Technical Report No. ENV-2020-007

Bighorn Reservoir 2017 Sedimentation Survey

Pick-Sloan Missouri Basin Program, Montana
Great Plains Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Sedimentation and River Hydraulics Group
Denver, Colorado

February 2020
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Disclaimer

Cover: Google Earth image of Bighorn Reservoir at Horseshoe Bend, dated July 10, 2006.

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14. SHORT ABSTRACT The 2017 multibeam bathymetric survey of Bighorn Reservoir was combined with a single contour at elevation 3,660 feet (digitized from USGS quad map) to produce a combined digital surface of the reservoir bottom. Analysis of these data indicates that at the top of flood control pool elevation (3,657 feet, Reclamation project vertical datum, RPVD), the reservoir would have a surface area of 16,026 acres and a storage capacity of 1,263,682 acre-feet. Since the original filling in 1965, the reservoir is estimated to have lost 118,629 acre-feet of storage capacity (8.6 percent) due to sedimentation. The dead storage pool volume has reduced to 90 percent of the original volume. The sedimentation level at the dam is at 3,208 feet (RPVD), which is 32 percent of the height between the original reservoir bottom and the top elevation of the dead storage pool.			
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Sedimentation and River Hydraulics Group, 86-68240

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Bighorn Reservoir 2017 Sedimentation Survey

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Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
DOI	Department of the Interior
ft	feet
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
NAD 1983	North American Datum, established 1983
NGVD 1929	National Geodetic Vertical Datum, established 1929
NGVD 1988	National Geodetic Vertical Datum, established 1988
Reclamation	Bureau of Reclamation
RPVD	Reclamation Project Vertical Datum
RSI	Reservoir Sedimentation Information
RTK	Real-Time Kinematic
sft	survey feet
TSC	Technical Service Center
USACE	United States Corps of Engineers
WY	Water Year

Executive Summary

Yellowtail Dam and Bighorn Reservoir are on the Bighorn River. The Shoshone River enters Bighorn Reservoir near Lovell, Wyoming. The dam is located near Ft. Smith, Montana, which is about 32 miles southwest from Hardin, Montana. The reservoir is approximately 72 miles long at maximum storage elevation and crosses the Wyoming/Montana border. The reservoir head and delta are in Wyoming about 10 miles east of Lovell, Wyoming.

A bathymetric survey of Bighorn Reservoir was conducted in 2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1965 and since the last survey in 2007,

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations,

3. Obtain sediment core samples from the reservoir bottom and analyze the erosion properties and physical properties, and

4. Obtain reservoir bottom survey for 2-dimensional numerical modeling for hydraulics and sediment transport in the Horseshoe Bend portion of the reservoir delta

The bathymetric survey was conducted utilizing two different vessels equipped with different SONAR equipment. Deployed from an 18-foot aluminum boat was a multibeam depth sounder interfaced with real-time kinematic (RTK) global positioning system (GPS) instruments (for horizontal positioning) to map the reservoir bottom. Through the canyon (approximately 45 miles of the reservoir) differential GPS was used due to the inability to effectively maintain communication with a survey base station for RTK positioning. A Sontek Acoustic Doppler Current Profiler (ADCP) was deployed from a 12-foot cataraft and interfaced with RTK GPS instruments for horizontal positioning to map the reservoir bottom in the delta area of the reservoir, primarily upstream of the causeway. The 2017 bathymetric survey of Bighorn Reservoir was combined with a single above-water contour of elevation 3,660 feet to produce a combined digital surface of the reservoir bottom. The 3,660 feet contour line was the same contour used to produce a surface for the 2007 survey (Ferrari 2010). This contour was used in the absence of Light Detection and Ranging (LiDAR) or photogrammetry to obtain elevation data.

This survey was conducted during two trips to the reservoir, July 6 – 11, 2017 and Aug 23 – 27, 2017, when the reservoir water surface elevation ranged between 3,642.82 to 3,645.94 feet, and 3,639.01 to 3,638.71 feet, respectively (Reclamation vertical project datum, RPVD). The top of Joint Use operations pool elevation is 3,640.00 feet. The top of the Active Conservation pool is 3,614.00 feet.

Analysis of the combined data sets indicates the following results:

- At reservoir water surface elevation 3,628.0 feet (RPVD), which is 10.71 feet below the lowest water surface at the time of survey, the reservoir surface area was 8,751 acres with a storage capacity of 878,340 acre-feet.

- At the top of flood control pool elevation (3,657.0 feet, RPVD), the reservoir has a surface area of 16,026 acres and a storage capacity of 1,263,682 acre-feet.

- Since the original filling of the reservoir in 1965, the reservoir is estimated to have lost 118,629 acre-feet of storage capacity (8.6 percent) due to sedimentation. Since the last reservoir survey in 2007, the reservoir is estimated to have lost 15,214 acre-feet of storage capacity (top of flood pool, 3,657 feet). This volume represents a sediment yield rate of 0.15 acre-feet per square mile per year (acre-feet/mi^2/year) in the previous decade, which is considered very low based on yield classification rankings as defined in Reclamation (2006).

- By 2017, the dead storage pool volume had reduced to 90 percent of the original dead storage volume. The sedimentation level at the dam is at 3,208 feet (RPVD), which is 32 percent of the height between the original reservoir bottom and the top elevation of the dead storage pool.

- Historic rates of reservoir sedimentation indicate a slightly decreasing trend in sedimentation rates since original reservoir filling.

A summary description of the dam, reservoir, and survey results is presented in Table ES-1.

Table ES-1. Reservoir Survey Summary Information

Reservoir Information

Reservoir Name	Bighorn Reservoir	**Region**	Great Plains
Owner	Bureau of Reclamation	**Area Office**	Montana
Stream	Bighorn River	**Vertical Datum**	RPVD
County	Bighorn	**Top of Dam (ft)**	3,660
State	Montana - Wyoming	**Spillway Crest (ft)**	3,593
Lat (deg min sec)	45° 18′ 26″	**Power Penstock Elevation (ft)**	3,450
Long (deg min sec)	107° 57′ 25″	**Low Level outlet (ft)**	3,300
HUC4	1008	**Hydraulic Height (ft)**	495
HUC8	10080007	**Total Drainage Area (mi^2)**	19,650
NID ID	MT00576	**Date storage began**	Nov. 4, 1965
Dam Purpose	Power, Flood Control, Irrigation	**Date for normal operations**	Dec. 1967

Original Design

Storage Allocation	Elevation (ft)	Surface area (acres)	Capacity (acre-ft)	Gross Capacity (acre-ft)
SURCHARGE	3,660	17,958	52,875	1,435,186
FLOOD CONTROL	3,657	17,298	258,968	1,382,311
JOINT USE	3,640	12,685	247,575	1,123,343
CONSERVATION	3,614	7,424	366,083	875,768
INACTIVE	3,547	4,197	489,329	509,685
DEAD	3,296.5	405	20,356	20,356

Survey Summary

Survey Date	Type of Survey	No. of Range lines or Contour Intervals	Contributing Sediment Drainage Area (mi^2)	Period Sedimentation Volume (acre-ft)	Cumulative Sedimentation (acre-ft)	Lowest Reservoir Elevation (ft)	Remaining Portion of Dead Storage (Percent)*
Original	Contour	20′ & 5′	10,321	----------	----------	--------	---------
1982	Range	51	10,321	53,951	53,951	3,620	80
2000	Range	RL 8 – 28	10,321	N/A	N/A		N/A
2007	Contour	20′ to 40′	10,321	49,464	103,415	3590	87
2017	Contour	5′	10,321	15,214	118,629	3,628	90

Notes

* The discrepancy in the dead pool volume is attributed to continually improving survey methods that result in improved mapping accuracy of the reservoir. The improved mapping provides a more accurate estimation of reservoir volume. In 1982 only range lines were surveyed, and reservoir bottom elevations were interpolated between those range lines.

Table ES-2. Elevation versus Area Table, all surveys.

Survey date	Original	1982	2007	2017
Vertical Datum	RPVD	RPVD	RPVD	RPVD
Elevation (ft)	**Area (acre)**	**Area (acre)**	**Area (acre)**	**Area (acre)**
3,220	79	51	67	76
3,260	220	208	220	236
3,296.5	405	--	367	398
3,300	421	400	378	418
3,340	722	679	582	626
3,380	1,134	1,045	876	896
3,420	1,696	1,667	1,524	1,277
3,460	2,367	2,351	2,315	2,375
3,500	3,311	3,244	3,204	3,142
3,540	4,048	4,016	3,868	3,885
3,547	4,197	--	3,996	4,002
3580	5,280	4,873	4,632	4,525
3,614	7,424	--	6,335	5,980
3,620	8,152	7,699	7,374	6,817
3,657	17,298	17,279	17,279	16,026
3,660	17,958	17,940	17,940	16,446

Table ES-3. Elevation versus Capacity Table, all surveys.

Survey date	Original	1982	2007	2017
Vertical Datum	RPVD	RPVD	RPVD	RPVD
Elevation (ft)	**Volume (acre-ft)**	**Volume (acre-ft)**	**Volume (acre-ft)**	**Volume (acre-ft)**
3,220	2,191	224	670	558
3,260	8,481	5,474	6,704	7,009
3,296.5	20,356	--	17,724	18,355
3,300	21,687	17,374	19,027	19,763
3,340	45,061	38,784	38,367	40,239
3,380	82,561	73,024	68,380	70,787
3,420	139,361	127,144	113,160	112,064
3,460	220,891	207,964	191,340	118,671
3,500	333,731	319,814	301,098	298,992
3,540	480,801	465,034	442,383	439,836
3,547	509,685	--	469,910	467,473
3,580	663,106	641,737	611,638	608,178
3,614	875,768	--	788,208	778,317
3,620	922,216	873,587	829,234	816,245
3,657	1,382,311	1,328,360	1,278,896	1,263,682
3,660	1,435,186	1,381,189	1,331,725	1,311,808

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1. Introduction

Yellowtail Dam is on the Bighorn River and forms the Bighorn Reservoir (sometimes referred to as Bighorn Lake). The dam is on the Crow Indian Reservation about 42 miles southeast of Billings, Montana and 32 miles southwest of Hardin, Montana. The reservoir is approximately 72 miles long at maximum water surface elevation and 66 miles long at the top of joint use storage. The reservoir head and delta are in Wyoming about 10 miles east of Lovell, Wyoming in the Bighorn Basin (Figure 1). The dam and reservoir are jointly operated by the Bureau of Reclamation and the US Army Corps of Engineers (USACE) as part of the Yellowtail Unit of the Pick-Sloan Missouri Basin Program . The Yellowtail Unit supplies irrigation water to more than 42,600 acres of farm land and produces 62,500 kilowatt (kW) on each of four generators.

Because all rivers transport sediment particles (e.g., clay, silt, sand, gravel, and cobble) and reservoirs tend to trap sediment, the reservoir storage diminishes over time. Reservoir sedimentation affects all elevations of the reservoir, even above and upstream of the full pool elevations. Cobble, gravel, and sand particles tend to deposit first forming deltas at the upstream ends of the reservoir while silt and clay particles tend to deposit along the reservoir bottom between the delta and dam. Periodic reservoir surveys measure the changing reservoir surface area and storage capacity and provide information for forecasting when important dam and reservoir facilities may be impacted by sedimentation.

As part of a research effort to better understand reservoir sedimentation, and ongoing operations and sediment monitoring activities, the Technical Service Center's (TSC) Sedimentation and River Hydraulics Group (86-68240) conducted a bathymetric survey of the underwater portions of the reservoir that were accessible by boat. This survey was co-funded by Reclamation's Science and Technology Office, Great Plains Regional Office, and the Montana Area Office. A complete bathymetric survey was conducted from July 6 – 11, 2017 and August 23 – 27, 2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1965 and since the last survey in 2007,

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations,

3. Acquire bed sediment samples and obtain soil physical properties and erosion testing of the reservoir bottom sediment in the delta, and

4. Obtain reservoir bottom survey and sediment properties for 2-dimensional hydraulic and sediment transport modeling in the Horseshoe Bend portion of the reservoir delta.

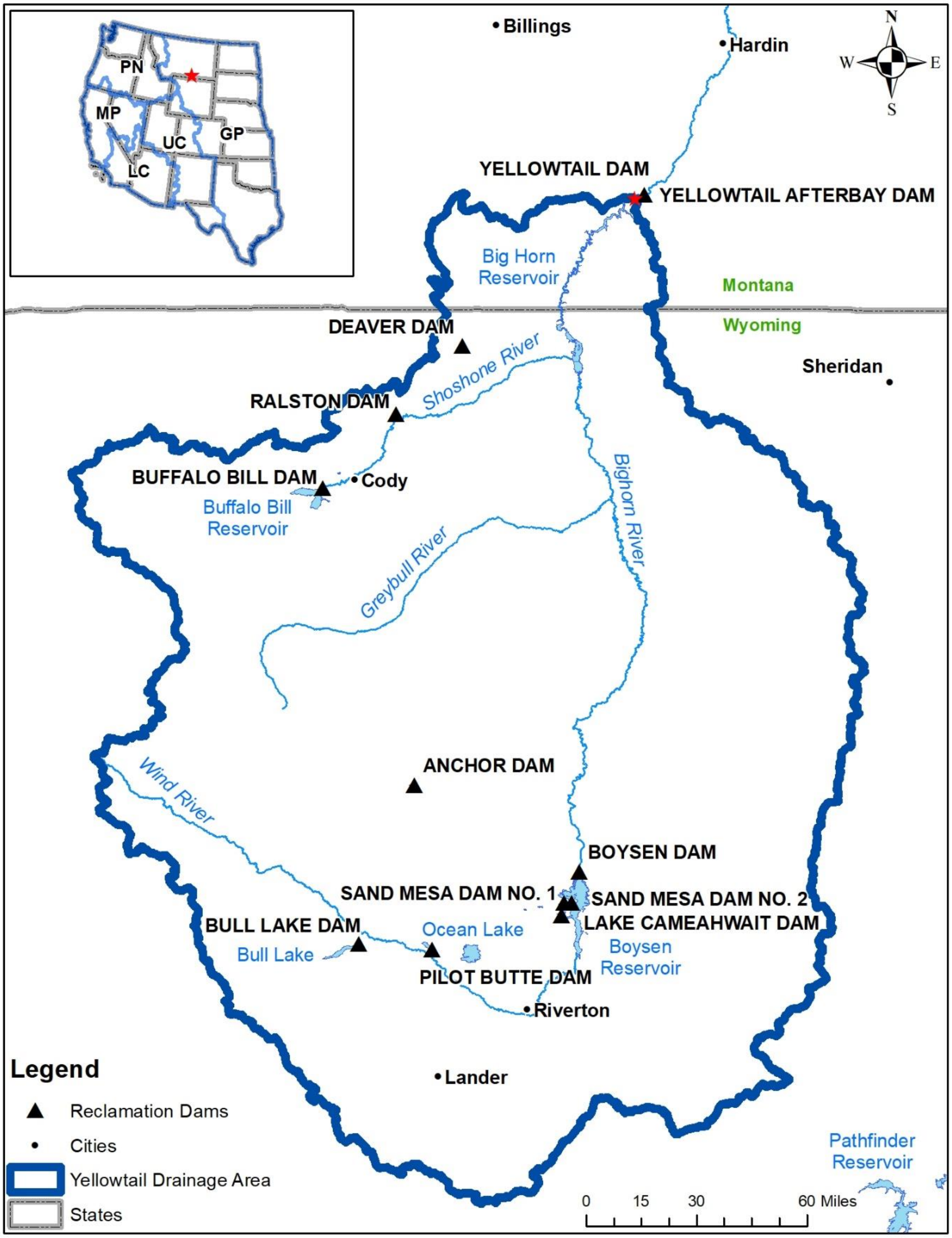


Figure 1. Location and watershed map of Yellowtail Dam and Bighorn Reservoir, 42 miles southeast of Billings, Montana.

The contents of the appendices to this report are listed below:

Appendix A provides more details of the hydrographic survey methods for both platforms. The bathymetric data were combined with a single contour at 3,660 ft to produce a digital surface of the reservoir bottom surface.
Appendix B provides more details about the methods used to generate surface area and storage capacity tables. Surface areas at 1-foot contour intervals were computed using Geographic Information System (GIS) software and ACAP-32 the was used to produce the reservoir surface area and capacity tables at 0.1 and 0.01-foot increments.
Appendix C contains contour maps using the 2017 survey data.
Appendix D contains cross section plots of the range lines.

2. Watershed Description

The watershed upstream from Yellowtail Dam has a total contributing drainage area of 19,650 square miles (mi^2). Boysen, Buffalo Bill and Anchor Reservoirs are within the Bighorn drainage. These dams were all completed prior to the construction of Yellowtail Dam. The drainage area of Boysen Reservoir (1952) is 7,700 mi^2, the drainage area for Buffalo Bill Reservoir (1910) is 1,498 mi^2, and the drainage area for Anchor Reservoir is 131 mi^2. The net sediment-contributing drainage area to Bighorn Reservoir is 10,321 mi^2 (Figure 1). The size of the drainage area for these reservoirs was taken from Stream Stats (USGS, 2019), which are slightly different from those published in the Project Data Book (Water and Power Resources Service, 1981). This watershed originates at the north end of Wind River Canyon, a deep canyon eroded across the Owl Creek Mountains of central Wyoming, and flows in a northerly direction across the Bighorn Basin before turning to flow in a northeast direction in a deep canyon eroded through the Bighorn Mountains (Clausen, 2019).

2.1. Geology

The Bighorn drainage area is bounded at the south by the Bridger and Owl Creek mountains. The Absaroka and Beartooth mountains lie to the west of the basin and extend northward to the Montana border, and in the eastern portion of the basin are the Bighorn Mountains. In many locations the mountain ridges extend well into the basin and include deeply cut canyons. In other areas the transition between the mountains and the plains is more gradual. Soon after the Bighorn River crosses into Montana it enters the Bighorn Canyon, which is 1,000 to 2,000 feet deep and includes several side canyons. The Bighorn Canyon is cut through Madison limestone and the river flowed over Bighorn limestone prior to dam closure (Fisher, 1906).

The watershed consists primarily consist of badlands, where grass and other low growing vegetation (e.g. sage) dominate. Land use activities within the watershed primarily consist of grazing and irrigated agriculture. These types of land use tend to increase sediment yields above natural levels. The mountainous portions of the basin support a variety of pine and aspen trees.

2.2. Climate and Runoff

Reservoir inflows are primarily from the Bighorn and Shoshone Rivers as well as releases from Buffalo Bill (Shoshone River), Boysen (Bighorn River), and Anchor (Owl Creek) dams. Based on Reclamation Hydromet data presented in Table 1, the mean annual runoff to Bighorn Reservoir is 2,440,000 acre-feet (Water Year (WY) 1966-2019). This runoff is primarily from snowmelt, rainfall, and upstream reservoir releases. The mean annual stream flow to the reservoir is 3,370 cubic feet per second (cfs). The ratio of reservoir storage capacity to the mean annual runoff is 0.52. This means that, when full, the reservoir stores a water volume equivalent to 189 days of mean annual stream flow.

U.S. Geological Survey (USGS) gauges for the primary streams contributing to Bighorn Reservoir are listed in Table 2. Plots of average daily discharge for WY 1966-2019 are shown in Figure 2 for the Bighorn River and in Figure 3 for the Shoshone River. A plot of annual reservoir inflow (computed in Hydromet, Reclamation 2019) is shown in Figure 4

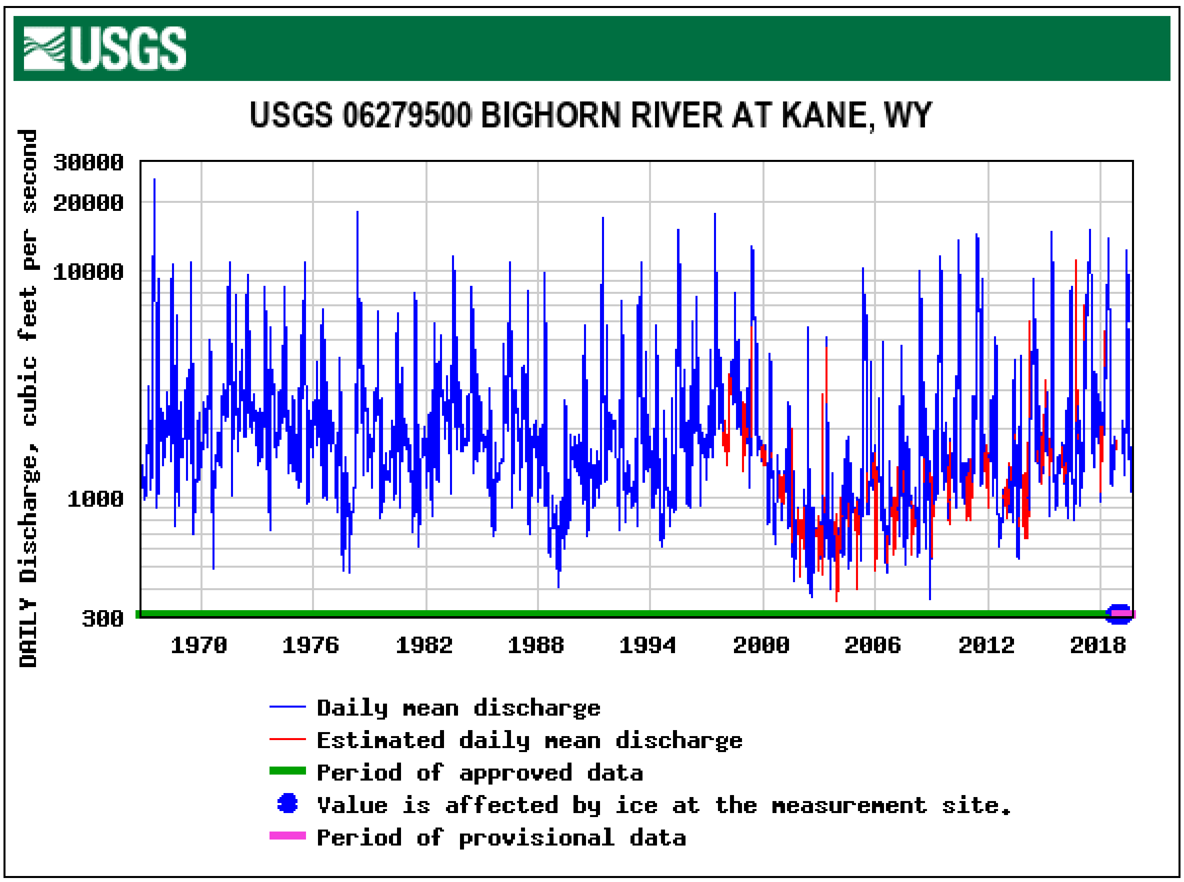


Figure 2: Plot of daily average streamflow for the Bighorn River at Kane, Wyoming.

Table 1. Bighorn Reservoir monthly computed Inflow values from Reclamation's Hydromet Data from WY 1966 to 2019 (in acre - feet).

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
1966	259974	190493	199977	154474	133467	123867	97759	129916	134947	103999	95954	116027	*1,740,853*
1967	137481	120433	114313	124481	135153	202385	144205	210324	930204	986387	175987	177348	*3,458,700*
1968	193093	209726	200514	189348	213652	231961	196072	202427	531882	191343	227111	218396	*2,805,525*
1969	216119	230793	201832	165006	194207	232514	213549	212068	326676	269910	126928	149374	*2,538,975*
1970	195434	189734	152827	139721	185856	198322	158289	280349	476666	296141	108414	154960	*2,536,716*
1971	178394	169235	154258	175057	194770	223493	226053	374443	662700	498407	162643	196368	*3,215,821*
1972	286871	235861	179751	207962	273023	287254	263128	285151	587537	276210	237458	200005	*3,320,210*
1973	232373	208597	184373	187062	159068	205861	198461	343582	349291	205865	141457	322195	*2,738,186*
1974	249872	201570	163759	150412	174184	207940	229780	282060	645936	425573	199062	164525	*3,094,675*
1975	189646	158728	157404	144821	126014	170325	200133	387526	551427	723996	225158	186545	*3,221,724*
1976	214151	161852	198534	201856	215341	241528	272293	322726	520179	241081	191130	186257	*2,966,926*
1977	208947	169513	203379	189441	132764	111372	138385	200003	148320	63146	80881	94481	*1,740,631*
1978	113880	89187	77485	64387	74952	170661	241432	488004	473461	625607	244927	223260	*2,887,245*
1979	242321	198706	179798	167507	133890	252109	227186	266718	285614	130630	160382	126074	*2,370,934*
1980	145715	134029	128375	117868	130047	159854	140219	214152	350321	295039	196167	215173	*2,226,961*
1981	165346	155192	146334	135144	118482	129204	92154	269242	505918	171555	126719	127944	*2,143,234*
1982	168918	149881	150244	124036	144931	188293	127789	140511	393914	411705	232403	225498	*2,458,122*
1983	299035	218802	207274	229440	212771	197399	150878	258959	563657	509268	209946	201606	*3,259,035*
1984	244284	205425	123011	155291	143220	198750	189066	363481	483482	320556	230656	230298	*2,887,520*
1985	219377	211882	175505	157932	132335	200531	154246	174176	139214	94364	92279	134384	*1,886,224*
1986	137616	88703	106134	118576	136140	194664	218715	315660	699616	425129	205810	204530	*2,851,291*
1987	184186	171469	135439	131635	155279	183656	177996	237864	238734	129116	141746	172902	*2,060,022*
1988	164322	141249	126919	113258	119400	136502	119841	316798	141922	75129	69747	94168	*1,619,254*
1989	105273	89814	59377	61079	53750	99460	100868	153795	215813	152243	126491	149575	*1,367,538*
1990	189723	144563	109017	115655	117907	138884	144528	198408	310248	213500	134355	121976	*1,938,765*
1991	138800	115599	81593	83771	98056	99572	128719	354583	833686	302231	148122	255159	*2,639,890*
1992	164175	144208	141731	151201	141065	113770	105706	199474	267898	228216	123952	143831	*1,925,227*
1993	144021	107799	77633	72610	74028	127056	102428	312402	388498	321513	180905	183303	*2,092,195*

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	total
1994	215805	119557	131895	124027	98934	156037	169813	213354	119899	84302	91185	132306	*1,657,115*
1995	147103	98239	72721	72735	91990	98666	86872	251964	674104	674560	228676	220328	*2,717,959*
1996	180401	126410	118530	117075	159831	234479	344463	351921	523538	352436	159197	172118	*2,840,399*
1997	157510	127573	112048	131504	165664	295948	328625	403610	821725	403423	329324	239490	*3,516,444*
1998	235963	135413	133028	133417	139213	216831	243985	256213	279357	470791	284911	258788	*2,787,912*
1999	223409	166262	133361	138127	131672	241955	195610	560880	810296	387576	233641	224400	*3,447,189*
2000	184774	153629	143552	135051	134459	132586	108369	227364	197048	109550	107091	142551	*1,776,023*
2001	154936	119200	108371	103079	85068	130254	102733	130955	153657	82515	68866	108352	*1,347,986*
2002	102385	81852	60765	63187	47968	82218	79224	91959	162653	74736	72404	110471	*1,029,822*
2003	116320	78170	58126	57477	47222	95562	73321	143356	244104	87467	78442	128750	*1,208,318*
2004	118773	78882	56420	29517	65389	70700	62007	108867	115878	105397	100245	129496	*1,041,572*
2005	117922	83697	53897	69649	65481	77625	104276	319224	453374	188167	145407	169266	*1,847,984*
2006	160938	104336	102148	107196	93829	126869	105978	183971	163588	74662	81932	127187	*1,432,634*
2007	125649	98734	82492	67362	77839	100240	100596	206669	219176	87460	91257	106722	*1,364,195*
2008	138105	95822	66328	66275	68017	86129	80868	291621	595103	330727	129608	184624	*2,133,227*
2009	151366	118907	98008	112025	112993	138615	142596	268251	771605	474082	188918	152344	*2,729,709*
2010	180715	141442	111822	134766	120794	137708	121407	341224	761330	280765	122345	119561	*2,573,880*
2011	122182	122633	122714	121862	111876	167356	245829	529353	1004222	792902	279243	196835	*3,817,006*
2012	213599	142344	132407	136214	137482	177239	149707	204741	238545	100162	102747	118781	*1,853,967*
2013	132473	111566	95183	90109	86785	109446	99371	180808	215132	132575	97312	157028	*1,507,787*
2014	185661	130342	96084	97343	102190	209493	316194	534290	522702	351694	199940	219974	*2,965,908*
2015	178926	136021	138758	133630	166422	161534	130504	311757	876918	223590	150146	134164	*2,742,369*
2016	133477	121080	116138	118116	123511	111466	122000	358275	422823	128698	135893	180908	*2,072,384*
2017	202620	139889	109224	120538	212901	306734	603393	812986	920417	616326	216433	219041	*4,480,502*
2018	277811	229846	177380	177336	158924	308210	391173	657088	896156	373453	171230	163010	*3,981,616*
2019	175383	154431	132924	128328	116099	173049	185456	354644	676935	461153	206877	208624	*2,973,904*

Table 2: Primary streams contributed to Bighorn Reservoir with USGS gages.

USGS Stream Gage		Drainage Area (mi^2)	Hydrologic Unit Code	Period of Record
Name	**Number**			
Bighorn R. at Kane, WY	06279500	15,762	10080010	10/01/1928 - current
Shoshone R. nr. Lovell, WY	06285100	2,350	10080014	10/01/1966 - current

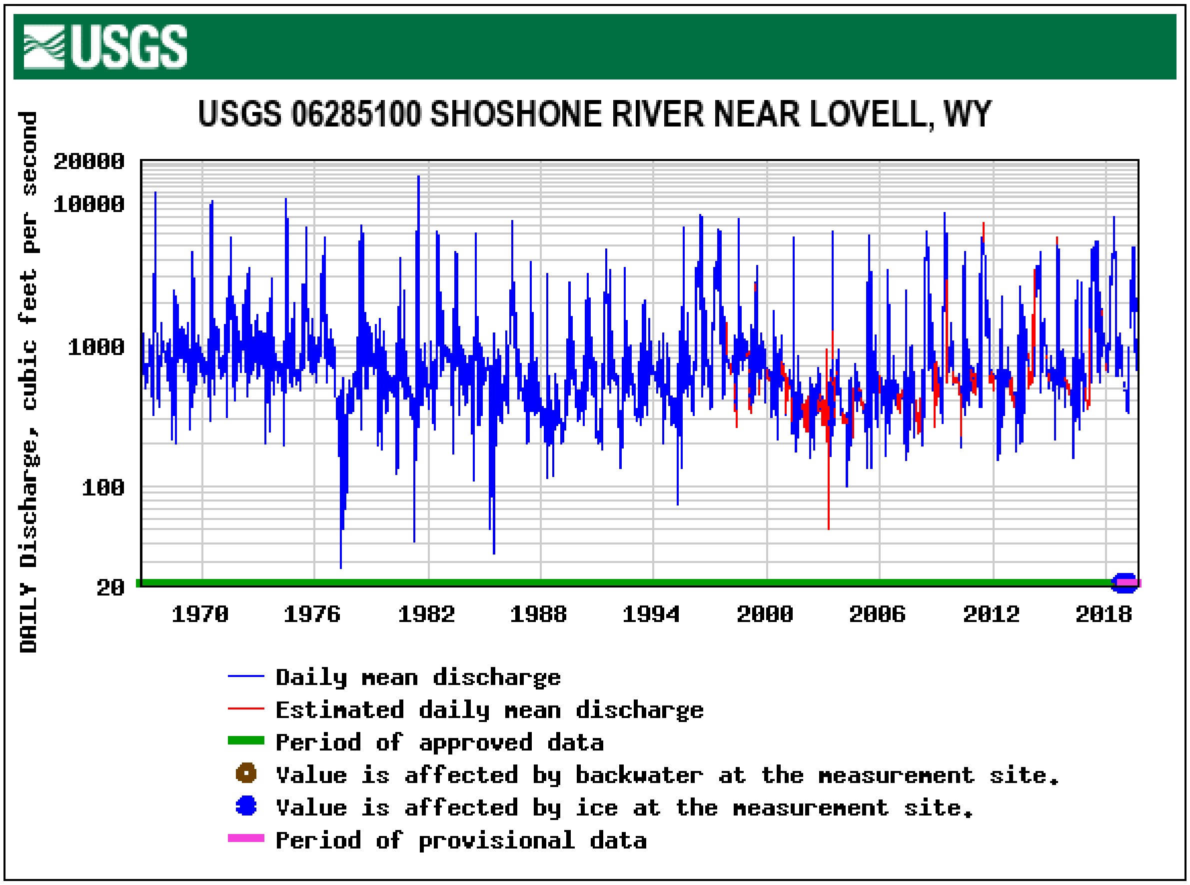


Figure 3: Plot of daily average streamflow for the Shoshone River near Lovell, Wyoming.

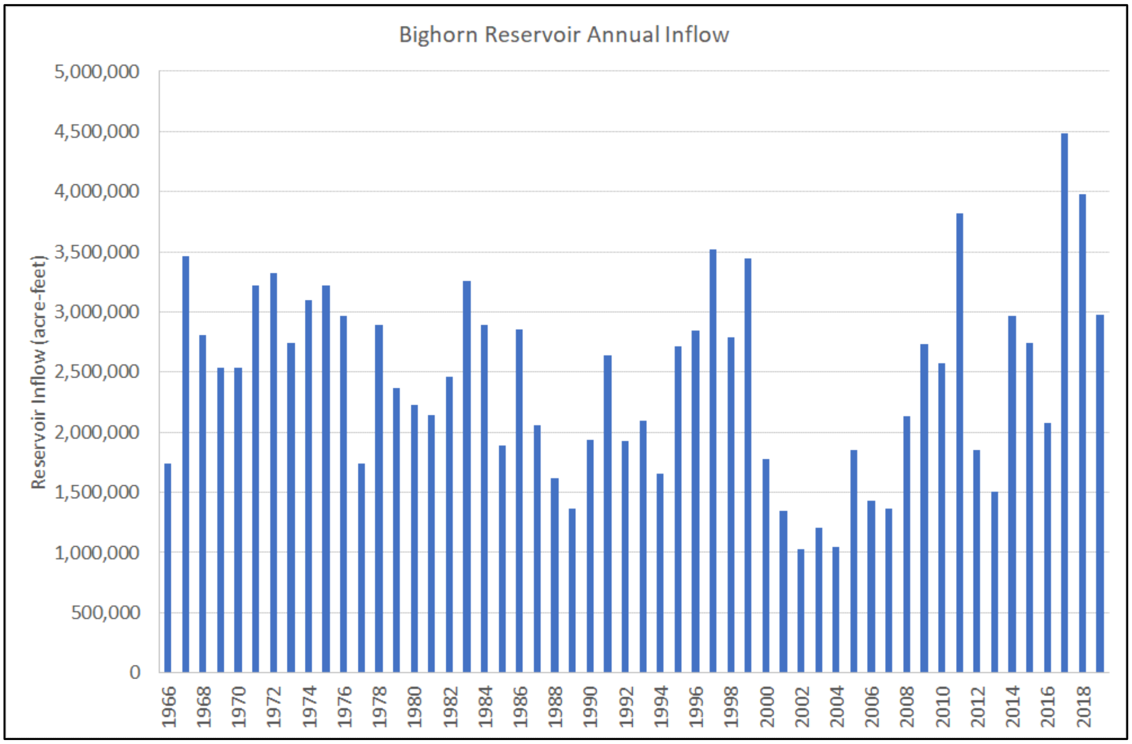


Figure 4. Plot of annual computed reservoir inflow (WY1966-2019). Data source: https://www.usbr.gov/gp-bin/arcweb_bhr.pl (Hydromet).

2.3. Dam Operations and Reservoir Characteristics

Yellowtail Dam is a concrete thin arch dam with a structural height of 525 feet and a height above the original stream bed of 494 feet. The crest length is 1,480 feet. Construction of this dam occurred between May 1961 and December 1967. Water storage began on November 4, 1965 with the closure of the diversion tunnel. Variable releases from the powerplant are regulated by the Yellowtail Afterbay Dam, which was constructed 2.2 miles downstream of from Yellowtail Dam. The afterbay dam is a 72-foot high concrete gravity structure.

The reservoir is widest in the delta portion approximately 1.8 miles downstream of the causeway (US 14 Alt., east of Lovell, Wyoming), where the width is approximately 8,300 feet. At Horseshoe Bend (approximately 9 miles north [downstream] of the causeway) it is approximately 3,000 feet wide. The reservoir downstream of Horseshoe Bend is in a narrow canyon with a typical width of 500 feet. A delta has formed near the upstream end and has progressed seven miles downstream of Horseshoe Bend. The historic reservoir water surface elevations in the Reclamation Project Vertical Datum (RPVD) are presented in Figure 5. Reservoir water surface typically fluctuates about 25 - 30 feet annually. The influence of reservoir operations on sedimentation in the delta is described in a report by the USACE (2010), which includes results of sediment transport modeling under various reservoir operation scenarios.

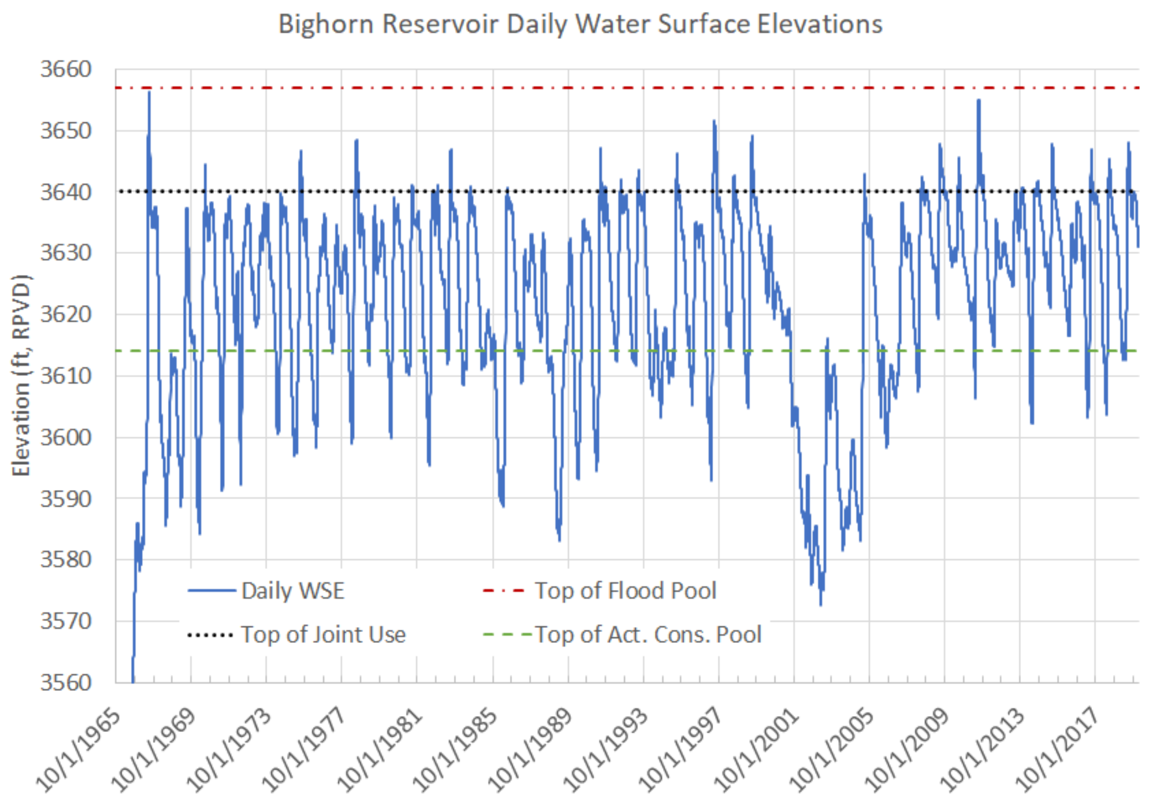


Figure 5. Historic Bighorn Reservoir water surface elevations (project datum). Data web source: www.usbr.gov/gp/hydromet. The top of dead pool elevation is 3296.50 feet.

There is no record of past reservoir sediment management activities. However, the Bighorn River System Issues Group has discussed various means to manage sediment in the delta. The U.S. Army Corps of Engineers published a study detailing multiple reservoir sediment management options (USACE, 2010). A sediment modeling study was performed in the Horseshoe Bend area to better understand the usefulness of a dike constructed in the reservoir to encourage sediment to bypass the recreation area and deposit in the canyon downstream (Hilldale, 2018). This dike in Horseshoe Bend was one of the suggestions put forth by the USACE.

3. Previous Reservoir Survey(s)

Prior to dam closure and initial reservoir filling, a range line survey was conducted between November 1962 and September 1964. Within the Bighorn Canyon, the underwater portion of each range line was surveyed and the river water surface elevation coincident with the survey was determined. Each range end was marked by a monument and surveyed to determine the horizontal and vertical positions so that the original surface areas and corresponding storage capacities could be measured (Ferrari 2010). Aerial photography of the reservoir area was flown in 1945.

From 1981 to 1982 a bathymetric survey of Bighorn Reservoir was completed (Blanton 1986). There was a variety of survey techniques employed during this survey due to the various reservoir conditions.

In 2000 select range lines were surveyed by the Sedimentation and River Hydraulics Group, although a report for this survey has not been located. Range lines 8 – 28 were surveyed, results and some details are provided in Ferrari (2010).

The reservoir was again surveyed in 2007 using single and multibeam SONAR (Ferrari 2010). The single beam SONAR transducer was only calibrated to a depth of 180 feet, beyond which a multibeam SONAR transducer was used. Range Line #1 was not surveyed due to access limitations near the dam. This survey did not extend upstream of Range Line 31 (at the causeway) due to low water surface elevations. The original and subsequent reservoir surveys are described in Table 3.

Table 3. Previous Bathymetric Reservoir Surveys. The survey reports can be accessed at https://www.usbr.gov/tsc/techreferences/reservoir.html.

Survey Year	Extent of Survey	Survey Method	Depth Sounder	Above water survey
1982	Full	Varied	Single Beam	None
2000	Partial	Unknown	Unknown	None
2007	Full	Surface Map	Single and Multibeam	None
2017	Full	Surface Map	Multibeam	None

4. Survey Control and Datum

For the 2017 survey, all bathymetry and GPS control measurements were collected in North American Datum (NAD 1983) Montana State Plane FIPS2500 (horizontal) coordinates, International Feet and NAVD 1988, using Geoid 12A, US survey feet elevations. During processing, all bathymetry and GPS measurements were converted to the RPVD for Yellowtail Dam. The vertical datum is based on the water surface elevation gage at Yellowtail Dam which is referenced to RPVD in US survey feet (sft).

The relationships among the various datums are as follows: RPVD is assumed equivalent to National Geodetic Vertical Datum (NGVD29); NAVD 1988 – NGVD29 = 2.63 sft (at Yellowtail Dam) NAVD88 – NGVD29 = 2.65 sft (at Highway 14A Causeway). The difference between NGVD 1929 and NAVD 1988 was computed using the US Army Corps of Engineers conversion program Corpscon v6.0.1. Corpscon uses National Geological Survey (NGS) data and algorithms to convert between various horizontal projections and vertical datums (www.agc.army.mil/Missions/Corpscon.aspx).

For the delta portion of the reservoir (within and upstream of Horseshoe Bend), GPS base station receiver was set up over multiple temporary monuments near the causeway and near the Horseshoe Bend boat launch for GPS RTK positioning. Precise coordinates for these monuments were determined using the Online User Position Service (OPUS, www.ngs.noaa.gov/OPUS) provided on line by the National Geodetic Survey (NGS). The position correction obtained from OPUS was applied to the bathymetry measurements where RTK GPS was utilized. In the canyon portion of the reservoir (downstream of Horseshoe Bend) where connection with a base station was not feasible, differential GPS was used for positioning.

5. Methods Summary

A complete, bathymetric survey was conducted during July and August 2017 from multiple boats using a multibeam depth sounder or an ADCP to continuously measure water depths for accessible portions of the reservoir. A large majority of the reservoir was surveyed using multibeam SONAR mounted to an 18-foot aluminum boat. The shallow portion of the delta upstream of the causeway was surveyed with an ADCP deployed from a raft. The ADCP produces 5 returns from each SONAR ping, a nadir position and 4 positions from transducers angled at 25 degrees from nadir. This results in 5 elevation values, with corresponding positions, per sounding (or 'ping'). The horizontal position of the moving boats was continually tracked using RTK GPS when a base station was utilized. A map of the data points collected with the ADCP is presented in Figure 6. A map of the point coverage of the multibeam SONAR in the Horseshoe Bend area is shown in Figure 7.

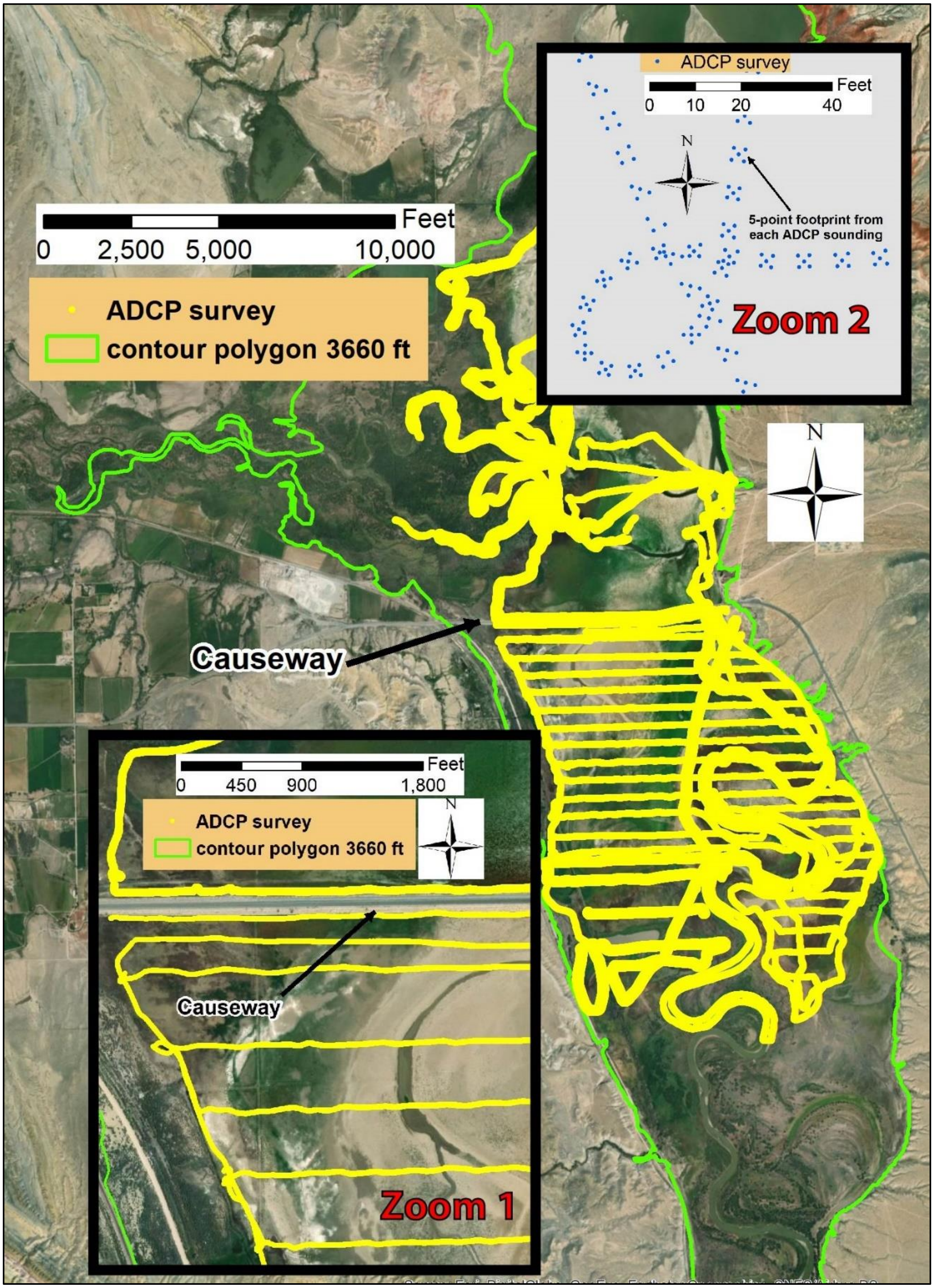


Figure 6. Map of bathymetric survey data coverage with the ADCP in the shallow delta areas. Zoom 1 shows a closer view of the coverage. Zoom 2 shows an extreme zoom to show the 5-point footprint of the ADCP SONAR capability.

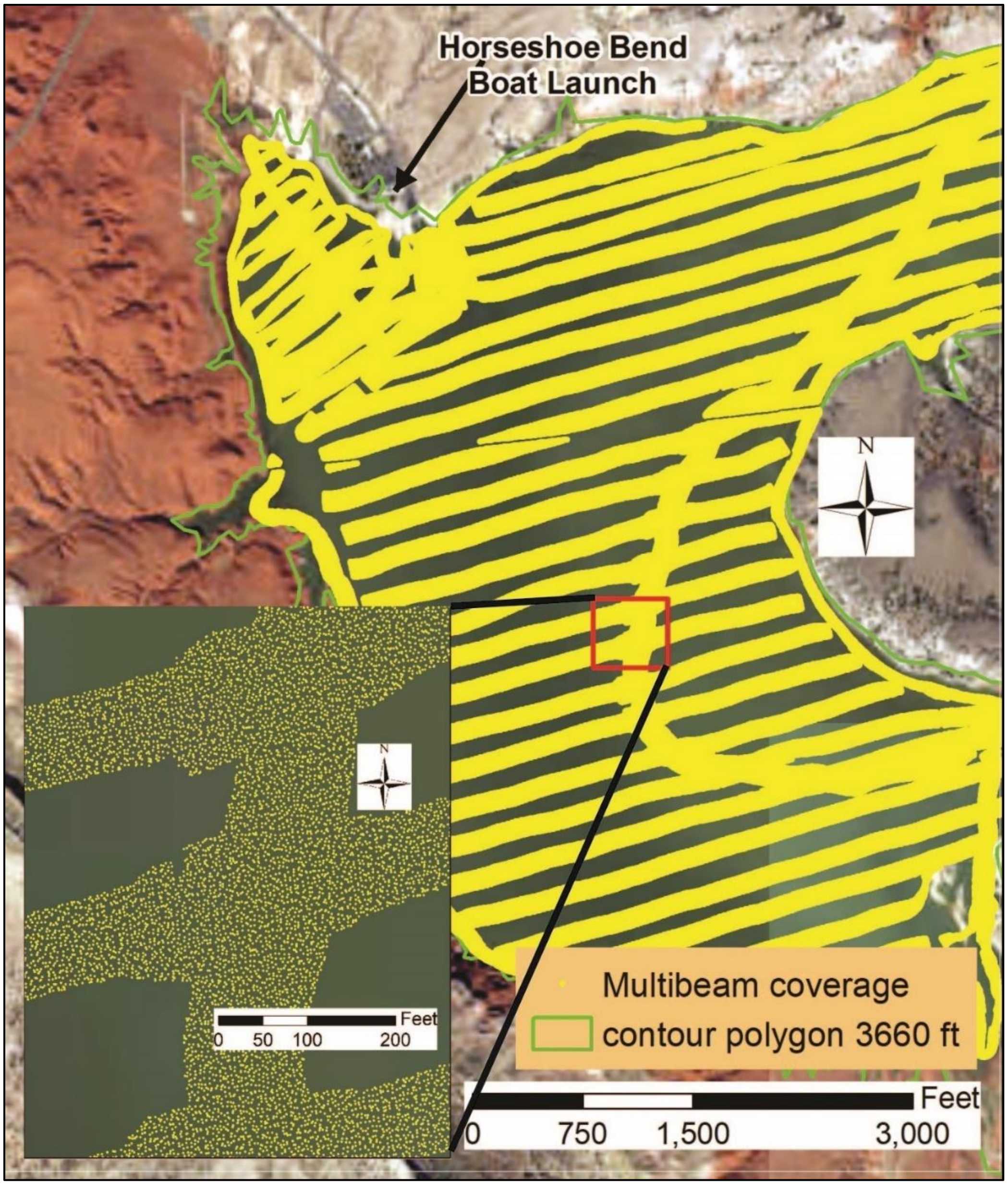


Figure 7. Map of bathymetric survey data coverage using the multibeam SONAR in the Horseshoe Bend area.

5.1. Collection of Sediment Cores

On July 11, 2017 seven sediment core samples were taken from the delta area for an analysis of physical properties and erodibility. The primary purpose of the sediment information was for the 2-dimensional sediment transport modeling (Hilldale 2018). The locations of the sediment cores are shown in Figure 8.

A VibeCore vibrating core sampler was attached to a 10-foot aluminum crane mounted to the same 18-foot aluminum used for the multibeam bathymetric survey for collection of reservoir bottom sediment cores (Figure 9). Clear acrylic tubes (8 feet long, 3 inch diameter) were mounted to the vibrating head powered by two 12 volt batteries connected in series. The VibeCore sampler works by being lowered through the water until the bottom tip of the sample tube just rests on the reservoir bed. The vibrating head is then turned on using the remote control box on the boat and the sample tube is pushed into the sediment through a combination of gravity and vibration until it reaches the head or encounters an impenetrable layer (SDI, 2012). The results of the sediment sampling are detailed in a technical memorandum by Armstrong (2017). Particle size distributions for the 7 sediment samples (at the bed surface) are shown in Figure 10. These distributions were all taken from the top of the sample, providing sediment size information at the bed surface. The coarser sediment (Samples BH4 & BH7) were taken from the main channel in the reservoir. The size distributions outside of the main channel are similar to those published by Blanton (1986).

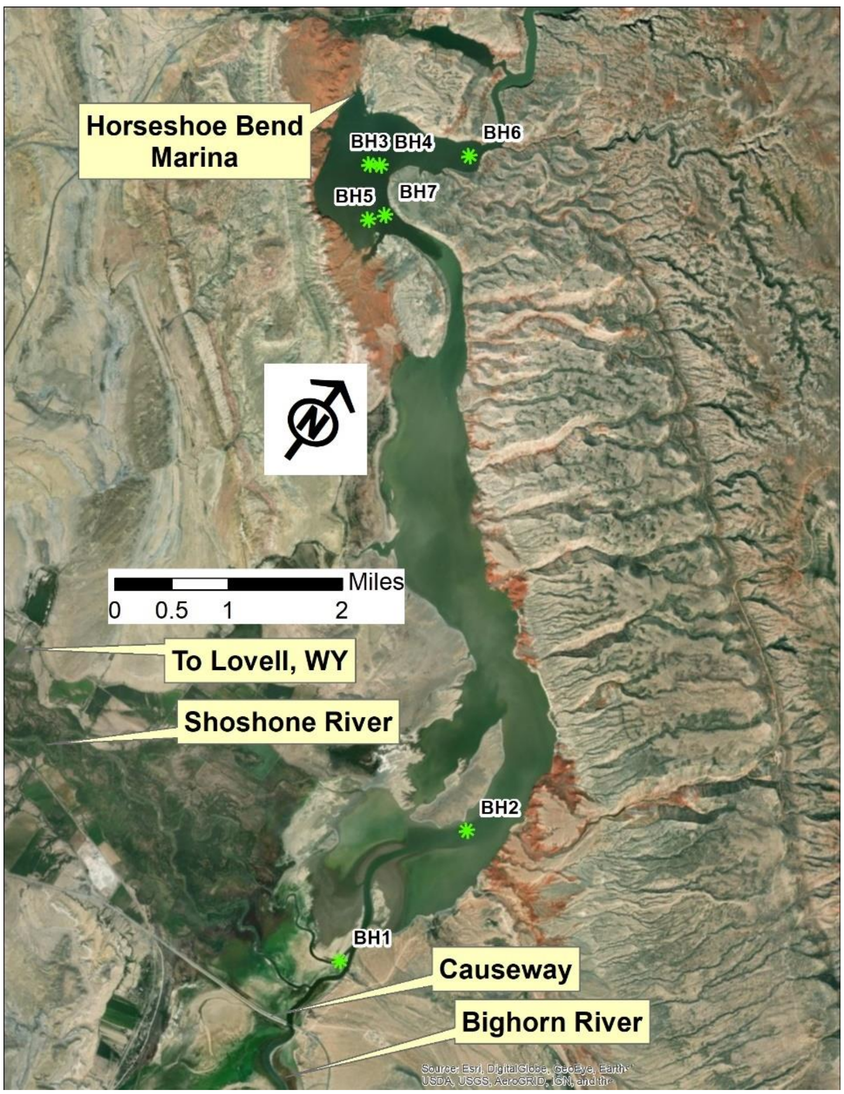


Figure 8. Map of 2017 sediment coring locations.

Figure 9. VibeCore sampling configuration mounted to the bow of an 18-foot aluminum boat (photo by Kent Collins).

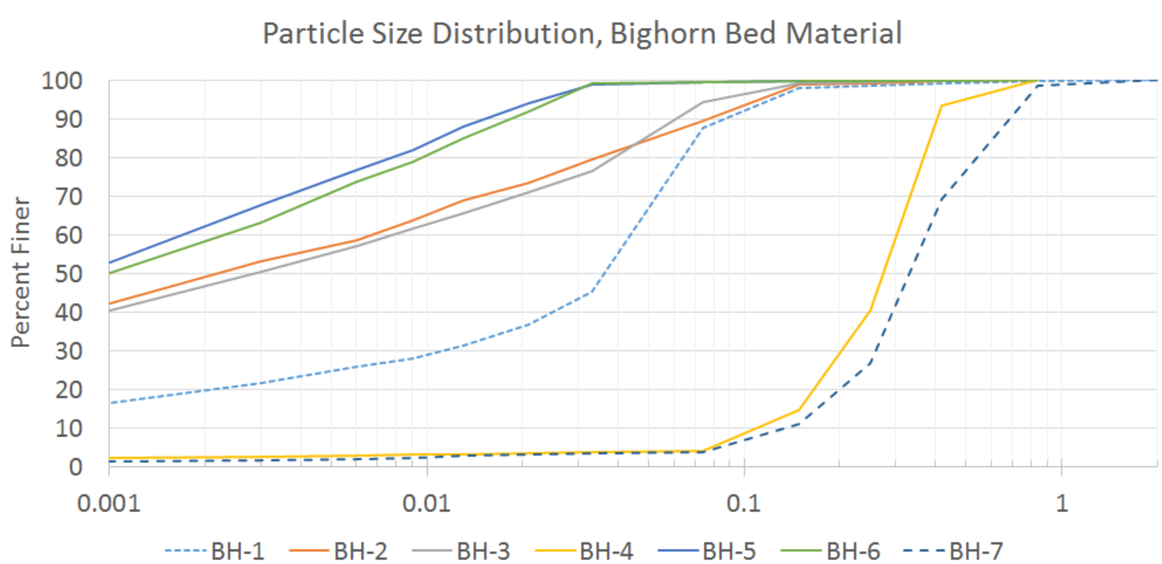


Figure 10. Particle size distribution in the surface layer of the sediment cores collected in July 2017 (from Hilldale 2018). Sediment size is shown on the horizontal axis in millimeters (mm).

6. Reservoir Surface Area and Storage Capacity

Tables of reservoir surface area and storage capacity were produced for the full range of reservoir elevations (Bighorn Reservoir 2017 Area and Capacity Tables, Reclamation 2020). Plots of the 2017 area and capacity curves are presented in Figure 11 along with curves from the 1965 (original), 1982, and 2007 surveys. For the 2017 survey, area and capacity curves are based on three different below-water elevations, depending on vessel and water elevation at the time of the survey. For the survey in the canyon it was assumed that bottom elevations approximately 10 feet and deeper were captured (3,628 feet elevation and below, RPVD). In the delta area downstream of the causeway it was assumed that bottom elevations were captured approximately 5 feet below the water surface, which corresponds to bed elevations approximately equal to 3,628 feet (July 2017) and 3,633 feet (August 2017) using the 18-foot aluminum boat. During the July 2017 trip (water surface 3,642.8 feet), while using the cataraft, it was assumed that bottom elevations are surveyed approximately 2 feet below the water surface (approximately 3,640.5 feet). Curves above these elevations are based on interpolated elevations to the 3,660 feet contour digitized from a USGS quad map. This is the same method used for the 2007 survey (Ferrari 2010), however the delta upstream of the causeway was not surveyed in 2007. A comparison of these curves indicates that largest reduction in surface area and storage capacity occurs between elevations 3,610 and 3,620 feet (RPVD).

The actual surface areas and storage-capacity volumes for above-water elevations may differ from the areas measured in previous surveys because of delta sedimentation, shoreline erosion, or use of older methods.

Above-water topography was represented by a single contour line at 3,660 feet. This contour line was digitized from a USGS contour map by Ferrari (2010). The USGS National Elevation Database (NED) maps are often less accurate than more recently acquired elevations using aerial data collection methods. Blanton (1986) mentions an aerial data collection for photogrammetry performed in 1945 resulting in a contour map with an interval of 20 feet. Blanton (1986) adjusted the 1945 contour data based on his 1982 survey information to obtain a new contour map and area-capacity tables. The 1982 survey only included the range lines.

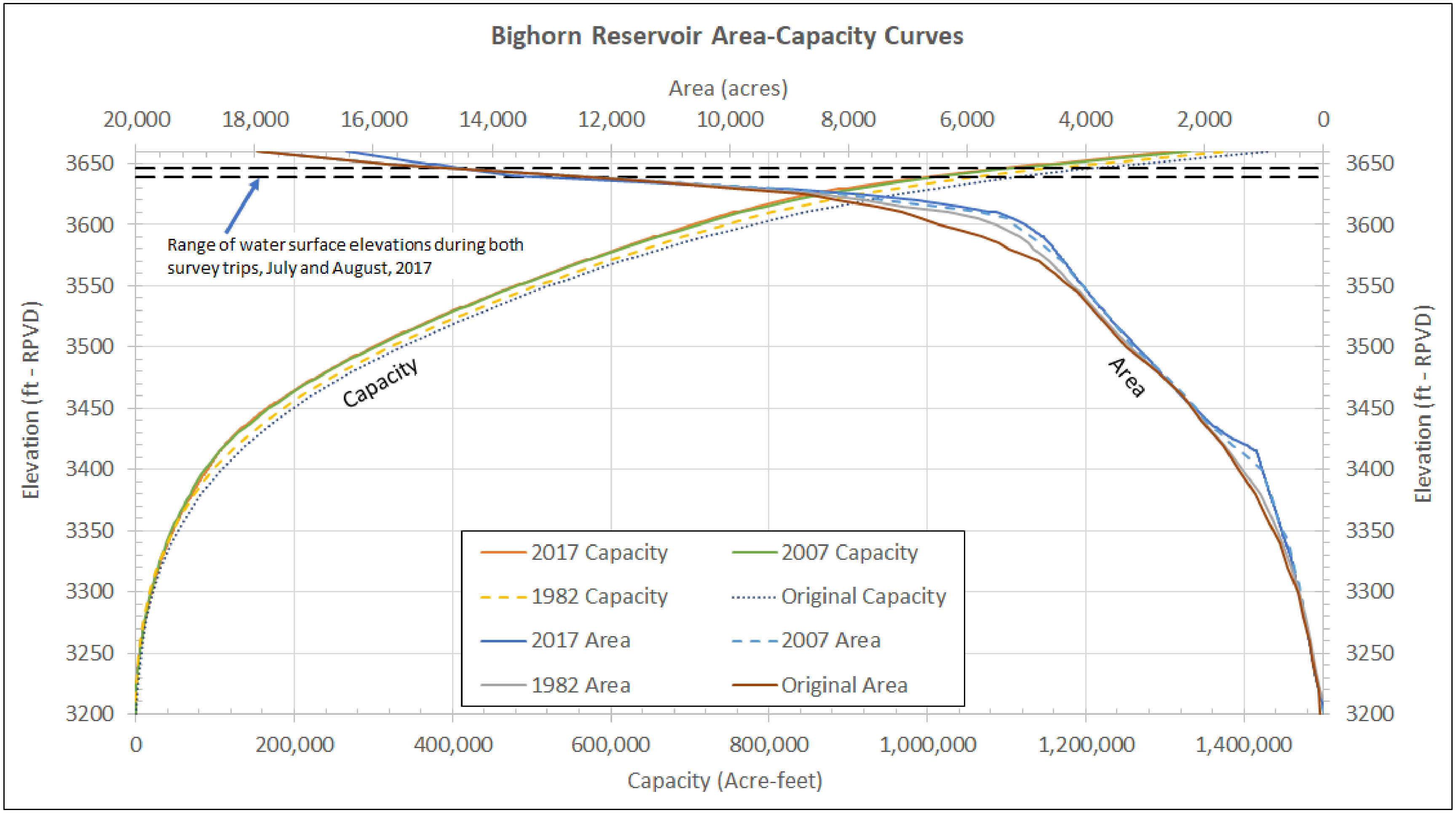


Figure 11. Plot of Bighorn Reservoir surface area and storage capacity versus elevation (RPVD). The upper extent of the bathymetric survey is typically 10 feet below the lowest water surface, in this case 3,628 feet.

7. Reservoir Sedimentation – Spatial Distribution

A longitudinal profile and representative cross sections of the 2017 reservoir bottom surface were developed to compare bottom elevations among various surveys. The longitudinal profile (Figure 12) shows that sedimentation is deepest at the delta front near Range Line (RL) 10, where approximately 80 feet of sedimentation has occurred since construction. Sediment deposition is also very deep between Range Lines 3 and 4 at the landslide, although available data do not provide a historic elevation at the landslide. It is important to consider that locations of deepest sediment accumulation do not necessarily correspond to the greatest volume of deposition. Bighorn Reservoir is quite narrow throughout much of its length but is quite wide in at its delta.

In the lower reservoir, 11.8 miles upstream of Yellowtail Dam, there is a landslide on the southern shore. The 1964 USGS contour map of this area shows the landslide, indicating that it has been there since reservoir filling. The runout of the landslide extends most of the way across the reservoir. As a result of the constriction, sediment has accumulated upstream of this feature and sediment passing the land slide is limited. Note the landslide location in the bed profile shown in Figure 12. A map of this landslide is shown in Figure 13. The profile shows the dramatic change in slope for the 2017 survey. A similar result is not shown in earlier surveys because only the bed elevations at range lines are included. This is an important feature when considering reservoir sedimentation and the life of the dead pool. This landslide was noted in Ferrari (2010) but not included in the profile data.

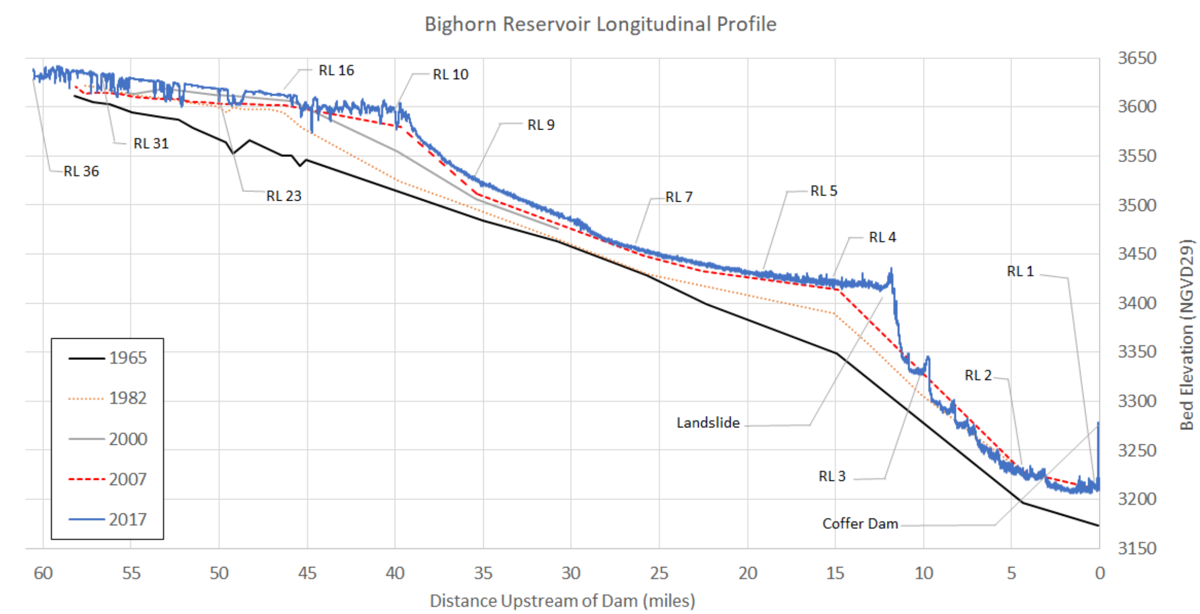


Figure 12. Longitudinal profile of Bighorn Reservoir bottom from the dam upstream to Range Line 36. The high point near the dam is the coffer dam remaining since original construction.

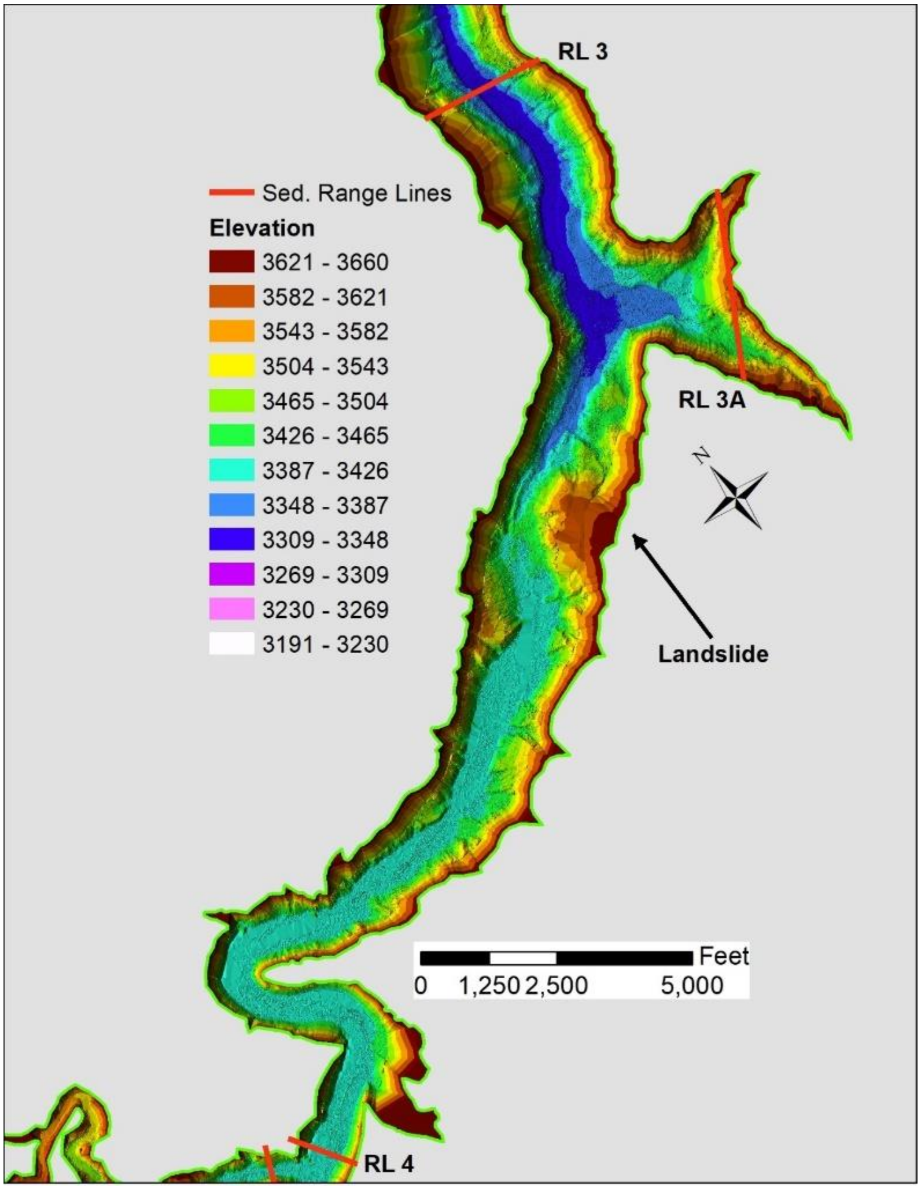


Figure 13. Map of Bighorn Reservoir showing the landslide between Range Lines 3 and 4.

To show the loss in reservoir capacity throughout the elevation range of Bighorn Reservoir, the 2017 reservoir capacity was subtracted from the original capacity at corresponding elevations. This results in a cumulative curve of capacity loss and the plot is shown in Figure 14. A steep slope in this graph indicates less capacity loss over a range of elevations. A shallower slope indicates a greater loss in reservoir capacity over an elevation range. There is a discontinuity in the curve above elevation 3,650 feet. This is attributed to poor representation of above-water data to create the complete reservoir surface. Although the cumulative sedimentation plot is useful, in some cases it is more instructive to view sedimentation in specific elevation bins, which is shown in Figure 15. This plot is able to demonstrate which portions of the reservoir are accumulating sediment at a more rapid rate than others. Figure 15 shows that the greatest volume of sedimentation occurs in the delta at elevations 3,580 feet to 3,620 feet. These elevations include portions of the active conservation and the joint use pools. Using the profile plot Figure 12 these elevations can be assigned an approximate stationing of Range Lines 10 through 23, which includes the Horseshoe Bend Recreation Area (nearest to RL 16).

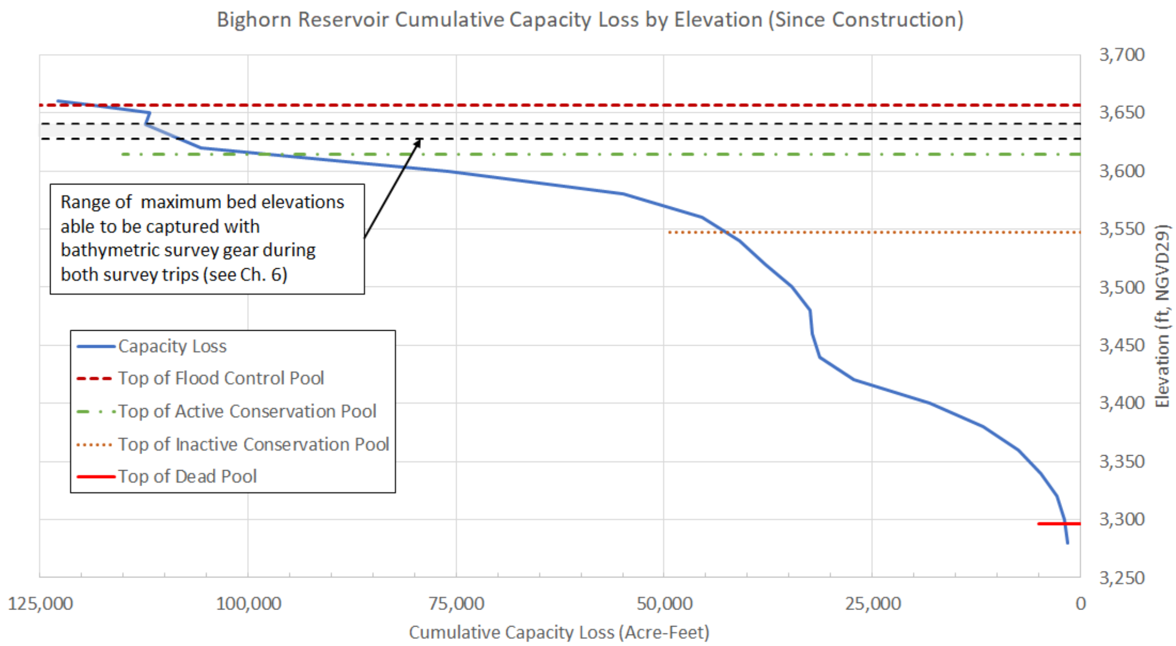


Figure 14. Plot of cumulative reservoir capacity loss throughout the elevation range of Bighorn Reservoir. The capacity loss values were obtained by subtracting the original reservoir capacity from the 2017 capacity at a given elevation. The discontinuity just below elevation 3,650 feet is due to the lack of proper elevation information for the above-water areas of the reservoir.

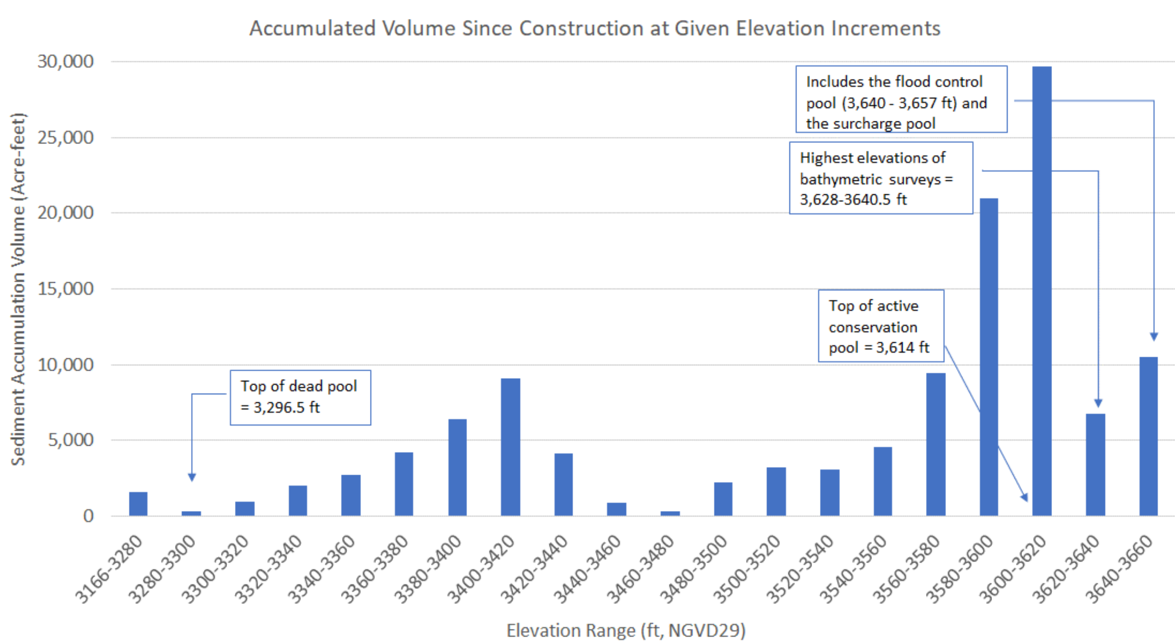


Figure 15. Column chart of sediment accumulation within 20-feet elevation bins.

An elevation map showing the results of the 2017 survey is shown in Figure 16 and Figure 17. These figures also indicate the locations of the sediment range lines. Figure 18 shows the delta area (Range Lines 11 – 36) in greater elevation detail. Cross sections at the sediment range lines are shown in Appendix D.

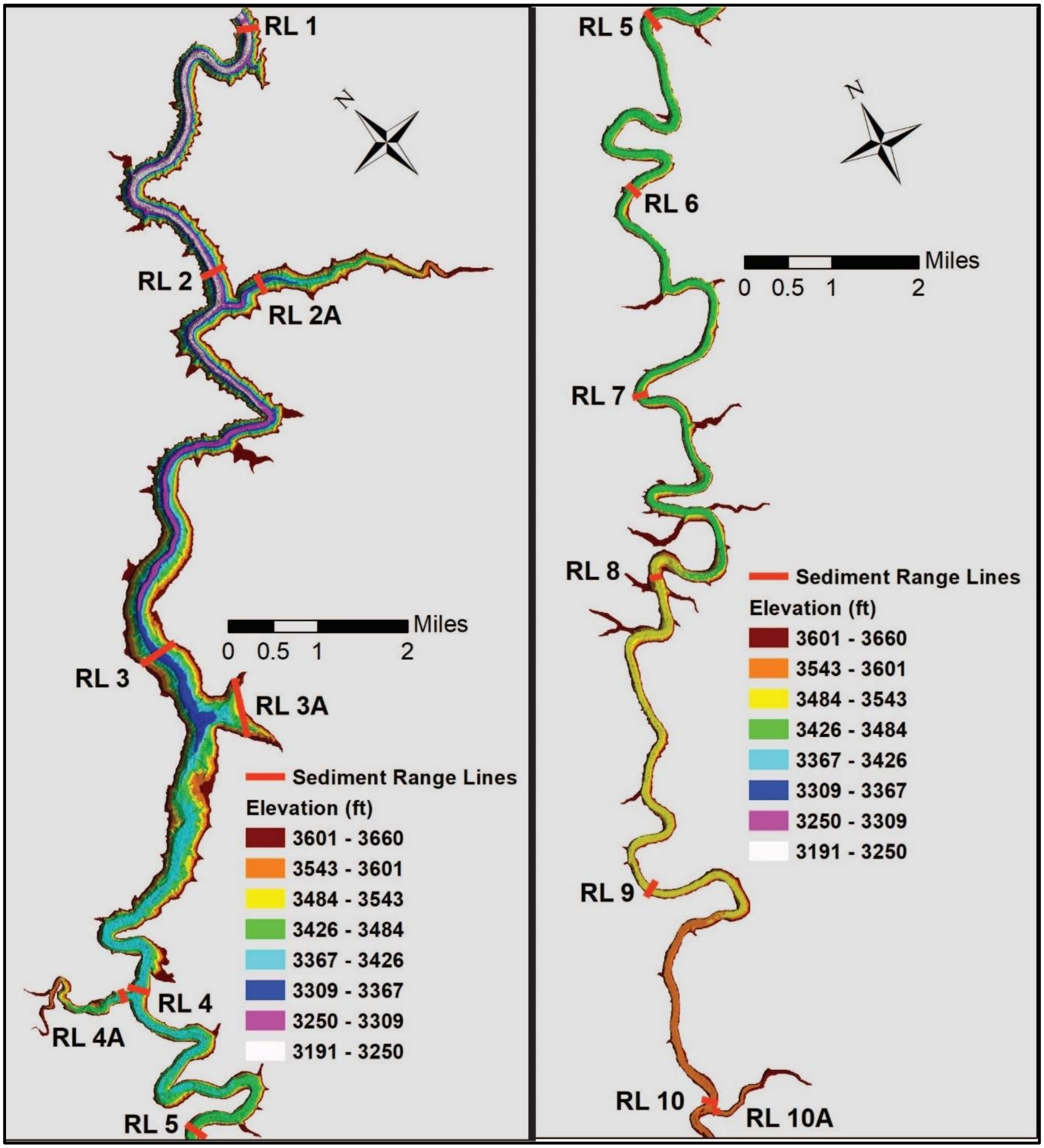


Figure 16. Reservoir surface elevation map and alignments of sediment Range Lines 1 - 10. Range Line 1 is nearest to Yellowtail Dam

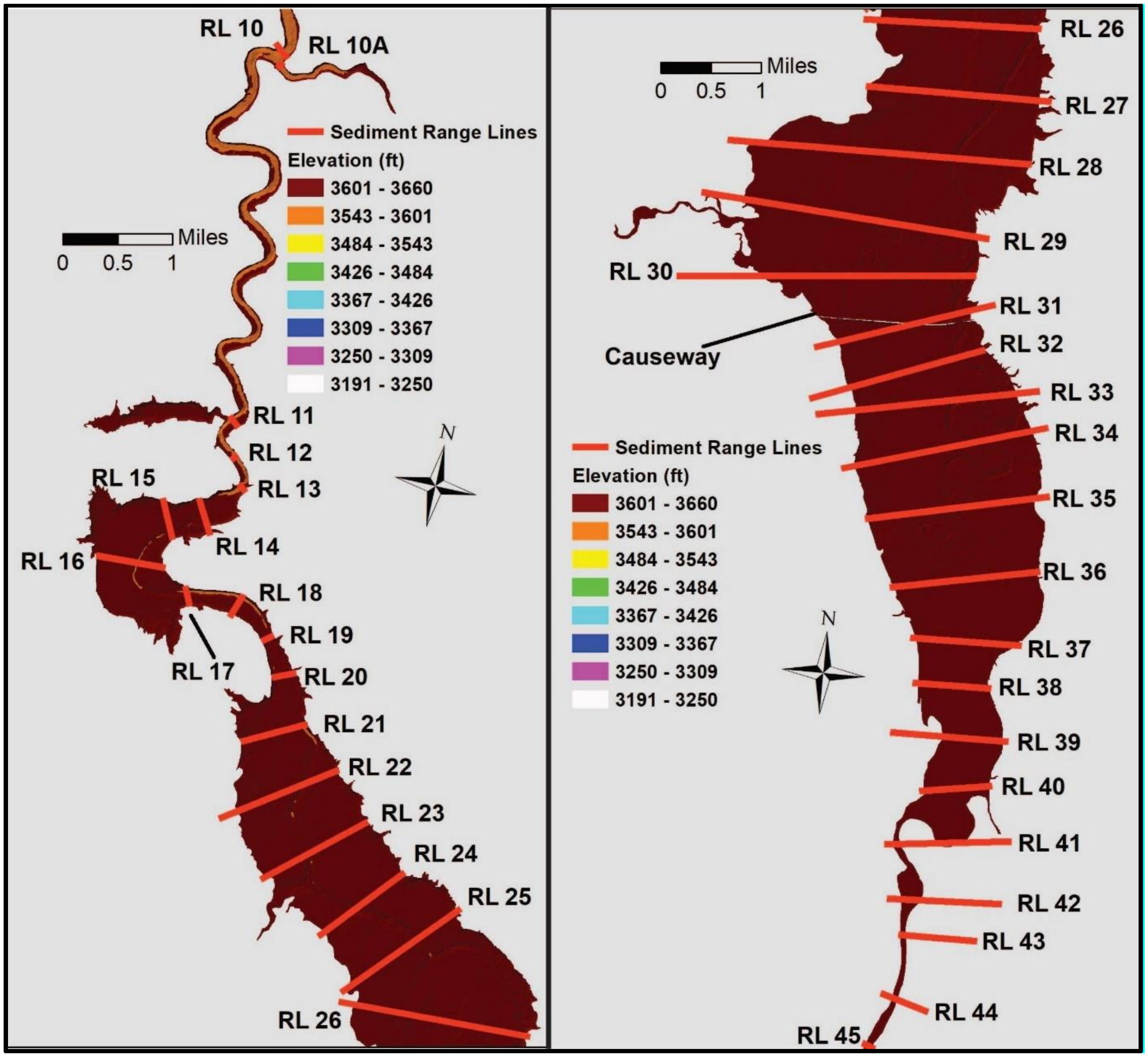


Figure 17. Reservoir surface elevation map and alignments of sediment Range Lines 10 - 44. Range Line 31 is nearest to the Highway 14 Alt causeway.

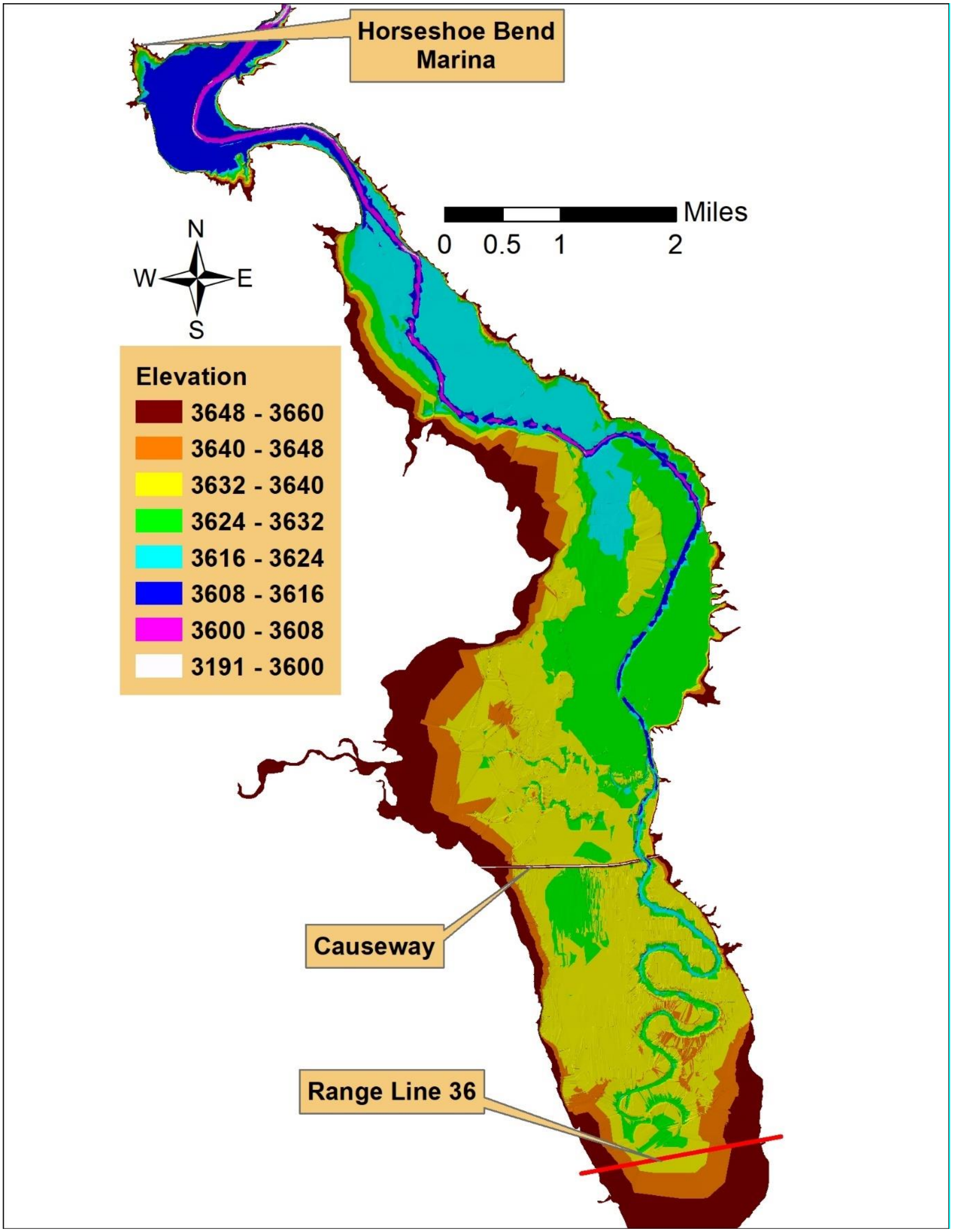


Figure 18. Elevation map of the delta area in Bighorn Reservoir.

8. Sedimentation Trends

Graphs of the historic reservoir capacity loss and cumulative reservoir sedimentation volume over time (Figure 19) indicate a slightly decreasing trend in the sedimentation rate since original filling.

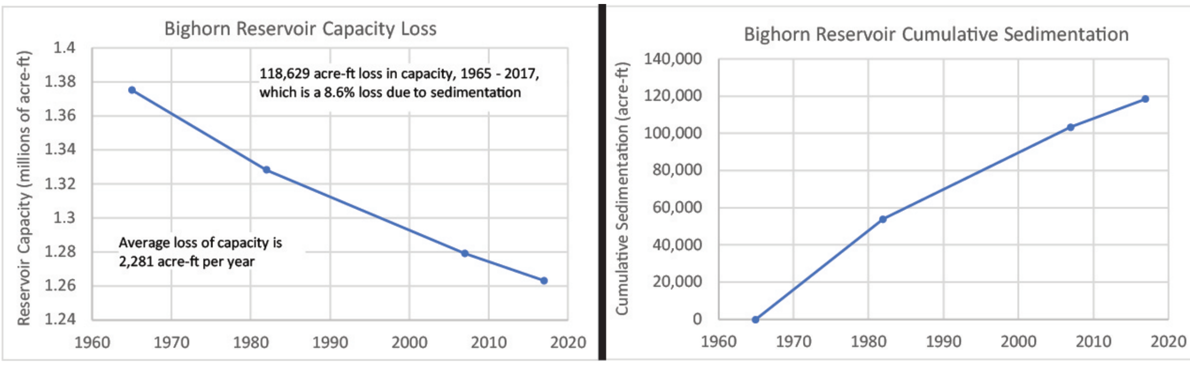


Figure 19. Reservoir capacity loss and cumulative reservoir sedimentation over time.

Sedimentation accumulates at all reservoir elevations and against the dam, although there are two locations in Bighorn Reservoir where the accumulations are greatest; the delta and upstream of the landslide (Figure 15). The dead storage capacity has reduced since the original reservoir filling, however the trend is misleading due to inaccuracies in older surveys using less accurate methods (interpolation between range lines) or incomplete surveys (the 2007 survey did not extend downstream of Range Line 1). The landslide is likely extending the life of the dead storage, as the top of the dead pool elevation is just downstream of Range Line 3. This fact makes it difficult to predict the remaining life of the dead storage. While sediment is passing the landslide, it is accumulating at a slower rate on the downstream side. Since 1964 Range Line 3 has aggraded 47 feet while Range Line 4 has aggraded 67 feet (see Appendix D). Range Lines 1 and 2 show no significant aggradation since the 1982 survey (Appendix D). When the slope of the reservoir bottom (Figure 12) upstream of the landslide equilibrates the sedimentation rate within the dead pool will accelerate. The slope of the reservoir bottom will equilibrate upstream of the landslide when the reservoir aggrades between the delta front (currently near Range Line 10) and the landslide (between Range Lines 3 and 4). This aggradation will appear as a mostly straight line in the profile graph (Figure 12) between the landslide and the delta front. Sedimentation in this region has occurred since the 2007 survey, as seen in Figure 12 at Range Lines 8 and 9 and in Appendix D

9. Conclusions and Recommendations

9.1. Survey Methods and Data Analysis

The 2017 bathymetric survey, combined with the 3,660 feet contour to represent the above-water topography, has been used to produce an accurate digital surface of the reservoir bottom. The accuracy of the 2017 map is limited between elevation 3,642.5 feet and 3,660 feet due to the absence of an above-water survey (LiDAR or photogrammetry). In this region the mapped elevations are linearly interpolated from the highest bathymetry point nearest to the contour. There was no opportunity to compare overlapping above- and below-water topography.

Reservoir surface areas were computed from this digital surface at 1-foot intervals to determine the 2017 storage capacity. Surface area and storage capacity were then interpolated at 0.1-foot and 0.01-foot intervals to create the updated area-capacity table. The difference in reservoir surfaces over time can be attributed to sedimentation, but also the differences in survey methods. The latest surface area and storage capacity curves compare reasonably well with the original curves and with curves from previous surveys. The 2017 survey was able to include the delta upstream of the causeway, which was not included in the 2007 survey due to low water. The use of modern survey methods (RTK-GPS, multibeam depth sounder, and a more complete survey) have produced a more accurate and precise digital surface of the reservoir bottom than past surveys using older methods and incomplete data.

9.2. Sedimentation Progression and Location

Over the span of 52 years, sedimentation has filled in 8.6 percent of the original storage capacity (evaluated at elevation 3,657 feet). The 2017 reservoir survey indicates that, since construction, the greatest amount of sedimentation occurred upstream of the delta front at Range Lines 10 - 23 and upstream of the landslide which is between Range Lines 3 and 4. An insignificant amount of sedimentation has occurred near the dam at Range Lines 1 and 2 and 90 percent of the original dead storage capacity remains as of 2017. Predicting the period until the dead pool is lost is difficult due to the influence of the landslide.

9.3. Recommendation for Next Survey

Based on the past rates of sedimentation, the next survey of Bighorn Reservoir is recommended within the next 20 years, no later than 2037. This assumes that no significant drawdown of the reservoir takes place and operations remain similar to the recent past (since 2008). A survey sooner than 20 years may be necessary if:

- Sediment accumulates in the delta area and becomes a concern, e.g. recreation at Horseshoe Bend,
- If reservoir operation result in a long period of water elevations below the top of the active conservation pool (Elevation 3614 feet RPVD), and
- If sediment contributions from the upstream watershed increased through increased storm runoff or is exacerbated by wildland fire.

It will be important to monitor aggradation downstream of Range Line 10 to the landslide because sedimentation rates past the landslide will dramatically increase when this portion of the reservoir aggrades. Normally the date to next survey is determined by the rate of aggradation within the dead pool and when it will be completely aggraded. Due to the difficulty in predicting this occurrence, an arbitrary date for the next-survey has been assigned for 20 years, with some caveats.

It is recommended that, prior to the next bathymetric survey, above-water topography is obtained using photogrammetry or LiDAR. This would greatly improve the quality of the map and thus the quality of the area-capacity table for higher water elevations in the exclusive flood pool. In this case, elevations above 3,628 feet to 3,640.5 feet (depending on the date of survey and the vessel used) are not accurate due to the lack of survey data and the reliability on the outdated USGS quad map. The aerial data should be collected at a low water elevation to capture as much of the reservoir as possible.

References

Armstrong, B., 2017. Bighorn Lake Sediment Erosion Testing Results. Bureau of Reclamation, Technical Service Center. Technical Memorandum #8530-2017-33, September.

Blanton, J.O.,1986. Bighorn Lake – 1982 Sedimentation Survey. Bureau of Reclamation report, REC-ERC-86-6, Denver, Colorado.

Ferrari, R.L., 2010. Bighorn Lake – Yellowtail Dam 2007 Sedimentation Survey. Bureau of Reclamation report, SRH-2010-12, Denver, Colorado.

Fisher, C.A., 1906. Geology and water resources of the Bighorn Basin, Wyoming. USGS Professional Paper No. 53, Gov't. Printing Office, Washington.

Clausen, E., 2019. Topographic Map Interpretation of Bighorn River-Wind River Drainage Divide Located East of Wyoming's Wind River Canyon, USA. Universal Journal of Geoscience 7(2): 56-67, 2019 http://www.hrpub.org DOI: 10.13189/ujg.2019.070202.

Hilldale, R.C., 2018. Pilot study of reservoir sustainability options: Bighorn Reservoir. Research and Development Office, Science and Technology Program, Denver, Colorado. Report #ST-2018-9344-01, December.

Reclamation, 2006. Erosion and Sedimentation Manual. Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. November.

Reclamation, 2019. Hydromet Data System, https://www.usbr.gov/gp/hydromet/. Accessed (11/11/2019).

Reclamation, 2020. Bighorn Reservoir 2017 Area and Capacity Tables. Technical Service Center, Sedimentation and River Hydraulics Group, Denver, Colorado. February.

SDI, 2012. VibeCore-D Operating Manual. Specialty Devices, Inc., Wylie, Texas.

USACE (2010). Bighorn Lake Sediment Management Study, Omaha District.

US Geological Survey. StreamStats, https://streamstats.usgs.gov/ss/ Accessed (12/4/2019).

Water and Power Resources Service, 1981. Project Data. U.S. Department of the Interior, U.S. Government printing office, Denver, Colorado.

Appendix A – Hydrographic Survey Equipment and Methods

The 2017 bathymetric survey was conducted during two trips to the reservoir, July 6 – 11, 2017 and Aug 23 – 27, 2017 when the reservoir water surface elevation ranged between 3642.82 feet to 3645.94 feet, and 3639.01 feet to 3638.71 feet, respectively (RPVD).

The survey was conducted along a series of predetermined planned survey lines (Figure 7). The survey lines were spaced closely enough so there would overlapping coverage from the multibeam depth sounder or close enough that liner interpolation of multi-beam depth data between survey lines would be adequate.

The survey employed two platforms to obtain a bathymetric survey. The primary platform was an 18-foot, flat-bottom aluminum Wooldridge boat powered by outboard jet and kicker motors (Figure A-1). This platform was used to survey all but the very shallow areas in the delta. Reservoir depths were measured from this boat using a multibeam echo sounder which consisted of the following equipment:

- variable-frequency transducer with integrated motion reference unit,
- near-surface sound velocity probe,
- two GPS receivers to measure the boat position and heading,
- an external GSP radio, and
- processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data.

The multibeam transducer emits up to 512 beams (user selectable) capable of projecting a swath width up to 120 degrees in 390 feet (120 meters) of water. At depths greater than 390 feet. the swath width narrows. The nadir beam is capable of measuring depths of 820 ft (240 meters). Sound velocity profiles were collected over the full water depth at various locations throughout the reservoir. These sound velocity profiles measure the speed of sound through the water column, which can be affected by multiple characteristics such as water temperature and salinity. These sound velocity profiles were used to calibrate the depth sounder.

The secondary platform was a cataraft equipped with a Sontek M9 ADCP (Figure A-2). Positions were obtained with RTK GPS mounted to the platform and heading was provided by the internal compass in the ADCP. Position, heading, and soundings (pings) were coordinated with Sontek Hydro-Surveyor software on a ruggedized laptop. This platform was primarily used to survey the very shallow portions of the delta, primarily upstream of the causeway (Figure 6). Additionally, there were some shallow areas near the delta of the Shoshone River that were surveyed with the cataraft and ADCP.

Figure A-1. Wooldridge boat with RTK-GPS and multibeam depth sounder system (Photo by Kent Collins).

Figure A-2. Photo of a cataraft rigged for bathymetric surveying (Photo by Reece Carpenter).

RTK survey instruments were used to continuously measure the survey boat's horizontal and vertical position and measure other ground control points and water surface elevations within and upstream of the Horseshoe Bend recreation area. Within the canyon area differential GPS was utilized for positioning. The GPS base station and receiver was set up on a tripod over a point with known coordinates overlooking the reservoir (Figure 6). Position corrections were transmitted to the GPS rover receiver using an external GPS radio and UHF antenna (Figure A-3). The base station was powered by a 12-volt battery.

Figure A-3. The RTK-GPS base station set-up used during the survey of Bighorn Reservoir (photo by Kent Collins).

The GPS rover receivers include an internal radio and external antenna mounted on a range pole (ground survey) or survey vessel (bathymetric survey). The rover GPS units receive the same satellite positioning data as the base station receiver, and at the same time. The rover units also receive real-time position correction information from the base station via radio transmission. This allows rover GPS units to measure accurate positions with precisions of ±2 centimeters (cm) horizontally and ±3 cm vertically for stationary points and within ±20 cm for the moving survey boat.

During the survey, a laptop computer was connected to the GPS rover receivers and echo sounder system. Corrected positions from one GPS rover receiver and measured depths from the multibeam transducer were transmitted to the laptop computer through cable connections to the processor box. Using real-time GPS coordinates, the Hypacksoftware provided navigational guidance to the boat operator to steer along the predetermined survey lines.

The Hypack hydrographic survey software was used to combine horizontal positions and depths to map the reservoir bathymetry in the Montana State Plane system. Water surface elevations from dam gage records and RTK GPS measurements were used to convert the sonar depth measurements to reservoir-bottom elevations in the RPVD. The multibeam depth sounder generates millions of data points. Sometimes fish, underwater vegetation, or anomalies mean that a small portion of depth measurements do not represent the reservoir bottom and these data are deleted during the post processing. Reducing this large data file is necessary, so a raster mesh is created in Arc GIS (10-foot square cells). For each raster mesh cell, the reservoir bottom elevation is assigned the median elevation of all available data points within that raster cell. The use of the median value reduces the influence of the highest and lowest elevations within the cell.

Appendix B - Computation of Reservoir Surface Area, Storage Capacity, and Sediment Volume

A digital surface of the reservoir bottom was generated in GIS using the processed bathymetric data points (easting, northing, and elevation) combined with available above-water data. Horizontal surface areas were then computed at 1-foot increments, using functions within ArcGIS, for the complete range of remaining reservoir elevations (3195 feet to 3660 feet, RPVD). These reservoir surface areas were then used in Reclamation's Area-Capacity (ACAP) Program, 1985 Version (Reclamation, 1985), to compute the storage capacity at these increments and then interpolate surface areas and storage capacities at 0.1 and 0.01-foot increments between each 1-foot interval.

The program uses the least squares method to predict the reservoir storage capacity between 1-foot intervals using the following equation over a certain elevation interval:

$$V = A_1 + A_2(y - y_b) + A_3(y - y_b)^2$$

where: V = storage capacity (acre-feet)
y = reservoir elevation
y_b = reservoir elevation at bottom of elevation increment
A_1 = intercept and storage capacity at elevation y_b (acre-feet)
A_2 = surface area at elevation y_b (acres) and coefficient for linear rate of increase in storage capacity
A_3 = coefficient (feet) for nonlinear rate of increase in storage capacity

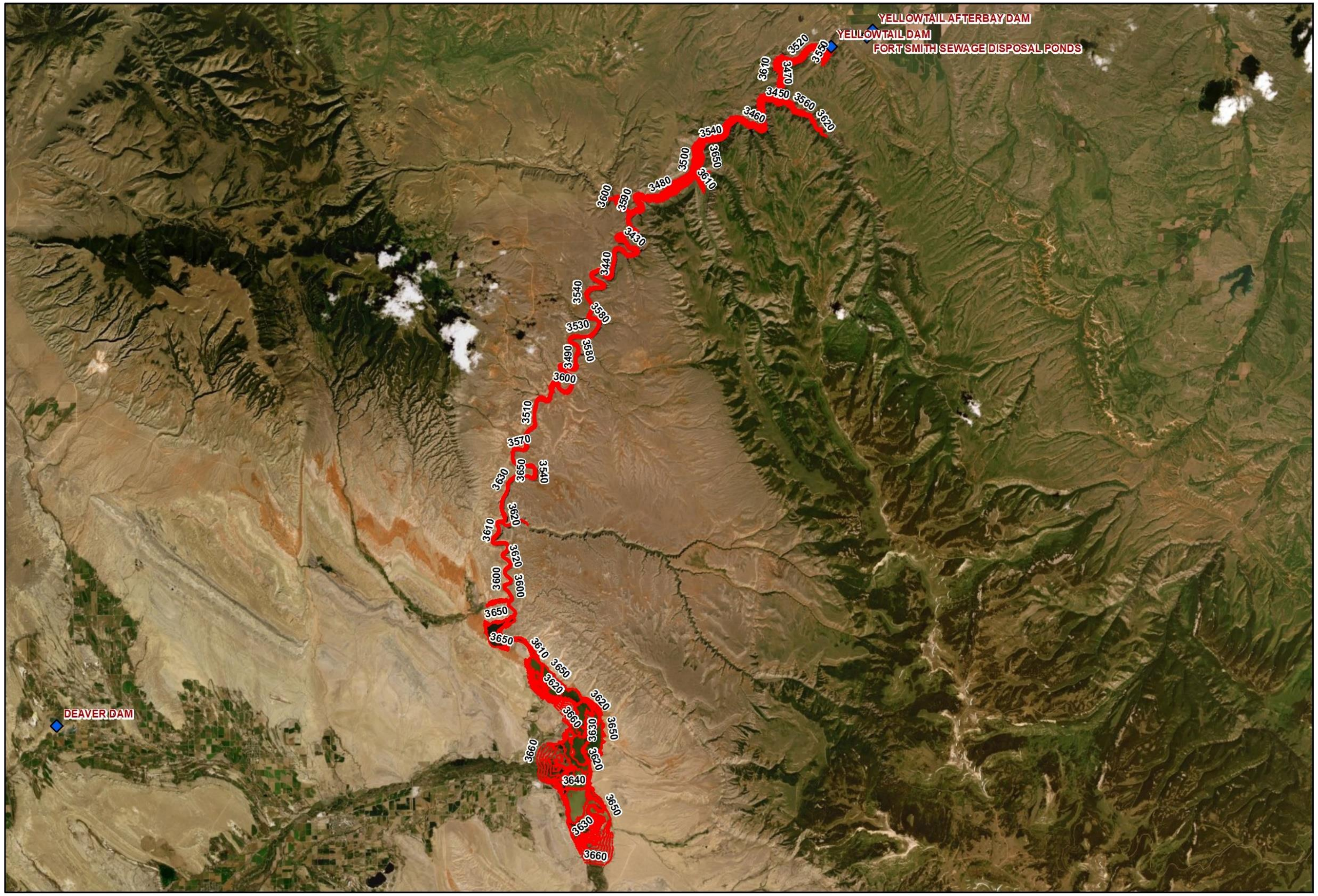
The reservoir surface area is computed from the derivative of the volume equation:

$$S = A_2 + 2A_3(y - y_b)$$

where: S = surface area (acres)

This method ensures that the given surface areas, and corresponding storage capacities, at the 1-foot intervals are not changed and there is a smooth transition in the interpolated values at the 0.01-foot intervals. The ACAP program produces the area and capacity tables for the full range of reservoir elevations. These data are documented in the report (Reclamation, 2019).

Appendix C – Contour Maps



Big Horn Lake Montana Elevation Contour Map

Overview Map

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

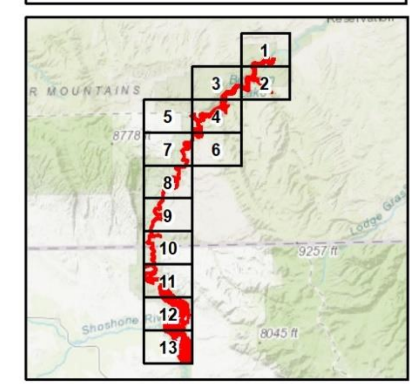
Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:250,000

0 17,500 35,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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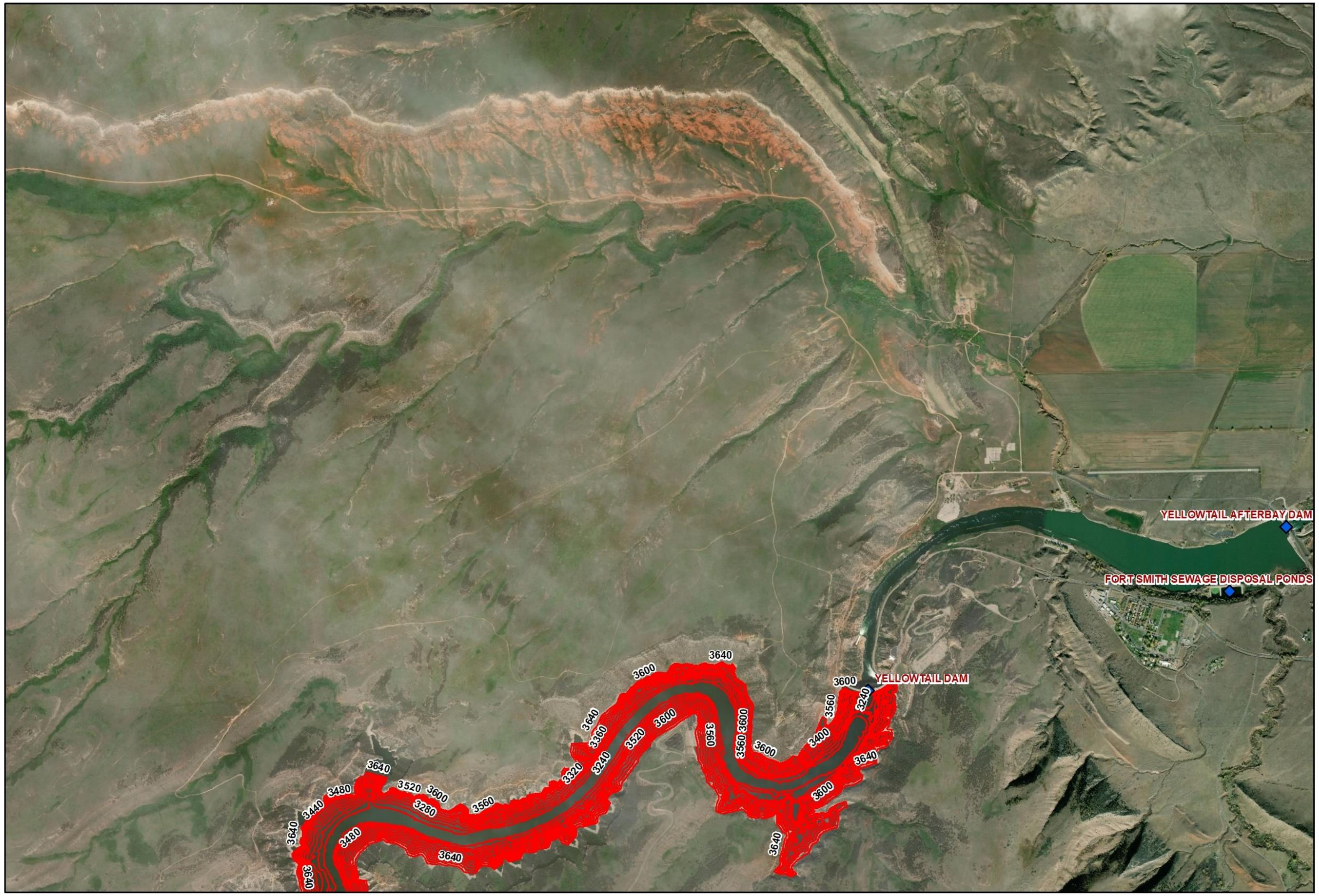


Big Horn Lake Montana Elevation Contour Map

Sheet 1

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

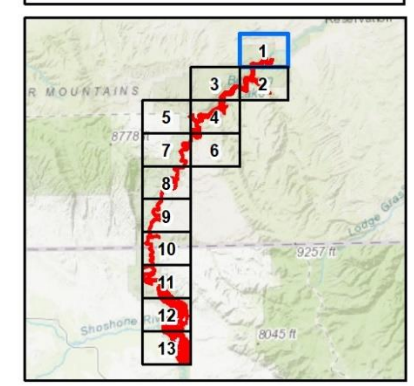
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

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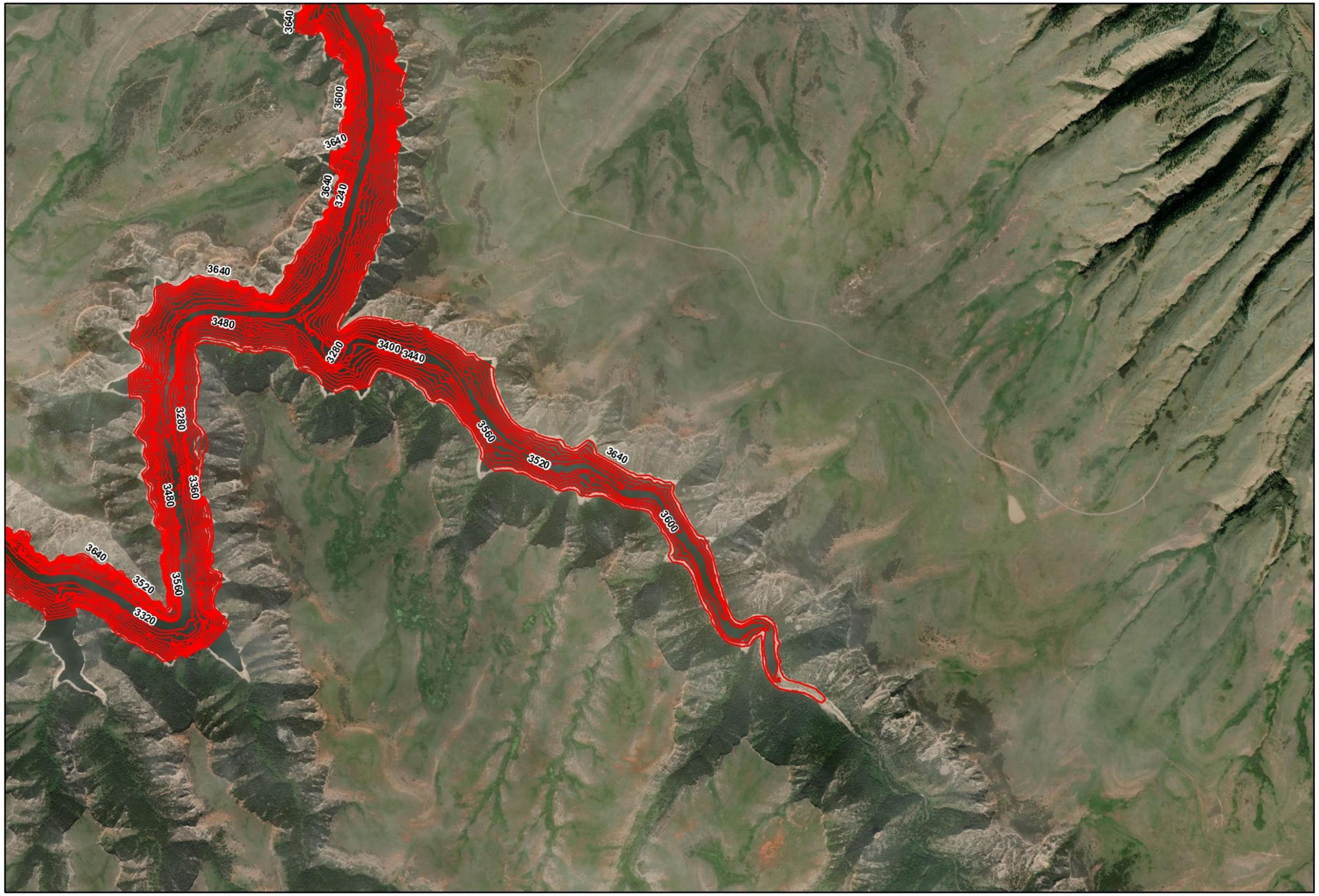


Big Horn Lake Montana Elevation Contour Map

Sheet 2

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

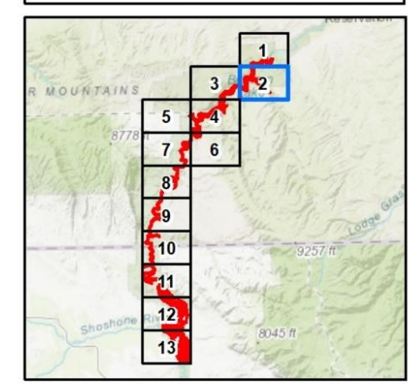
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

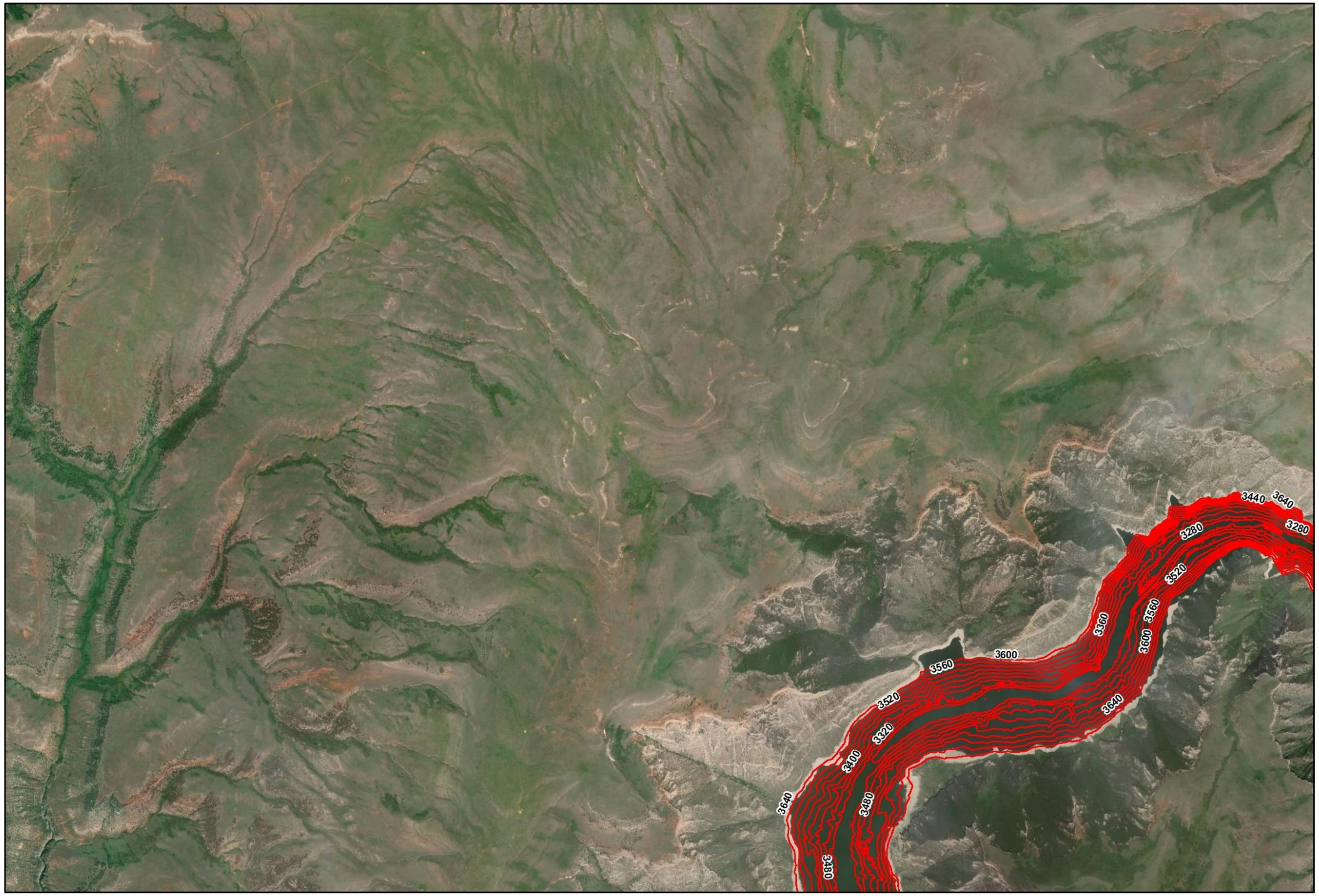
N

Scale 1:25,000

0 1,800 3,600 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Big Horn Lake Montana Elevation Contour Map

Sheet 3

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

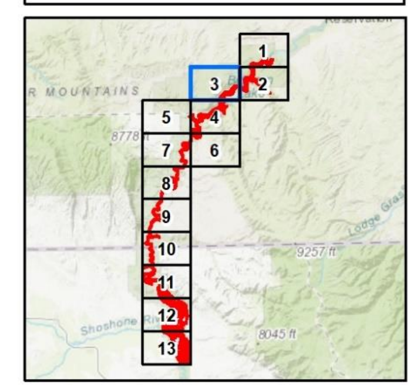
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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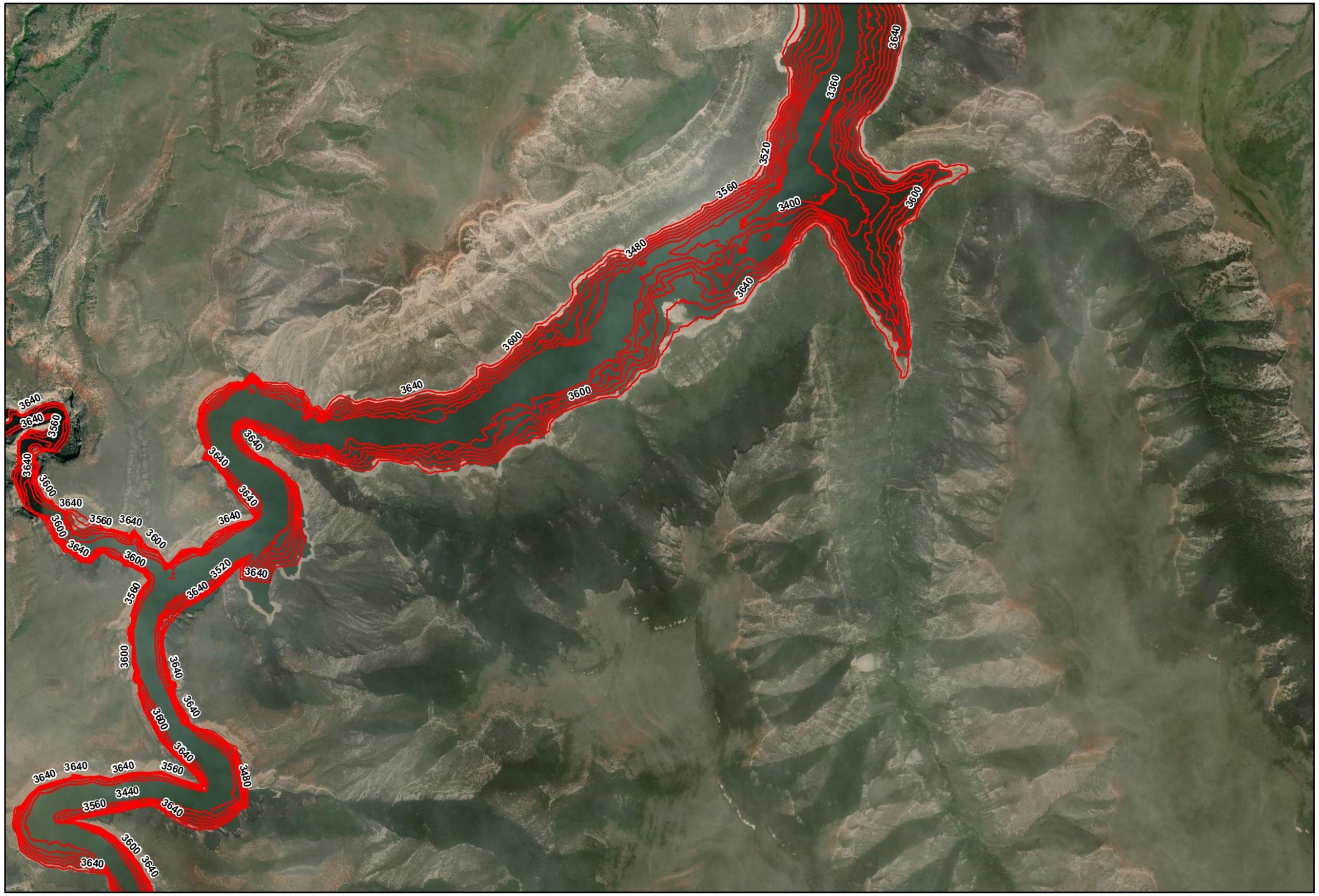
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Big Horn Lake Montana Elevation Contour Map

Sheet 4

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

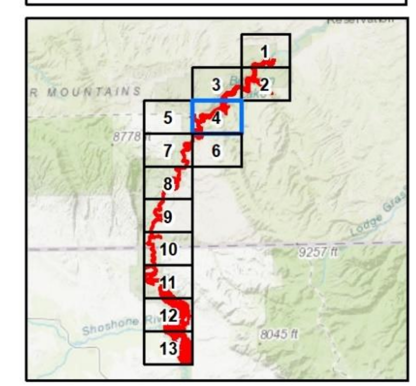
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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Big Horn Lake
Montana
Elevation
Contour Map

Sheet 5

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

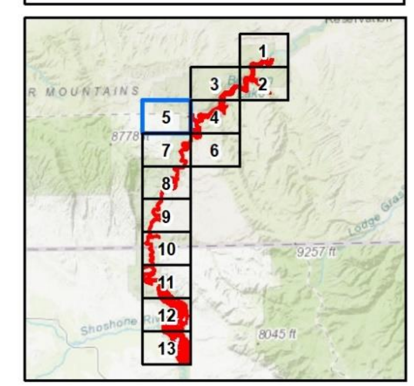
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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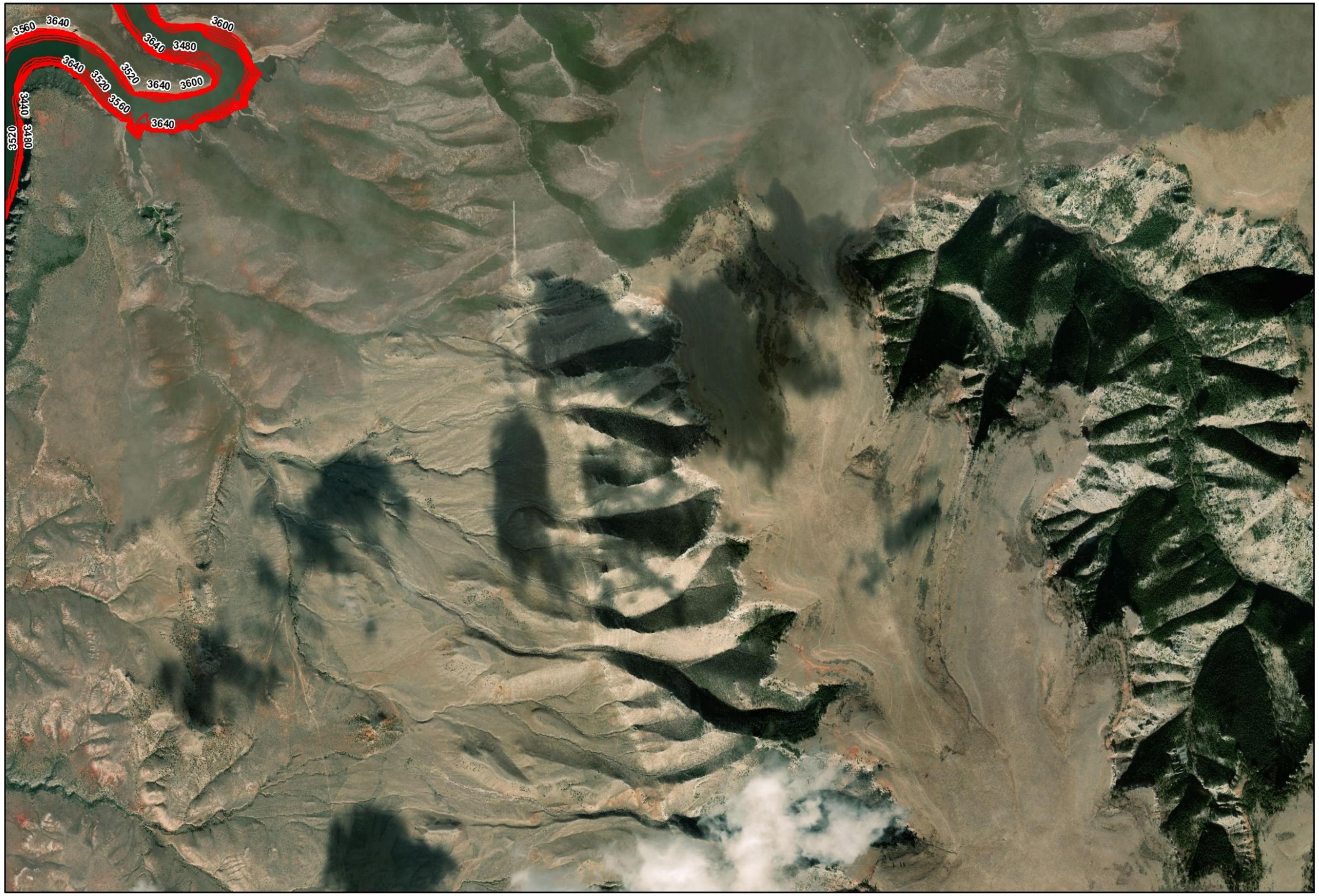


Big Horn Lake Montana Elevation Contour Map

Sheet 6

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

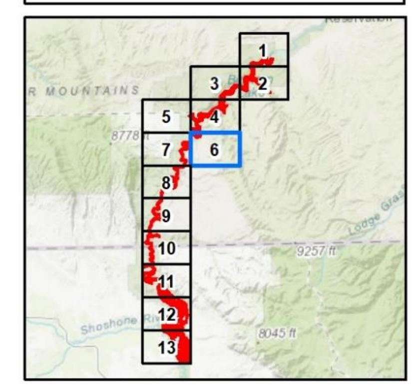
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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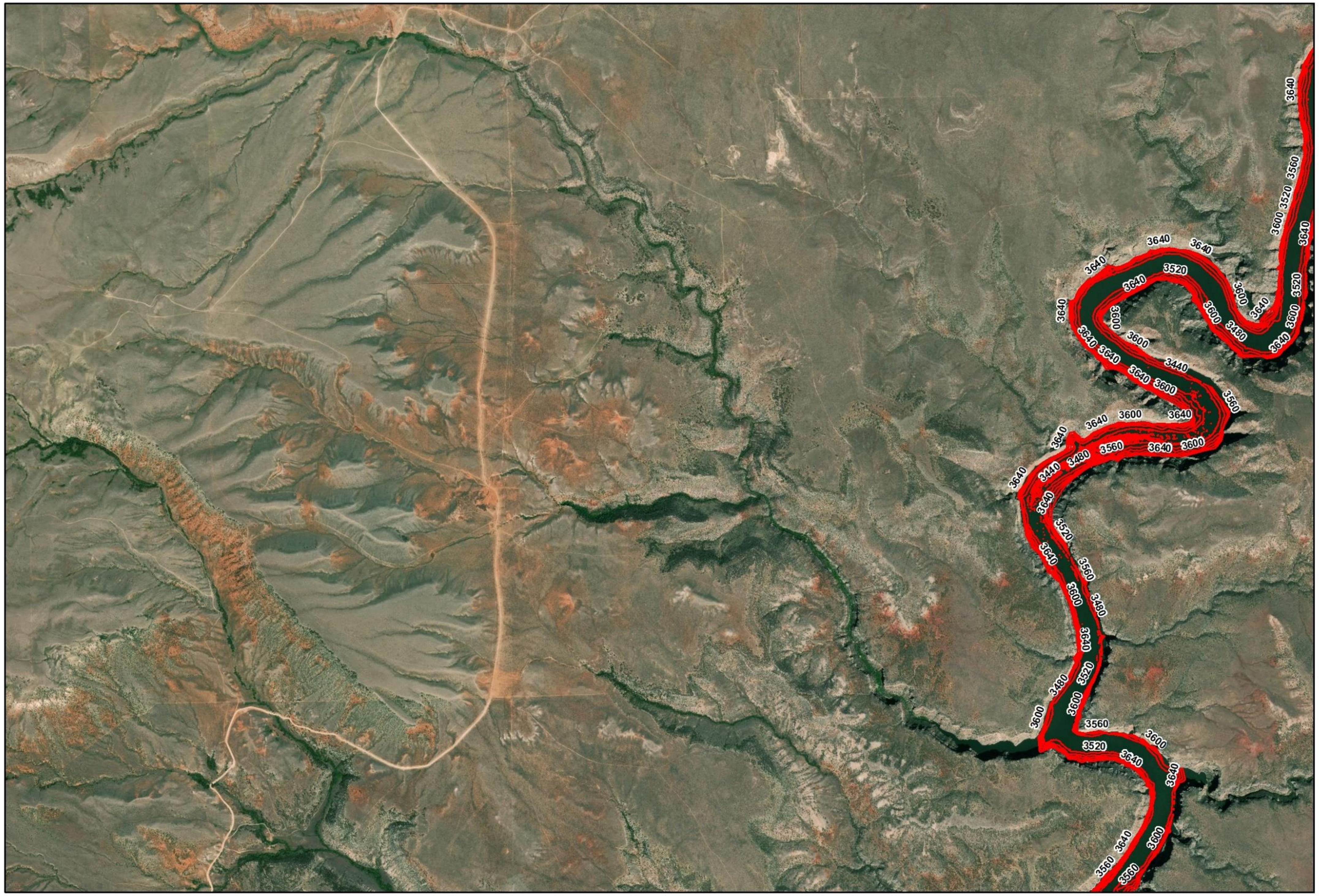
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Big Horn Lake
Montana
Elevation
Contour Map

Sheet 7

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

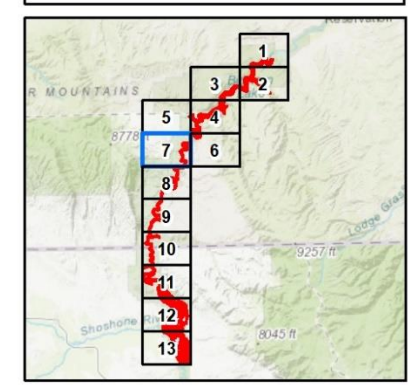
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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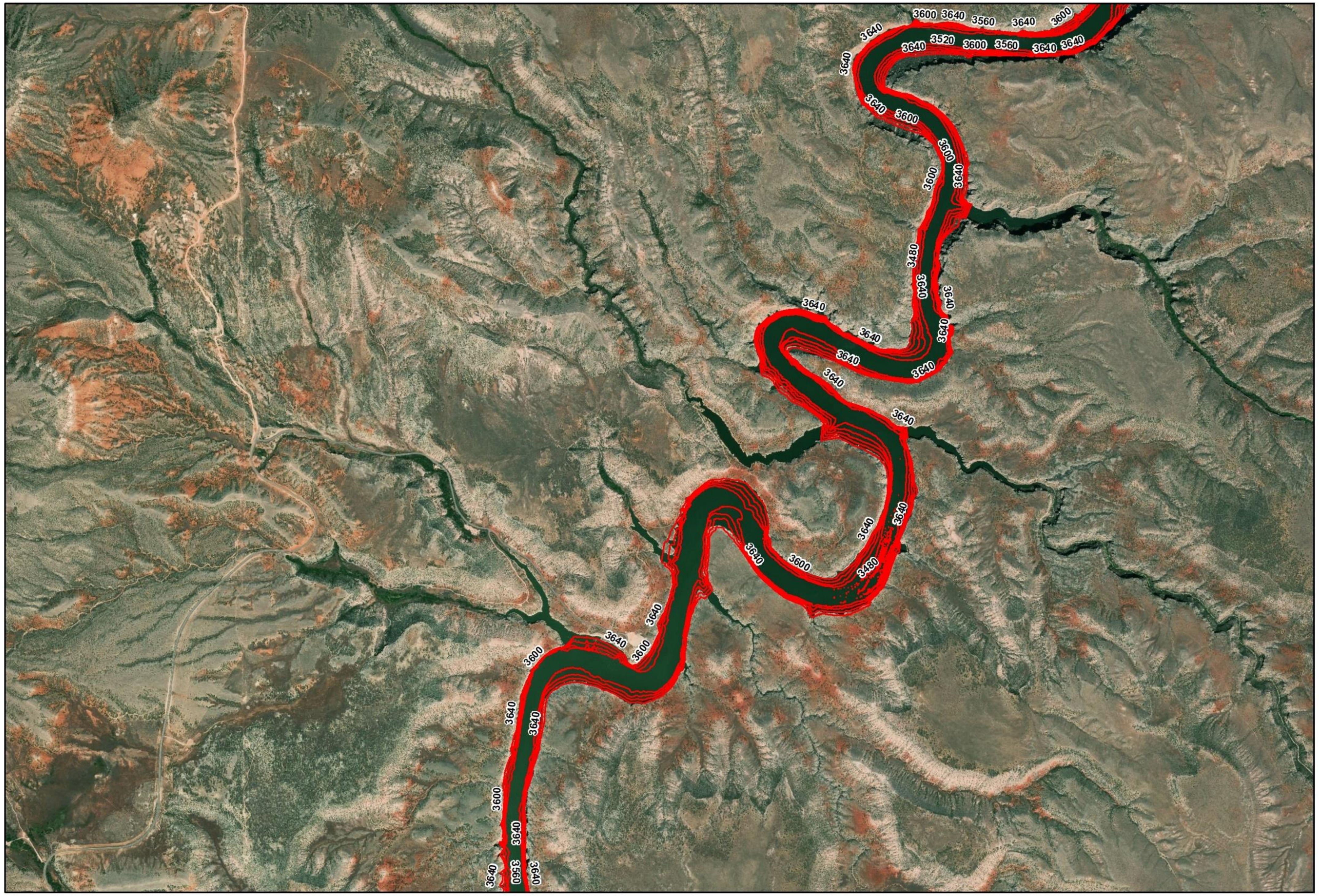


Big Horn Lake
Montana
Elevation
Contour Map

Sheet 8

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

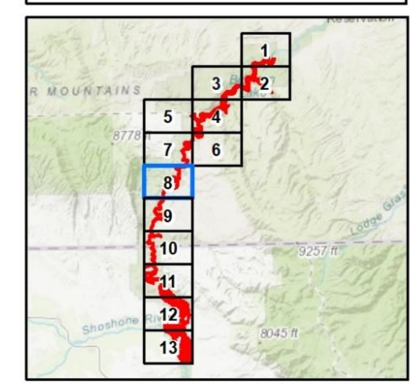
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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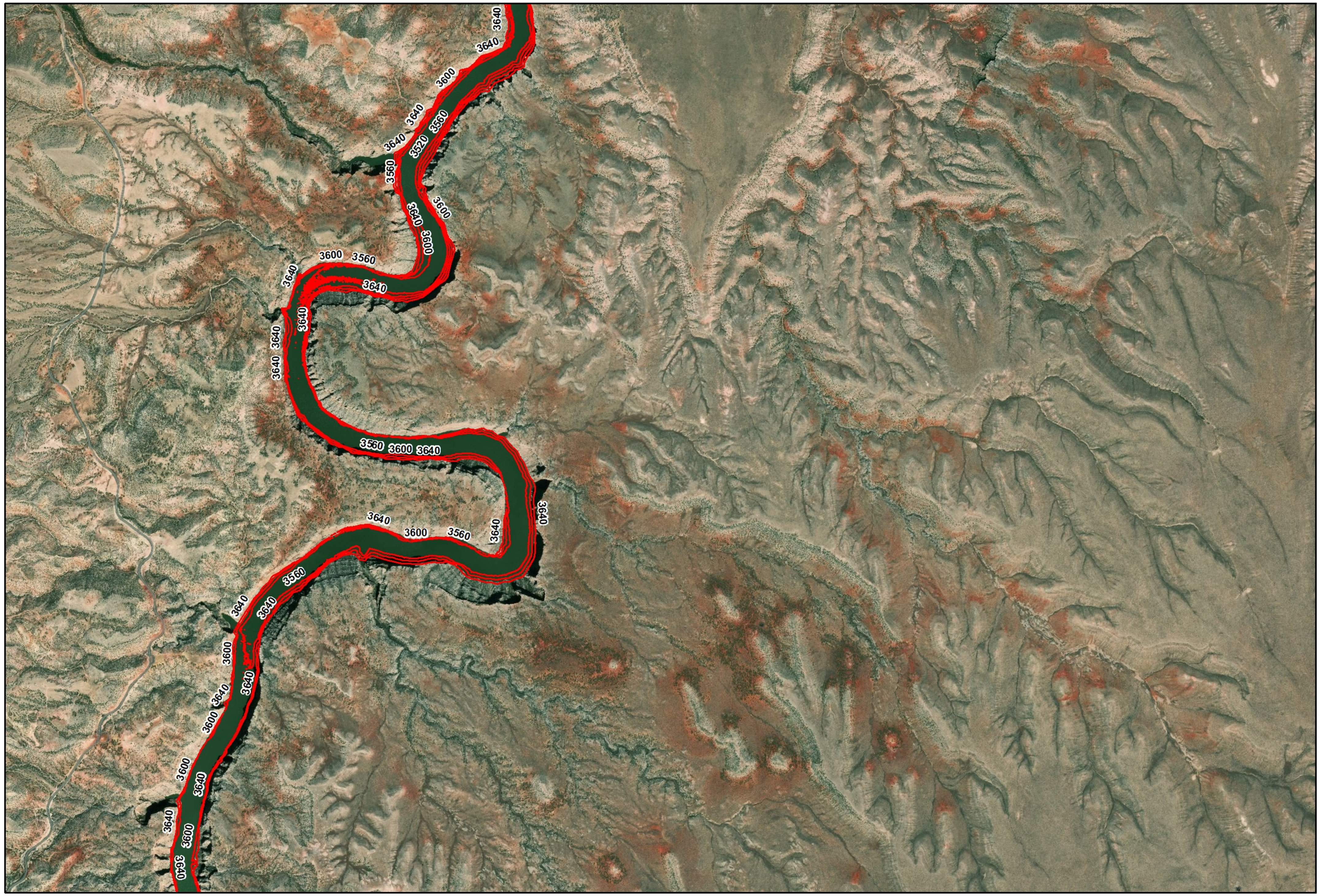


Big Horn Lake
Montana
Elevation
Contour Map

Sheet 9

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

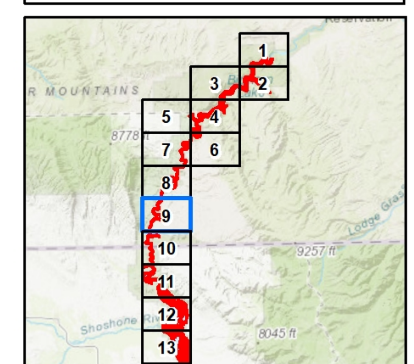
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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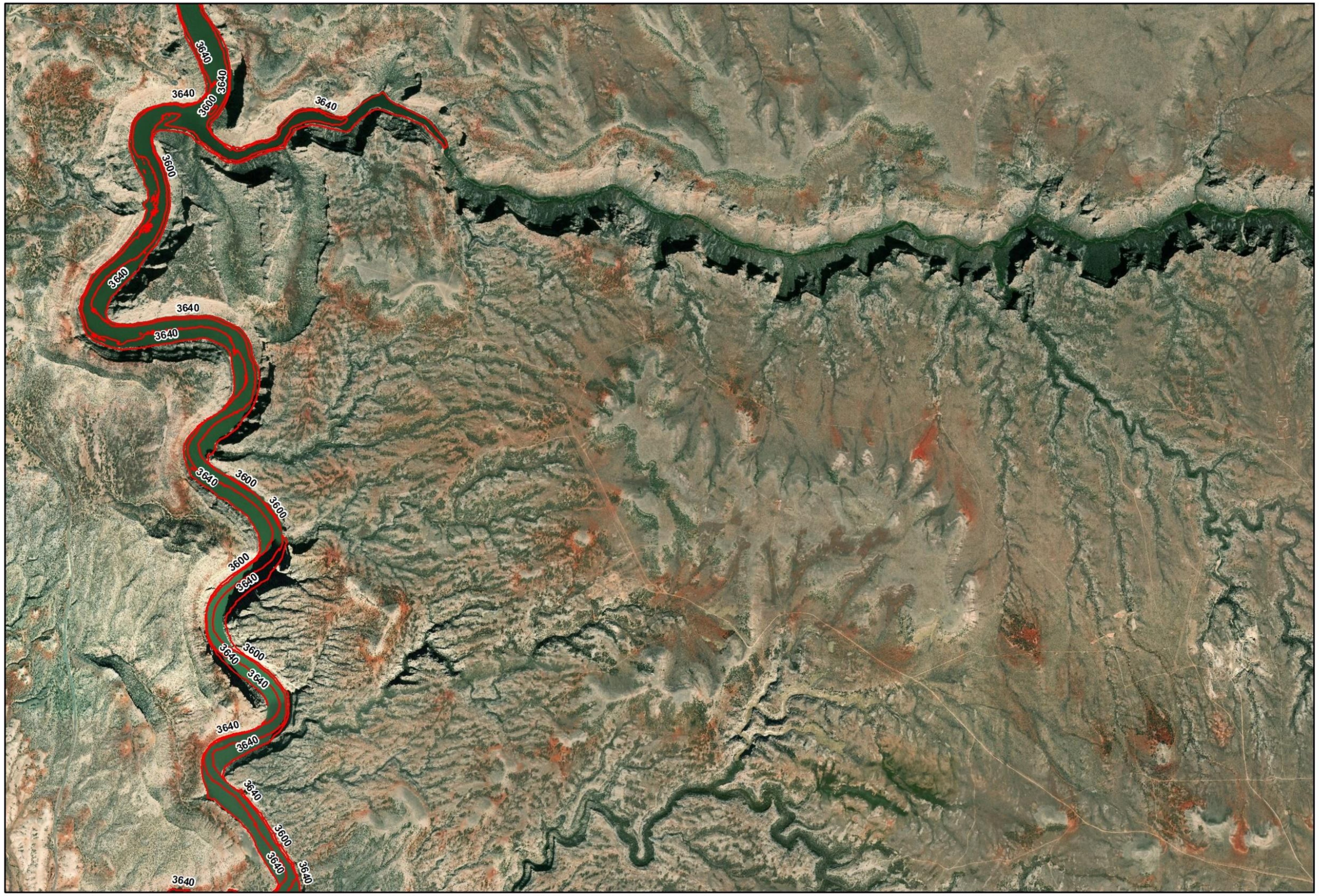


Big Horn Lake Montana Elevation Contour Map

Sheet 10

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface Elevation Gage at Yellowtail Dam Referenced to Reclamation Project Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

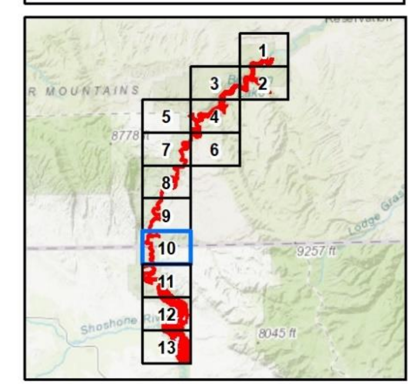
Forty Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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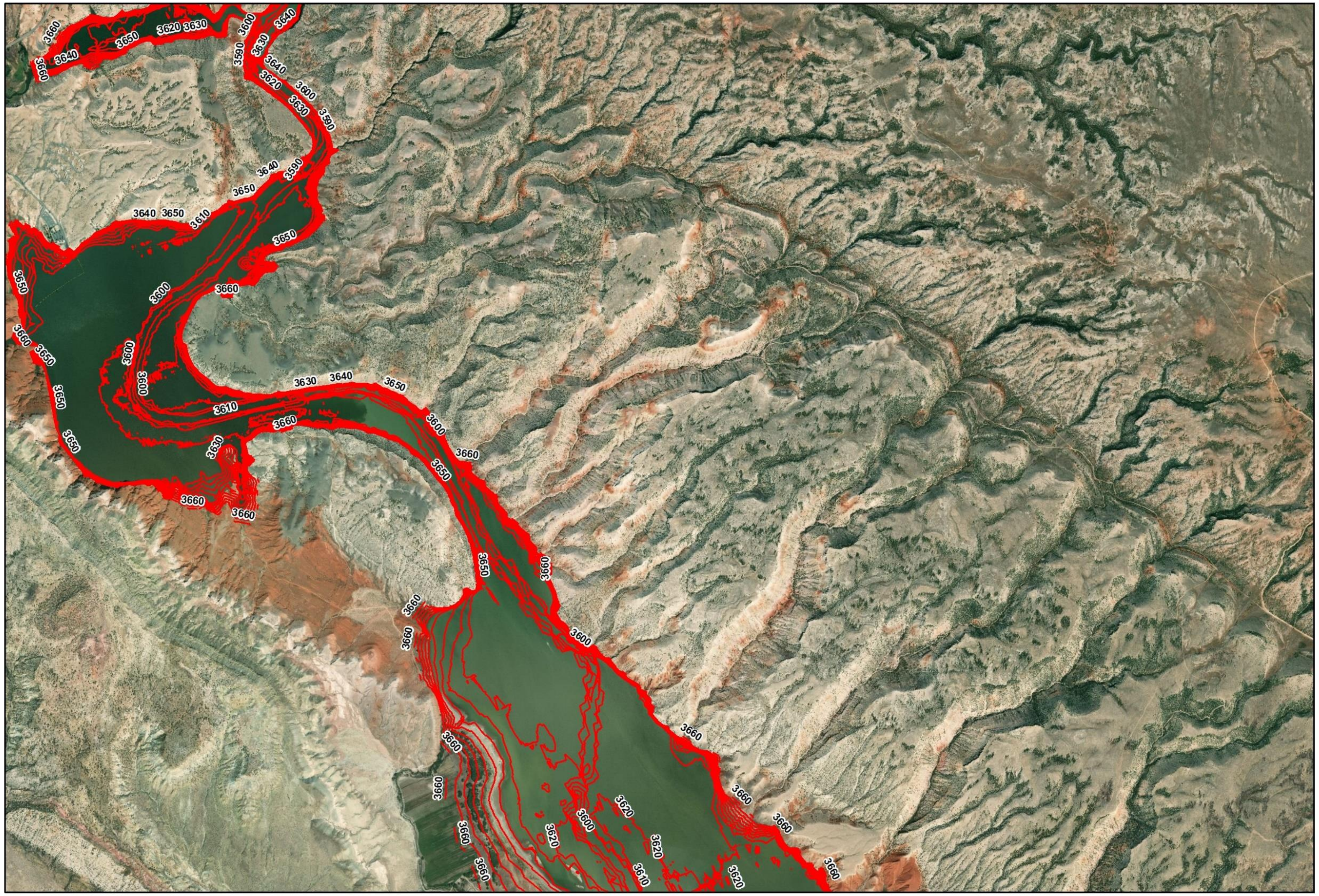


Big Horn Lake
Montana
Elevation
Contour Map

Sheet 11

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

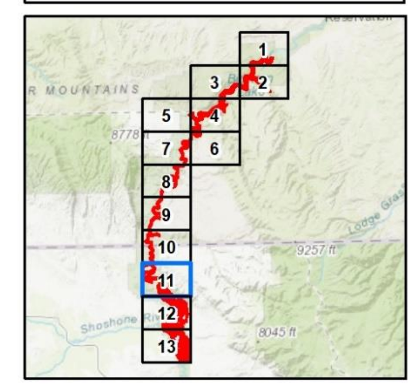
Five Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

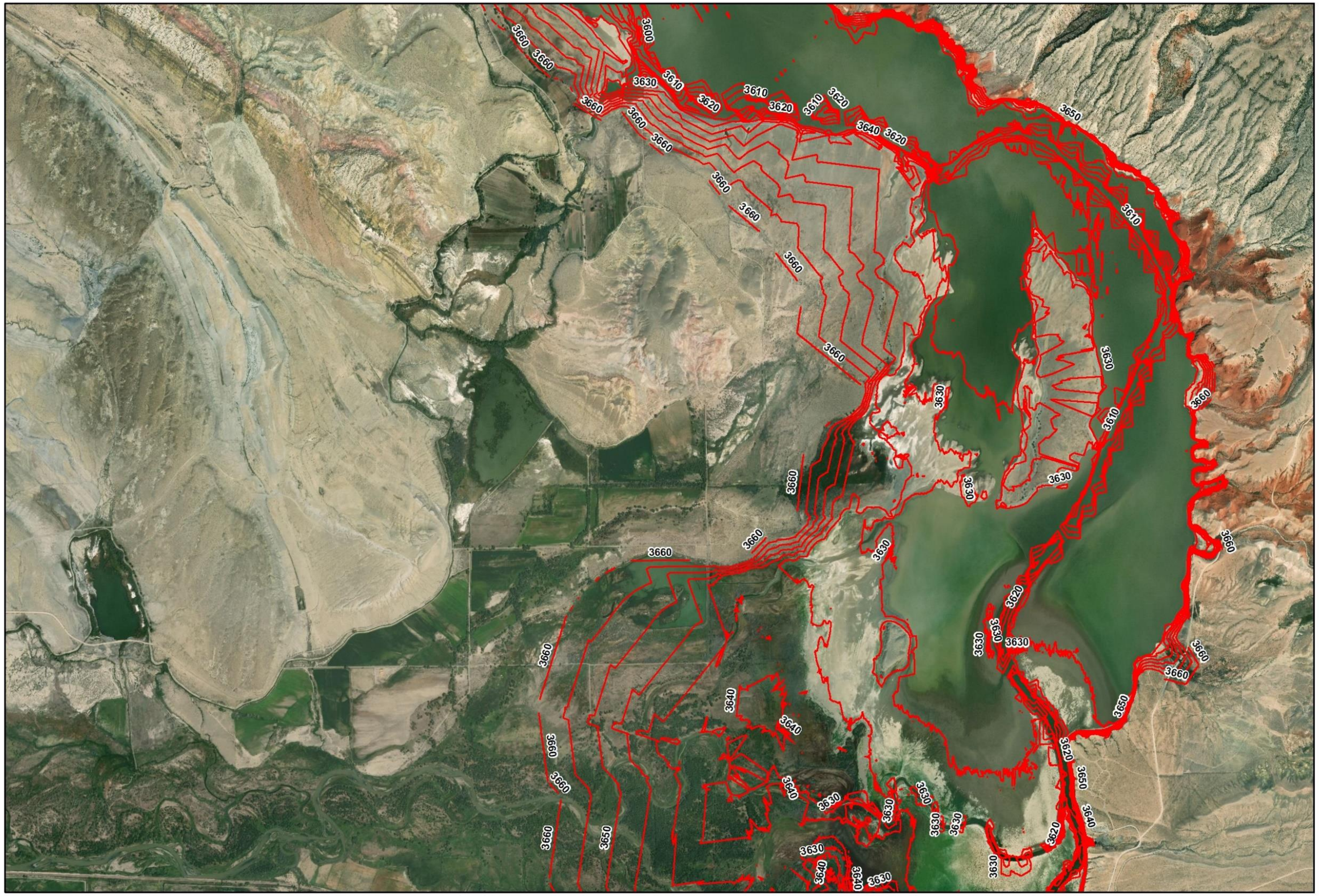
N

Scale 1:25,000

0 1,800 3,600 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Big Horn Lake Montana Elevation Contour Map

Sheet 12

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

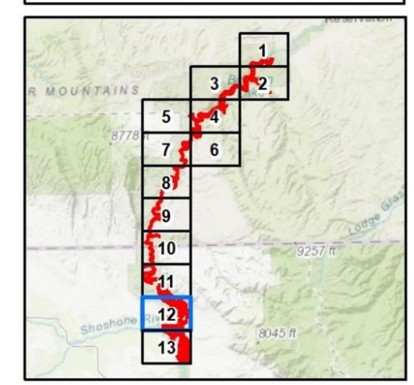
Five Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

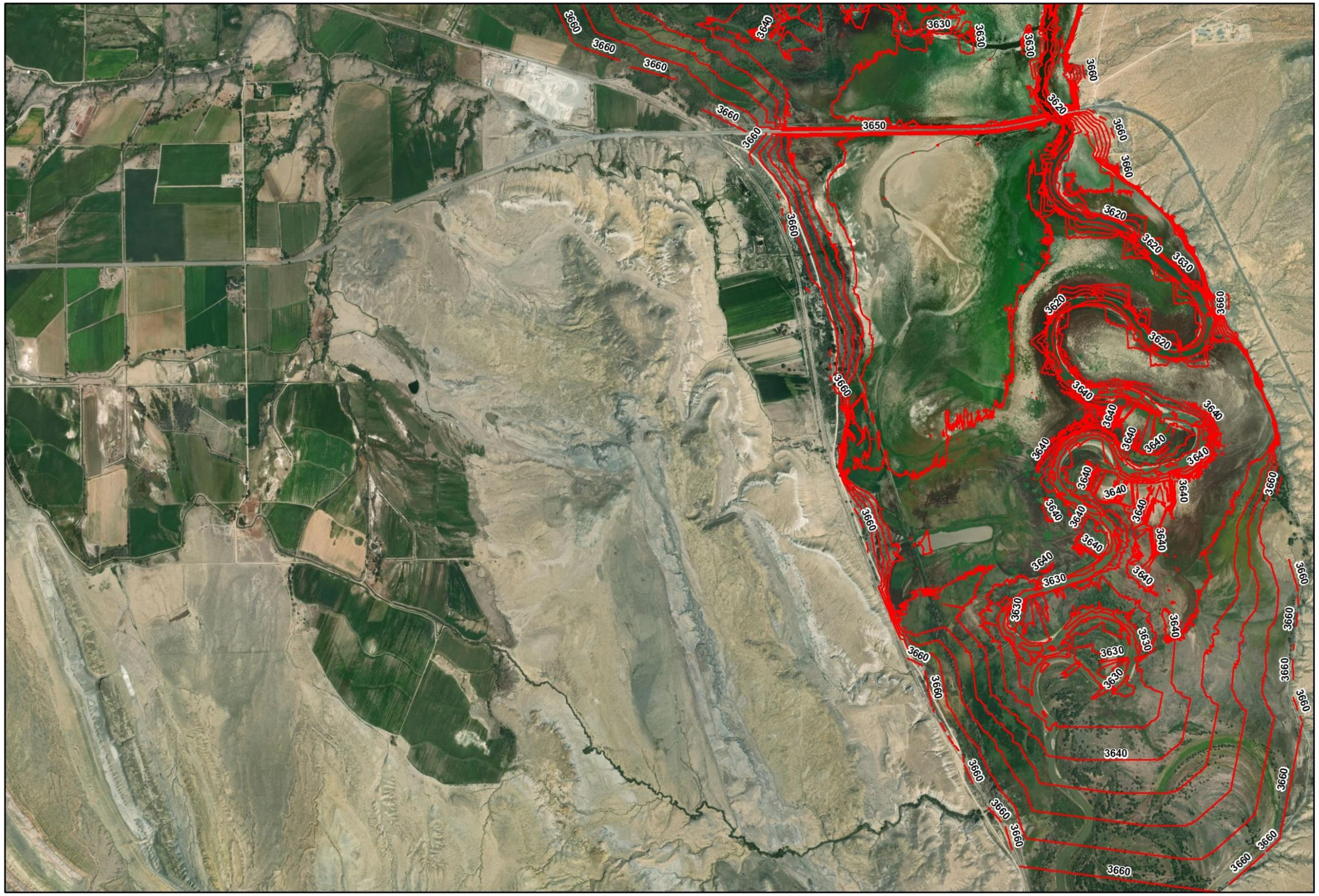
N

Scale 1:25,000

0 1,800 3,600 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



Big Horn Lake
Montana
Elevation
Contour Map

Sheet 13

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Montana Zone FIPS 2500
International Feet

Vertical Datum Based on Water Surface
Elevation Gage at Yellowtail Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
US Survey Feet
RPVD ≈ NGVD29
NAVD88 – NGVD29 = 2.63 sft
(at Yellowtail Dam)
NAVD88 – NGVD29 = 2.65 sft
(at Hwy 14A Causeway)

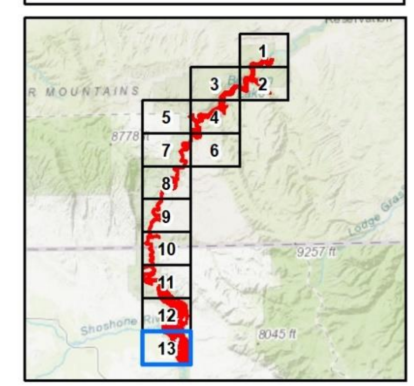
Five Foot Contour Interval

Primary Data Source:
2017 Bighorn Reservoir Study

N

Scale 1:25,000

0 1,800 3,600 Feet



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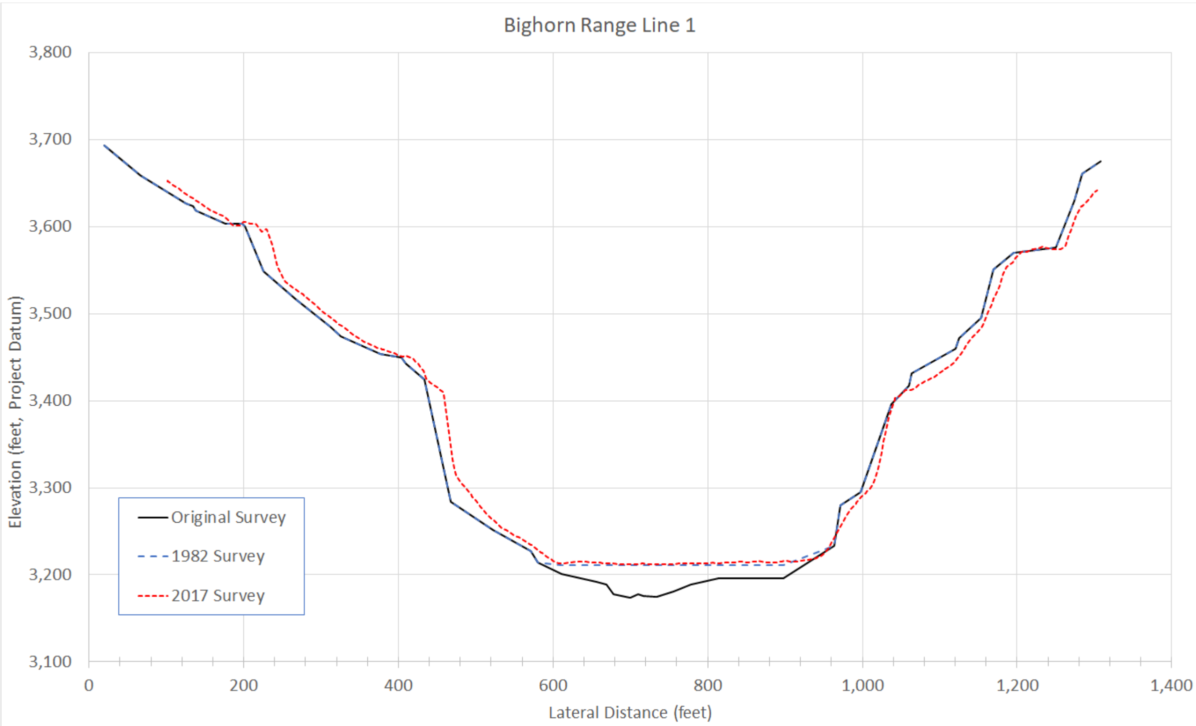
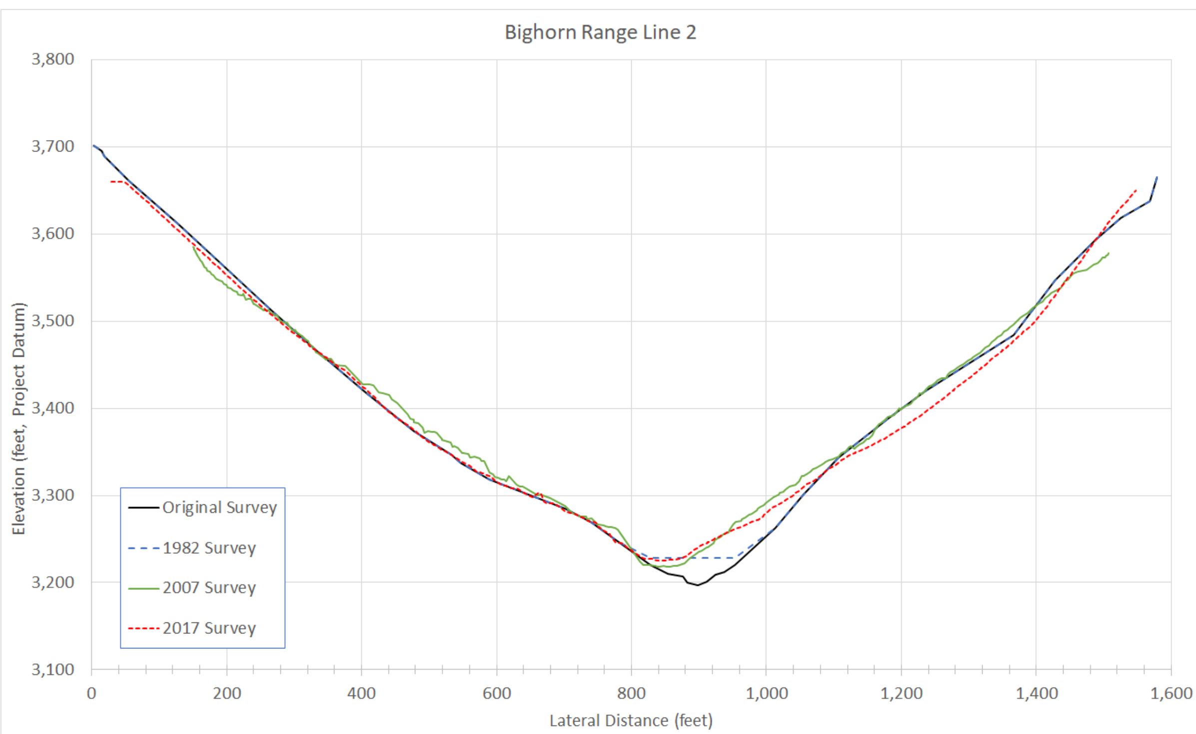
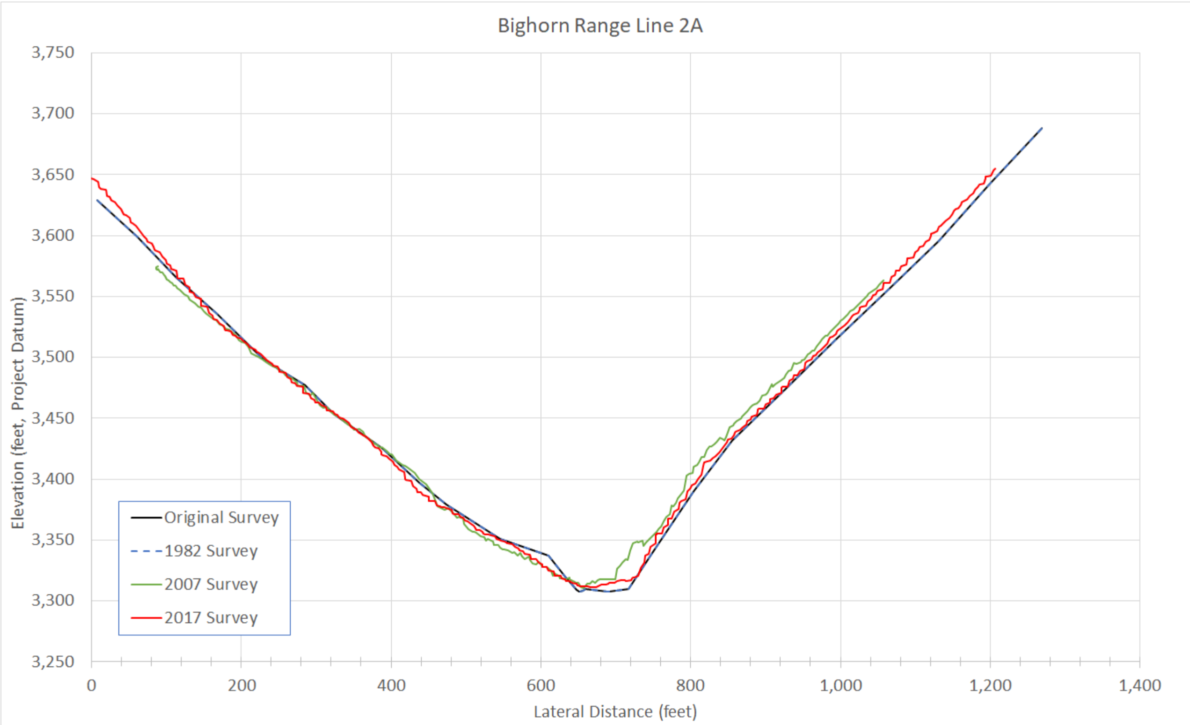
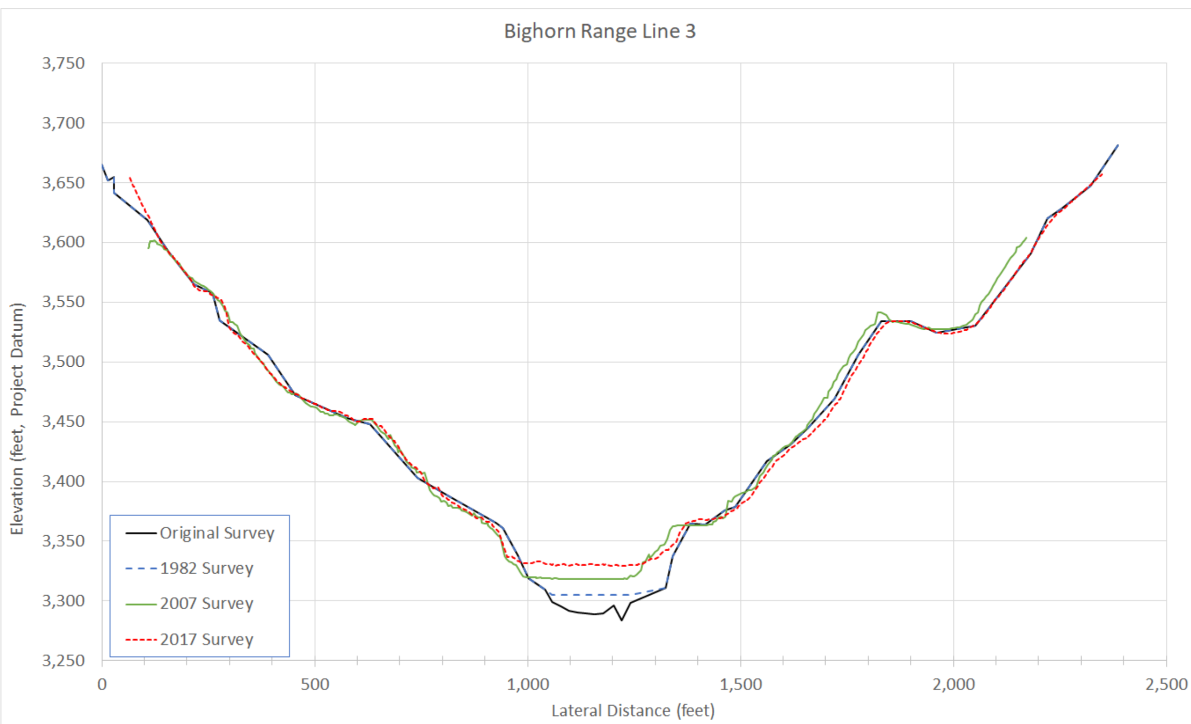
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

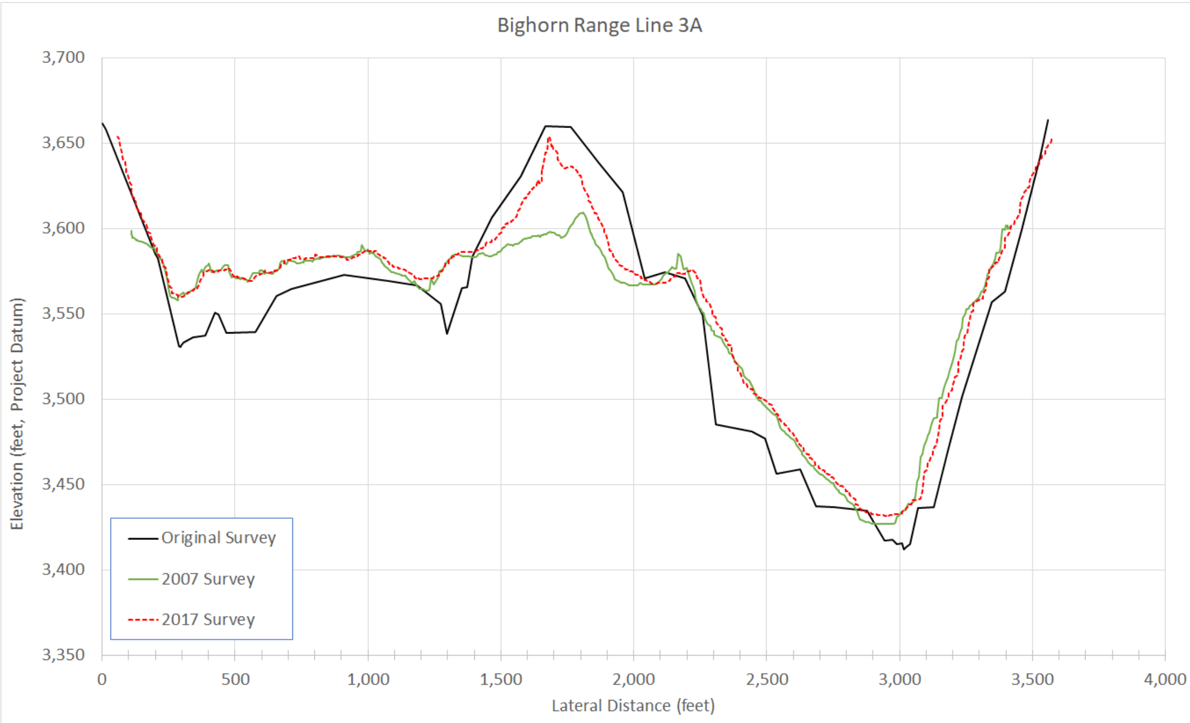
Appendix D – Cross Section Plots of Range Lines 1 – 36

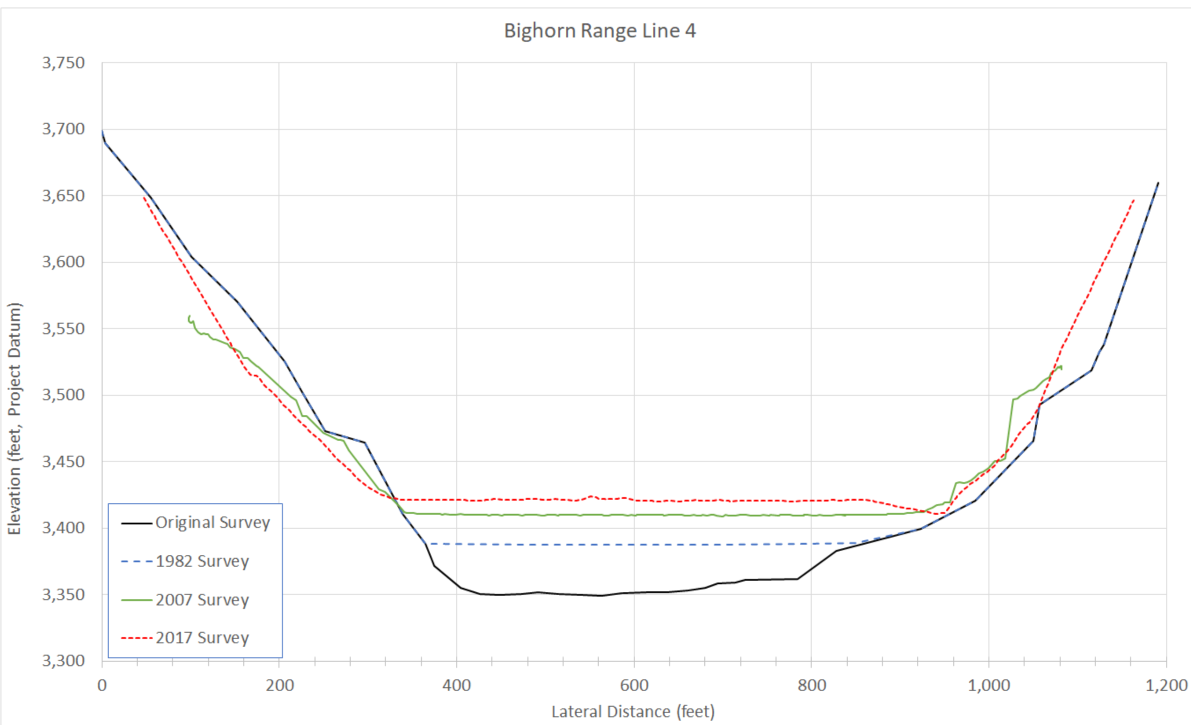

Bighorn Range Line 1
3,800
3,700
3,600
3,500
3,400
3,300
3,200
3,100
Elevation (feet, Project Datum)
0
200
400
600
800
1,000
1,200
1,400
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey

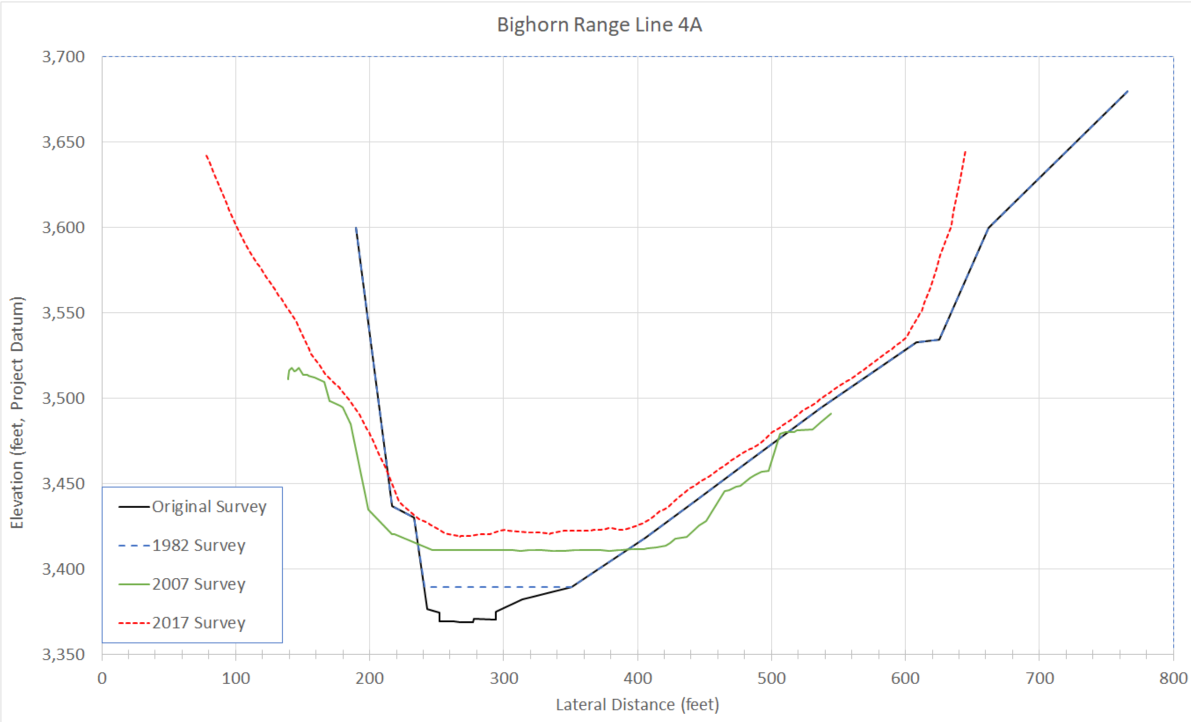

Bighorn Range Line 2
3,800
3,700
3,600
3,500
3,400
3,300
3,200
3,100
Elevation (feet, Project Datum)
0
200
400
600
800
1,000
1,200
1,400
1,600
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

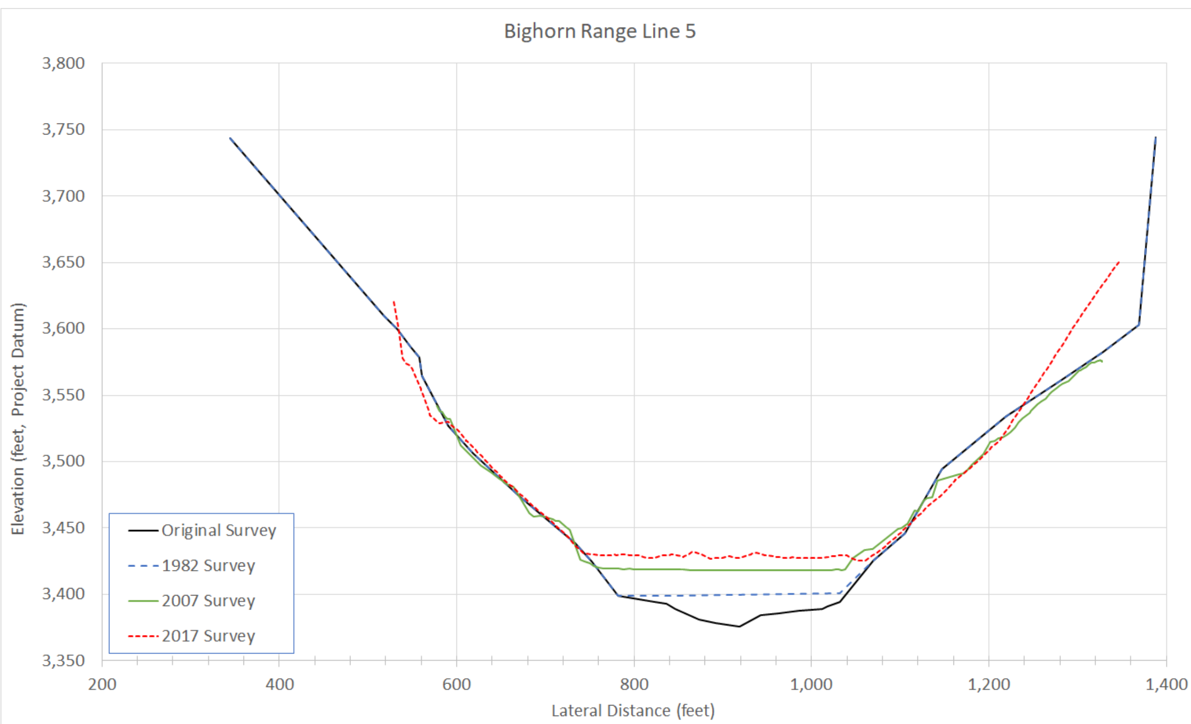

Bighorn Range Line 2A
Elevation (feet, Project Datum)
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
3,300
3,250
0
200
400
600
800
1,000
1,200
1,400
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

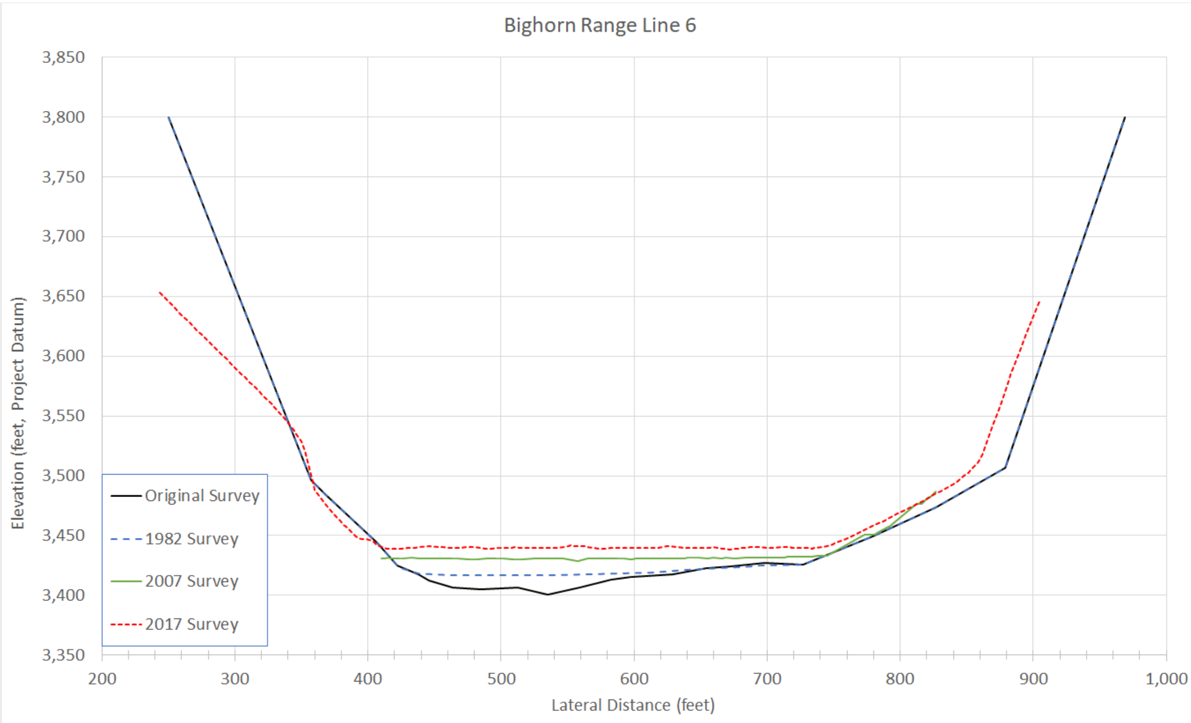

Bighorn Range Line 3
Elevation (feet, Project Datum)
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
3,300
3,250
0
500
1,000
1,500
2,000
2,500
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

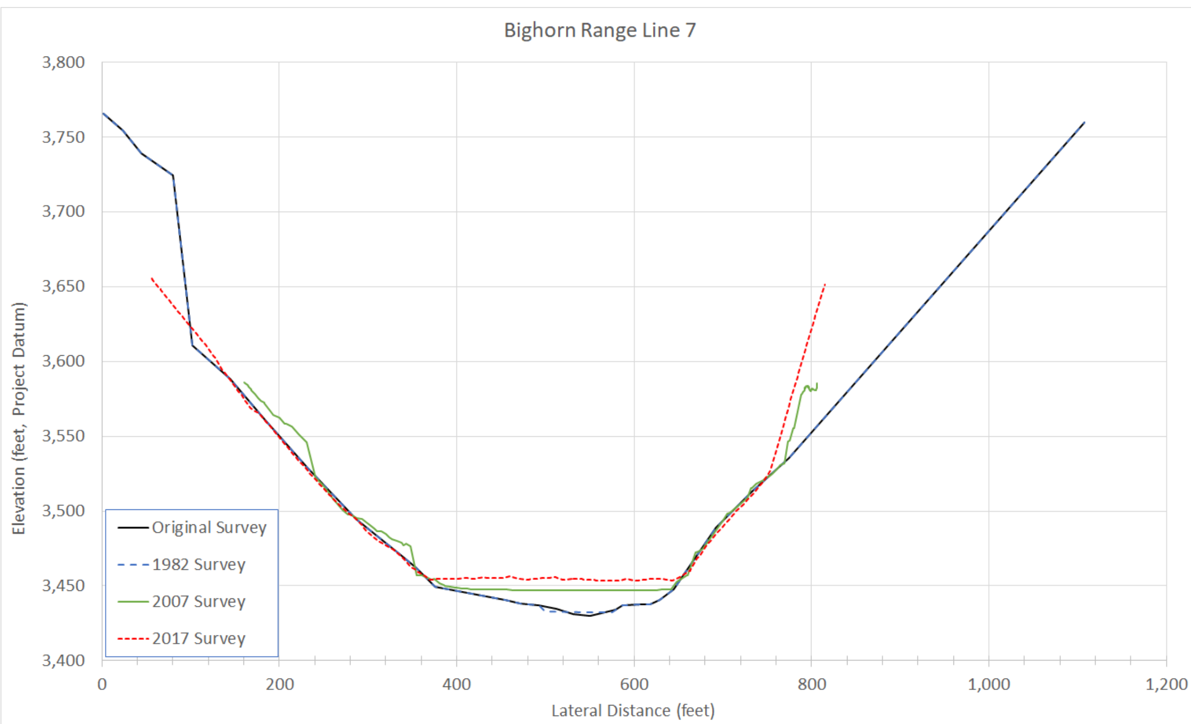

Bighorn Range Line 3A
Elevation (feet, Project Datum)
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Lateral Distance (feet)
Original Survey
2007 Survey
2017 Survey

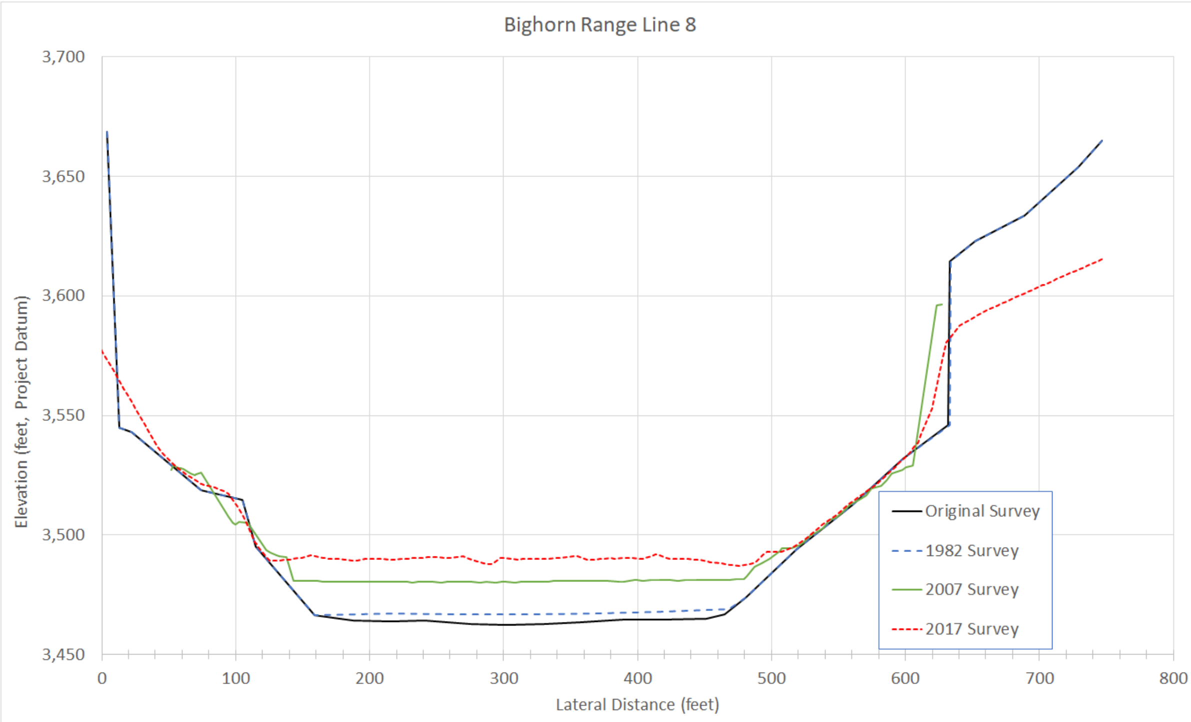

Bighorn Range Line 4
Elevation (feet, Project Datum)
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
3,300
0
200
400
600
800
1,000
1,200
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

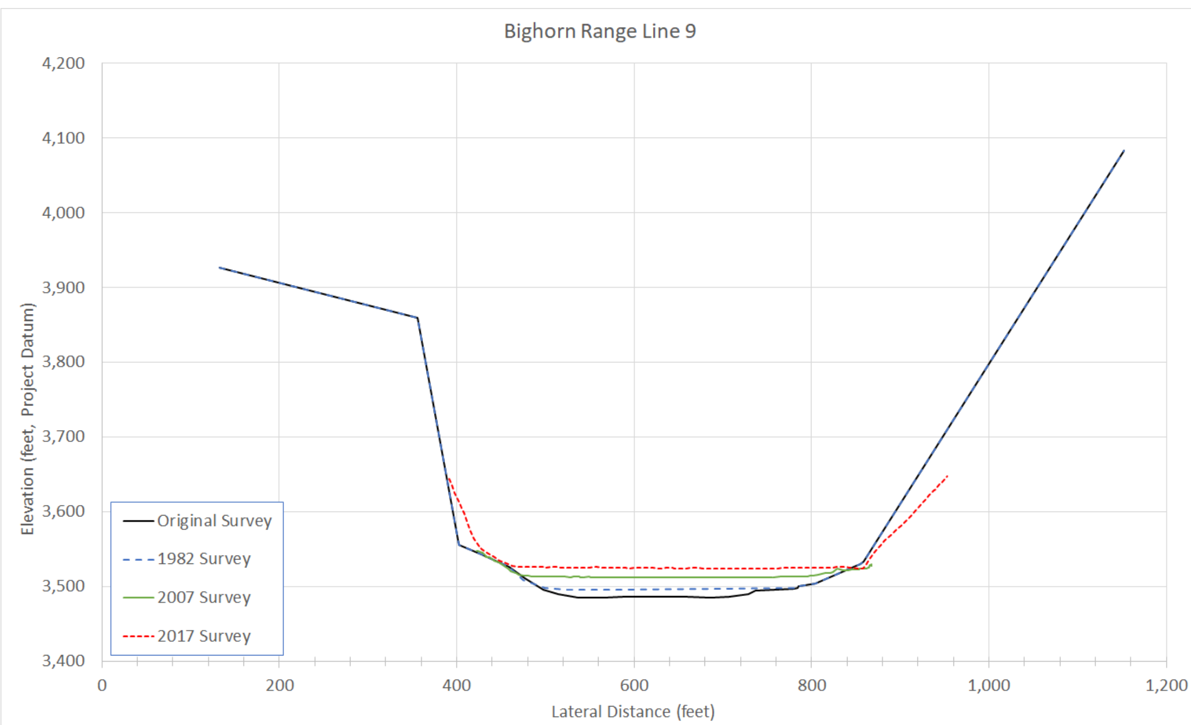

Bighorn Range Line 4A
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
Elevation (feet, Project Datum)
0
100
200
300
400
500
600
700
800
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

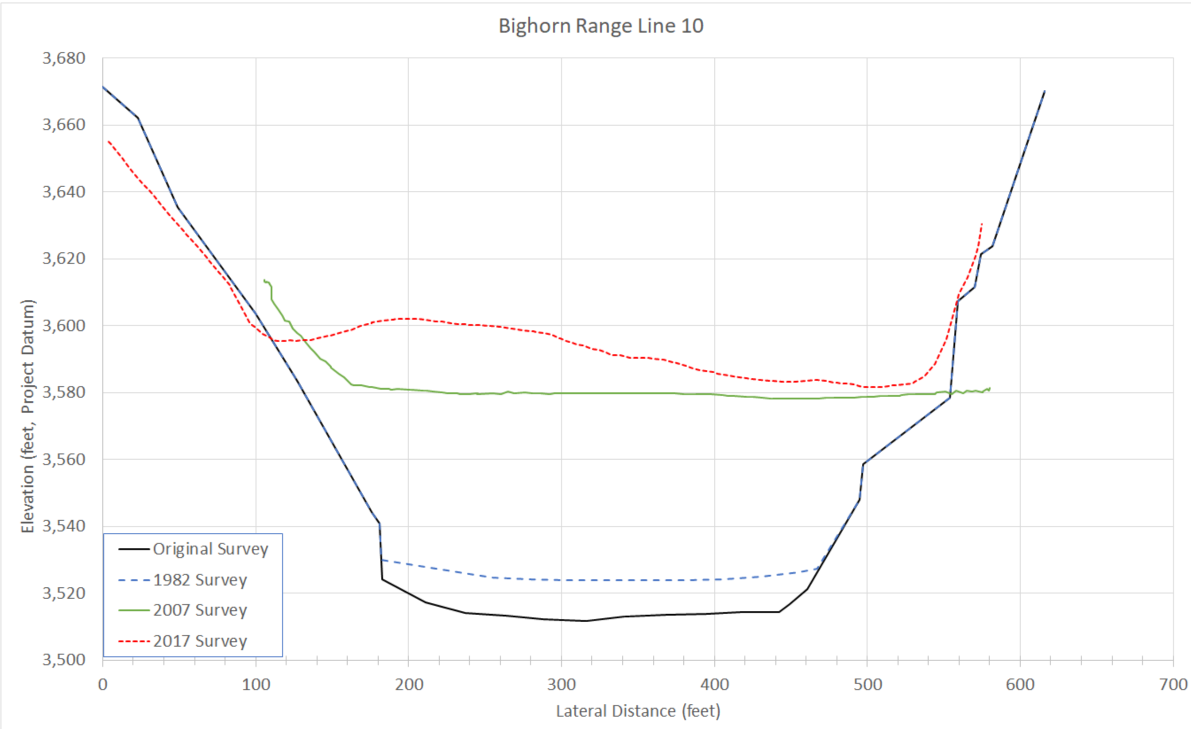

Bighorn Range Line 5
3,800
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
Elevation (feet, Project Datum)
200
400
600
800
1,000
1,200
1,400
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

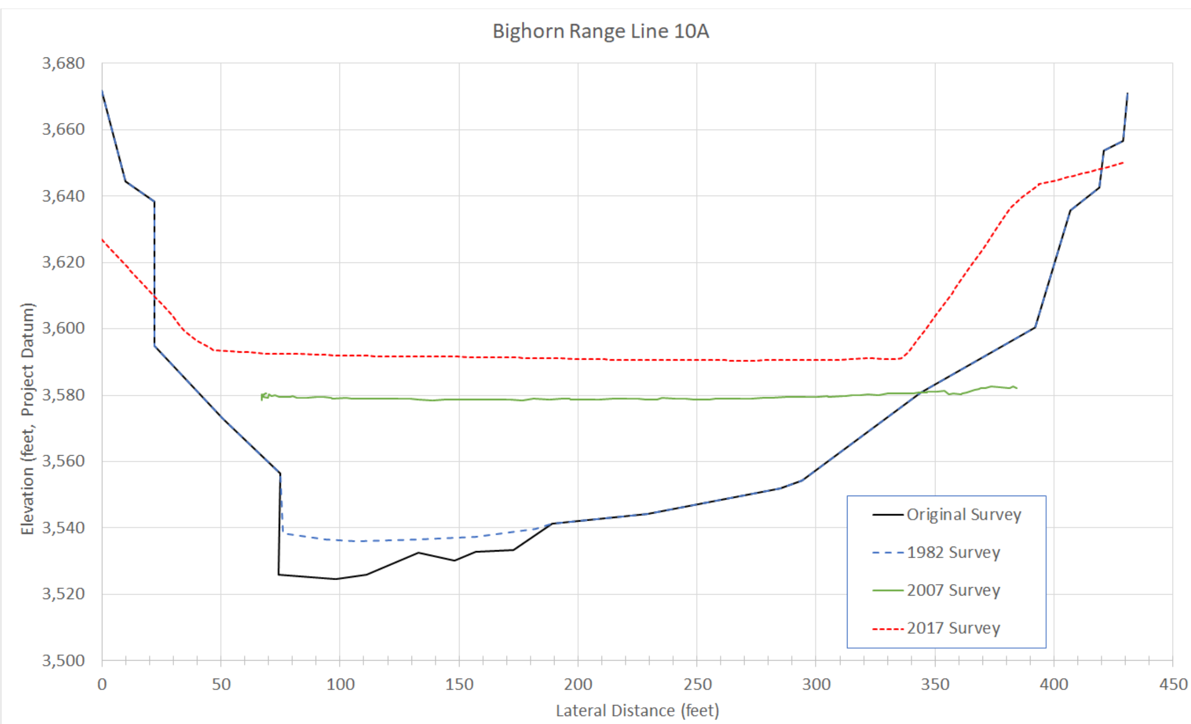

Bighorn Range Line 6
Elevation (feet, Project Datum)
3,850
3,800
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
3,350
200
300
400
500
600
700
800
900
1,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

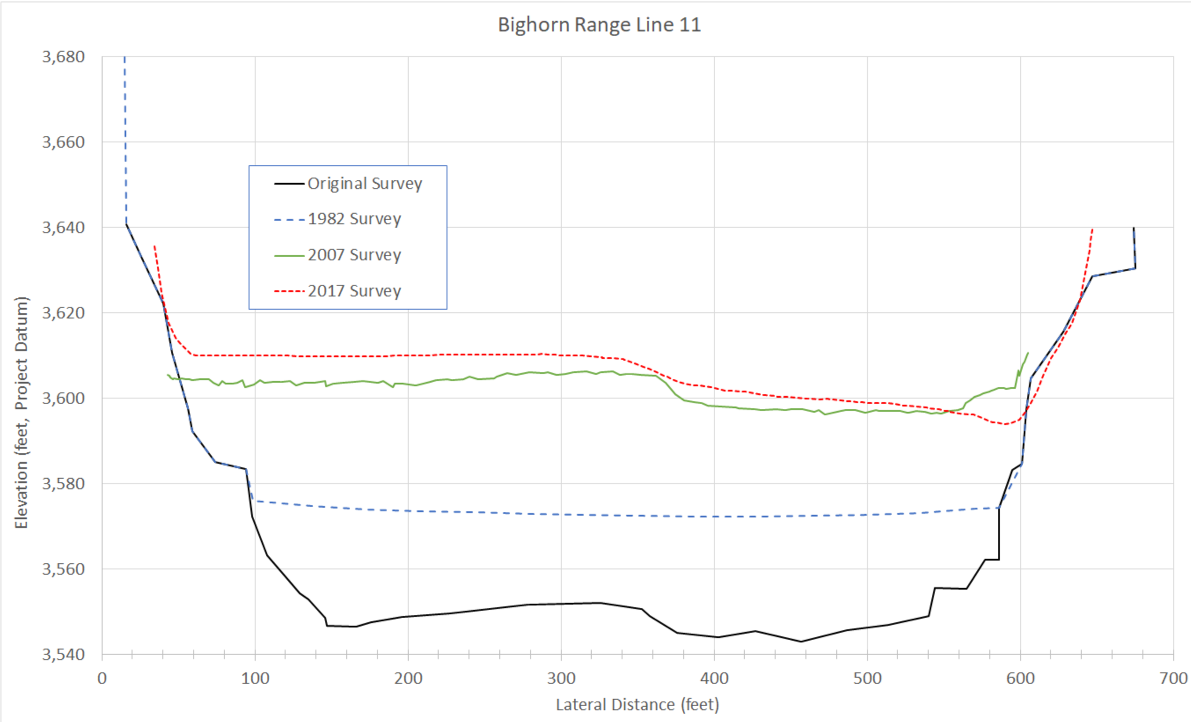

Bighorn Range Line 7
Elevation (feet, Project Datum)
3,800
3,750
3,700
3,650
3,600
3,550
3,500
3,450
3,400
0
200
400
600
800
1,000
1,200
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

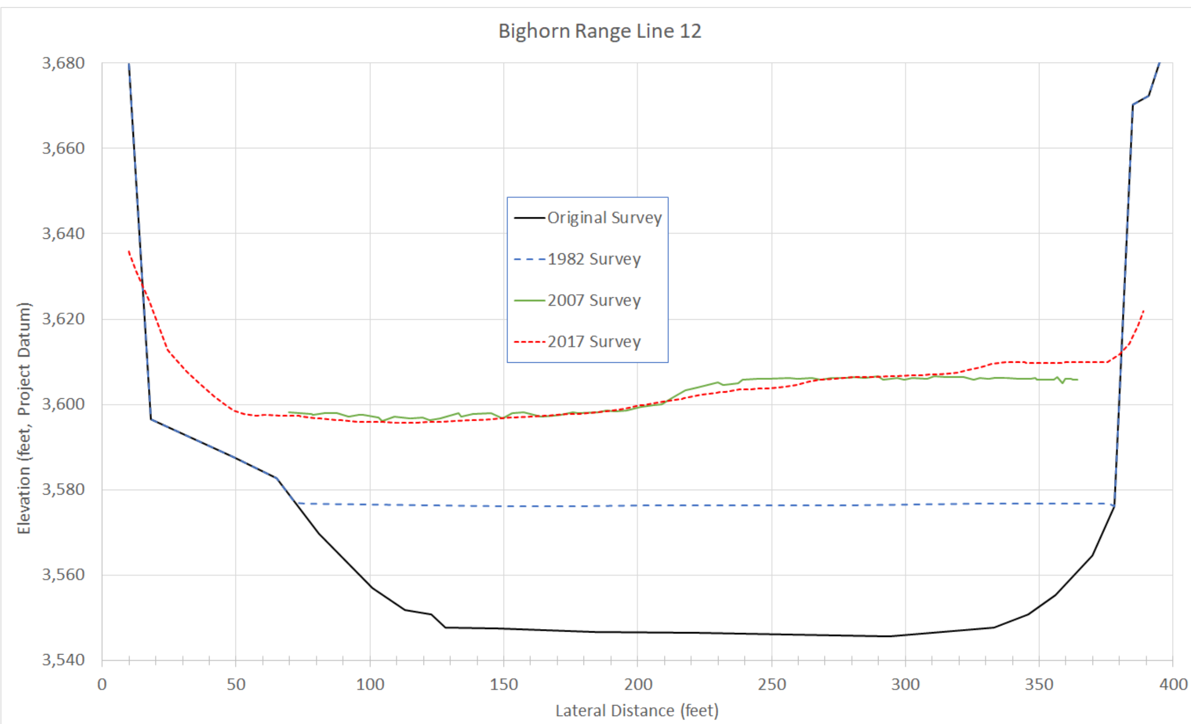

Bighorn Range Line 8
3,700
3,650
3,600
3,550
3,500
3,450
Elevation (feet, Project Datum)
0
100
200
300
400
500
600
700
800
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

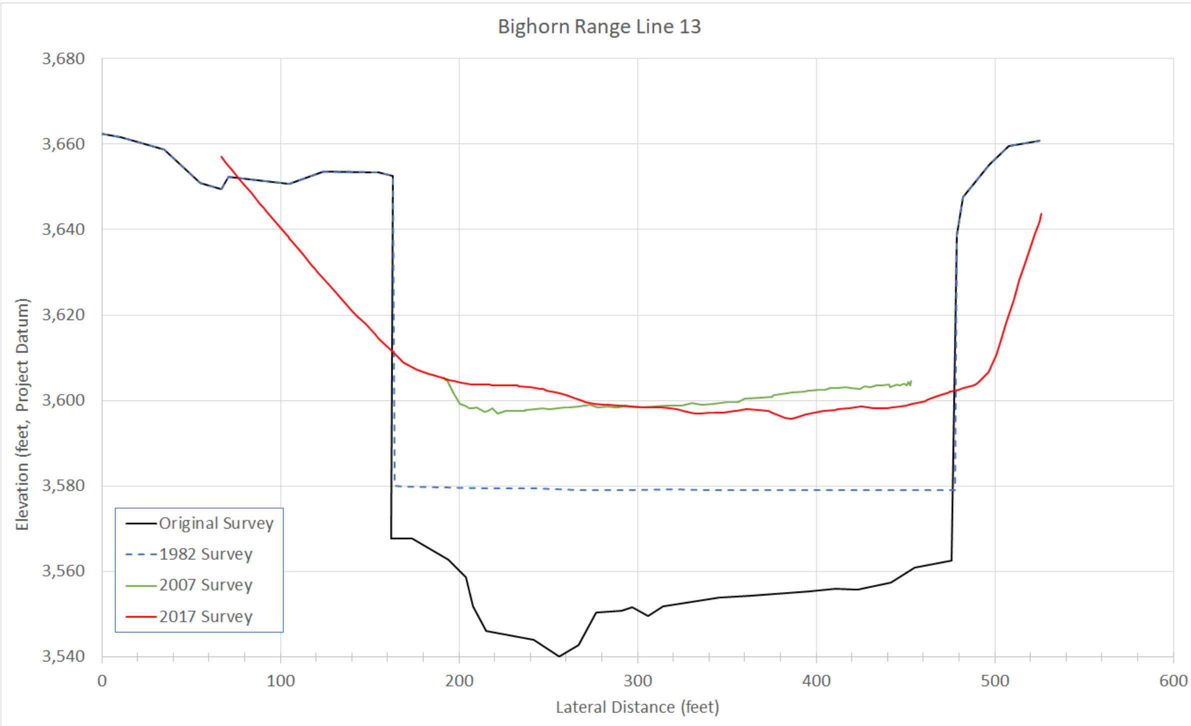

Bighorn Range Line 9
4,200
4,100
4,000
3,900
3,800
3,700
3,600
3,500
3,400
Elevation (feet, Project Datum)
0
200
400
600
800
1,000
1,200
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

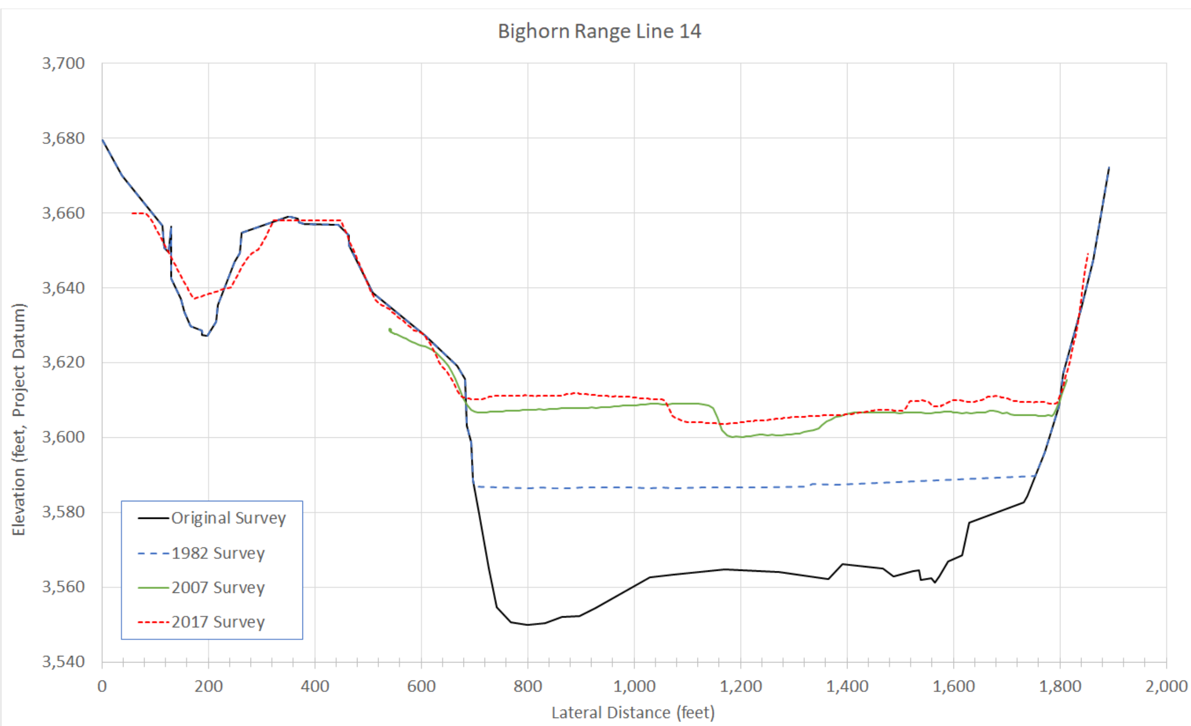

Bighorn Range Line 10
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
3,520
3,500
0
100
200
300
400
500
600
700
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

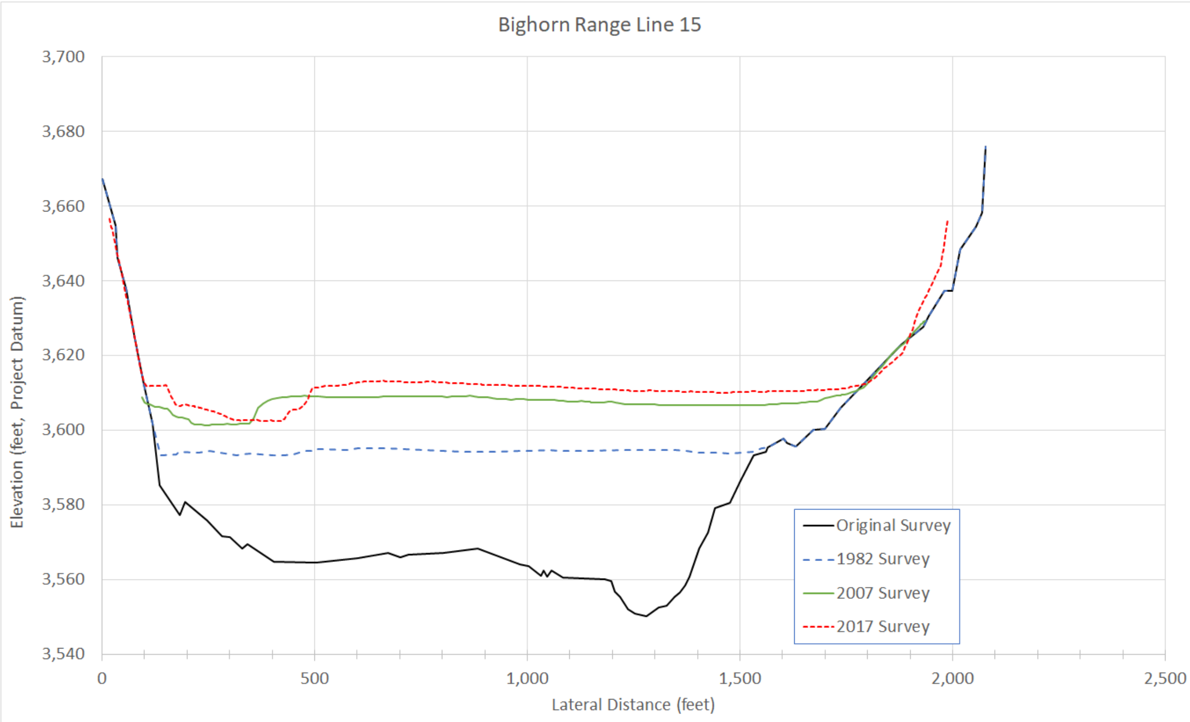

Bighorn Range Line 10A
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
3,520
3,500
0
50
100
150
200
250
300
350
400
450
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey


Bighorn Range Line 11
Original Survey
1982 Survey
2007 Survey
2017 Survey
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
0
100
200
300
400
500
600
700
Lateral Distance (feet)

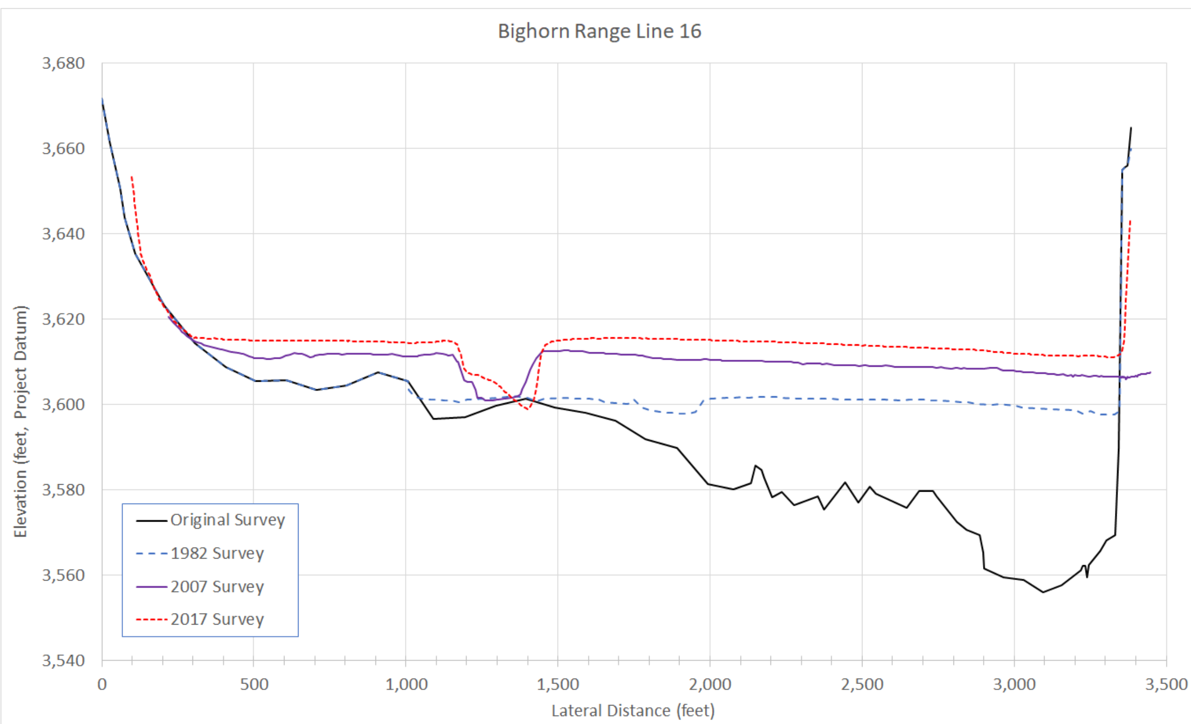

Bighorn Range Line 12
Original Survey
1982 Survey
2007 Survey
2017 Survey
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
0
50
100
150
200
250
300
350
400
Lateral Distance (feet)


Bighorn Range Line 13
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
Elevation (feet, Project Datum)
0
100
200
300
400
500
600
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

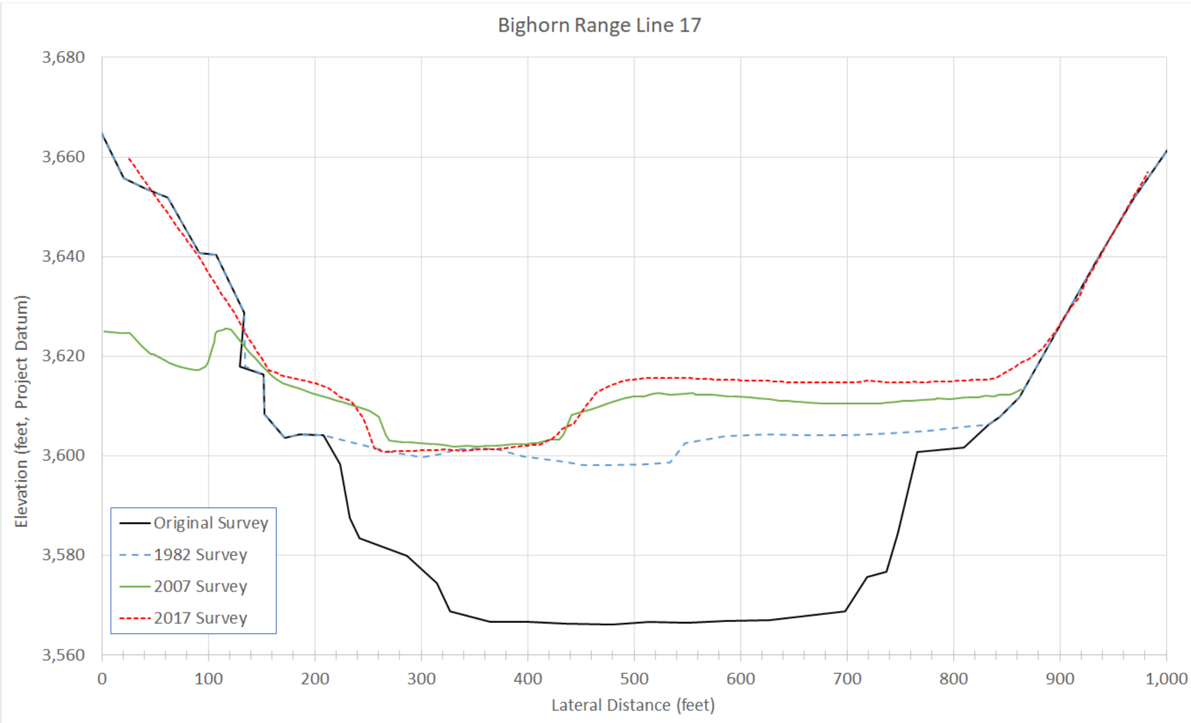

Bighorn Range Line 14
3,700
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
Elevation (feet, Project Datum)
0
200
400
600
800
1,000
1,200
1,400
1,600
1,800
2,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

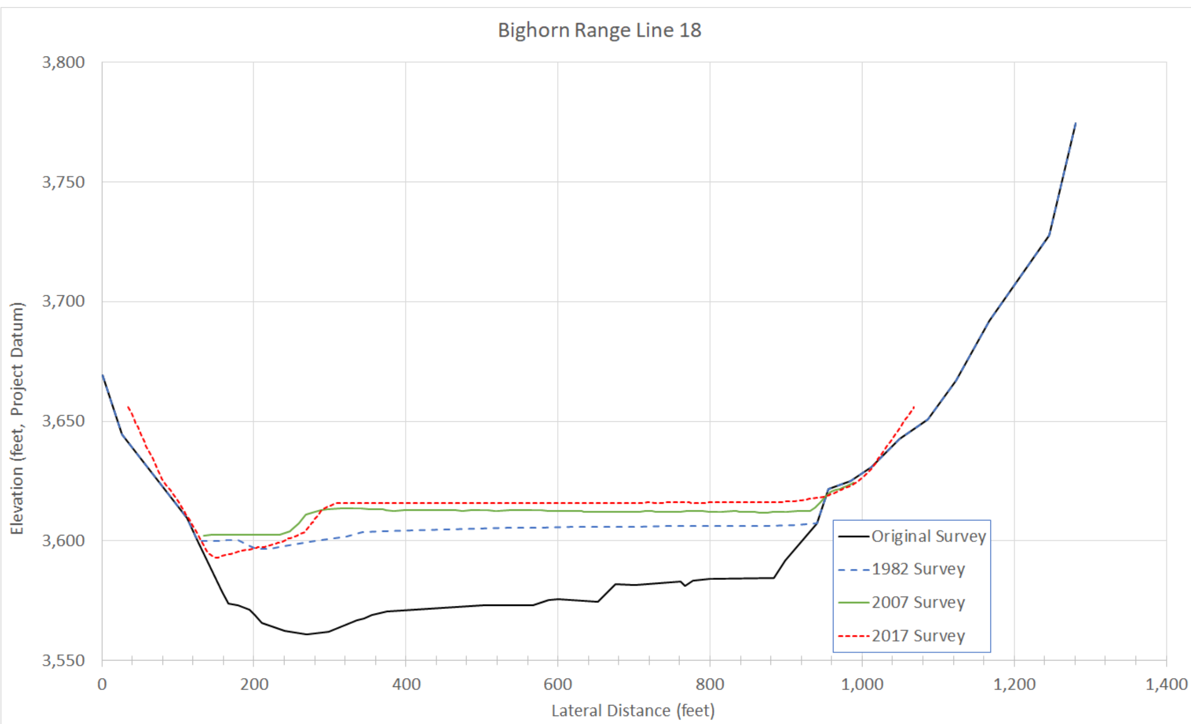


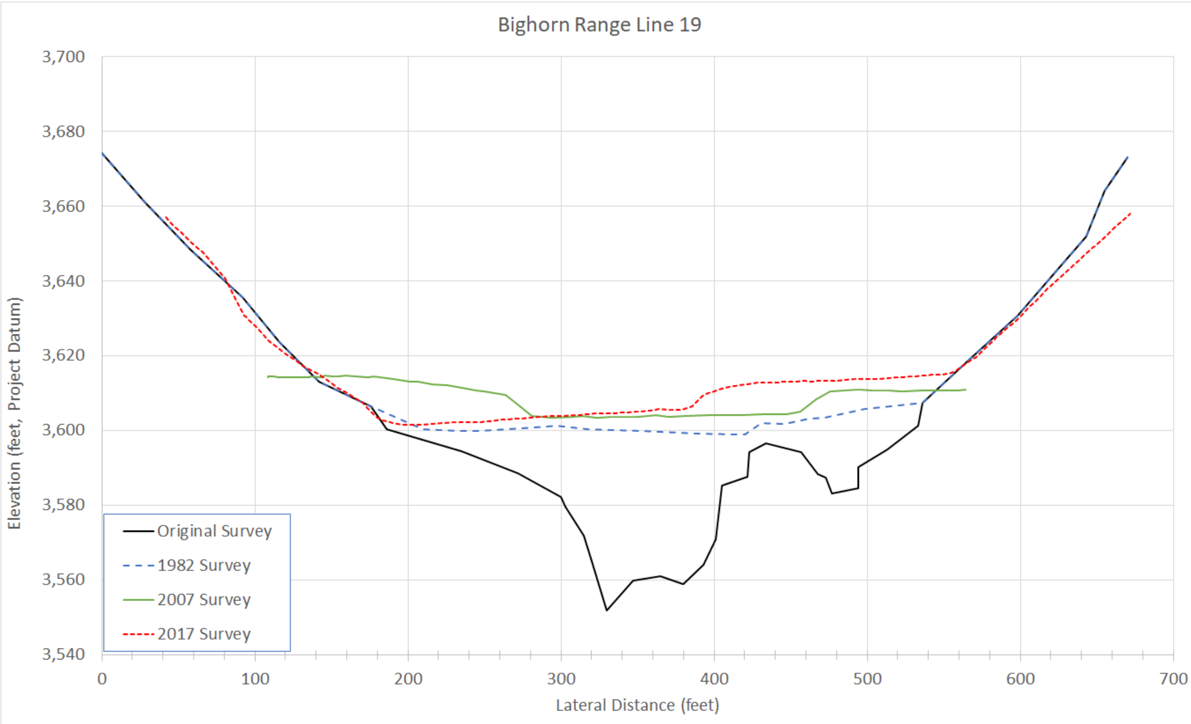
Bighorn Range Line 15
Elevation (feet, Project Datum)
3,700
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
0
500
1,000
1,500
2,000
2,500
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey



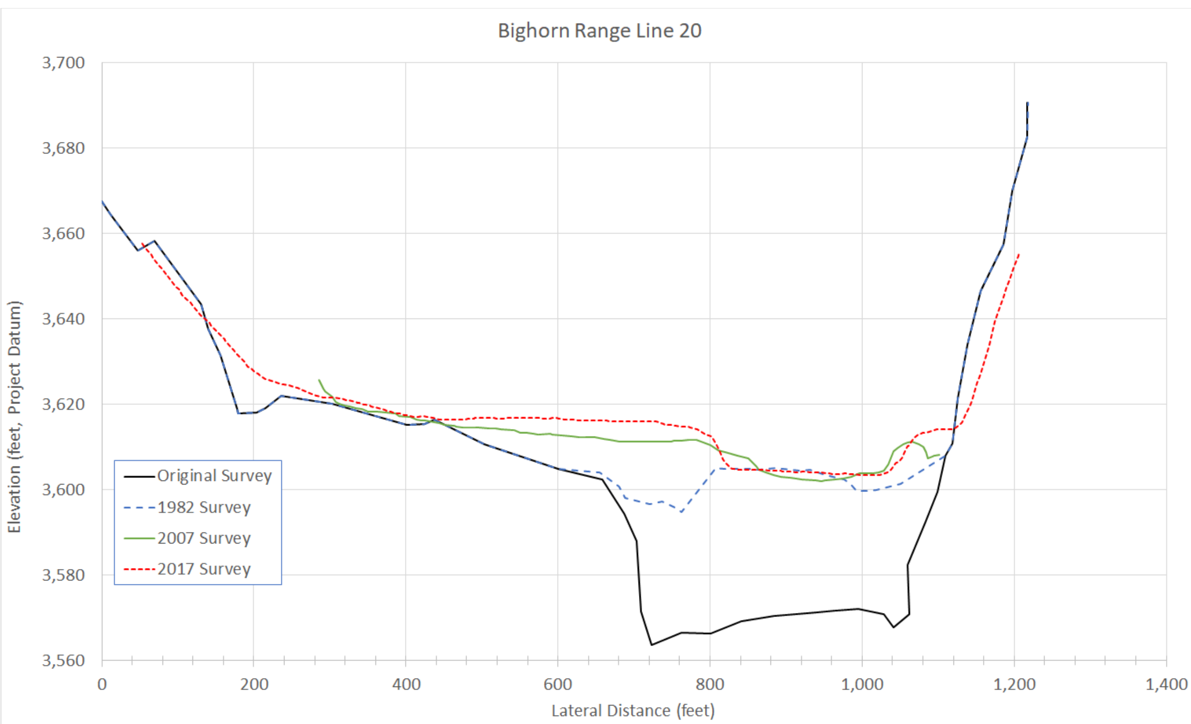
Bighorn Range Line 16
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey


Bighorn Range Line 17
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
0
100
200
300
400
500
600
700
800
900
1,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

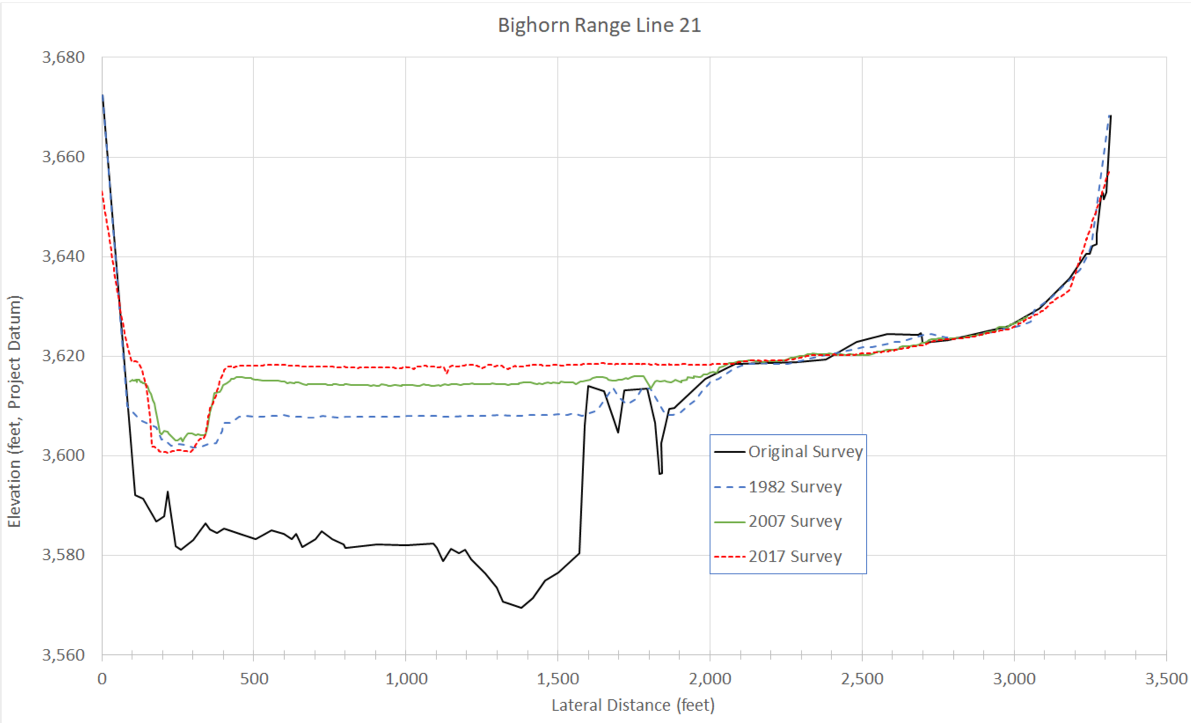

Bighorn Range Line 18
Elevation (feet, Project Datum)
3,800
3,750
3,700
3,650
3,600
3,550
0
200
400
600
800
1,000
1,200
1,400
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

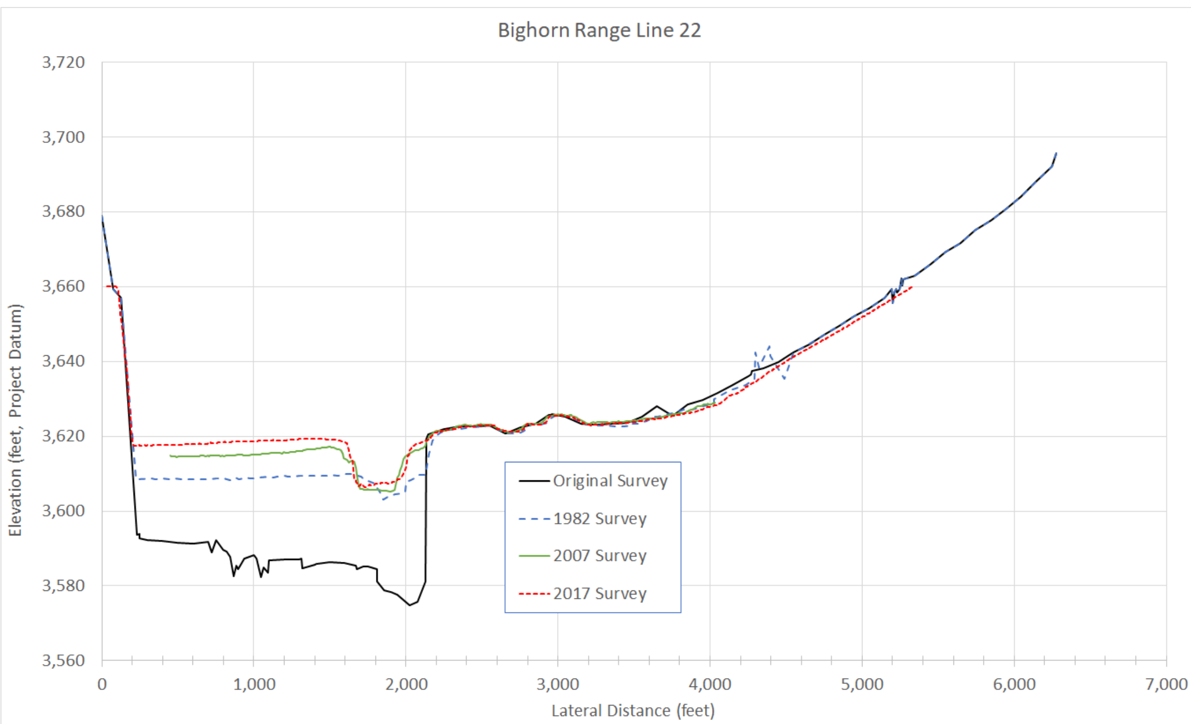


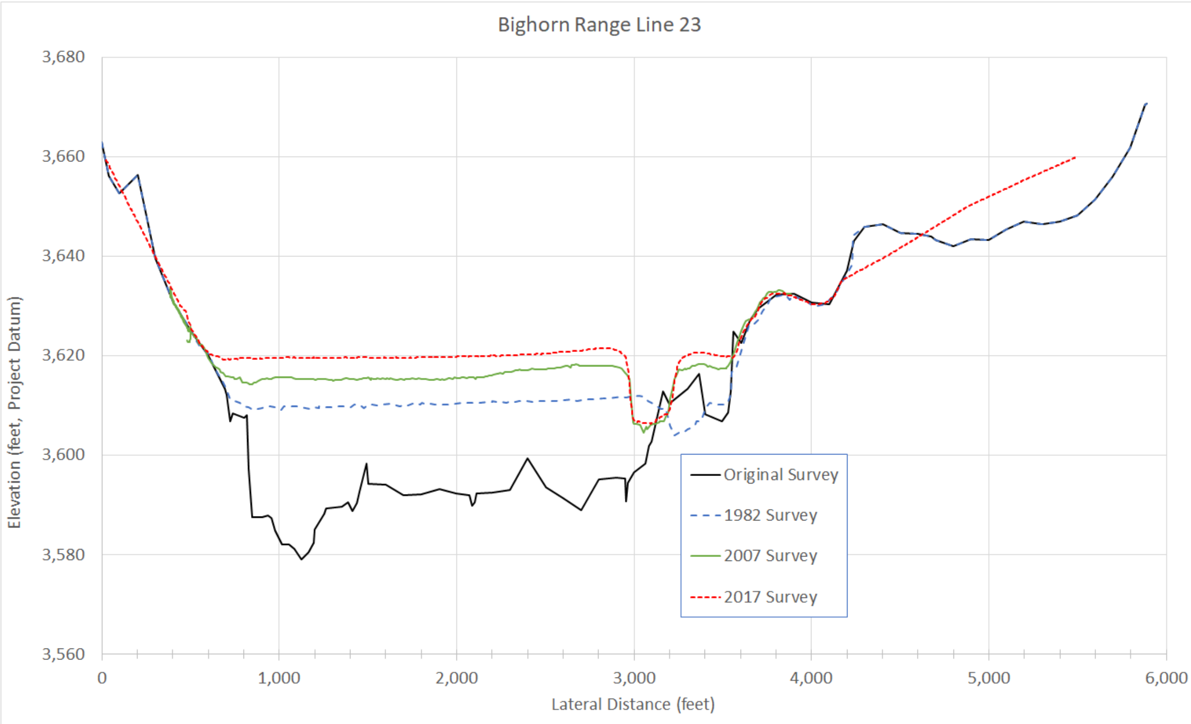
Bighorn Range Line 19
Elevation (feet, Project Datum)
Lateral Distance (feet)
3,700
3,680
3,660
3,640
3,620
3,600
3,580
3,560
3,540
0
100
200
300
400
500
600
700
Original Survey
1982 Survey
2007 Survey
2017 Survey

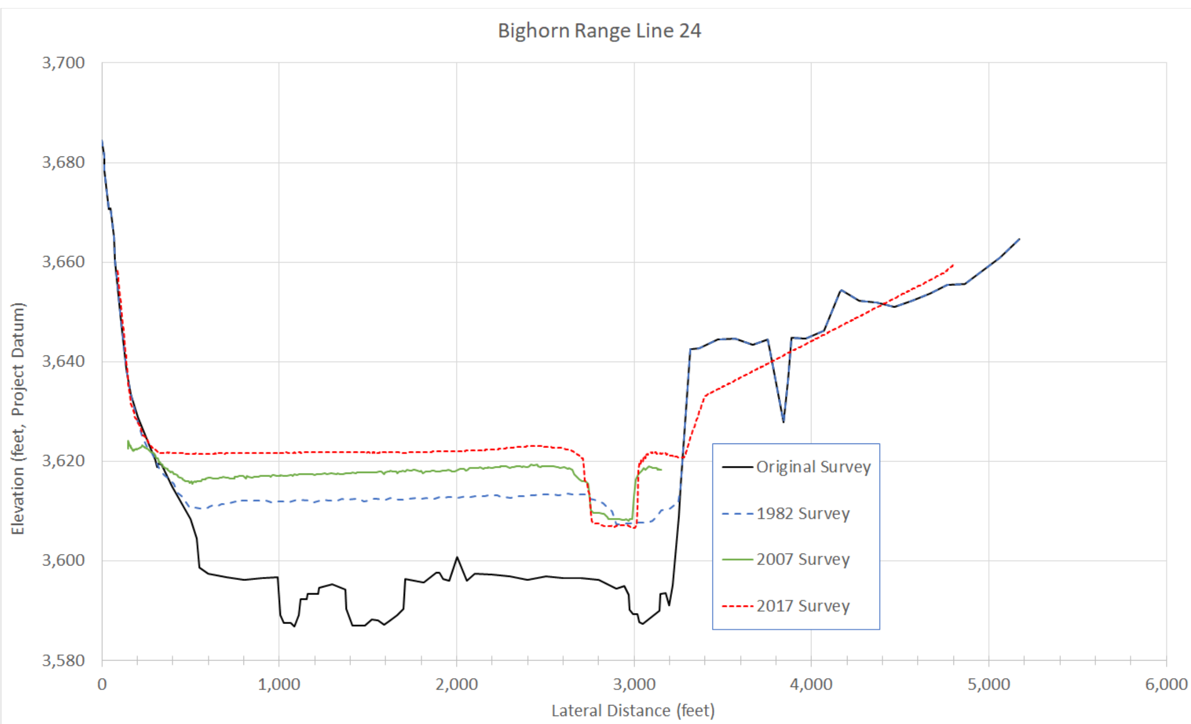


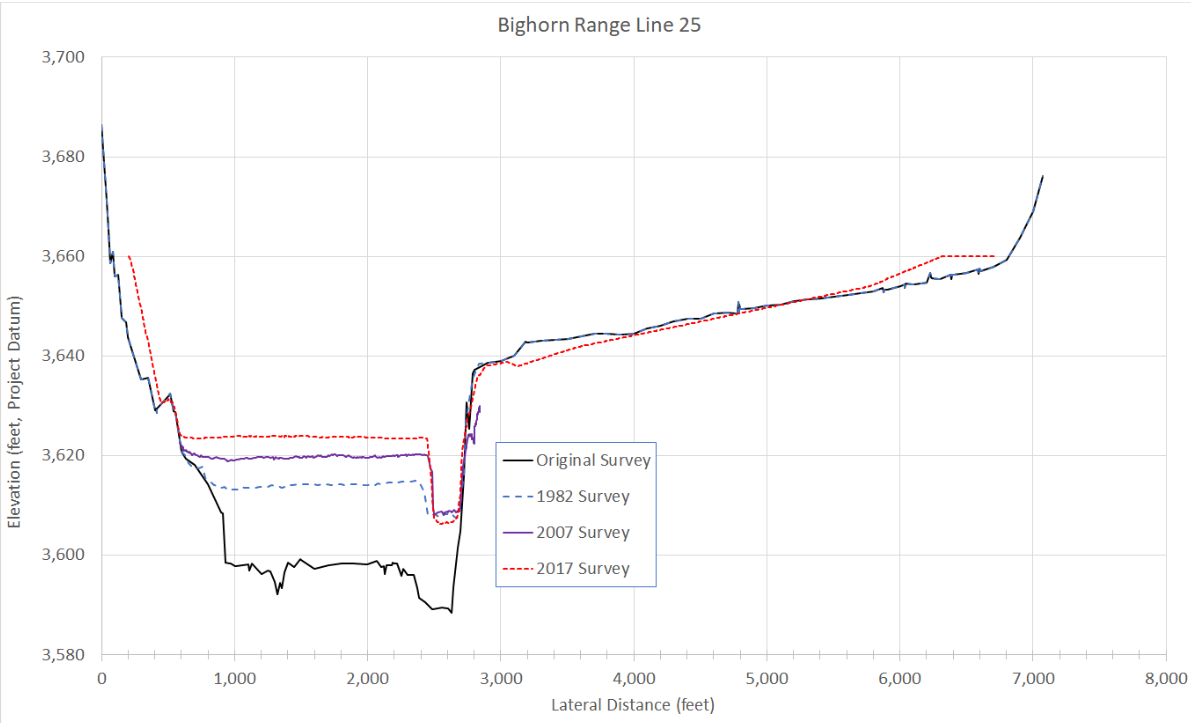
Bighorn Range Line 20
Elevation (feet, Project Datum)
Lateral Distance (feet)
3,700
3,680
3,660
3,640
3,620
3,600
3,580
3,560
0
200
400
600
800
1,000
1,200
1,400
Original Survey
1982 Survey
2007 Survey
2017 Survey

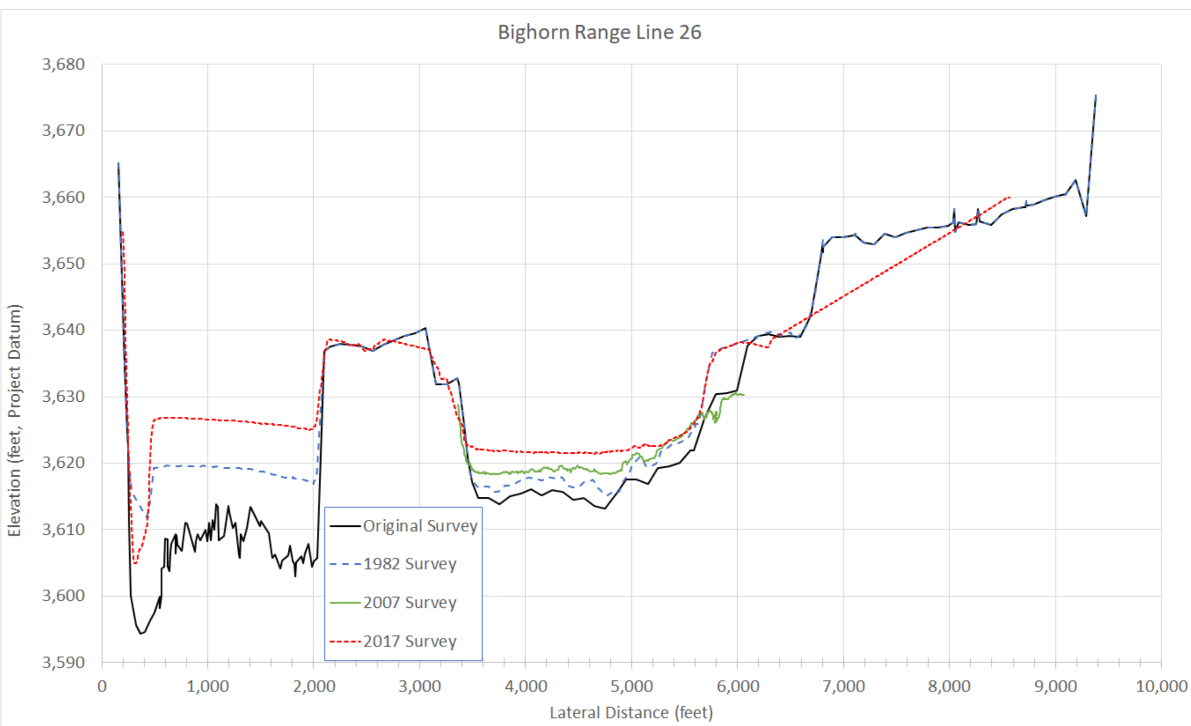

Bighorn Range Line 21
3,680
3,660
3,640
3,620
3,600
3,580
3,560
Elevation (feet, Project Datum)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

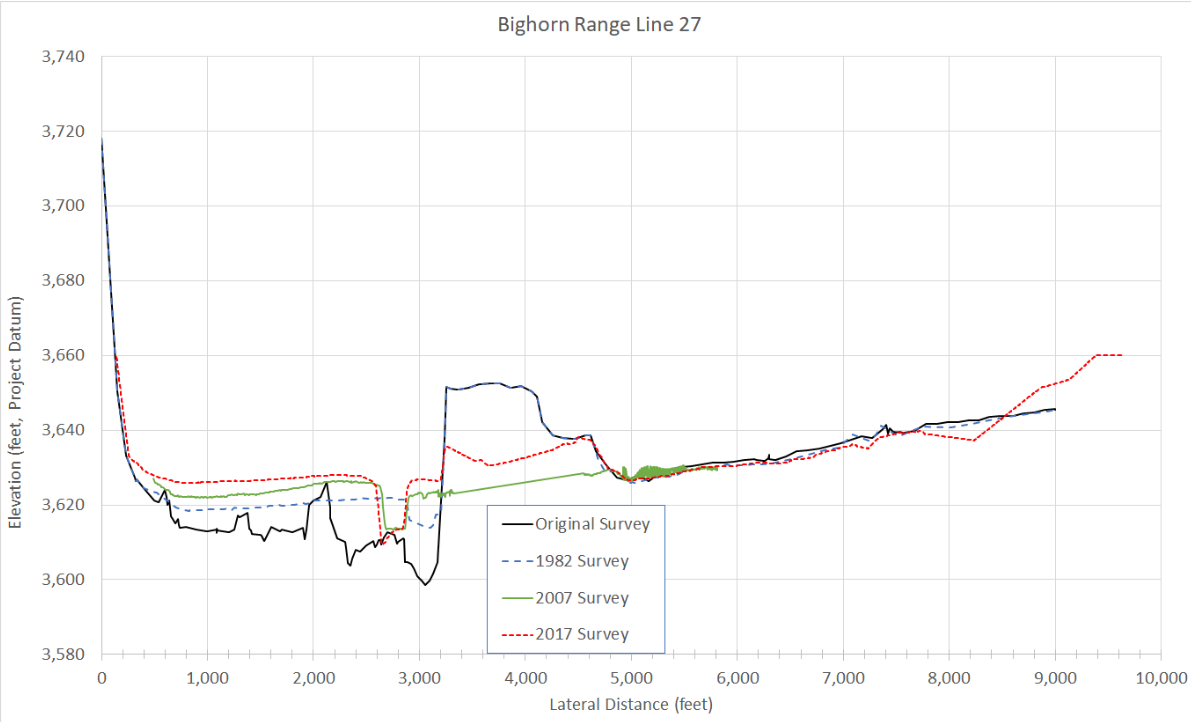

Bighorn Range Line 22
3,720
3,700
3,680
3,660
3,640
3,620
3,600
3,580
3,560
Elevation (feet, Project Datum)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

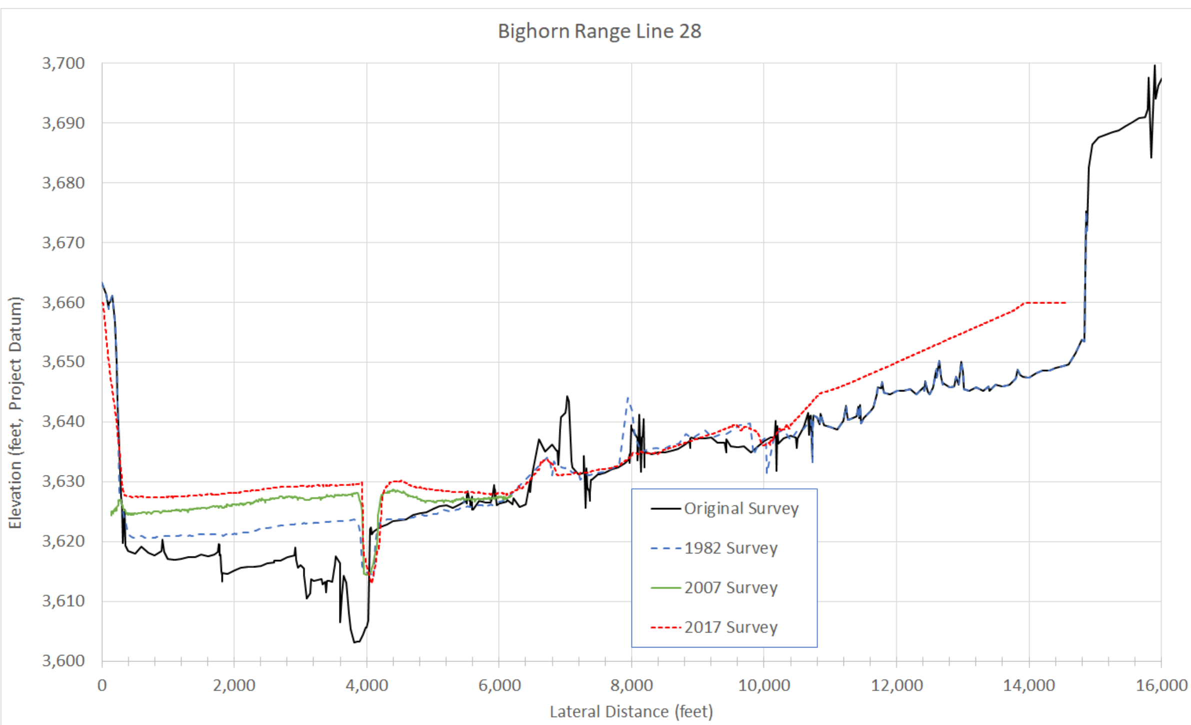

Bighorn Range Line 23
Elevation (feet, Project Datum)
3,680
3,660
3,640
3,620
3,600
3,580
3,560
0
1,000
2,000
3,000
4,000
5,000
6,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

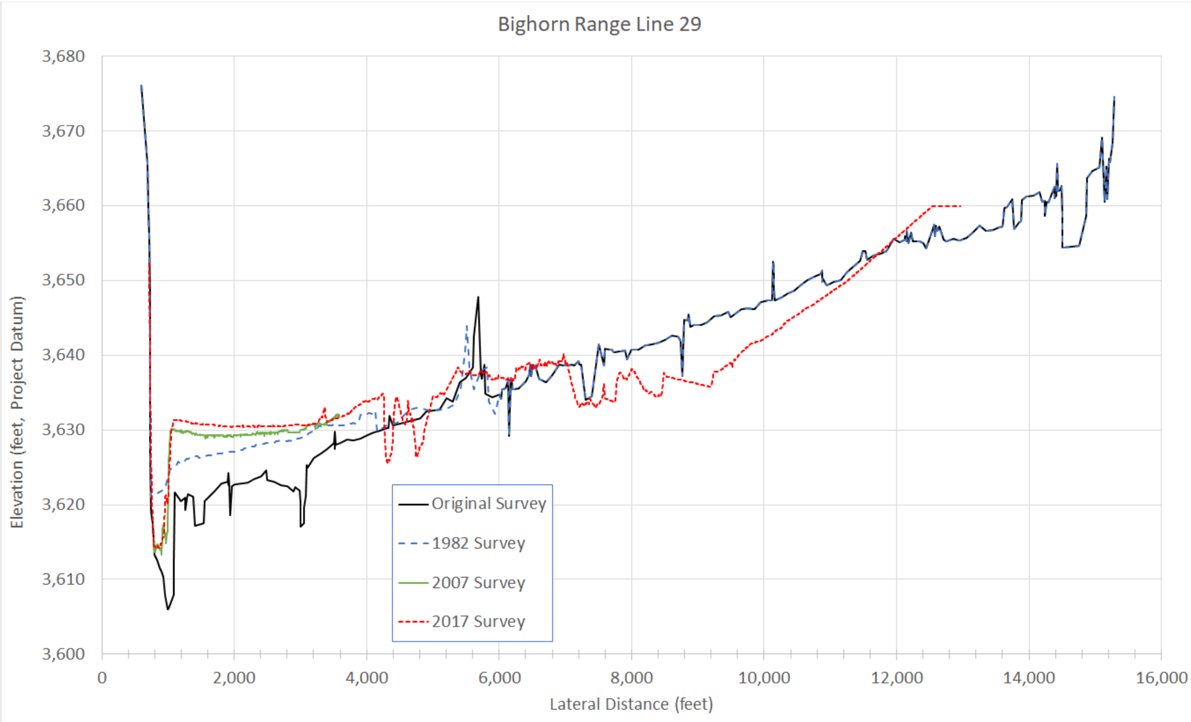

Bighorn Range Line 24
Elevation (feet, Project Datum)
3,700
3,680
3,660
3,640
3,620
3,600
3,580
0
1,000
2,000
3,000
4,000
5,000
6,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

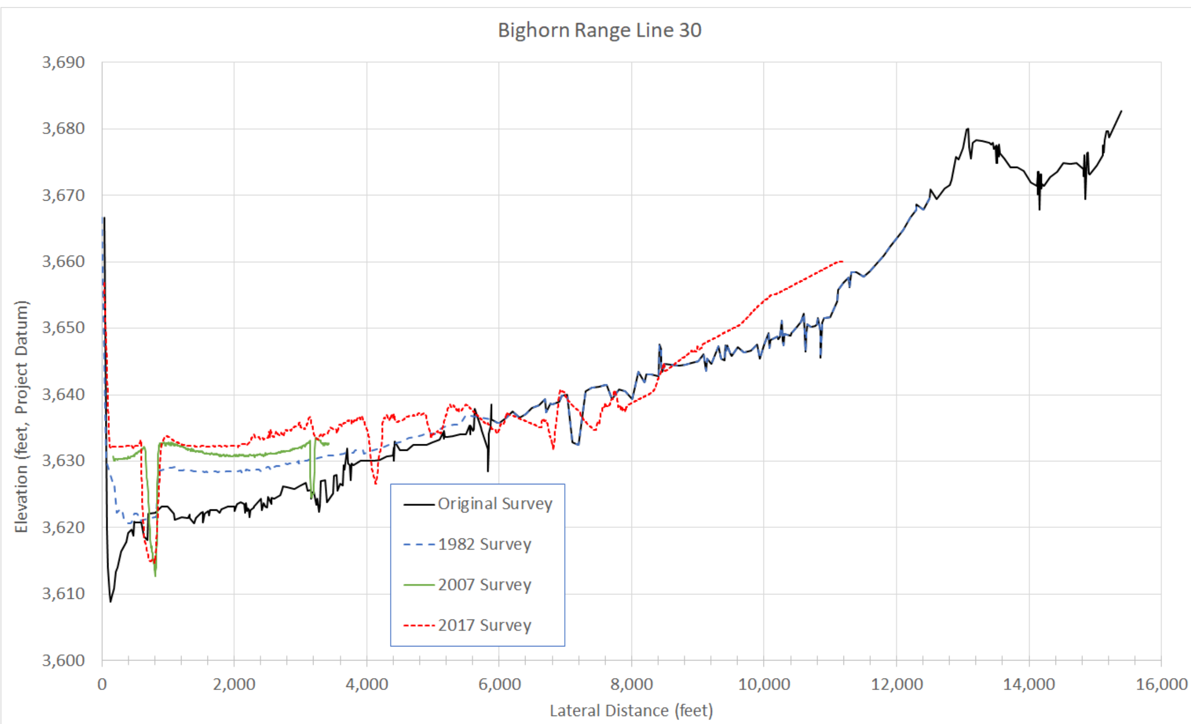

Bighorn Range Line 25
Elevation (feet, Project Datum)
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

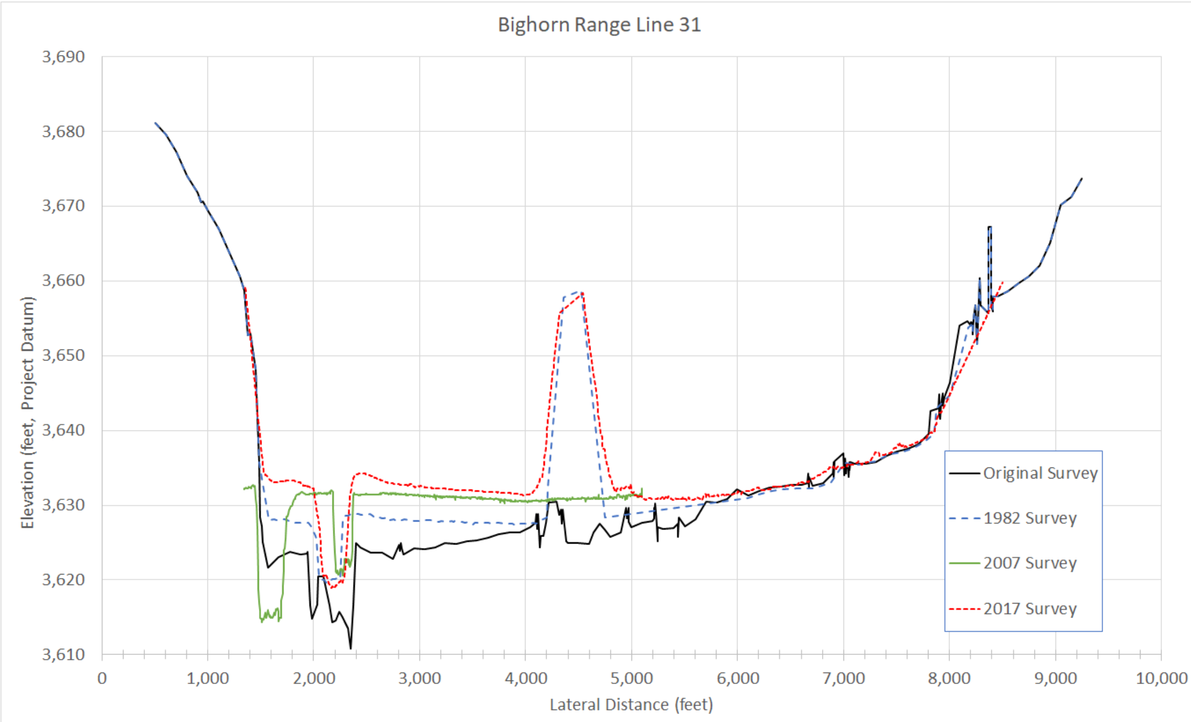

Bighorn Range Line 26
Elevation (feet, Project Datum)
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey


Bighorn Range Line 27
Elevation (feet, Project Datum)
3,740
3,720
3,700
3,680
3,660
3,640
3,620
3,600
3,580
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

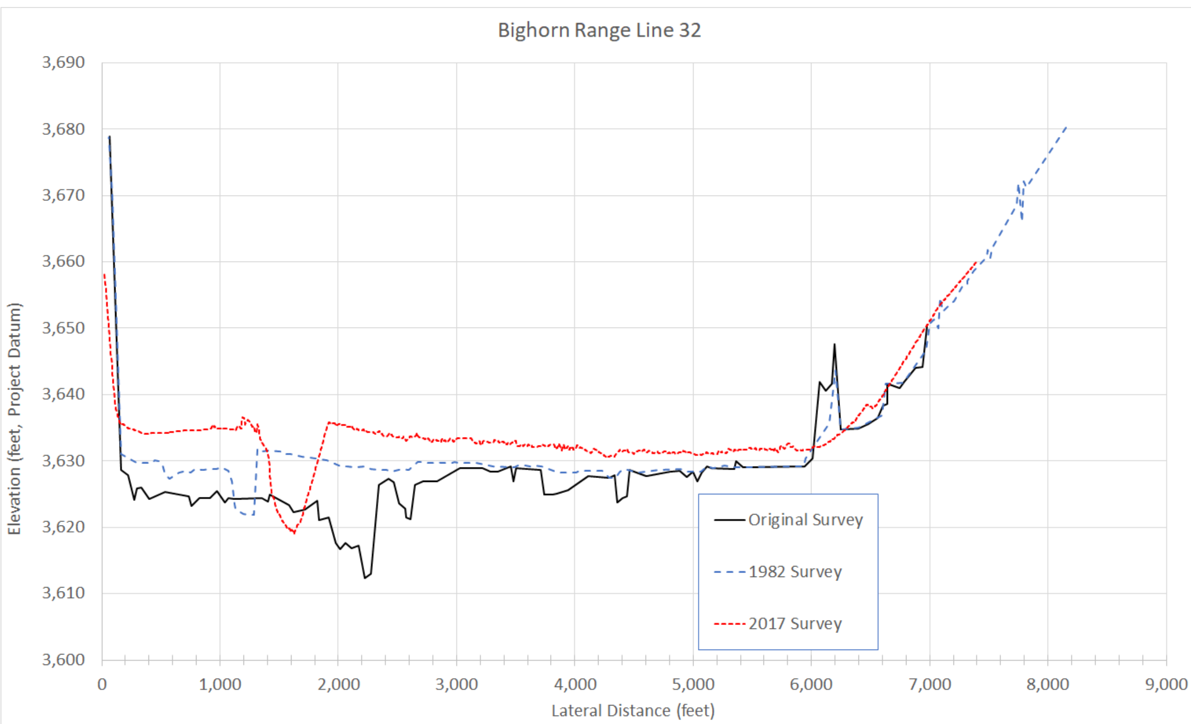

Bighorn Range Line 28
Elevation (feet, Project Datum)
3,700
3,690
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
3,600
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey


Bighorn Range Line 29
Elevation (feet, Project Datum)
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
3,600
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

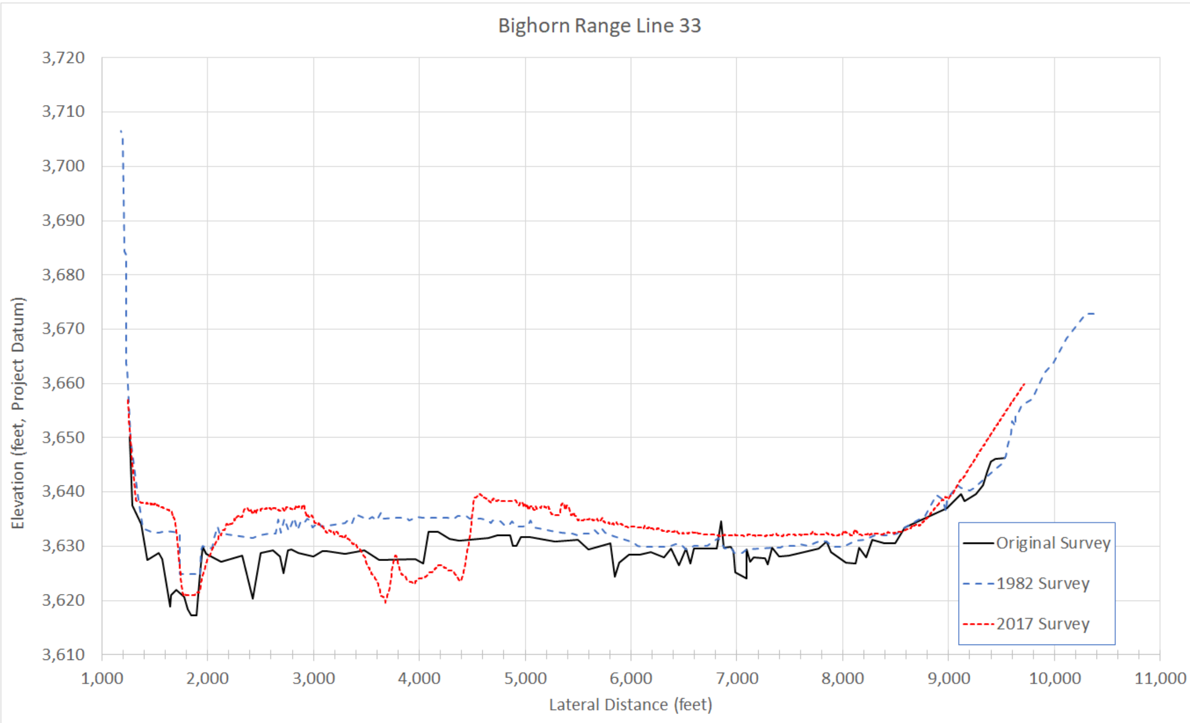

Bighorn Range Line 30
Elevation (feet, Project Datum)
3,690
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
3,600
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

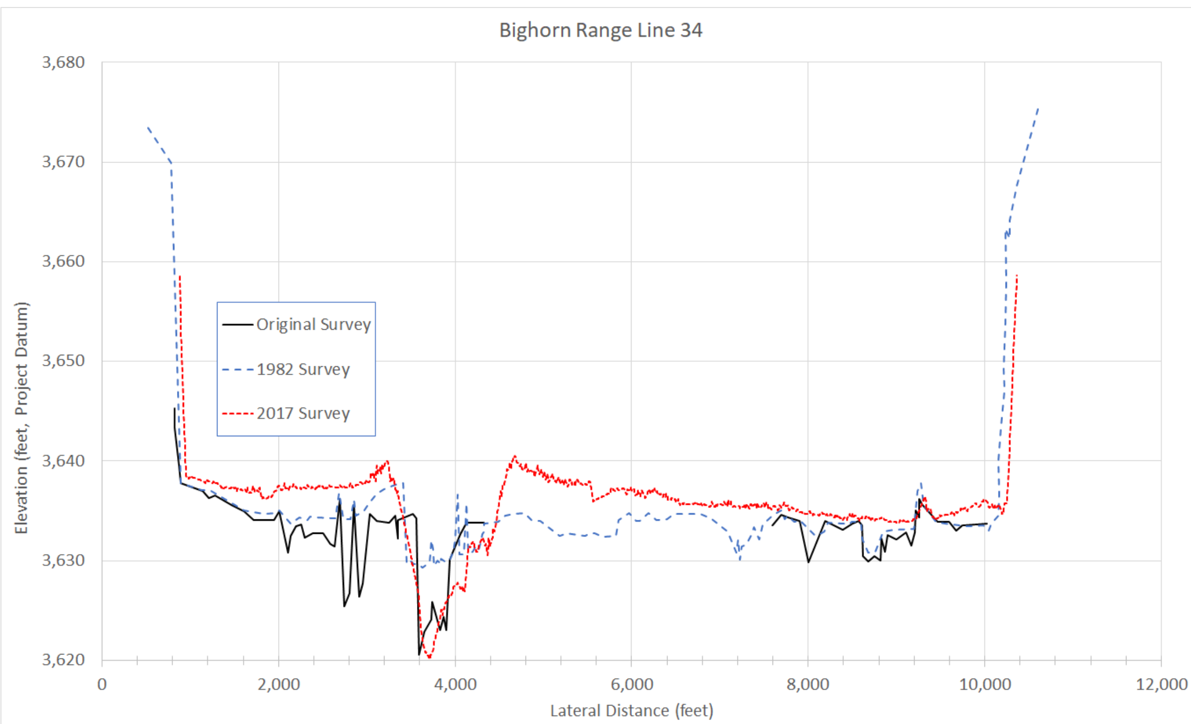


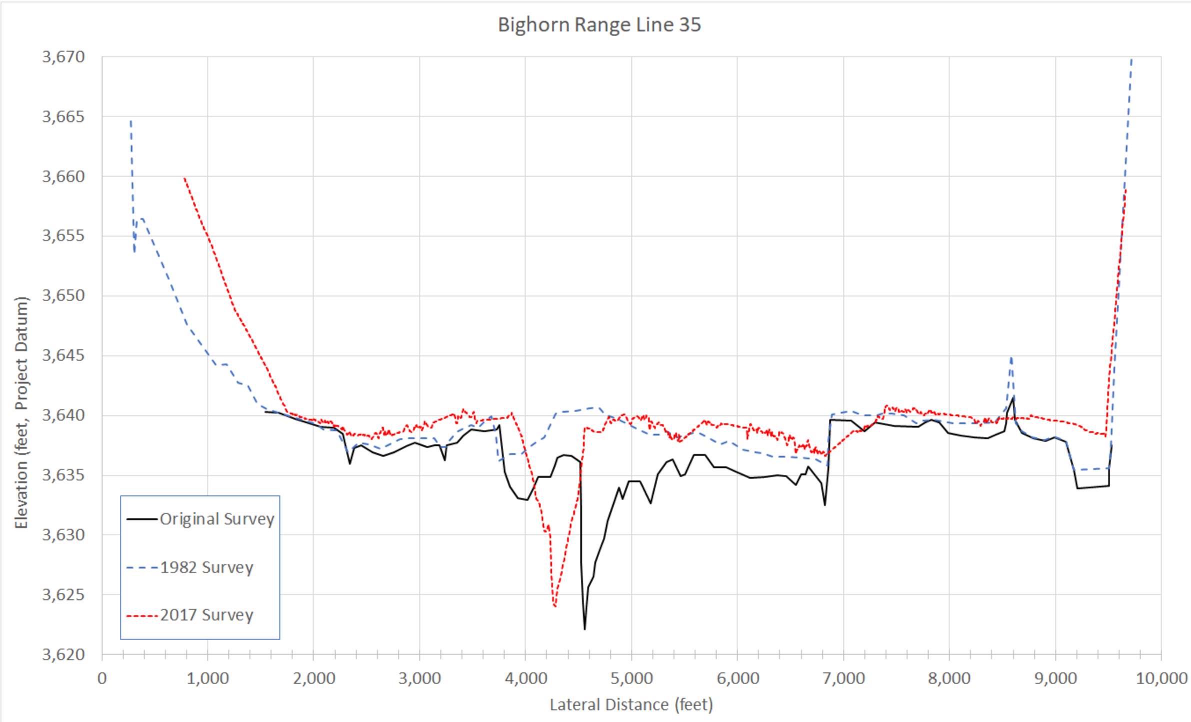
Bighorn Range Line 31
Elevation (feet, Project Datum)
3,690
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
Lateral Distance (feet)
Original Survey
1982 Survey
2007 Survey
2017 Survey

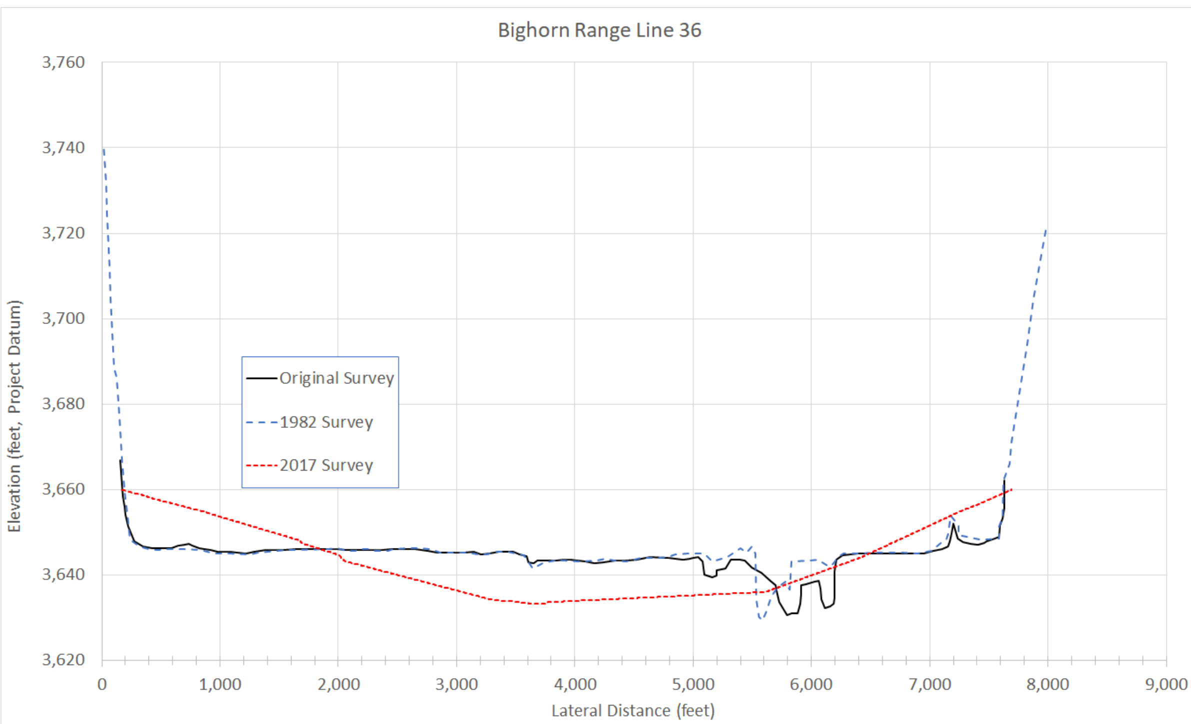


Bighorn Range Line 32
Elevation (feet, Project Datum)
3,690
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
3,600
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey


Bighorn Range Line 33
3,720
3,710
3,700
3,690
3,680
3,670
3,660
3,650
3,640
3,630
3,620
3,610
Elevation (feet, Project Datum)
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
11,000
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey


Bighorn Range Line 34
3,680
3,670
3,660
3,650
3,640
3,630
3,620
Elevation (feet, Project Datum)
0
2,000
4,000
6,000
8,000
10,000
12,000
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey


Bighorn Range Line 35
3,670
3,665
3,660
3,655
3,650
3,645
3,640
3,635
3,630
3,625
3,620
Elevation (feet, Project Datum)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
10,000
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey


Bighorn Range Line 36
3,760
3,740
3,720
3,700
3,680
3,660
3,640
3,620
Elevation (feet, Project Datum)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
Lateral Distance (feet)
Original Survey
1982 Survey
2017 Survey