

Appendix F: Section V. Water Use in the Yellowstone River Basin

Methods for Estimating Water Use for State Water Plan

Consumptive Use

Irrigated Agriculture

There are a number of sources of information on irrigated acreage in the Yellowstone River Basin. The DNRC Water Rights Database contains a variety of information on water rights claims and permits with irrigation as the use and each of these is associated with an irrigated acreage. This database is based on information established to provide the water-right holder with a legal entitlement to a maximum rate of water diversion associated with a particular amount and location of irrigated acreage.

While this information serves the intended purpose well, it is not adequate for an inventory of consumptive use for several reasons. First, the data provides information on the maximum amount of use that would occur (for example, full-service irrigation on all acres) in a year that is not constrained by physical water availability—in other words no water shortages would occur throughout the irrigation season; second, not all drainages in the Yellowstone Basin have been adjudicated and the final amounts of diversion rate and acreage determined; third, a variety of logistical and economic factors influence how much irrigation occurs in any given year.

To account for these potential limitations, a process was developed to map irrigated acreage in the Yellowstone Basin (and across the state) for the purpose of providing an estimate of consumptive use for a typical year. The year 2007 was selected because of water-supply conditions and the availability of supporting information, including the number of cloud-free Landsat scenes.

Estimate of existing irrigation.

Several sources of data that were used to map existing irrigation in a Geographic Information System.

DOR FLU data:

The Montana Department of Revenue has a GIS coverage of land use that evaluates irrigated lands for property taxes. This data (FLU) is state wide and includes data from the RWRCC and DNRC's evaluation of existing uses. The FLU data has large parcel data that has limited value for individual field evaluation. Because it is important to have unique irrigated parcels for the evaluation of consumptive water use, the FLU coverage was intersected with the BLM's GCDB (legal land description) coverage to obtain a FLU coverage that has a maximum parcel size of the GCDB data. This GIS file was then used to select those parcels that do not include the other DNRC data (described below).

DNRC Water-Rights Mapper data:

The DNRC has a GIS program that is used by its claims examiners to evaluate SB76 filed claims in the Montana water-rights adjudication process. This evaluation is based on 1980 imagery and includes areas that are not included in the previous data. The data that is not included is added to the data set.

Montana Water Resource Survey (WRS):

Information on irrigated acreage in the Wyoming portion of the basin was provided by GIS files obtained from the Wyoming State Engineer's State Water Plan website. Although this information is used in this assessment, its use does not constitute acceptance or endorsement of its veracity and accuracy. The Montana Water Resources Surveys are a comprehensive county by county assessment of Montana's historical water use. Data were collected and published from 1943 thru 1965 by the State Engineers Office, and from 1966 thru 1971 by the Water Conservation Board (both predecessors of the DNRC). Most published surveys consist of two parts: Part I, a known historical account of water use in the county; and Part II, survey maps of current water use at the time of publishing. The survey data were derived from courthouse records in conjunction with individual landowner contacts, field investigations and aerial photography. Data collected from other agencies and resources were also used. Although dated, this information is an excellent data source, which details irrigated acreage at a specific time in history. These data were integrated with the DOR FLU, DNRC Water Rights Mapper, and other information to provide a present day estimate of irrigated acreage in Montana.

Final Irrigation GIS Data:

All of the data sets were filtered to eliminate polygons less than 5.0 acre in size and an ESRI shapefile was produced with the following attribute:

Irr_id: unique numbers for each polygon in the coverage. This id number can be used to link to the original data sets.

Proj: this attribute describes which data set was used for the polygon.

Class: HKM's irrigation evaluation.

Unit: RWRCC unit that was used.

Crop: crop type if available in the base data.

Sys: type of irrigation system if available in base data.

Acres: polygon size in acres.

Basin: Water Court basin id.

Irrcode: WRS code (this code can be used to identify irrigation district lands vs. private lands).

Estimation of Consumptive Use Associate with GIS-Mapped Irrigated Acreage

The Idaho Department of Water Resources, in Cooperation with agricultural engineers at the University of Idaho Kimberly Research and Extension Center, and NASA, have developed the METRIC method for estimating evapotranspiration (ET) and consumptive use from Landsat satellite imagery and ground-based weather station data. This information is very accurate and has been collected and analyzed to provide consumptive use information in the Flathead Valley to support estimates of consumptive use for the CSKT Compact, hydrologic modeling in the Smith River basin, and in the Wyoming portions of the Powder and Tongue River basins to support Montana's U.S. Supreme Court litigation with Wyoming.

Use of METRIC requires considerable planning, on-the-ground data collection, and was beyond the scope of the State's current water planning effort (see the website below for more information on METRIC). The METRIC method, and the one developed for the State Water Plan, are based on the fact that ET consumes energy and Landsat satellite sensors can measure that energy use which can then be translated into an amount of water used by vegetation.

<http://www.kimberly.uidaho.edu/water/>

DNRC Method for Estimating consumptive Use

DNRC Water Resources Division agricultural engineers, GIS analysts, and hydrologists developed a less data intensive method, than METRIC, for estimating statewide ET and consumptive use from irrigated acreage. This procedure falls within a class of methods referred to as vegetation-index methods—although the process does incorporate the Landsat thermal band (band 6) to help overcome some of the limitations of pure vegetation-index methods. The method relies on processing of weather station data (primarily the USBR's Hydromet stations) and Landsat 5 and 7 scenes and information contained in multispectral bands 1-7.

Processing Landsat Scenes.

A single Landsat scene is roughly 100 miles by 100 miles and has a pixel resolution of about 100 feet by 100 feet which is suitable to map individual irrigated fields. 35 Landsat scenes were required to cover Montana entirely. For the five month irrigation season, May through September, 175 scenes were required. The scenes were selected based on image dates in 2007 having less than 30% cloud cover.

A false color composite image was created in the format of Path_Row_Date (P_R_D) using bands 7_4_3 and projected into Montana State Plane spatial coordinates. A preliminary transpiration grid was then created by subtracting band 3 from band 4 and eliminating cell values less than 1 and greater than 200. This grid was named in the format of TPRD. Any values that have values less than 1 are assumed to have no transpiration (nor plant growth). Values over 200 are generally edge or other anomaly cell values. A preliminary Evaporation grid was then created by taking band 6 and eliminating all cell values less than 100 and greater than 200. This grid was given the name format of EPRD. These processes were accomplished in Arc Info.

Cloud masking

Clouds have a significant impact on cell values in a Landsat scene and need to be removed before the scene is analyzed. We used USGS EROS Datacenter Landsat products that provide data needed to remove the cloud impacted cells (Indsr.P_R_D). The Indsr data has 16 subdataset that can be used for evaluations of cloud cover and masking. The subdataset 16 (Fmask) has a compilation of clouds (value 4), shadows (value 2), water (value 1), and other areas (value 0). We combined the value 0 data with the TPRD and EPRD, which eliminates the data affected by clouds and water, which are not appropriate for the Landsat-based evapotranspiration analysis.

Determine Hot and Cold cell pixel values - Irrigation grid mask

The Landsat process we developed analyzes the relative 30 meter pixel (90 feet by 90 feet) values in each scene. This process requires the selection of pixels representing areas of highest water use (cold pixel), and those representing areas of lowest water use (hot pixels). This process requires a subjective interpretation by a skilled agricultural engineer with an understanding of the area and how water is being used. It is a time-consuming process and subject to inconsistencies.

The process was automated to select cold and hot pixel values for irrigated lands. To do this, an irrigation grid mask was developed for each Landsat scene. The grid is developed by clipping the existing irrigation shape file (SWP_irr_bg_5.shp) with the outline of the scene boundary and converting it to a grid with unique ids with a naming format of Path_Row_Clip_Irrigation (PRCI).

PRTD cold pixel value

The TPRD grid was then combined with the PRCI grid to create a masked grid that includes only those areas that are irrigated and have no cloud cover. The cold pixel value is determined by selecting the highest 1 percent of cell values and assigning the lowest cell value of that subset as the cold pixel value (CPV). For the TPRD grid, the hot pixel value is 1. The field Trf (Transpiration reference) was then added to the TPRD grid and the cell valued was calculated as:

$$Trf(4,2) = TPRD \text{ cell value} / CPV$$

EPRD hot and cold pixel values

The EPRD grid was then combined with PRCI grid to find the highest and lowest 1 percent of the cell values and set the cold pixel value (CPV) as the highest cell value of the lowest 1 percent, and set the hot pixel value (HPV) as the lowest cell value of the highest 1 percent. Then a field Erf (Evaporation reference) was added to the EPRD grid and the cell value calculated as:

$$Erf(4,2) = (HPV - EPRD \text{ cell value}) / (HPV - CPV)$$

Using this calculation, some values are less than 0; those values that are higher than the lowest values of the 1 percent of the selected set. These values were then set to 0. The E and the T grids were then combined to create a grid with ET values. The resulting E and T grids now have field (Trf and Erf) values ranging from 0.00 to greater the 1.15. The values greater than 1.15 are mostly edge anomalies or cloud edges and are not used in this evaluation. After this, the E and T grids for reference E (Erf) and reference T (Trf) values less than 1.15 were selected and a new grid calculated ETPRD :

$$ETPRD = (Erf + Trf) * 50 \text{ as an integer}$$

This results in an ETPRD grid having integer cell values and cell counts. When completed for all Landsat scenes, we have ETrf grids that estimate reference water use for each Landsat scene. The cloud and water surfaces have been removed and the grids can now be related to weather station data to estimate water use. At this point, one can evaluate any land cover polygon for water use for each available Landsat scene, and extrapolate the values to seasonal water use.

Irrigation ETrf Evaluation by Landsat scene

In this process, the irrigated land in a Landsat Path_Row with the ETPRD, is gridded for its specific location. Then the cell values are summarized for each irrigated field IDs and the average ETrf is calculated for each of the irrigated fields. The first step is to combine the irrigation clip grid (MPR) for the Path Row in the “Irr grid” directory for each of the Landsat ETPRD. This combined grid will have cell attributes for each of the unique irrigated field IDs of “Count” and “ETPRD”. A field for “ET” (8,0) is added, then calc = Count * ETPRD and save. Then summarize on MPR (unique irrigated field id). Sum Count and sum ET, then add a new field “ETrf” (5,1) and calculate:

$$ETrf = Sum_ET / sum_Count \text{ (and save)}$$

The ETrf is the average reference ET value for each unique field id for that PRD Landsat scene. This summary table is then joined to the irrigation polygon shape file for that P_R (PRim) and new fields are added to that shapefile:

$$CPR(6,0) = Sum_Count$$

$$ETPR(5,1) = ETrf$$

This process is then repeated for each of the dated Landsat scenes in that Path_Row.

Irrigation Water Diversion and Consumption

Consumptive use for each individual parcel was derived via the Landsat-ET estimation procedure described previously.

Field application was based on the method of irrigation (if available – FLU data only) and the county in which each parcel was located. If the method of irrigation was identified as pivot, then an application efficiency of 80% was assumed. If the method of irrigation was otherwise identified (sprinkler, flood) or not indicated at all (WRS data), then the field application was calculated using on-farm efficiencies from the Water Conservation and Salvage Report for Montana (SCS, 1978). In cases where a county was represented in more than one basin (Deer Lodge, Lewis & Clark, Silver Bow, Fallon, Wibaux), the highest reported efficiency was used.

After the individual field applications were determined, the fields were aggregated by county and assigned to source (groundwater or surface water) based on the percentages identified in the USGS 2000 Water Use document.

Diversion/withdrawals were calculated based on the source of the water supply (groundwater, surface water) and the county in which each parcel was located. If the source was groundwater, conveyance efficiency was assumed to be 100%. If the source was surface water, then the amount of water withdrawn was calculated using conveyance efficiencies from the Water Conservation and Salvage Report for Montana (SCS, 1978). In cases where a county was represented in more than one basin (Deer Lodge, Lewis & Clark, Silver Bow, Fallon, Wibaux), the highest efficiency reported was used.

After the consumptive use, field application, and amounts withdrawn were calculated, each parcel was assigned to 8 digit HUCs based on location. This assumes that the source HUC and place of use HUC are identical, which are not necessarily the case.

Evaporation (major reservoirs)

Evaporation was taken directly from the USGS 2000 Water Use document. These were calculated using surface areas from the USGS (Ruddy and Hitt, 1990), evaporation rate from the 1982 NOAA map (based on 1956-1970 pan data), and 1961-1990 PRISM data. In a few cases, where sufficient data was available, USGS values were compared to estimates produced via a water balance approach.

Livestock Water Use

The number of livestock (Cows, Sheep, Hogs) was taken from NASS data for 2010 - consistent with the 2010 USGS documentation. Water withdrawn was estimated using the assumptions applied in the USGS 2010 report:

Beef Cattle:	15 gpd/head
Dairy Cattle:	23 gpd/head
Hogs and Pigs:	5 gpd/head
Sheep:	2 gpd/head

All water withdrawn was assumed to be consumed.

Assignment of source was based on county percentages of groundwater and surface water originally assigned in the 1986 DNRC document. These percentages originated from water rights permits issued at the time of that report.

Assignment to HUC was performed by assuming uniform distribution of stock - consistent with the 2010 USGS documentation.

Municipal and Domestic Water Use

Public (Community) Water Supplies

Public water supplies (PWS) were identified via two sources: 1) Montana Public Water System Sources database (MT- DEQ, accessed through the Montana GIS portal – data published 9/19/2012); and 2) the EPA Safe Drinking Water Information System (SDWIS). For each source, all active systems classified as community systems, or consecutive connections to community systems were initially selected. Non-Transient, Non-Community (NTNC) and Transient, Non-Community (TNC) were not included.

These two data sources result in an overlapping dataset for state regulated systems along with a unique dataset of tribal PWS from SDWIS. The state regulated systems were combined by applying the following rules:

When available, use the DEQ population numbers rather than SDWIS.

Remove systems in the DEQ data if identified as “Closed” in SDWIS.

Remove systems in the DEQ data if classified as NTNC or TNC in SDWIS.

Remove systems from DEQ or SDWIS if source of water was identified as “Purchased”.

Remove systems in the DEQ data if readily identified as water bottling/condition firms not already removed under 4).

Remove DEQ systems not identified in SDWIS if there are no resident users.

Include SDWIS systems not listed in the DEQ database.

HUCs and counties for SDWIS systems not found in the DEQ database were assigned by searching/cross-referencing:

DEQ Montana Drinking Water Watch Database – for primary source of consecutive connections

DNRC Water Rights Query System

MBMG GWIC database

Tribal websites

Topographic maps

Resident users for three systems in the DEQ database (resorts) were revised based on information from the DEQ Montana Drinking Water Watch Database. These systems were identified by preliminary comparison of county PWS residents with countywide population estimates. In the case of two counties (Silver Bow and Gallatin), initial estimates of PWS resident users exceeded the county-wide population. PWS users for cities and towns (as designated by the 2010 Census) were adjusted to populations reported in the 2010 census. Water withdrawn by each PWS was estimated using values of per capita

day use reported by county in the USGS 2010 document applied to the number of resident users. An additional 10 gallons per day was applied to non-resident users of the PWS.

Consumptive Use by PWS was assumed to be 37% of withdrawals (DNRC, 1975; USGS, 1986), consistent with USGS 2010 document. One exception to this is the City of Butte, which withdraws water from the Big Hole River (HUC 10020004) for use in the Upper Clark Fork River (17010201). In this case, all water withdrawn from the Big Hole River is assumed to be consumed.

(Note: The 37% consumptive use percentage appears to have originated from the results of a questionnaire sent to public water supplies. The resulting statistics indicated that of the water withdrawn, 62% was used by residential users (who consumed 50%) and 38% was used by industrial users (who consumed 15% - per USGS unpublished data). The resulting overall consumption percentage $(.62)(.5) + (.38)(.15) = .367$ or 36.7%.)

Domestic (Self-Supplied)

The number of self-supplied domestic users was calculated by subtracting PWS resident users spatially located within each HUC from 2010 population estimates (also by HUC). The number of PWS resident users spatially located within each HUC may differ than PWS resident users served by the source HUC.

The amount of water withdrawn by domestic users was assumed to be 78 gpd per person (DNRC, 1986; DNRC, 1975) - consistent with the 2010 USGS documentation. Per the 1986 document, this estimate of water use was derived from statistics of municipal systems serving less than 55 users.

Consumptive Use by PWS was assumed to be 50% of withdrawals. This is consistent with the 50% residential use assumed in PWS estimates (mostly consisting of lawn irrigation), and is comparable to recent estimates of consumptive use provided by the DNRC to WPIC.

All domestic water use was assumed to be from groundwater sources. This differs from the USGS procedure, which indicates groundwater sources of 95 percent statewide.

Industrial Water Use

Self-Supplied Industrial

Duplication of the USGS procedure for industrial users in 2010 was not possible. Instead, past USGS estimates (1985 through 2000 - where both HUC and county estimates were provided, and 2005 which provided only usage by county) were analyzed to determine HUC assignment of those counties where the majority of the water use occurred. Then, applying these HUC assignments to the 2005 USGS data updated estimates were provided (representing 90% of the statewide industrial water use). All other industrial use estimates remain as reported in the 2000 water use document.

Thermoelectric

Thermoelectric users were identified from Energy Information Administration reporting (EIA923 – Power Plant Operations Report, Schedule 8D: Cooling System information). Six projects were identified in the report, three of which reported withdrawals and consumptive use for cooling:

Colstrip (Rosebud County)

J E Corette Plant (Yellowstone County)
Hardin Generator Project (Big Horn County)

There are additional thermoelectric projects in the state (EIA –Electricity Data Browser, accessed 9/12) that did not appear in the EIA 923 Report. There are also projects listed in the water rights database for power generation (likely as a complimentary use, but not necessarily) that are not found in the EIA data. However, the list above is comparable to previous reports (DNRC, USGS) – with some allowance for new plant construction and variation in annual generation needs.

With regard to consumptive use, the Corette plant reported only a small percentage of withdrawals as consumed. Both the Hardin Generator Project and Colstrip reported consumptive use equivalent to withdrawals. Assignment of generators to HUC was performed through cross-referencing EIA data, the DNRC Water Rights Information System, and topographic maps.

Hydropower

Hydropower projects were primarily identified from the EIA – Electricity Data Browser (User Generated Report: List of Plants for All Fuels, Montana, All Sectors, accessed 9/12). The recently restarted Flint Creek project was not included in the EIA data and was identified by the basin hydrologist. Projects were then sorted into three categories:

Federal facilities where electricity is generated but is generally not the primary purpose of the project (Canyon Ferry, Fort Peck, Yellowtail, Libby, Hungry Horse);

Facilities where the primary purpose is electricity generation (PPL, Avista, and PacifiCorp);

Facilities where electricity is generated but may not be the primary purpose of the project (Broadwater, Tiber, Turnbull Hydro projects, South Dry Creek Hydro, Flint Creek).

Plant capacity and 2010 Net Generation was taken from the EIA (Except for Fort Peck – USACE data, and Ryan Dam – which upgraded to 60 MW in 2013).

Turbine capacity was taken from water rights filings associated with generation – since water rights were typically filed at turbine capacity. *It should be noted that most projects have additional flow rights above and beyond turbine capacity in order to fill and store water behind the dams.*

2010 Water Use was determined by one of three methods:

1. If a gage was located immediately downstream of a project, with no significant tributary flows between the dam and the gage, then daily flows were used to estimate water use – subject to the maximum flow capacity of the project.
2. In the case of Fort Peck, this was reported by the USACE.
3. In all other cases, the 2010 water use was estimated by applying a ratio of generation to water use – derived from the generation and turbine capacity of the project. These ratios were constructed in units of KW/cfs in order to compare them with previous “turbine factors” employed by the DNRC in the Missouri River Model and cited later in the Smith River EA Addendum (the ratios are comparable).

Assignment of generators to HUC was performed through cross-referencing EIA data, the DNRC Water Rights Information System, and topographic maps.

Notes:

1. There are additional hydropower projects planned or in development based on water right permit applications. These projects do not involve new reservoir construction, but rather use projects already in use for other purposes (irrigation). Such projects have been applied for and permitted by Gibson Dam Hydroelectric Co. LLC, Clark Canyon Hydro LLC, and Diamond T Bar Ranch Inc (for a second generating unit off the South Dry Creek Hydro project canal).
2. Hydropower facilities are normally considered non-consumptive. However, many of these projects are associated with large reservoirs from which water evaporates. Additionally, at smaller scales, some of these projects may divert water from one watershed for use in another (South Dry Creek Hydro) – in which case they would be considered 100% consumptive.
3. The estimates of water use in 2010 may be misleading since the use of water by hydroelectric facilities is more accurately represented by the water rights – turbine capacity for the projects and evaluated on a basis of flows. In most cases, these projects have a right to use all of the water from a source, with flows in excess of capacity (and thus potentially available for additional appropriation) occurring only for a few weeks or months of the year.
4. In the case of USACE projects, the issue of water rights and water use is more complicated.

Non-Consumptive Use

Lakes and Reservoirs

Bighorn Basin

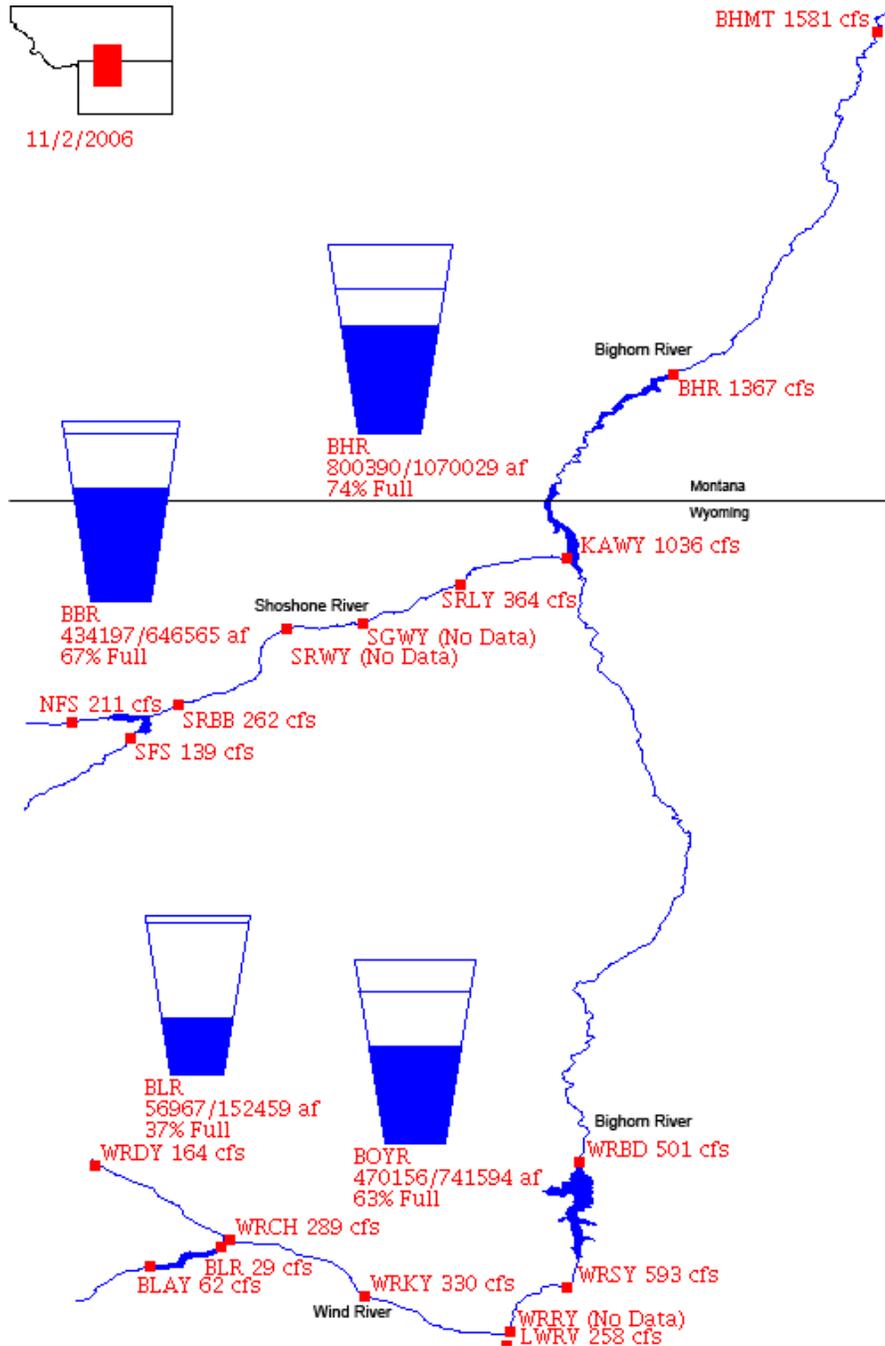
The Bighorn River originates in the Wind River, Absaroka, and Bighorn Mountains of Wyoming. It is the largest of the Yellowstone River Compact tributaries with a total basin area of 22,885 square miles. Approximately 14 percent of the basin (3,067 square miles) is located north of the stateline in Montana. Major tributaries to the Bighorn in Wyoming include the Wind, Popo Agie, and Shoshone Rivers. The Little Bighorn River (1,294 square miles) originates in Wyoming and joins the Bighorn River near Hardin, Montana. The Bighorn Basin is the most diverse of the Compact tributaries with respect to basin characteristics (geology, soils etc.), land use and water management. Streamflow in the basin is highly regulated by main-stem and tributary storage and extensive land has been developed for irrigation in both states.

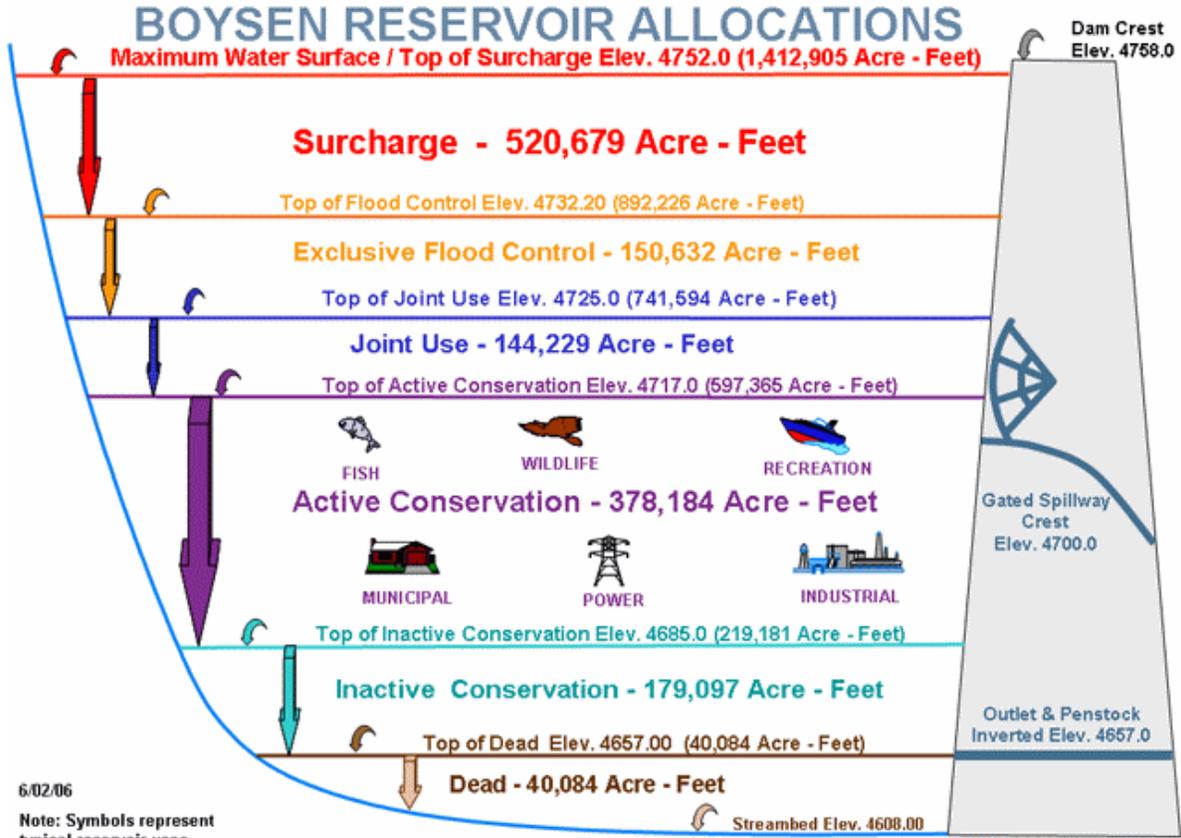
Wyoming has developed extensive main-stem and tributary storage in the Bighorn Basin. Reservoirs with pre-1950 water rights have a total capacity of about 1,766,000 acre-feet. Of these, the Boysen project is the largest (829,000 acre-feet) and the only main stem reservoir in Wyoming.

Boysen Reservoir

Boysen Reservoir was constructed by USBR and was completed in 1952 with a capacity of 757,000 acre-feet (active storage and 819,760 acre-feet total capacity) under Wyoming Permit 5576 Res. with a priority date of October 22, 1945. Additional allocations (e.g. surcharge, flood control) are shown below.

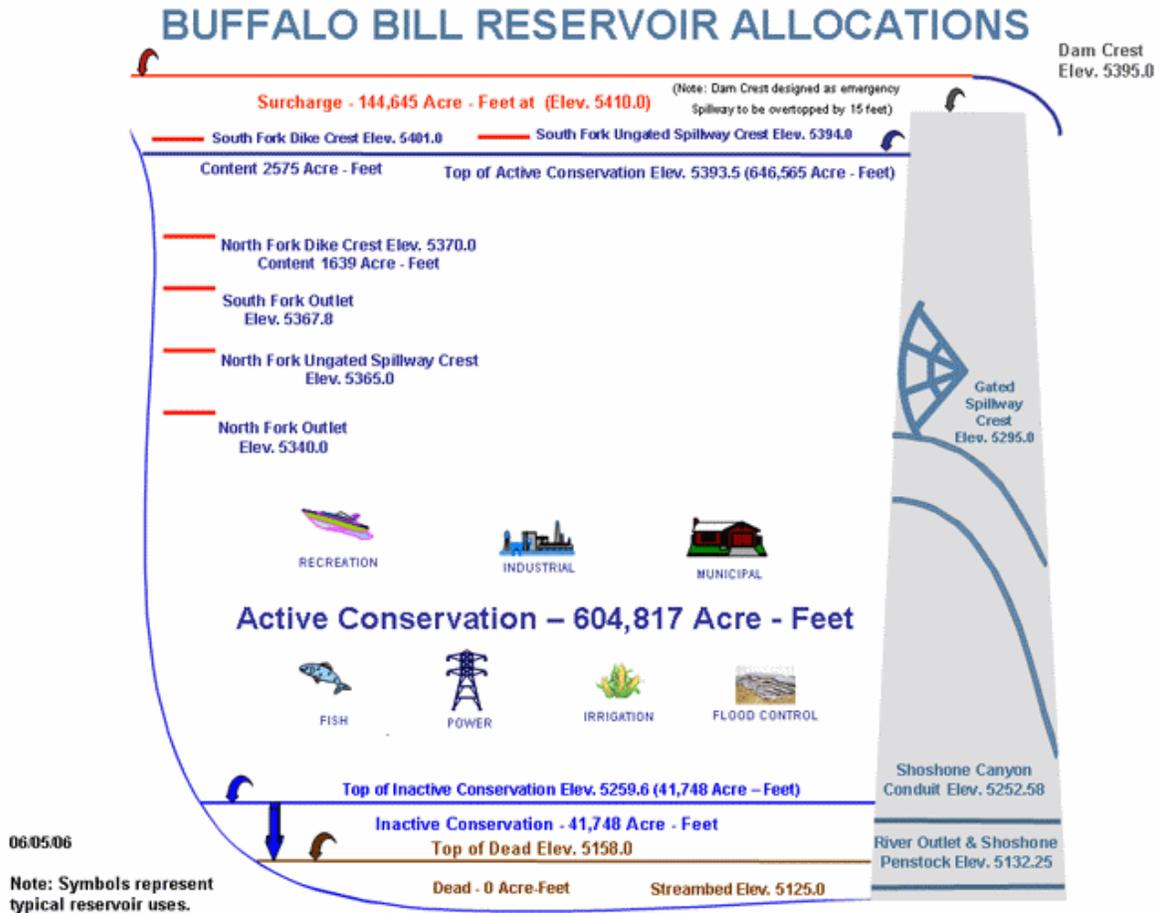
Figure 1. Schematic showing location of Bighorn, Boysen, Buffalo Bill and Bull Lake Reservoirs in Montana and Wyoming.





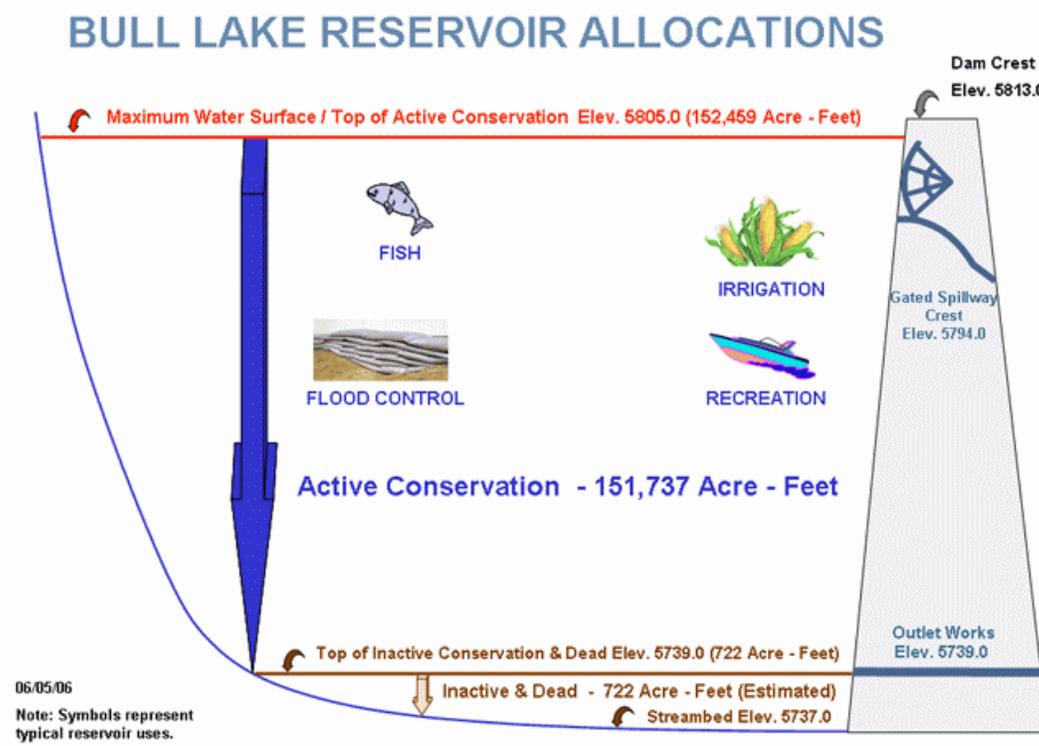
Buffalo Bill Reservoir

Buffalo Bill Reservoir was constructed by USBR between 1905 and 1910 and has several water rights with priority dates as follows: 3-5-1904 =159,00acre-feet, 9-?-1905=297,100 acre-feet, 6-?-1980=187,940 acre-feet; Total active reservoir capacity is approximately 604,817 acre-feet (due to capacity loss from sedimentation ??). Buffalo Bill's power generation capacity was upgraded in 1993 or 1994 ?



Bull Lake Reservoir

Bull Lake Reservoir was constructed by USBR with a priority date of 12-26-1906 for 151,191 acre-feet.



Bighorn Reservoir and Yellowtail Dam

Yellowtail dam was constructed in the mid-1960's and began storing water in 1967. Pertinent facts about the dam and reservoir are summarized in Table 1. (Yellowtail Dam & Bighorn Lake Water Supply & Operations Meeting, 2006). The storage project is multi-purpose and USBR coordinates with numerous entities in an attempt to meet project objectives; in a series of low-water years, the various uses given in Table 1 compete for allocation of water. Inflow to the project is generated primarily from snowmelt runoff in the Bighorn/Wind River basin, and USBR coordinates reservoir management with two other large upstream storage projects in the basin--Boysen Dam on the Wind River and Buffalo Bill Dam on the Shoshone River (Figure 1). Based on 1967 to 2005 data, USBR has estimated that about 30 percent of the annual inflow to Bighorn Reservoir is from unregulated gains downstream of the Boysen and Buffalo Bill projects. Of the remaining inflow Boysen supplies about 42 percent and Buffalo Bill supplies 28 percent (Yellowtail Dam & Bighorn Lake Water Supply & Operations Meeting, 2006).

The USBR's general operating objectives are summarized in Table 2 and Figure 2. Priority of stored allocations (e.g. uses) was not examined, but they may actually follow the order listed in Table 2. Figure 1 appears to represent reservoir storage allocations as idealized in the original design and operation plan. Bighorn Reservoir operations management (for example, regulating outflow to store water for subsequent release and maintaining various reservoir pool elevations) is a shared responsibility of USBR and U.S. Army Corps of Engineers (USACE).

Table 2. USBR GENERAL OPERATING OBJECTIVES: Bighorn Reservoir

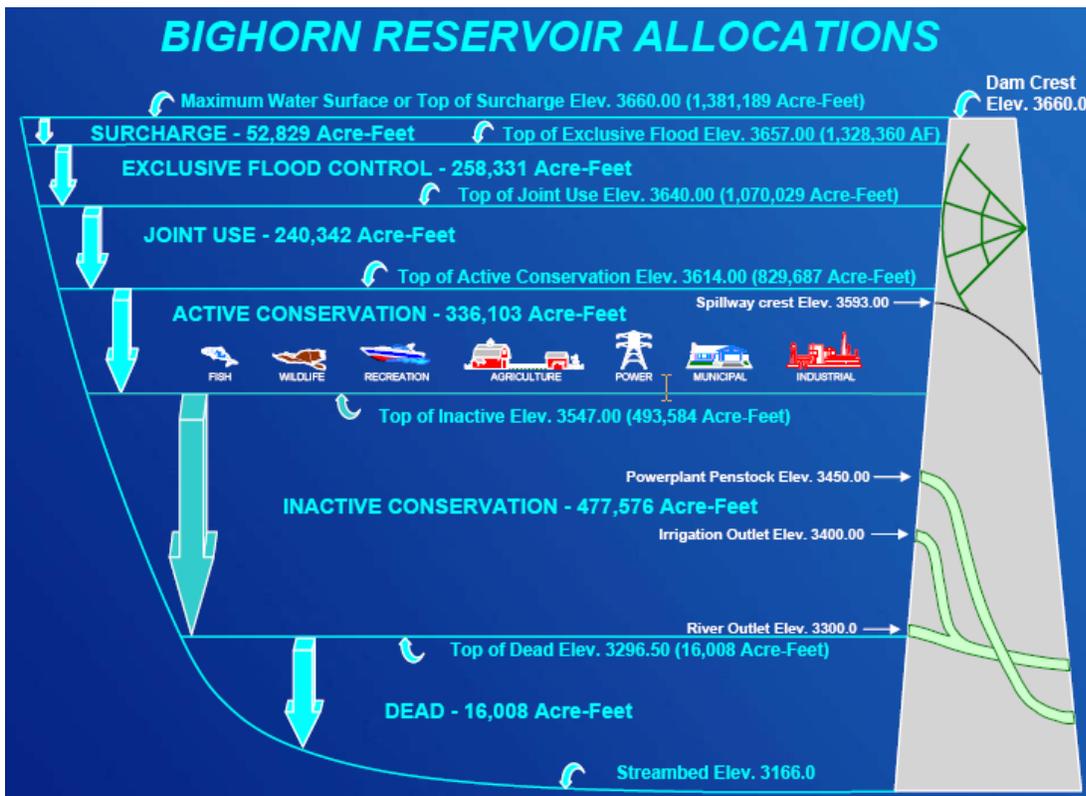
- Recognize all downstream senior water rights.
- Meet contractual commitments for stored water.
- Maintain adequate storage space for flood control.
- Maximize the power benefits.
- Maintain lake levels for recreation, reservoir fishery, and waterfowl interests.
- Maintain river flow levels for river fishery.

USBR manages water up to the top of the *active conservation* pool (elevation 3,614 feet) At that point, USACE participates with USBR in management of the *joint use pool* (3,614 feet to 3,640 feet). Beyond the 3640.0 foot elevation, the reservoir pool is managed exclusively for flood control. The *exclusive flood control pool* represents a dedicated volume of water (259,000 acre-feet) allocated for storage and regulation of flood water, and was likely determined by design hydrology studies of flood duration, size, and frequency. The flood control pool is managed (as to an extent, are other allocations) based on knowledge of downstream constraints (e.g. mandated or preferred maximum and minimum outflows), and forecasts of seasonal runoff. For example, if the precipitation and snowpack information from the early spring indicate the chance of certain volume of runoff within a specified period of time, then the exclusive flood control pool must be drawn down to an elevation that will store the predicted runoff. Runoff forecasts are generally tracked through the fall, winter and spring, and the operating plan is modified by increasing or decreasing outflows to meet target reservoir pool elevations on certain dates.

In general, it is easier meet the objectives listed in Table 2 during a series of average and above average years of runoff. This is due to the obvious reason that more water is normally better than less water, but also because the reservoir includes flood control as a primary objective, and this partially constrains the amount of carry over storage possible from year-to-year. A further complication is that regulated

outflows from upstream reservoirs (primarily Boysen and Buffalo Bill) contribute roughly 70 percent of the inflow to Bighorn Reservoir. Each reservoir is operated with a separate set of constraints (see Table 2) and associated target pool elevations and outflows, and these are modified, in part, based on forecasts of seasonal inflows. Although Boysen, Buffalo Bill and Bighorn Reservoir operations are coordinated through a joint management effort, in a series of dry years it would be difficult, if not impossible, to meet all of the established beneficial uses of stored water³. Another joint-reservoir management problem concerns errors in forecast inflows. Bighorn Reservoir pool levels are managed, in part, based on forecast inflows and outflows from the upstream reservoirs, and errors in these forecasts may accumulate in a downstream direction. Consequently in a series of dry years it may be difficult to adjust Bighorn Reservoir operations to compensate for erroneous inflow forecasts.

Figure 2. Bighorn Reservoir Storage Allocation

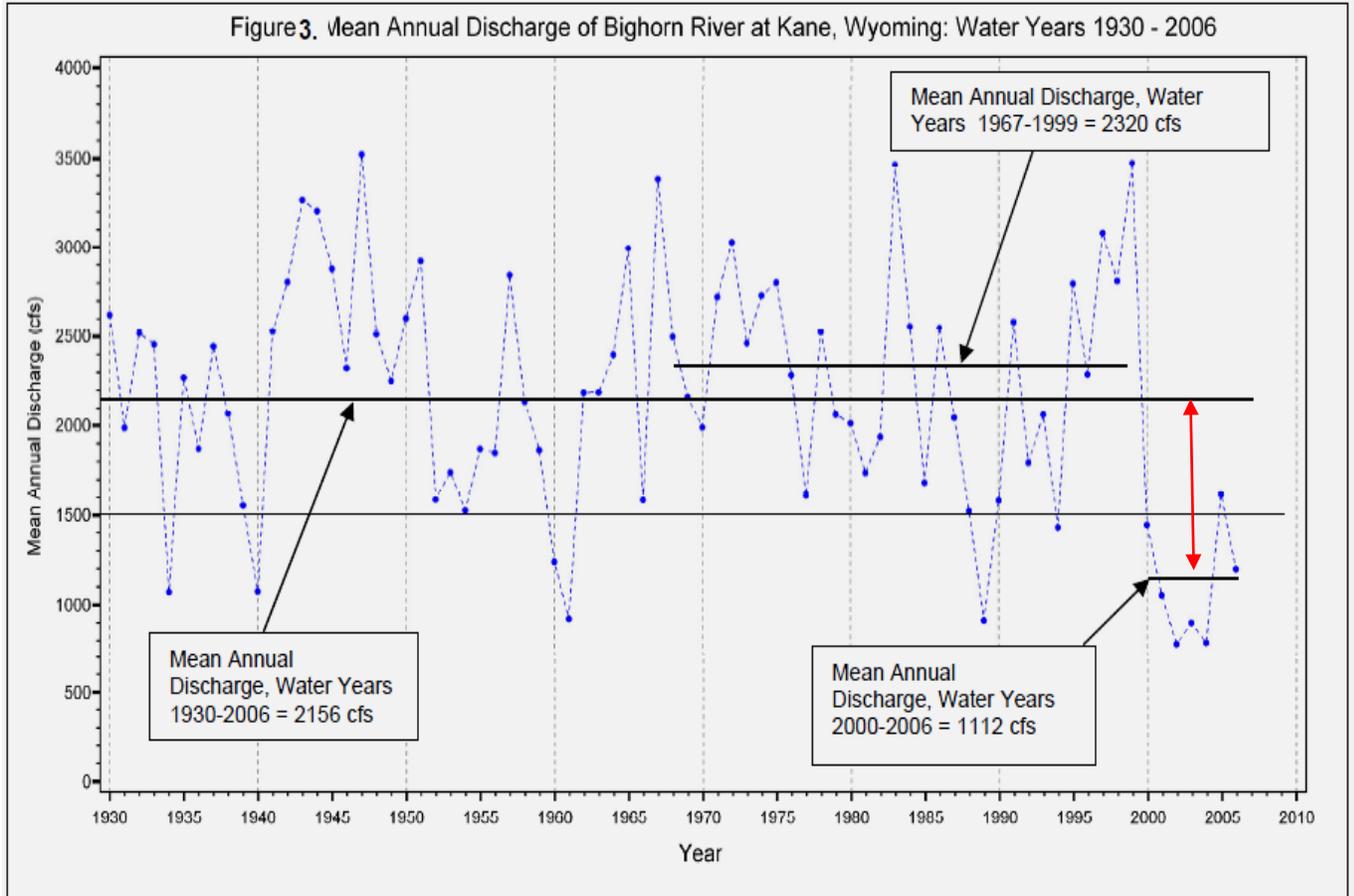


Historical Bighorn Reservoir Operations

Bighorn Reservoir inflow, outflow, end-of-month contents, and forebay⁴ elevation data (USBR Hydromet website, accessed [date]) were used to examine how USBR has historically operated the reservoir. Comparing general trends in inflow, outflow, contents, and elevation, over the 1966 to 2006 period, it is evident that beginning in 2000 the pattern of variation changed largely due to the onset of a persistent

⁴ Forebay elevation is the water-surface elevation of the reservoir pool measured just upstream of the dam. With the exception of spring runoff conditions, when backwater effects may increase water-surface elevation in the upstream end of the pool, forebay elevation is representative of water-surface elevation throughout the pool.

drought in the Bighorn drainage. This is especially evident in a graph showing long-term average annual flow of the Bighorn River at Kane, Wyoming, which is representative of historical inflow to Bighorn Reservoir (Figure 3).



Average mean annual discharge for the 77-year period, 1930-2006 is 2,156 cfs; at the same station, average mean annual discharge for the period 1967 (when Bighorn Reservoir began significant water storage) to 1999 was 2,320 cfs. Over the most recent 6 years, 2000-2006, the average mean annual discharge was only 1,112 cfs⁵, or about 47 percent of the 1967 to 1999 value. Water years 2000-2004 are the most persistent sequence of low annual flows that has occurred in the 77-year record.

**Historical and Recent Variation:
Inflow, Outflow, Contents and Elevation**

⁵ Expressed as a total volume of water these values amount to 1,560,500 acre-feet; 1,679,200 acre-feet; and 804,860 acre-feet, respectively.

Figure 4 shows monthly Bighorn Reservoir inflow, outflow, end-of-month contents, and forebay elevation. Comparison of inflow and outflow for average and above average runoff years for the period 1966-1999, shows that reservoir storage reduced annual peak monthly flows by about 30 to 50 percent. In most of the years from 1966-1999, the annual inflow (Figure 3) was equal to or greater than 1,500 cfs⁶ and water allocation problems were minimal—even in below average water years.

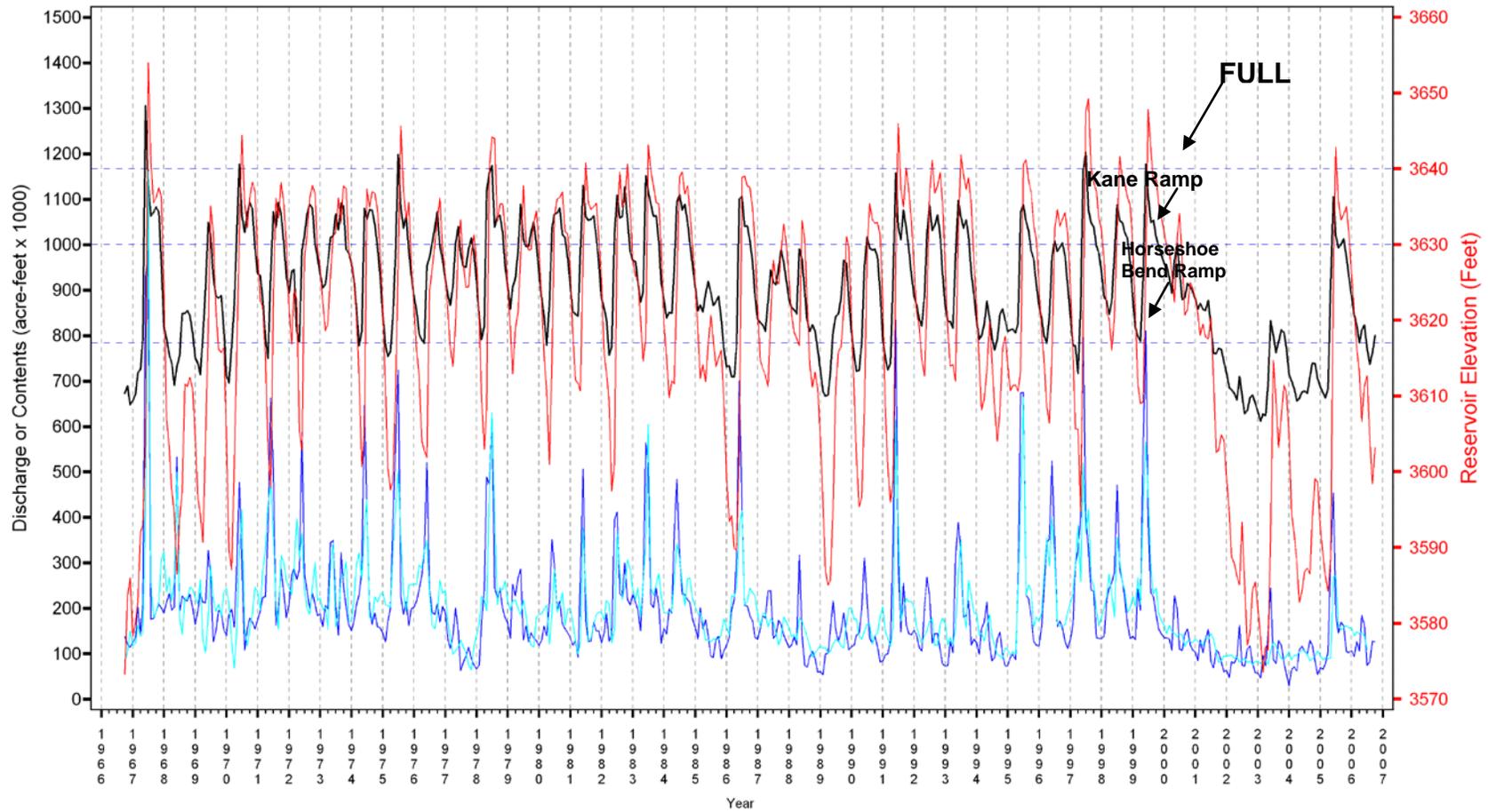
From 2000 to 2006, however, there were no large annual inflows, and reservoir contents, outflow, and elevations declined relative to values for 1966-1999. For example, the monthly volume of outflow from 2000 to 2006 varied closely around a value of about 100,000 acre-feet, an amount equivalent to a constant mean daily discharge of 1,680 cfs for a month⁷. (Note that this is a rough approximation and outflows were somewhat higher in spring months and in 2005-2006). Reservoir elevation and contents show similar trends toward lower values over the 2000-2006 period, with the exception of 2005 due to improved runoff (significant late spring rain). Annual 2005 runoff, although significant relative to 2004 and 2006, was only about 75 percent of the 77-year average. Yet this amount was sufficient to fill the pool, maintain a pool elevation greater than 3630 feet from June-October 2005, and maintain outflows of about 3,000 cfs from April to December 2005.

Historically, during average and above average runoff years, the lowest annual forebay elevations have generally occurred in the winter as the reservoir is drawn down to provide flood pool storage. The lowest forebay elevations have occurred during drought years, such as 1988-89 and 2002-04; in addition, the lowest forebay elevations in drought years tend to occur, or persist, through the summer and fall recreation season.

⁶ A year-round, constant discharge of 1500 cfs is equivalent to the reservoir contents at full pool (for example, at a reservoir elevation of 3640 feet the capacity is 1,070,000 acre-feet).

⁷ Discharge values shown in the figures are given in monthly volumes of runoff, to convert these to an average daily discharge (for a given month) in cubic feet per second (cfs), divide the monthly volume by ~59.5.

Fig4.3. Big Horn Reservoir Inflow, Outflow, Contents and Elevation, 1966 to 2006



Big Horn Reservoir Operations: 1966 to 2006

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1. Computed Inflow (ac-ft, monthly total x 1000) 2. End-ofMonth Reservoir Contents (Ac-ft x 1000) 3. Outflow (Big Horn R nr StXavier--Ac-ft x 1000)