 600 yr. However, if the normal, pre-1970s pattern of periodic droughts resumes, as is more likely, the FRSs will fill with sediment within 30 to 45 yr.

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