RECLAMATION

Managing Water in the West

Hydraulic Laboratory Report HL-2006-06

Hungry Horse Selective Withdrawal System Evaluation 2000 – 2003

Hungry Horse Project, Montana
Pacific Northwest Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Group
Denver, Colorado

September 2006

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Reclamation designed, constructed, and evaluated a unique selective withdrawal system use to control power plant release temperatures from Hungry Horse reservoir into the south fork of the Flathead River in Montana. In 1994, preliminary studies and a final design were completed. The selective withdrawal system was constructed and installed in 1995. Initial hydraulic and biological performance data indicated the system conforms well to results from preliminary studies. Furthermore, State of Montana's water quality criteria established to improve aquatic habitat in the Flathead River below the dam are now being achieved. This report presents the results of a hydraulic and thermal evaluation of the Hungry Horse Dam selective withdrawal system.

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Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Disclaimer

Cover Photograph of Hungry Horse dam and the selective withdrawal structure was taken by the author

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GLOSSARY

Confluence. The place where two streams meet, or the stream that is formed from two joining streams.

Degree-day. A unit of measurement equal to number of degrees of departure from the daily river temperature guidelines.

Discharge. Volume of water that passes a given point within a given period of time.

Diurnal. Daily, especially pertaining to actions which are completed within 24 hours and tend to be repeated every 24 hours.

Endangered species. A species or subspecies whose survival is in danger of extinction throughout all or a significant portion of its range.

Endangered Species Act (ESA) of 1973. This act provides a framework for the protection of endangered and threatened species.

Epilimnion. The top, warmer layer in a thermally stratified reservoir layer. This layer has the warmest water and has a fairly constant temperature. The layer is readily mixed by wind.

Fall turnover. The process where vertical circulation in a reservoir will, over time, completely overturn and mix the full reservoir water mass. This process can also occur in the spring.

Forebay. Impoundment immediately upstream from a dam or hydroelectric plant intake structure.

Gate submergence. The depth of overdraw dictated by the position of the control gate.

Head loss. The energy lost from a flowing fluid due to friction, transitions, bends, etc.

Hypolimnion. The bottom, coldest layer of a reservoir. Water temperatures are usually uniform in this layer.

Isotherm. A line drawn on a plot or chart linking all points of equal or constant temperature.

Isothermal. Having a uniform temperature throughout the water column, without thermal gradients.

Line sink. A selective withdrawal intake that has longer horizontal dimension when compared to the vertical dimension. Spillways or submerged weirs are examples of a line sink.

Mainstem. The main tributary of a stream

Metalimnion. See thermocline.

Overdraw mode. A selective withdrawal operation where water is drawn over the top of a gate to take water from near the reservoir surface.

Penstock. A pipeline or conduit, designed to withstand pressure surges, conveys water from a forebay or reservoir to power-producing turbines, or pump units.

Penstock temperatures. The temperature of water flowing through an individual penstock.

Piezometer. An instrument which measures pressure head or hydraulic pressures on a flow surface of a spillway, gate, or valve.

Point sink. A selective withdrawal port that has similar vertical and horizontal dimensions. A gate or penstock intake are examples of a point sink.

Reservoir turnover. See Fall Turnover**.**

Root mean square (RMS) error - A statistic used as a measure of the dispersion or variation in a distribution, equal to the square root of the arithmetic mean of the squares of the deviations from the arithmetic mean.

Selective withdrawal systems – structural feature of a dam that allows water to be taken from a variety of elevations throughout the water column in order to manage the release water quality.

Seiche. A wave usually caused by strong winds and/or changes in barometric pressure.

Steady state condition. When model input values are nearly constant for 4 to 5 consecutive hours.

Stratification. Thermal layering of water in a reservoir. Reservoirs usually have three zones of varying temperature, the epilimnion, the metalimnion, and the hypolimnion.

Surface temperature . Temperature measurements collected from just below the water surface to a depth of 5 ft.

Selective withdrawal system head loss. Additional head loss attributed to the selective withdrawal system.

System head loss. Total head loss from the forebay to the piezometer taps on the penstock upstream from the turbine scroll case.

Thermal stratification. Layers of different temperatures in bodies of water.

Thermocline. The middle layer of a thermally stratified lake or reservoir with a rapid temperature decrease with depth. Also called metalimnion.

Thermowells. A mechanical device that is used to measure fluid temperature in a conduit without having the sensor in contact with the fluid. They are used to provide isolation between a temperature sensor and the environment (either liquid, gas, or slurry). A thermowell allows the temperature sensor to be removed and replaced without compromising either the ambient region or the process.

Threatened. A legal classification for a species which is likely to become endangered within the foreseeable future.

Turbine bearing cooling water temperature. The temperature of water supplied to the turbine bearings for cooling purposes. At Hungry Horse powerplant this water is supplied from the penstock so it is an excellent indicator of penstock water temperature.

Velocity. Rate of flow of in feet per second. The time rate of displacement of a fluid particle from one point to another. Velocity is a vector quantity that has magnitude and direction.

Vortex. Water rotating about an axis. A revolving mass of water (whirlpool) in which the streamlines are concentric circles and in which the total head is the same.

ACRONYMS

ADCP	Acoustic Doppler Current Profiler
cfs	cubic feet per second
EPA	U.S. Environmental Protection Agency
ft^2	square feet
HGHM	Hydromet water quality monitoring station for the tailwater below Hungry Horse Dam
lb/in^2	pound per square inch
MDFWP	Montana Department of Fish, Wildlife, and Parks
MDEQ	Montana Department of Environmental Quality
TDG	Total dissolved gas
MW	megawatt
psig	pound(s) per square inch gauge
RMS	root mean square
SOP	Standing Operating Procedures.
STORET	EPA's water quality database

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Abstract

Reclamation designed, constructed, and evaluated a unique selective withdrawal system use to control power plant release temperatures from Hungry Horse reservoir into the south fork of the Flathead River in Montana. In 1994, preliminary studies and a final design were completed. The selective withdrawal system was constructed and installed in 1995. Initial hydraulic and biological performance data indicated the system conforms well to results from preliminary studies. Furthermore, State of Montana's water quality criteria established to improve aquatic habitat in the Flathead River below the dam are now being achieved. This report presents the results of a hydraulic and thermal evaluation of the Hungry Horse Dam selective withdrawal system.

Purpose

This research project evaluated the hydraulic performance of the selective withdrawal system at Hungry Horse Dam for the years 2000 through 2003. Reservoir temperature profiles, reservoir elevations, flow rates, penstock temperatures, and river temperatures were collected to document system performance. The scope of this project focused on selective withdrawal only and did not include a physical limnology component. The evaluation used the U.S. Army Corps of Engineers' SELECT Model to predict downstream river temperatures by analyzing reservoir temperature profile, powerplant outflows, and control gate elevations for periods of selective withdrawal operations. The SELECT model's performance was evaluated by comparing predicted and measured release temperatures.

Application

This evaluation of the selective withdrawal operations at Hungry Horse Dam can be used as a guideline for future operations at the dam. Performance characteristics of this type of selective withdrawal system can be used to evaluate future operations of this structure or similar designs at other dams. The SELECT Model's ability to predict the release water quality for this structure is an important consideration when modeling this structure-type for future applications of the model.

Hungry Horse Project Description

Reclamation operates the Hungry Horse Dam, which is in northwestern Montana about 20 miles northeast of Kalispell on the south fork of the Flathead River (figure 1).

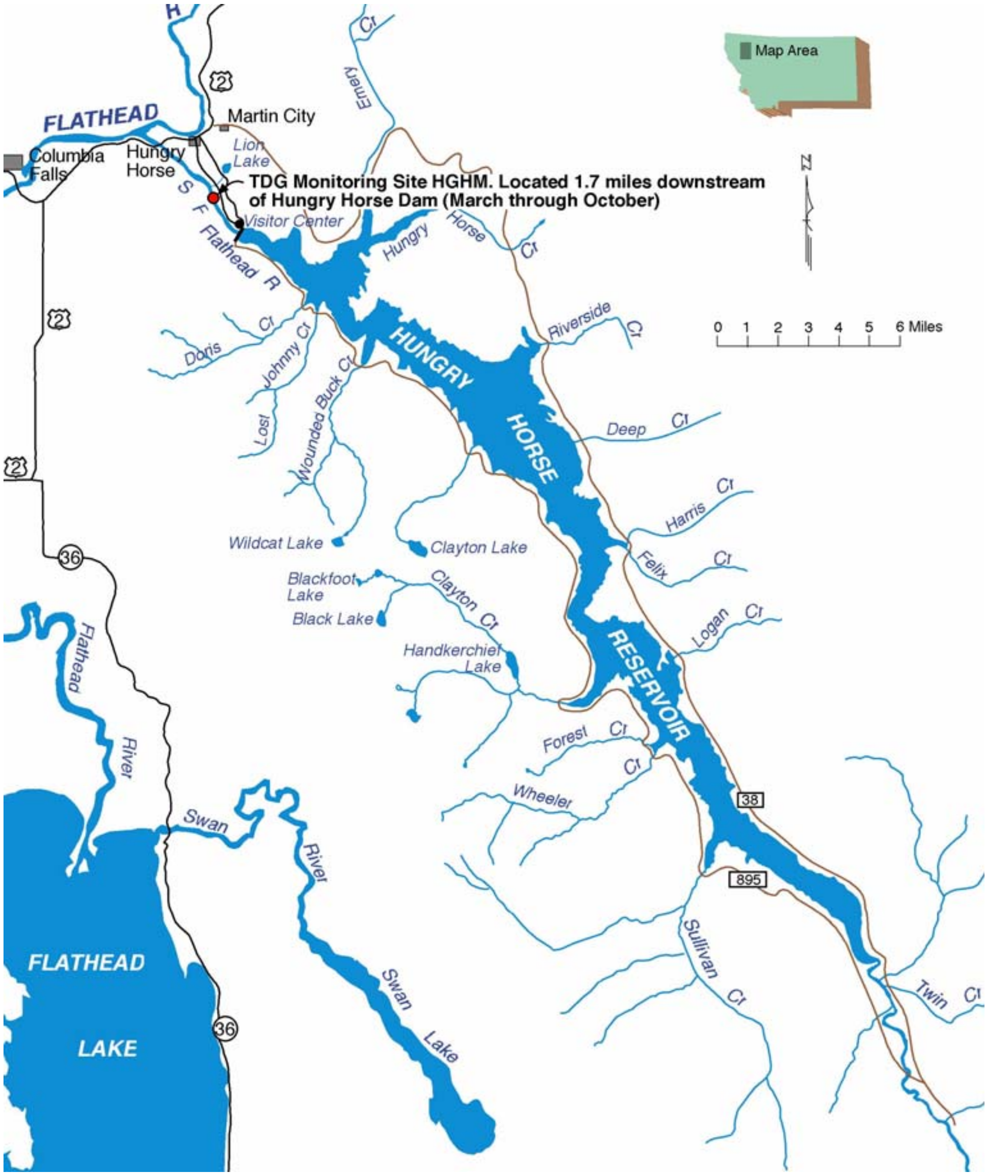


Figure 1. Location map for Hungry Horse Dam and Reservoir, including forebay and tailrace temperature monitoring locations.

Hungry Horse Dam and Powerplant

The dam was constructed between 1948 and 1953 and was the world's third largest and second highest concrete dam when completed. With a crest length of 2,115 feet and a structural height of 564 feet, the concrete arch dam impounds 3,468,000 acre-feet of water at a maximum water surface elevation of 3560 feet. The Hungry Horse Project provides hydroelectric power to the Pacific Northwest, flood control for the Columbia River Basin, irrigation and recreation. Four penstocks transport water to the 428 megawatt (MW)-capacity powerplant. Intakes for the dam's four penstocks are about 240 feet below the maximum water surface elevation. The total capacity of the power plant is 428 megawatts. Hydroelectric generation has averaged slightly less than one billion kilowatt-hours annually. The generators can be operated to meet base or peak power.

Hungry Horse Dam Releases

Powerplant discharges range from 145 to 13,000 cfs. In addition, there are three outlet works conduits with a maximum release capacity of 14,000 cfs. The outlet works releases water from the hypolimnion about 360 feet below the maximum water surface elevation, 3560 feet. A morning-glory spillway with a maximum capacity of 50,000 cfs operates when the reservoir is nearly full and releases surface water.

Penstock intakes withdrawal water from Hungry Horse Reservoir about 240 feet below the maximum water surface elevation. These hypolimnetic releases from the powerplant were nearly constant at 40 degrees Fahrenheit (°F). Typically, reservoir drawdown starts in the fall and continues through the winter to generate electric power and to provide storage space for flood control. Releases during the spring months are determined by anticipated runoff, power needs, reservoir storage required for flood control, along with the goal to refill the reservoir by July. From July through September, the reservoir is operated to try to maintain a full reservoir for recreation. The cycle begins again in October.

For a typical water year, the reservoir elevation will fluctuate approximately 80 feet. The maximum draw down of record was 188 feet. The reservoir elevation can be drawn down approximately 1.0 feet in a 24-hour period with minimum inflow and full power plant operation.

During the spring and early summer, releases from Hungry Horse Dam provide a minimum contribution to the total flow in the Flathead River. As the Middle and North Forks of the Flathead River begin to decrease in natural flow, Hungry Horse power generation releases become the major source of flow into the main stem of the Flathead River, causing an undesirable reduction in river temperature. Reservoir releases are used to meet the 3,500 cfs minimum flow requirement as set by the State of Montana. In addition, the Hungry Horse powerplant can provide peaking power generation that can create rapid fluctuations in river flows and temperatures – up to 10 to 15 °F. These fluctuations in river temperature have resulted in thermal shock to fish and aquatic insects. Furthermore, low release temperatures are unacceptable for native threatened and endangered fish habitat and cause predation by non-native fish species (Reclamation, 1996).

Selective Withdrawal System Background

Installing a selective withdrawal system at Hungry Horse Dam resulted from 15 years of study and a long-term collaboration between the following stakeholders: Reclamation, State of Montana agencies, Native American tribes, Federal congressional representatives, Flathead Basin Commission, Northwest Power Planning Council, nongovernmental organizations, environmental groups, U.S. Forest Service, and the Bonneville Power Administration. In 1991, the stakeholder group produced a report, *Fisheries Mitigation Plan for Losses Attributable to the Construction and Operation of Hungry Horse Dam* (Fraley, et. al., 1991), that included the views of a broad range of interests. Development of the mitigation plan included a 14-month scoping and consultation process where the public and interested parties helped identify issues and the advantages and disadvantages of specific mitigation alternatives. This public involvement program was critical to the developing a consensus on the final mitigation plan.

Fishery Issues

On June 10, 1998, the U.S. Fish and Wildlife Service published a final rule in the *Federal Register* to list the Klamath River and the Columbia River bull trout population segments as threatened under the Endangered Species Act (ESA). Cold water releases from Hungry Horse Reservoir have been identified as a factor in the bull trout's decline in the Flathead River—a tributary to the Columbia River. In addition, lake trout, drawn upstream from Flathead Lake by the cold river temperatures, prey on bull trout, compounding the problem. Westslope cutthroat trout are also a species of special concern and have been affected by the post-dam temperature conditions in the Flathead River below Hungry Horse Dam. The effects of Hungry Horse releases on Flathead River temperatures are most significant in the 18-mile upper reach of the river between the mainstem confluences of the South Fork and Stillwater Rivers. This upper reach has been identified as having the most productive habitat for the westslope cutthroat trout and is more typical of a natural river system. The environmental impacts have been quantified, including fish growth, fish reproduction, and aquatic insect communities. The Montana Department of Fish, Wildlife, and Parks (MDFWP) developed a computer model to monitor and predict the impact of temperature on fish growth. MDFWP estimated that fish growth potential in the river would increase two to five times with the installation of selective withdrawal at Hungry Horse Dam (Marotz et al., 1994).

Investigation of insects and fish in the tailwater are ongoing. Unfortunately, preliminary results revealed that other management changes such as new minimum flows and ramping rates, and new catch and release regulations for cutthroat trout make it very difficult to isolate the direct effects of selective withdrawal. However, laboratory studies clearly show that water temperatures between 50 and 59°F are optimal for trout growth.

Selective Withdrawal System

Reclamation designed a selective withdrawal system that would allow withdrawing warm water from the reservoir to recreate the pre-dam temperature regime. In general, water temperatures remain warmer than pre-dam conditions during the winter when the selective withdrawal system is not in use and slightly cooler, by design, during the warmest summer months. Targeted water temperatures during spring are sometimes unattainable because the reservoir surface waters are not warm enough.

The principle design objective for the Hungry Horse selective withdrawal system was to provide an independent system for each of the four penstock intake structures to allow near-surface withdrawals from the reservoir to meet temperatures objectives for the Flathead River. The system required effective performance over the full range of reservoir level fluctuations of up to 160 feet below the maximum reservoir water surface elevation of 3,560 feet. The system must also be able to withdraw directly into the penstock intakes during times when the reservoir is isothermal (winter months) to minimize system head losses.

Figure 2 is a schematic of the selective withdrawal system. A semi-cylindrical gate system was installed inside each trashrack structure to provide selective withdrawal capability. Each gated system is made up of three gates, which travel in the existing bulkhead guides.

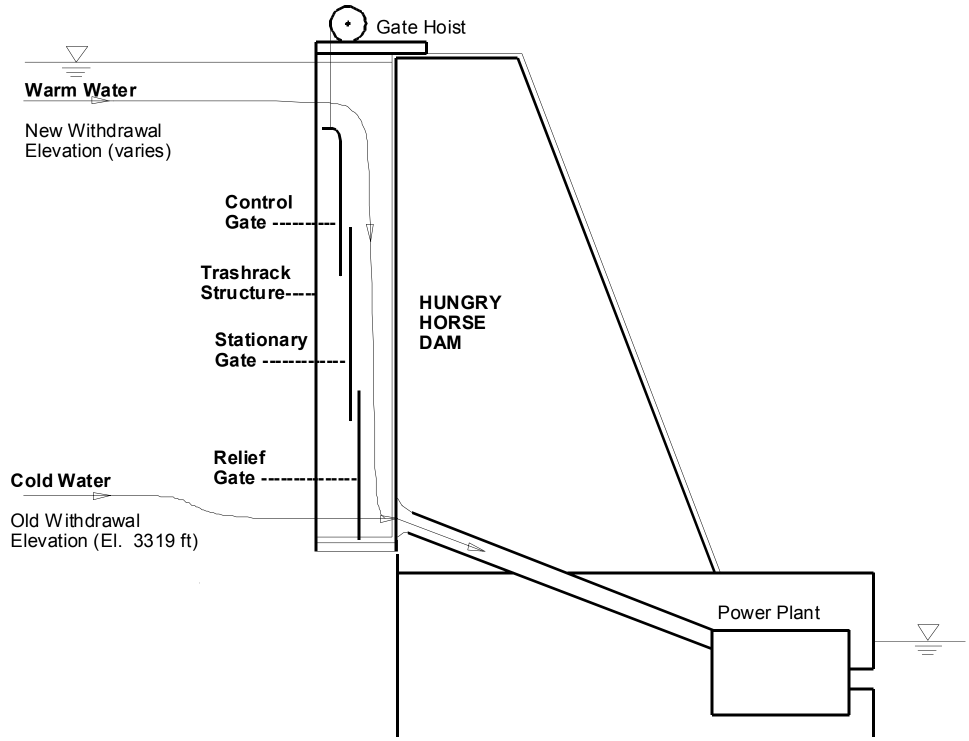


Figure 2. A sectional view of the selective withdrawal system installed at Hungry Horse Dam in 1995.

The gates were fabricated from rolled structural steel plates that were reinforced with channel or wide flange beams. All equipment was designed to safely resist a positive differential head of 7.0 feet and a negative differential head of 10 feet (associated with water hammer). These gates are:

- Upper gate (control gate) which selects the intake depth to regulate water temperature

- Center gates (stationary gates) which are used to create a seal between the upper and lower gates

- Lower gate (relief gate) which blocks the entrance to the existing penstock intake and has relief panels designed to open under excessive differential pressures

Control gate (upper gate) This gate is approximately 100 feet high with a bell-mouth shaped crest to reduce entrance head losses. The control gates are also semi-cylindrical in shape with an inside radius of 10.8 feet (figure 3). Each gate is suspended and operated by a 60-ton, dual drum, wire-rope hoist. The hoist is capable of raising the gate to the hoist deck or lowering the gate 120 feet with a travel rate of 1.6 feet per minute. The gate can be raised or lowered under a 4.0 feet head differential load. As the control gate is lowered, it passes down around the stationary gates like a telescope.

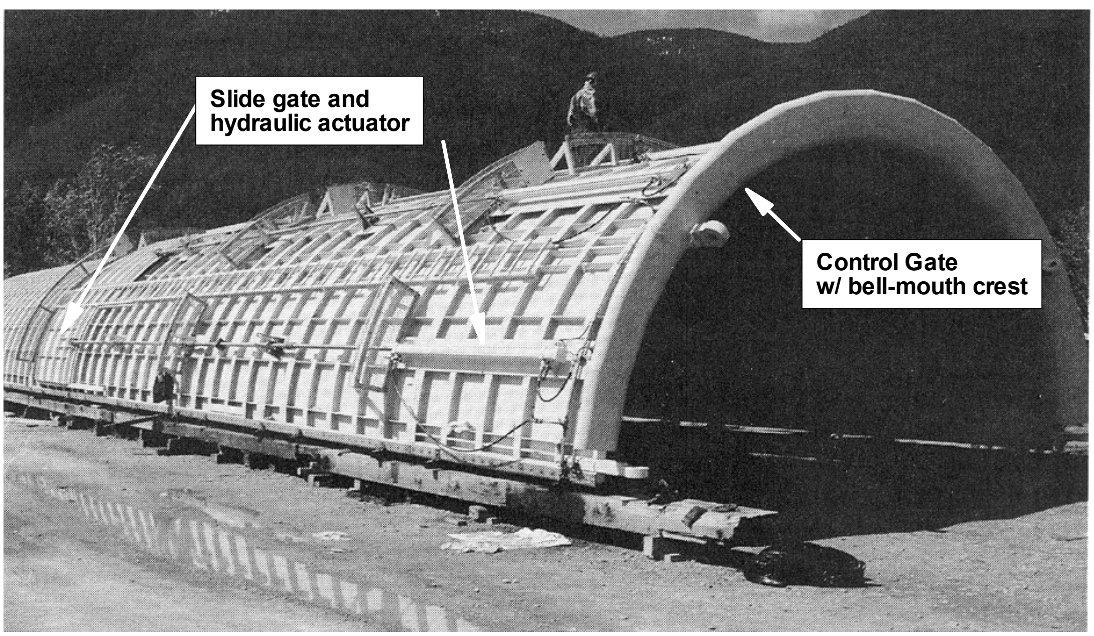


Figure 3. Photograph of the 100-ft-long control gate. Warm surface water flows over the bell-mouthed crest and can be blended with cooler water that flows through five slide gates located 50 feet below. A worker on the gate helps illustrate the size of the gate.

The position of the control gate will determine the depth of overdraw, or what is referred to as gate submergence. The submergence depth is the key variable for determining what water temperature will be passed through the turbines. In general, the lower the submergence setting the warmer the release temperature would be. However, excessive head loss, vibration, and air entraining vortices could become a concern. Conversely, if the submergence is excessive, too much cold water may be discharged. The control gates can be operated from the hoist deck of each intake structure or from the power plant control room. A minimum of 20 feet of submergence is needed to prevent turbine damage from air entraining vortices (computed using results from a physical model study [Kubitschek, 1994]).

Within the control gate, about 50 feet from the top of the control gate, are five small slide gates (approximately 5 feet wide by 7 feet high) operated by hydraulic actuators. The hydraulic actuators have an 8.0 feet stroke length and use biodegradable operating fluid to operate all five slide gates simultaneously. The slide gates will provide additional temperature operating flexibility. If too much plankton is being withdrawn from near the reservoir surface, the gates can be opened to allow water deeper in the reservoir to be withdrawn. The small gates can be operated locally at the hoist deck on the top of each intake structure or in the powerplant control room. However, slide gate positions can only be monitored in the control room.

Center gates (stationary gates) These gates are actually three independent gates with a total height of 100 feet. The upper stationary gate is approximately 20 feet high and the intermediate and lower gates are each 40 feet high. The stationary gates are also semi-cylindrical with a 10.3 feet inside radius. The stationary gates were installed in the bulkhead guides and are normally left in the lowered position.

Lower gate (relief gate) This gate is approximately 38 feet high. Each gate is semi-cylindrical with an inside radius of 9.54 feet. Each relief gate contains 35 relief panels. Each panel is approximately 2 feet high by 4 feet long. Each relief panel has two shear pins designed to fail when a uniform load of 2.60 pound per square inch (lb/in^2) is applied against the upstream side of the relief panel. This is equivalent to a head differential across the panel of 6.0 feet of water. The relief panels together provide about 257 square feet (ft^2) of relief area for each unit, which is the open area required to safely pass the unit's maximum capacity (3070 cfs). The relief panels were designed to open inward. Opening will occur if the control gate or stationary gates are operated incorrectly, creating excessive differential pressures. The relief panels were not designed to relieve pressure transients caused by water hammer which can result from a power generation load rejection. To minimize peak water hammer pressures, the governor closure times were increased for the generator wicket gates.

System Operation

A detailed description of the gate system operation is given in *Design Summary – Selective Withdrawal System, Hungry Horse Dam, Hungry Horse Project, Montana* (Reclamation 1996). Normally, the selective withdrawal system is operated in an overdraw mode. During selective withdrawal operations, the control gate can not be positioned less than 30 feet below the reservoir surface. Other conditions that influence the amount of submergence selected by system operators include: head losses, position of the slide gates, reservoir elevation, surface debris accumulation, and the flow rate required by the power generating units.

Under normal conditions, the hoists are operated to position the control gates at the required depth to provide the desired release temperatures. Each control gate has a normal travel of approximately 100 feet (i.e., 120 feet below the maximum reservoir water surface elevation of 3560 feet). This travel length enables the control gate to maintain the minimum 20 feet submergence over the full range of normal reservoir fluctuations. During certain periods of the year, it may be necessary to open the intermediate slide gates, located in the control gate. These gates were added to reduce the withdrawal of plankton-enriched water from the reservoir. During winter months, the reservoir is isothermal and the selective withdrawal system will not be used. When not in use, the control gates are lowered to their lowest position and the relief gates are raised to the top of the trashrack structure to minimize system head loss.

Instrumentation and Methods

Data collection of reservoir and river conditions was needed to carry out the selective withdrawal evaluation at Hungry Horse Dam.

Selective Withdrawal System Operations

Project operators kept notes in their log book on forebay elevation, control gate elevations, and river temperatures. A supervisory control and data acquisition system logged hourly power production from each of the four generators. Flow had to be calculated because the penstocks at Hungry Horse Dam are not equipped with flowmeters. The flow rate passing through each turbine was calculated by prorating the river flow rate according to the ratio of power from a specific generator to total plant power generation in megawatts.

Hungry Horse Reservoir Temperature Profiles

Reservoir forebay temperature profiles were measured from May 18, 2000 to October 14, 2003. A string of Onset Stowaway® Tidbit® temperature loggers was attached to a log boom in the reservoir forebay (figure 4) about 0.3 miles uplake from the dam. Fifteen temperature loggers measured reservoir temperatures throughout the water column at a sampling interval of 15 minutes. The accuracy of the thermistors used in the Tidbits is ±0.4°F and their calibrations were checked in an environmental chamber before installation. The shallowest temperature logger was placed 5 feet below the water surface to minimize temperature gain from solar radiation. Temperature loggers were more closely spaced toward the water surface to accurately measure temperature gradients in the thermocline. To better describe the extent of the epilimnion, another temperature logger was added to the string at a depth of 15 feet in August 2000. Table 1 lists the locations of the 16 temperature loggers in the water column. No temperature profiles were recorded in the summer of 2002 because the temperature string was deployed improperly.

Table 1. Depths of temperature loggers on the forebay temperature profile string.

Temperature Logger ID	Depth (ft)
BR01	5
BR02	10
BR19 *	15
BR03	20
BR04	30
BR05	45
BR06	60
BR07	75
BR08	90
BR09	120
BR10	150
BR11	180
BR12	210
BR13	260
BR14	310
BR15	360

* Added to string on August 29, 2000

MDFWP provided historical reservoir temperature profiles for analysis for the years 1983 to 1989 and 1991. The biweekly temperature profiles were collected by MDFWP to support the Hungry Horse reservoir temperature modeling project (Ferreira, et al., 1992). The Emery profiling site was used for analysis and is located about 3.0 miles uplake from the dam. A query of the U.S. Environmental Protection Agency (EPA) water quality database, STORET (http://www.epa.gov/storpubl/), returned found some monthly (summer and fall) water temperature profiles at 12 sites in Hungry Horse reservoir for the years 1977, 1978, and 1982. The STORET data were reviewed but were not used for this evaluation.

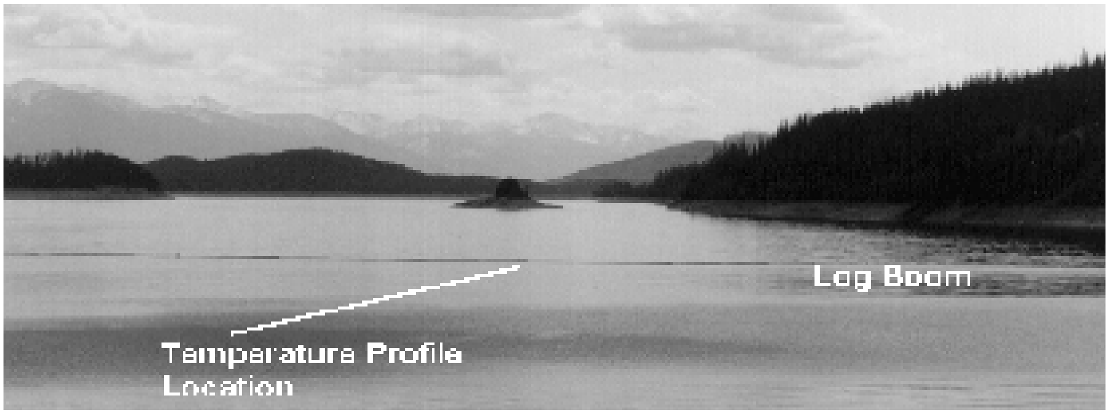


Figure 4. Photograph of forebay temperature profiling string location. The string is located about 0.3 miles uplake from Hungry Horse Dam.

Reservoir Operations

Reclamation's Hydromet database was used to collect Hungry Horse reservoir operations including: elevation, storage, discharge, river temperatures, and meteorological data. Reservoir releases are measured at a U.S. Geological Survey gaging station (USGS 12362500 South Fork Flathead River near Columbia Falls, MT) located 1.7 miles downstream from Hungry Horse Dam. Data quality from this site was rated good by the USGS and no changes (shifts) were made to the rating during this study.

Weather Data

Reclamation maintains a weather station at Hungry Horse Dam as part of Hydromet program (Site ID: HGWM) and the station monitors air temperatures and cumulative precipitation. Data from this site were available for this study but were not pertinent. The only weather data used during this study were wind speed and direction collected at Glacier Park International Airport located about 14 miles southwest of Hungry Horse Dam.

Reservoir Release Temperatures

River Temperature Logger

A river temperature logger (Onset Stowaway® Tidbit®) was installed along the left bank of the South Fork of the Flathead River about ½ mile downstream from Hungry Horse Dam. The accuracy of the thermistor used in the river logger is ±0.4°F and its calibration was checked in an environmental chamber prior to installation. The river temperature logger was installed in a slotted pipe and attached to a 20-foot length of chain. The chain was locked to an anchor driven into a rock fissure (figure 5). The probe was deployed to measure river temperature every 15 minutes.

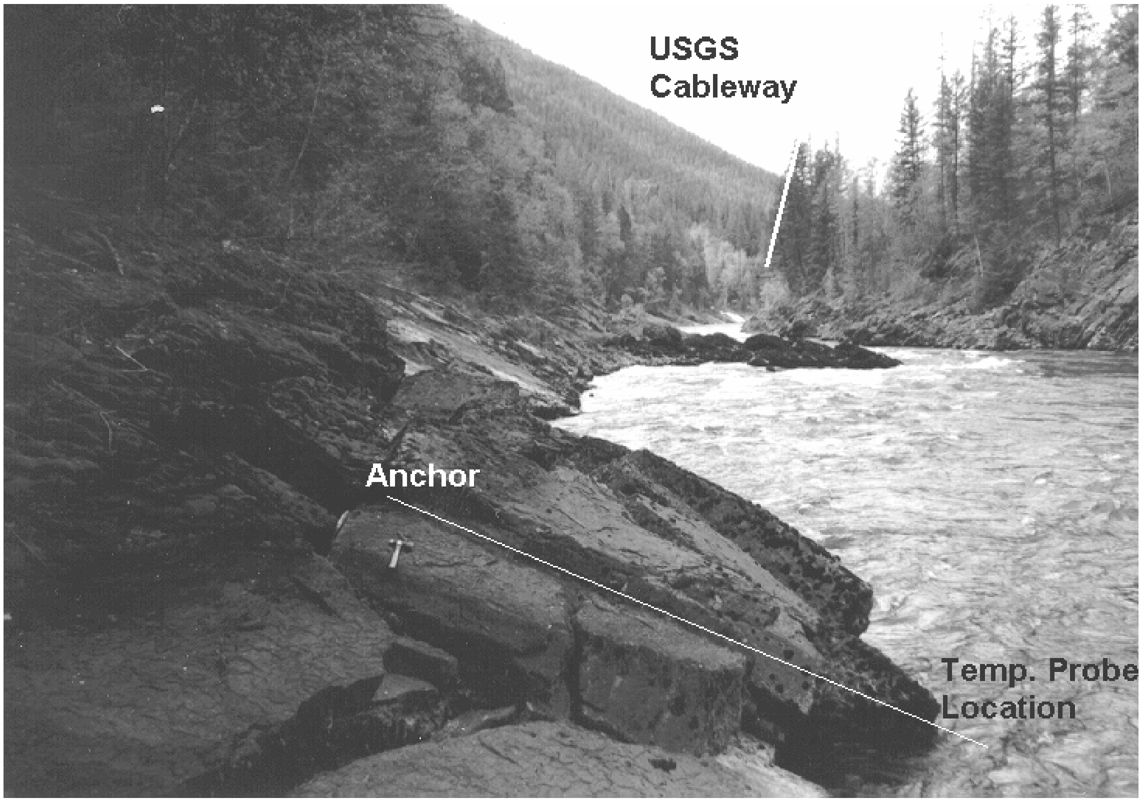


Figure 5. Photograph of the river temperature measurement site located just upstream from an abandoned USGS cableway.

This site was selected because it offered good protection from debris. In addition, the river should have been thoroughly mixed at this location since the river passes through two bends and two sets of rapids upstream of this site. This Global Positioning System (GPS) site location is N48º 20' 29.9" and W114º 01' 24.6".

Total Dissolved Gas Monitoring Station

A total dissolved gas (TDG) monitoring station (Reclamation's HYDROMET station I.D. HGHM) was installed in 1998 on the south fork of the Flathead River, 1.7 miles downstream of Hungry Horse Dam (figure 1). This site is about 1.2 miles downstream from the Onset river temperature logger. The present TDG monitoring plan for Hungry Horse Dam releases requires the instrumentation to be installed prior to the first outlet works spills, but no later than March 15 and remain in-service through September 15 or until forecast spills are completed (Reclamation, 2000). A contractor is responsible for the calibration and maintenance of equipment used at this monitoring site.

During this study, the TDG monitoring station collected barometric pressure, total dissolved gas pressure, oxygen pressure, and water temperature at a fifteen minute interval. Data were transmitted every four hours via satellite to the HYDROMET database located in Boise, Idaho.

Penstock Water Temperatures

Onset HOBO® H8 Pro Series temperature loggers were installed on the turbine-bearing cooling water supply lines to measure water temperature for each penstock at 15 minute intervals. The accuracy of the thermistors used in the penstock loggers is ±0.4°F and their calibrations were checked in an environmental chamber before installation. These temperature measurements were used to determine if there were operational differences between individual selective withdrawal structures. These data were also used to compute flow-weighted average temperature for powerplant releases.

Project operators use this temperature monitoring equipment to set the selective withdrawal control gates to achieve the desired release water temperature. Each bearing cooling water line has two thermowells, one containing a dial-type temperature gage and the other containing the newly installed temperature logger (figure 6). The Onset loggers were inserted into existing thermowells. The diameter of the temperature probe was increased from 0.20- to 0.25-in. by wrapping aluminum tape around the probe tip. Silicone grease was used to couple the temperature probe to the thermowell. All four penstocks were equipped with identical temperature loggers.

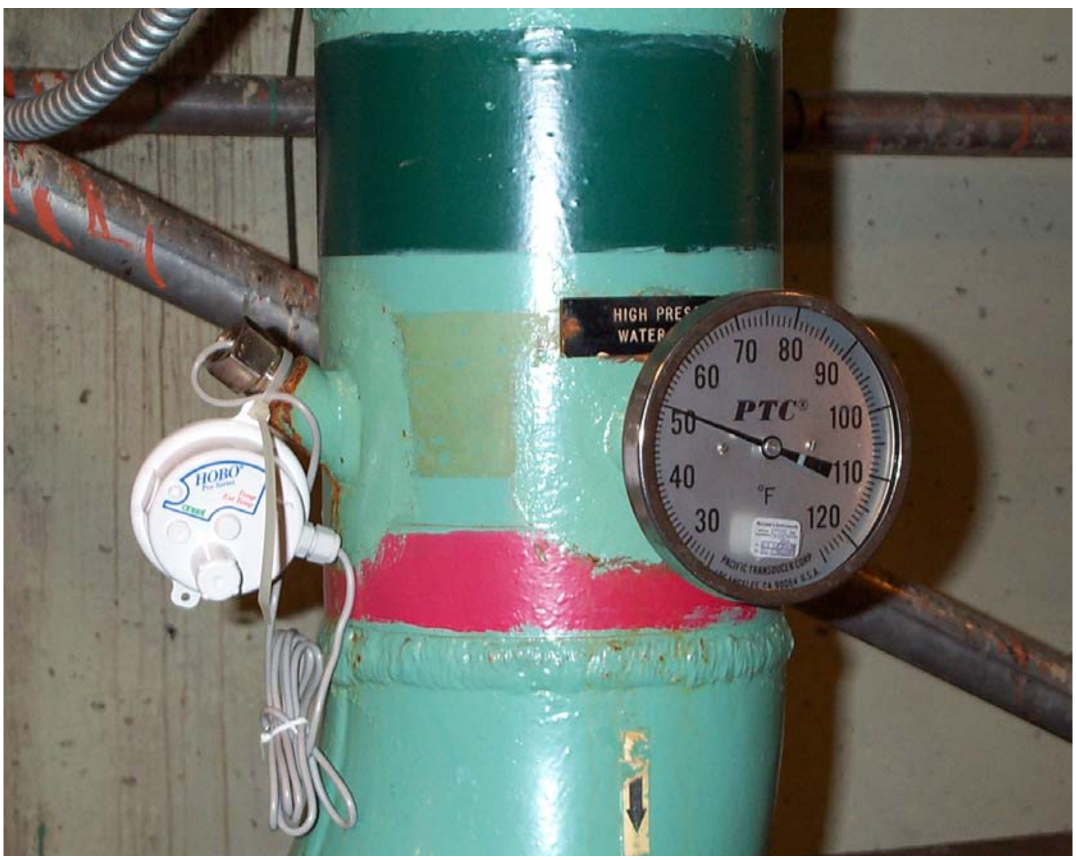


Figure 6. Photograph of a typical bearing cooling water temperature logger installation. The temperature loggers were inserted into an existing thermowell. A dial-type temperature gauge in a second thermowell is also shown.

Control Gate Operations

A MicroDAQ 100 lb/in^2 (absolute) pressure/temperature logger was installed on the selective withdrawal control gate serving unit No. 4. The specified accuracy of the pressure and temperature sensors were ±0.1 percent full scale pressure and ±0.9°F, respectively. The pressure sensor was calibrated prior to installation using a dead-weight tester. Data were logged in fifteen-minute intervals from June 21 until October 17, 2001. The transducer was mounted inside the control gate, about one foot below the gate crest, to prevent damage from debris collection (figure 7). This pressure logger monitors control gate movements, head on the gate, and water temperatures entering the intake. The logger was removed in October to prevent damage from freezing. In 2002, the pressure logger was re-installed on the unit No. 4 control gate and logged hourly data from June 27 until October 29. For this season, an hourly logging interval was selected to conserve battery power. A pressure logger was not used during the 2003 tests because the transducer was not functioning properly when it was to be installed.

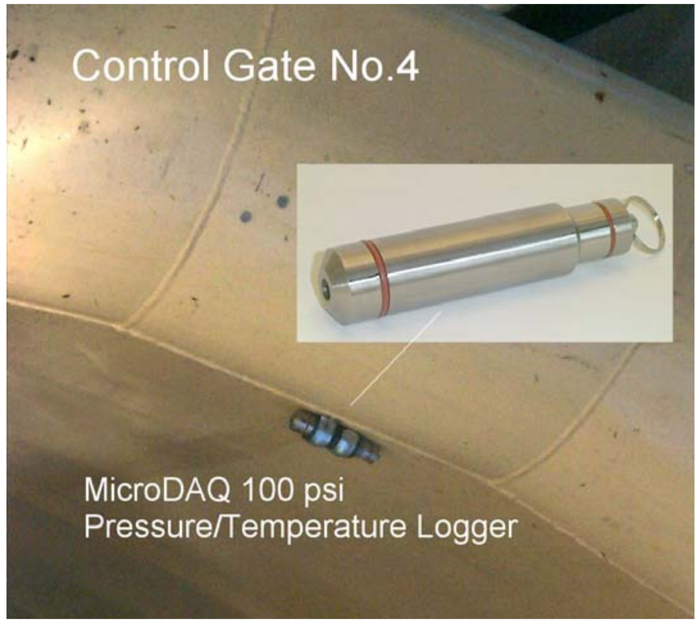


Figure 7. Photograph of pressure/temperature logger mounted inside the unit No. 4 control gate.

Scroll Case Pressure Measurements

A MicroDAQ pressure/temperature logger (s/n M5916) was installed on the scroll case pressure piping on penstock No. 4. The specified accuracy of the pressure and temperature sensors were ±0.1 percent full-scale pressure and ±0.9 °F, respectively. The pressure sensor was calibrated before installing using a dead-weight tester. These pressure measurements were used to determine the headloss attributed to the selective withdrawal system and the penstock. Throughout this report, this headloss measurement will be referred to as the “system headloss”. The pressure gauge piping has a 1/4-inch drain valve used to receive the 1/4-inch NPT fitting on the 500 pound(s) per square inch gauge (psig) pressure logger (figure 8). The pressure logger was programmed to collect pressures every 30 minutes.

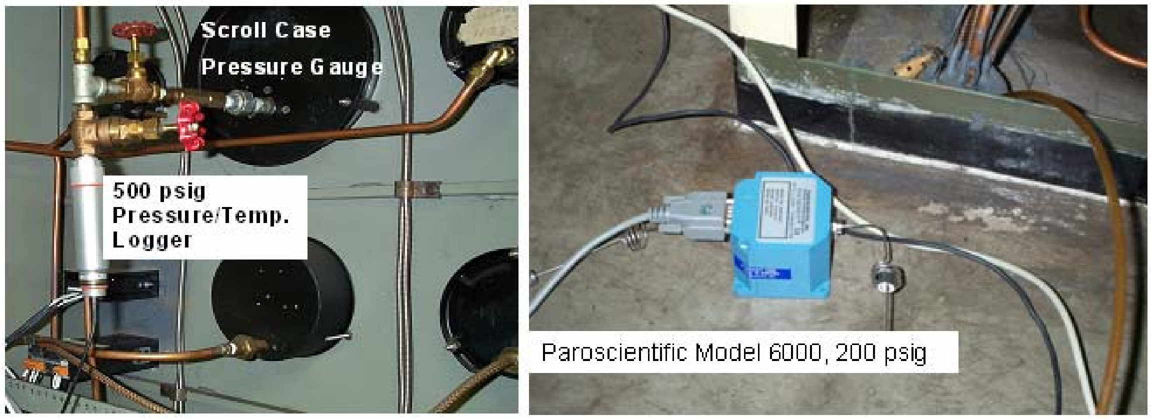


Figure 8. Photographs of MicroDAQ pressure logger connected to scroll case piezometer line (left) and Paroscientific pressure transducer which replaced the MicroDAQ logger (right).

Analysis of the initial set of MicroDAQ pressure measurements showed that uncertainty in the pressure data was too large to accurately isolate the system headloss from the total reservoir head. As a result, the MicroDAQ logger was replaced with a Paroscientific Model 6000 pressure transducer with an uncertainty of ± 0.008 percent full scale (figure 8). The Paroscientific pressure transducer was used to determine head loss characteristics for a wide range of flows, reservoir levels, and control gate positions. Note that a gate position change also changes the submergence.

ADCP Measurements

A Workhorse 300 kHz broadband Acoustic Doppler Current Profiler (ADCP) from RD Instruments was used to gather velocity profiles near the selective withdrawal system. The ADCP was equipped with normal and high-resolution profiling modes. High-resolution profiling mode (water mode 11) was used for velocity measurements because current speeds were very low. ADCP system configuration settings used at Hungry Horse were:

Depth of sensor (below surface): 2.0 ft		Blanking Distance: 1.64 ft
Compass correction: 0^{o}		Magnetic Variation:16.1^{o} E
Firmware: v16.21	Beam Angle: 20^{o}	Frequency: 300 kHz
Orientation: Down	Pattern: Convex	Bin Size: 0.66 ft
Water Mode: 11	Bottom Mode: 5	No. of Bins: 100
Pings/Ensemble: 5 water, 4 bottom		Sound Adsorption: 0.04 dB/ft
Intensity scaling factor: 0.43 dB/count		Salinity: 0.00 ppm

Velocity profiles were measured at three locations with respect to the selective withdrawal system (figure 9):

- Near (100 feet uplake from dam)
- Mid (400 feet uplake)
- Far field (1200 feet uplake)

Minimizing the boat speed was critical to achieve good bottom-tracking and velocity measurements. To minimize boat speed, the boat was moored to the trash racks, a debris sweeper boom, and the log boom for near, mid, and far field profiles, respectively.

During ADCP data collection, units No. 1 and No. 3 were each generating 67 MW and the power plant discharge was about 4000 cfs.

Weather conditions are an important consideration when trying to measure small currents in a reservoir where anchoring is not practical. Weather conditions during ADCP data collection were clear and calm.

A laptop computer was used to configure the ADCP and control data collection and for data storage. ADCP profiling sites were located in earth coordinates using a GPS receiver. The GPS receiver was connected to the computer so that GPS data were recorded simultaneously within the ADCP data file.

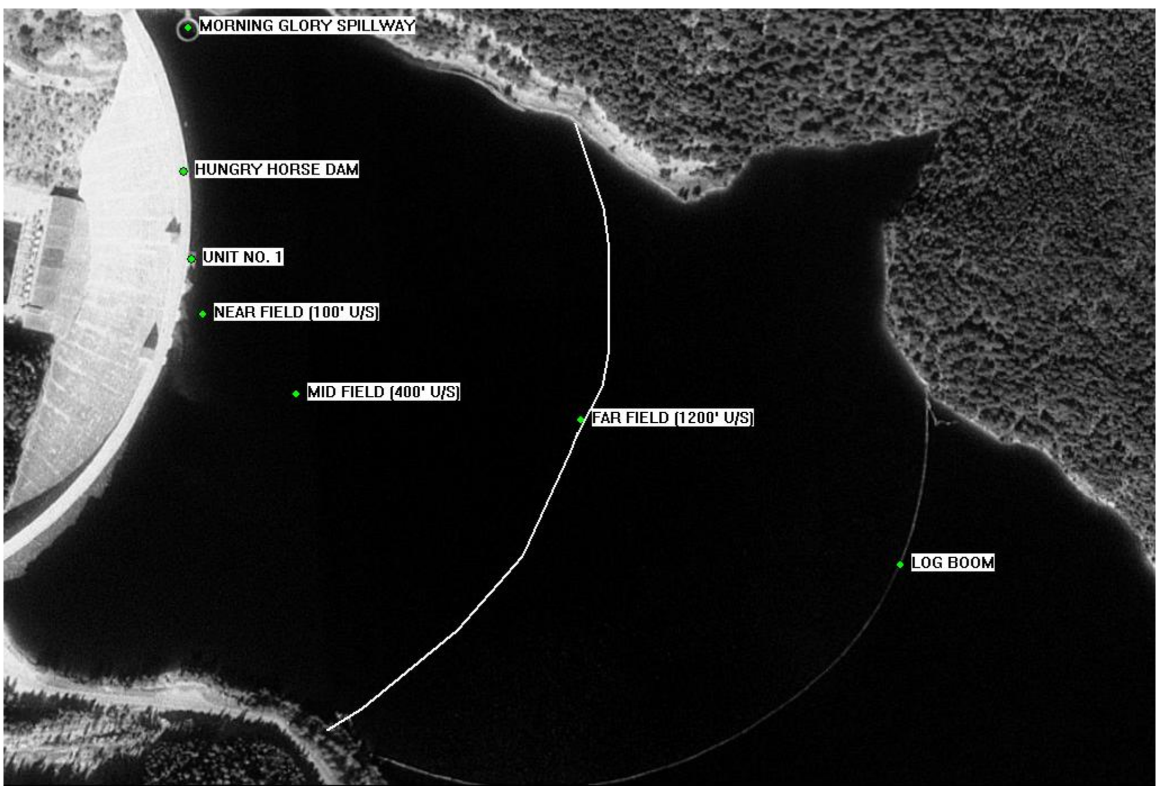


Figure 9. Aerial photograph of the Hungry Horse forebay with annotations of the ADCP profile locations. The approximate location of a new log boom is sketched through the far field location. USGS took this photograph on August 26, 1991.

Results

Reservoir Operations

A key component to this study was collecting a detailed record of reservoir operations. Most of the data were obtained from Reclamation and USGS databases.

Discharge from Hungry Horse Dam was one of the most important parameters. River discharges were an important component to this study because there are no flowmeters on the penstocks. To evaluate the accuracy of the USGS gaging station (USGS 12362500 SF Flathead River near Columbia Falls, Montana), 13 gage readings and corresponding stream gaging measurements over the duration of this study were compared. This comparison showed an average discrepancy in flows of 0.14 percent and a maximum discrepancy of 6 percent. The reservoir release patterns during selective withdrawal operations were very similar for years 2000, 2002, and 2003 and indicated the typical temperature regulation and flow augmentation plan for the Flathead River. Typical summer discharges ranged between 4,000 and 6,000 cfs. However, river flow rates in 2001 were held below 3000 cfs because of dry weather conditions and below normal storage in Hungry Horse reservoir. River flow rates were highest in 2002 when releases peaked around 10,000 cfs in May. Average daily reservoir releases for calendar years 2000 through 2003 are shown in figure 10.

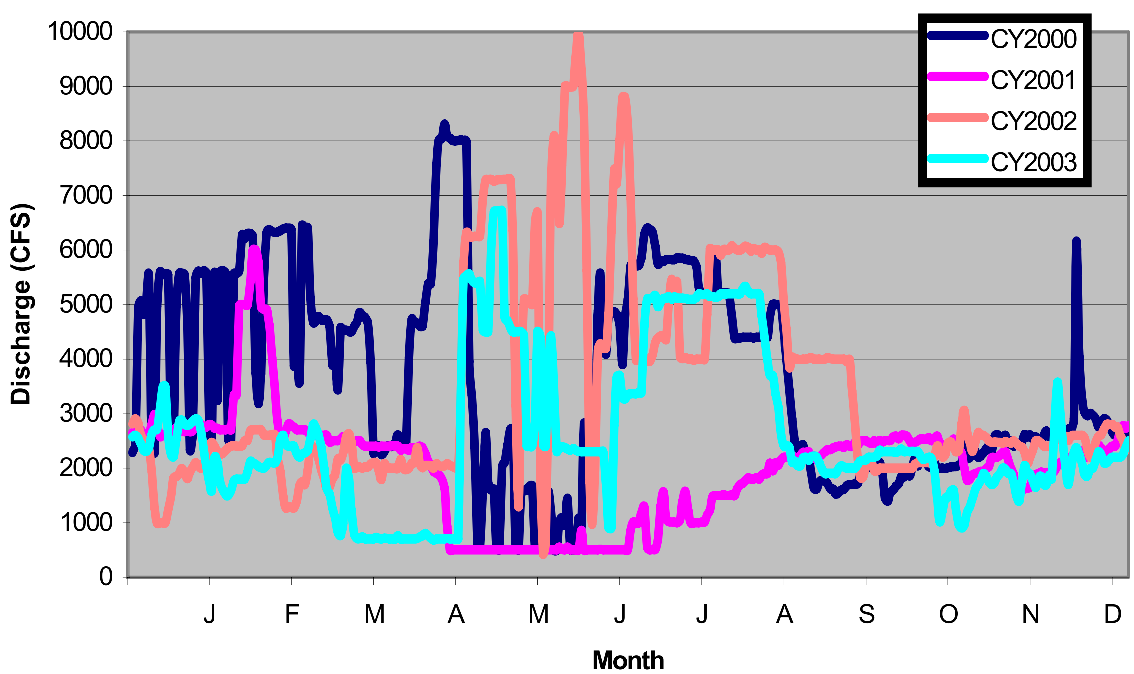


Figure 10. Plot of average daily releases from Hungry Horse Dam, 2000 through 2003.

Reservoir storage patterns during this study were very similar each water year, with the exception of 2001 when below normal spring runoff resulted in lower than normal reservoir storage. The wettest year was 2000 when flood control releases occurred several times through out the winter and early spring. The driest year was 2001 and the reservoir elevation ended up being 18 feet lower than normal. For years 2000, 2002, and 2003 the reservoir filled by early June and was drawn down until the following March. Average daily reservoir water surface elevations for calendar year's 2000 through 2003 are shown in figure 11.

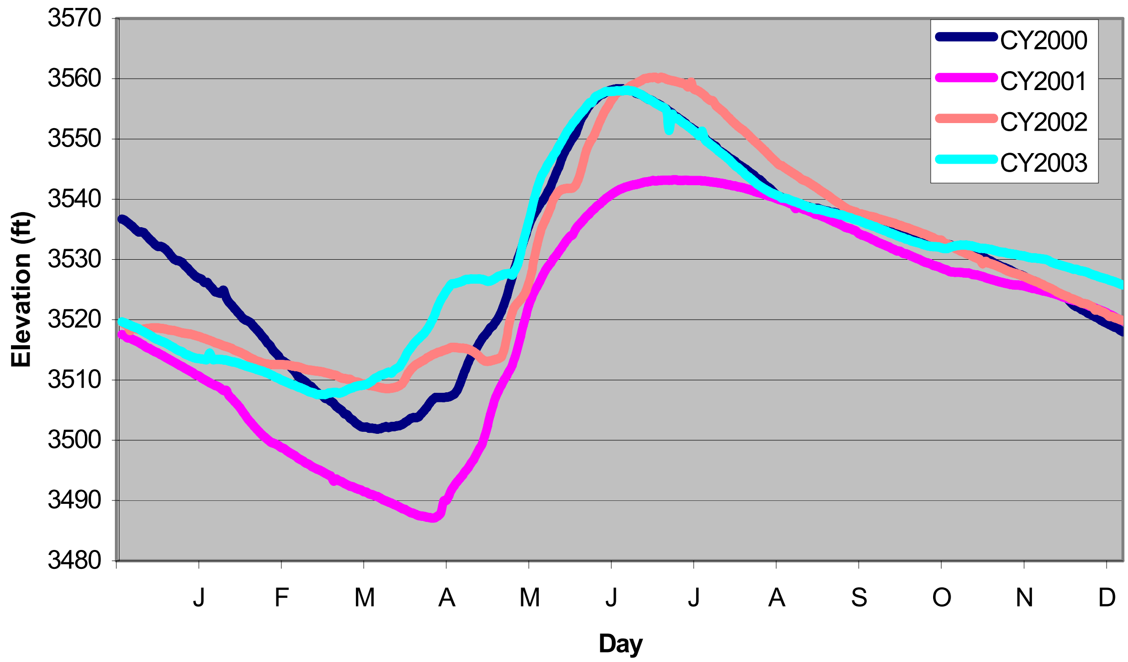


Figure 11. Plot of average daily reservoir elevations, 2000 through 2003. These data show the typical drawdown and filling schedule used at Hungry Horse.

Selective Withdrawal System Operations

Control gate elevations during selective withdrawal operations for years 2000 through 2003 are listed in tables 2 to 5. These tables display the average daily reservoir elevation and submergence for each control gate change. In 2001 and 2002, the pressure transducer located inside control gate unit No. 4 was very useful for checking the control gate operation records. For example, the pressure logger detected an unreported control gate change on October 10, 2001, as noted in table 3.

Table 2. Control gate changes and submergence depths in 2000.

Date	Control Gate Elevation (ft)	Avg. Reservoir Elevation (ft)	Submergence (ft)
Before 6/21/00	All gates at 3319	3555.81	236.81
6/21/00	All gates to elevation 3532	3556.29	24.29
7/11/00	All gates to elevation 3530.5	3556.71	26.21
7/26/00	All gates to elevation 3525	3552.14	27.14
8/10/00	Gates 1, 2, 3 to elevation 3510.2, 3509.7, and 3511.6, respectively *	3546.84	> 35.24
10/18/00	All gates taken out of service	3533.6	Offline
* Gate elevations may have been incorrectly reported.			

Table 3. Control gate changes and submergence depths in 2001.

Date	Control Gate Elevation (ft)	Avg. Reservoir Elevation (ft)	Submergence (ft)
Before 6/21/01	All gates at 3319	3537.5	218.5
6/21/01	All gates to elevation 3508	3538.0	30.0
7/13/01	All gates to elevation 3513	3543.0	30.0
9/5/01	All gates to elevation 3508	3538.6	30.6
9/13/01	Gates 2, 3 to elevation 3539	3537.2	Offline
9/24/01*	Gates 1, 4 to elevation 3505	3535.1	30.1
9/27/01	Gate 2 to elevation 3505	3534.4	29.4
10/1/01**	Gate 1, 4 to elevation 3503	3533.3	30.3
10/10/01	Gates 4 to elevation 3502	3531.7	29.7
* Gate change reported by operators, but not detected by pressure transducer on control gate #4. ** Gate change detected by pressure transducer on gate #4, but not reported by operators.			

Table 4. Control gate changes and submergence depths in 2002.

Date	Control Gate Elevation (ft)	Avg. Reservoir Elevation (ft)	Submergence (ft)
Before 6/27/02	All gates at elevation 3319	3505.8	186.8
6/27/02	All gates to elevation 3520	3555.4	35.4
7/10/02	All gates to elevation 3525	3559.6	34.6
7/12/02	All gates to elevation 3530	3559.9	29.9
8/01/02	All gates to elevation 3526	3557.2	31.2
8/07/02	All gates to elevation 3519	3554.9	35.9
8/20/02	All gates to elevation 3516.5	3549.3	32.8
8/29/02	** Gate 4 to elevation 3513.5	3545.6	32.1
9/10/02	All gates to elevation 3509	3543.9	34.9
9/17/02	** Gate 4 to elevation 3503.5	3544.0	40.5
10/18/02	** Gate 4 to elevation 3500.0	3534.3	34.3
10/31/02	All gates to elevation 3319	3531.7	212.7
Note: system head loss tests were conducted on 9/11/02 so gate 3 submergences varied throughout the day.			
** Gate change detected by pressure transducer on gate #4, but not reported by operators			

Table 5. – Control gate changes and submergence depths in 2003.

Date	Control Gate Elevation (ft)	Avg. Reservoir Elevation (ft)	Submergence (ft)
Before 6/3/03	All gates at elevation 3319		
6/3/03	Gate 1 online elevation unknown	3544.2	
6/11/03	Gates 2&4 to elevation 3521.2	3550.5	29.3
6/16/03	Gate 3 online elevation Unknown	3553.8	
6/17/03	Gate 1 to elevation 3533	3554.3	29.7
7/10/03	Gate 3 to elevation 3526	3557.0	31.0
7/16/03	All Gates to elevation 3525.4	3555.4	30.0
7/22/03	All Gates to elevation 3522.4	3553.4	31.0
7/28/03	All Gates to elevation 3520.9	3551.4	30.5
8/4/03	All Gates to elevation 3518.0	3548.8	30.8
8/6/03	All Gates to elevation 3516.5	3548.0	31.5
8/11/03	All Gates to elevation 3514.5	3546.1	31.6
8/14/03	All Gates to elevation 3512.0	3544.8	32.8
8/21/03	All Gates to elevation 3510.0	3542.2	32.2
8/26/03	All Gates to elevation 3495.0	3540.9	45.9
8/28/03	All gates to elevation 3500.0	3540.5	40.5
9/9/03	All gates to elevation 3509.0	3538.6	29.6
9/18/03	All gates to elevation 3504.0	3537.5	33.5
10/2/03	Gate 2 out of service	3535.4	
10/3/03	Gate 3 out of service	3535.2	
10/4/03	Gate 4 out of service	3535.0	
10/6/03	Gates 1 out of service	3534.7	

Gate submergence was computed as the difference between the water surface and control gate elevations at the time of the gate change. Typically, control gate submergences were maintained greater than 30 feet, the minimum recommended in the designer's operating criteria to prevent relief gate shear pin failures as well as debris accumulation at the structure. For years 2000 through 2003, gate submergence averaged 28.2, 30.0, 34.2, and 32.7 feet, respectively. In 2002 and 2003, operators maintained greater gate submergences to reduce debris entrainment because there was significant debris accumulation at the gates.

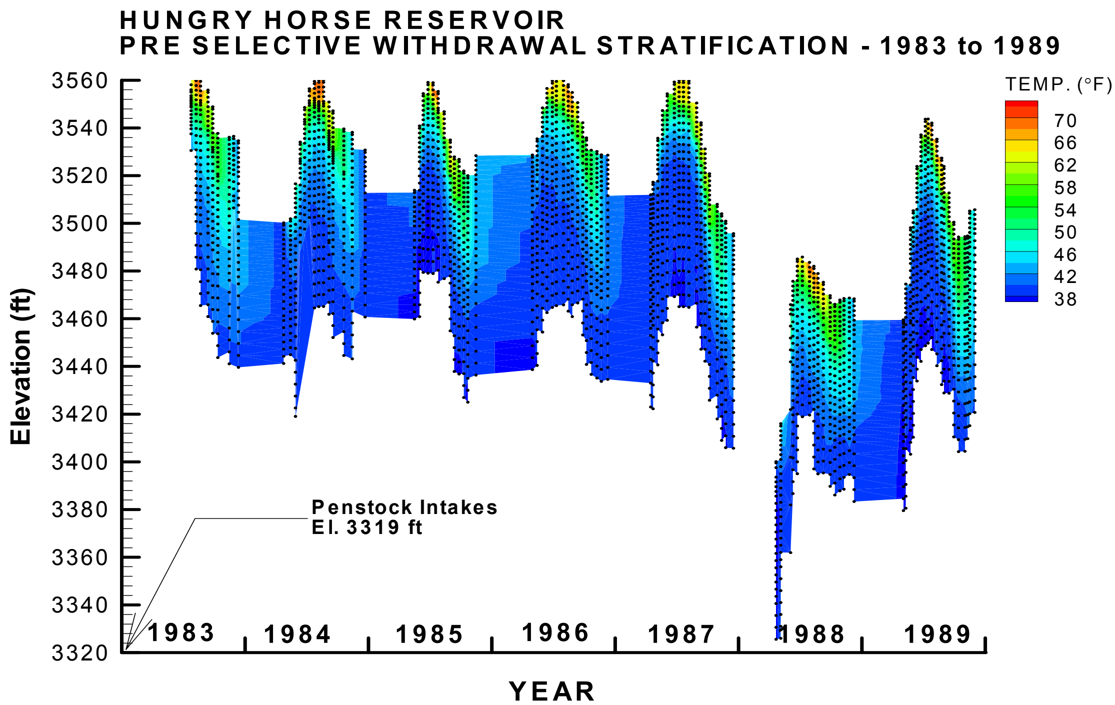
Modification of Reservoir Forebay Temperature Profiles

The MDFWP studied the benefits of adding selective withdrawal to Hungry Horse Dam during most of the 1980's. These studies provided an extensive data set of Hungry Horse reservoir temperature profiles from 1983 to 1989. These biweekly profiles were used to compare with post selective withdrawal temperature profiles to determine changes that may be attributed to selective withdrawal. Figure 12 shows two temperature contour plots of all the pre-selective withdrawal reservoir temperature profiles collected in Hungry Horse reservoir. The upper plot shows the temperature contours with respect to reservoir elevation and illustrates the variability in water surface elevation throughout the 1980s. The lower plot shows temperature contours with respect to water depth which illustrates the year-to-year uniformity of epilimnion thickness and thermocline strength. This plot also shows the typical pattern of deep mixing associated with low-level releases for the months of July, August, September, and October.

It is interesting that in 1988 the reservoir was drawn down to elevation 3384, filled to elevation 3490, and then drawn down to elevation 3466, and the resulting stratification was not appreciably different from other years. This is expected because epilimnion thickness is a function of solar radiation and wind energy inputs that occur at the air-water interface. So unless variations in reservoir elevation result in changes in wind speed or solar radiation conditions, it is unlikely that reservoir stratification patterns will change appreciably. However, for extreme droughts when the reservoir depth becomes shallower than the combined epilimnion and thermocline depth it is possible to get changes to the typical stratification characteristics.

For this selective withdrawal evaluation, forebay temperature profiles were monitored from 2000 through 2003. Figure 13 shows two contour plots of all the reservoir temperature profiles collected in Hungry Horse reservoir for this evaluation. These contour plots summarize the deployments and show periods of no data. The upper plot shows the temperature contours with respect to elevation and illustrates the variability in water surface elevation throughout the evaluation period. The lower plot shows temperature contours with respect to water depth and illustrates the uniformity of epilimnion thickness and thermocline strength throughout the months of July, August, September, and October. The lower plot illustrates how surface withdrawal eliminates the deep water mixing observed in the pre-selective withdrawal temperature profile data.

For both pre- and post selective withdrawal data sets, fall turnover (isothermal conditions) occurred in late November or early December and ended in late April or early May for years 2000 and 2001.



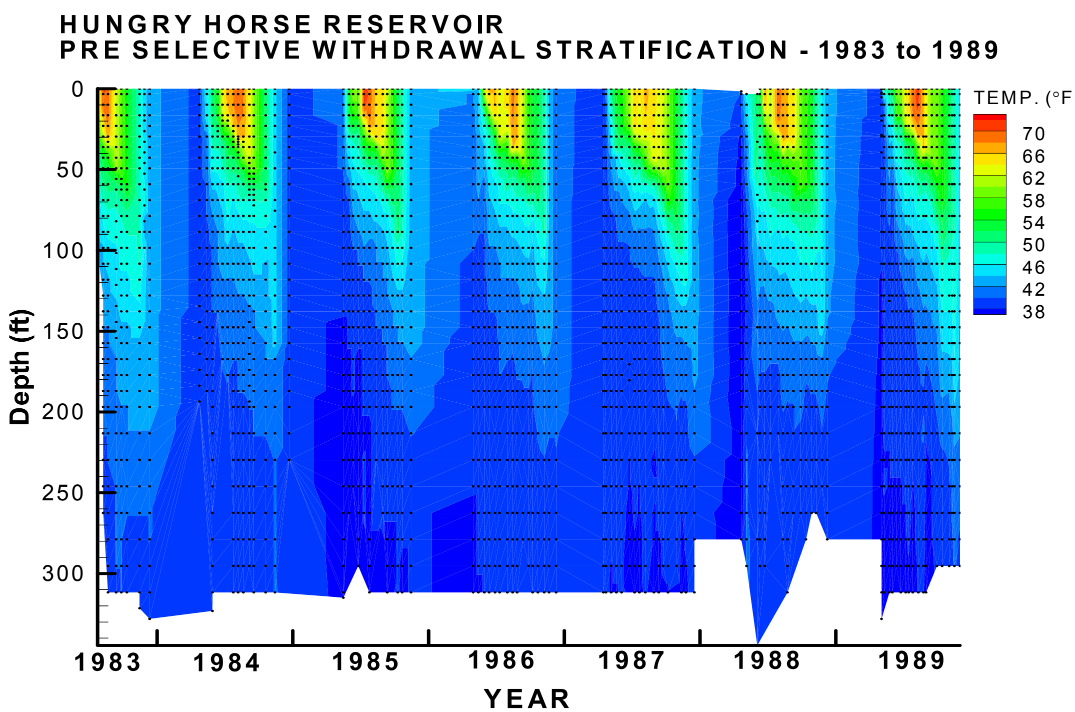
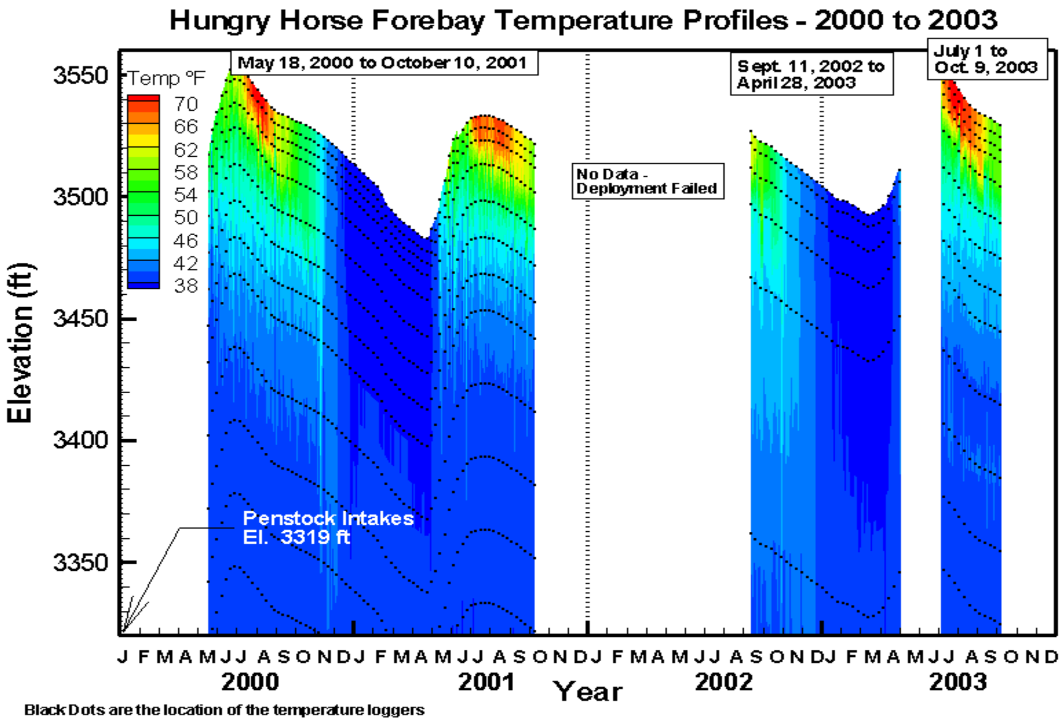


Figure 12. Contour plot of MDFWP temperature profiles collected in Hungry Horse Reservoir from 1983 through 1989. The upper plot shows stratification and the variability of reservoir water surface elevation. The lower plot shows forebay stratification with respect to water depth. Black dots indicate temperature profile data points.



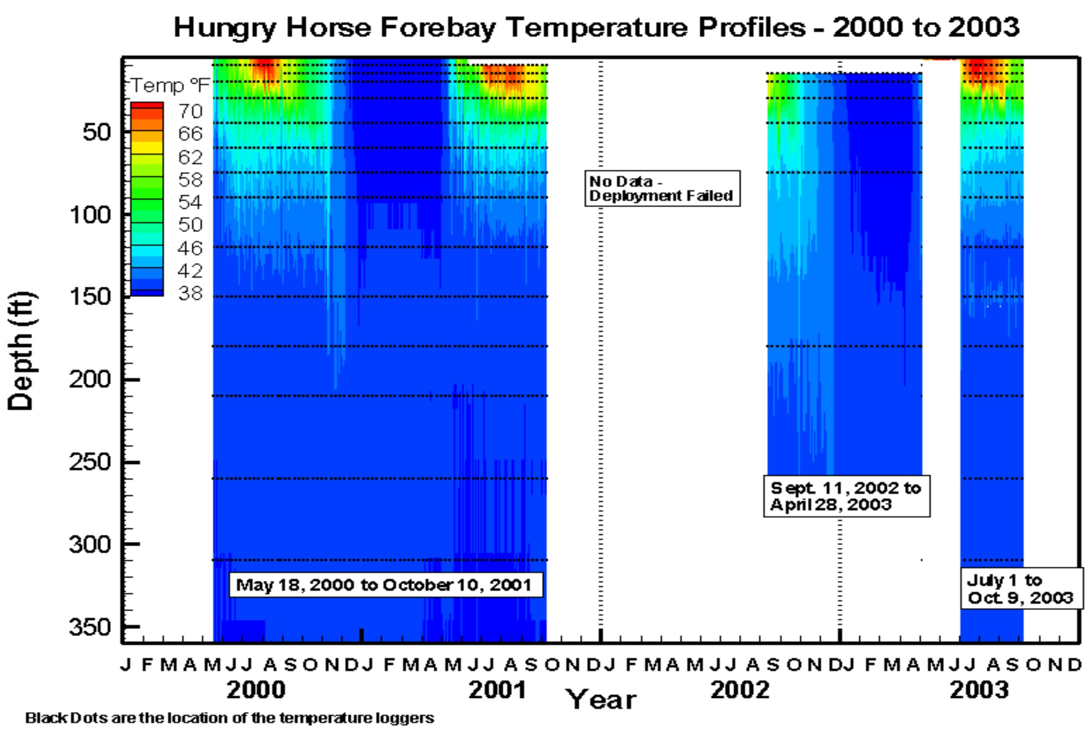


Figure 13. Contour plot of temperature profiles collected in Hungry Horse Reservoir. The upper plot shows periods of stratification and reservoir elevation fluctuations. The lower plot shows forebay stratification with respect to water depth.

The high resolution forebay temperature profile data allowed the identification and analyses of short-term variations in stratification. These variations in stratification can be viewed in detailed plots of reservoir stratification shown in figures 14 and 15.

The most prevalent temperature fluctuations were generated by surface seiches which formed when winds from the southeast were aligned with the maximum reservoir fetch and pushed warm surface water toward the dam. During an extreme seiche in August 2003, the epilimnion in the Hungry Horse forebay thickened from 20 to 60 feet deep.

Two types of surface seiches were commonly observed in the Hungry Horse temperature profile data sets:

- **Diurnal seiches** occurred in the evening hours when the prevailing winds were from the southeast. These seiches typically subsided in the early morning hours when the winds dissipated. Diurnal seiches were observed almost every day in the months of July and August. For instance, diurnal seiches in the years 2000, 2001, and 2003 totals were:

    - August 2000 had 27 diurnal seiches
    - August 2001 had 25 diurnal seiches
    - August 2003 had 26 diurnal seiches

- **Storm seiches** are generated by storms and can prevail from one to several days. Likewise, depending on wind direction the seiche can result in a thickening or thinning of the epilimnion. Figure 15 contains a 55 °F isotherm which clearly illustrates the internal wave activity associate with both seiche types.

In general, storm seiches produce larger internal wave amplitudes than diurnal seiches. Storm seiches can have a significant impact on selective withdrawal release temperatures. For one seiche event in August 2003, a thinning of the epilimnion caused a 6 ^{o}F decrease in river temperature which persisted for several hours until the seiche subsided and the normal temperature stratification was re-established. Figure 16 illustrates this by comparing the forebay water temperature at a constant 30-foot depth and the penstock release temperature for August 1-11, 2003. The temperature logger at 30-foot was selected for analysis because it was at the same elevation as the control gate and the epilimnion tends to oscillate between depths of 20 and 40 feet. As expected, the two data sets track each other very closely.

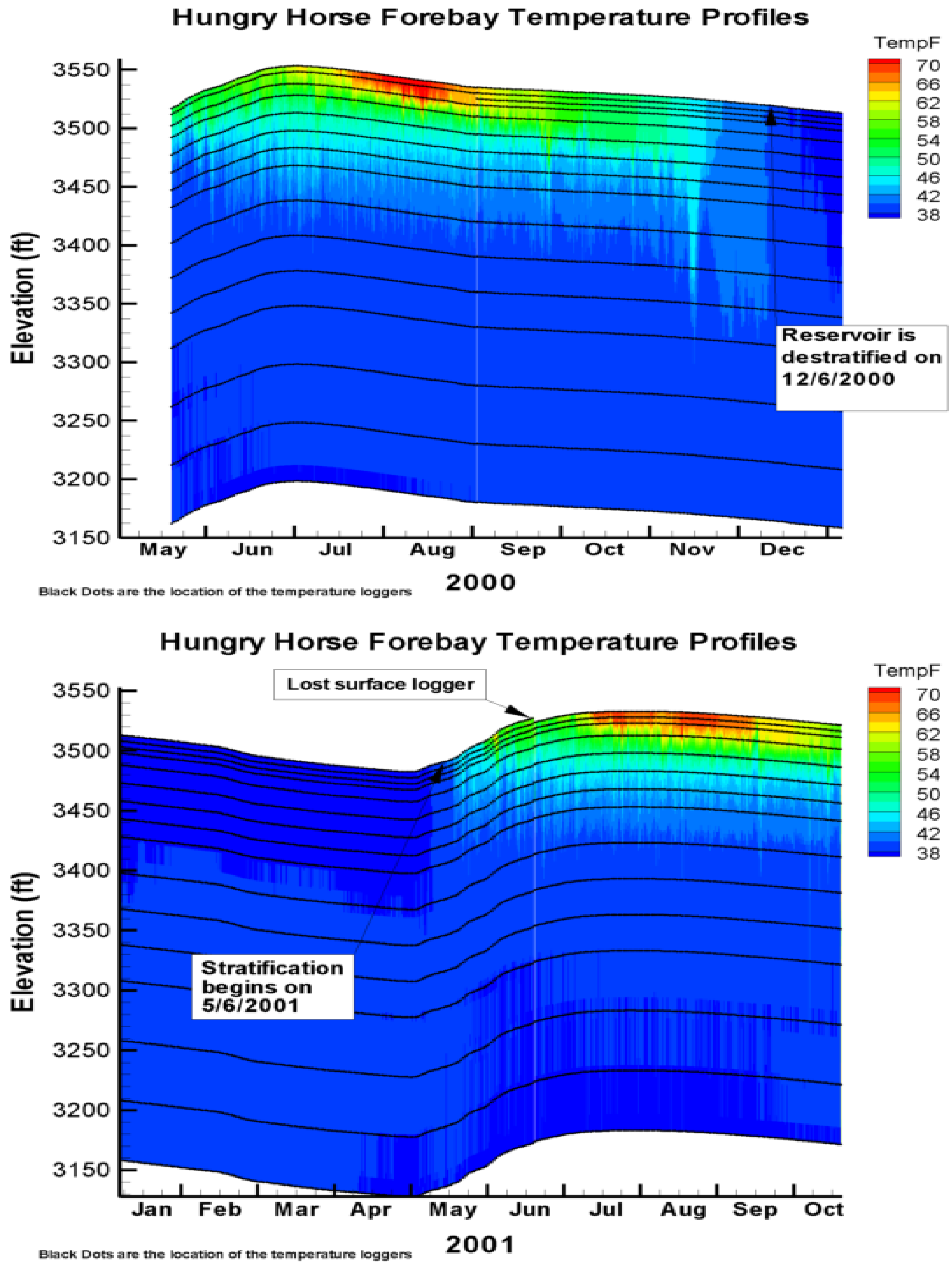


Figure 14. Contour plot of temperature profile data collected upstream from Hungry Horse Dam for the years 2000 (top) and 2001 (bottom). These plots illustrate the onset, development, and breakdown of thermal stratification in Hungry Horse reservoir.

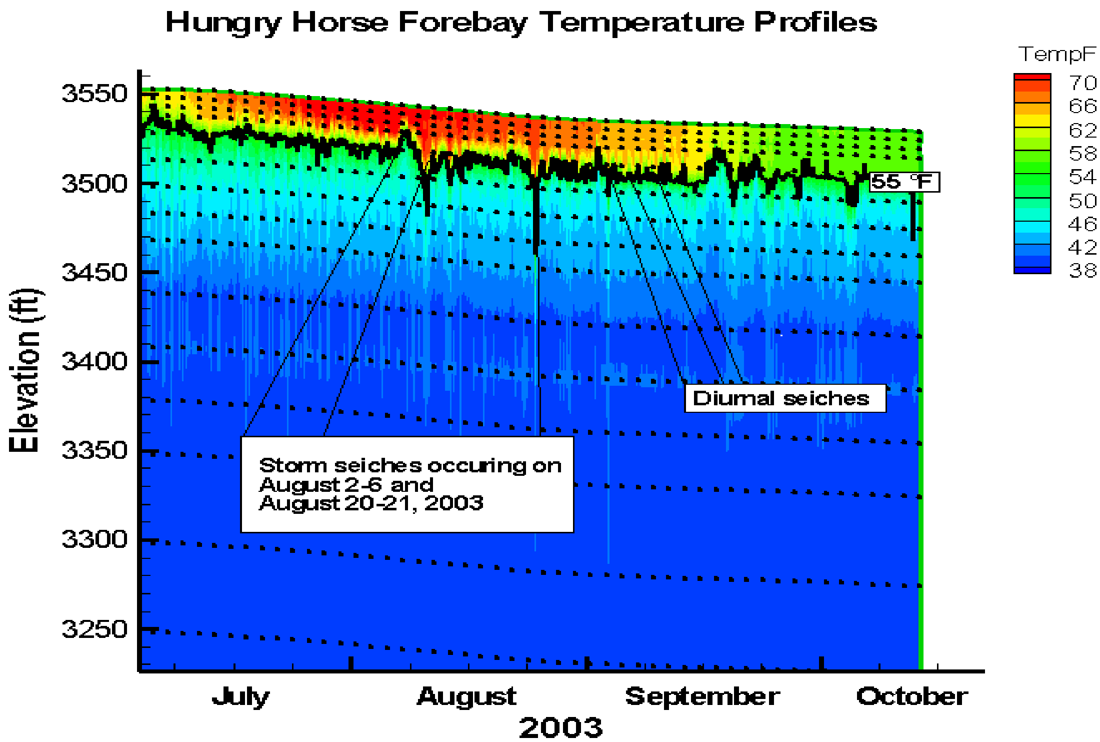


Figure 15. Contour plot of temperature profile data collected upstream from Hungry Horse Dam. This plot contains data from July 1 to October 17, 2003. This plot shows several periods in August where diurnal and storm seiches changed the vertical extent of the epilimnion. The black contour line is the 55 °F isotherm which clearly illustrates the internal wave activity.

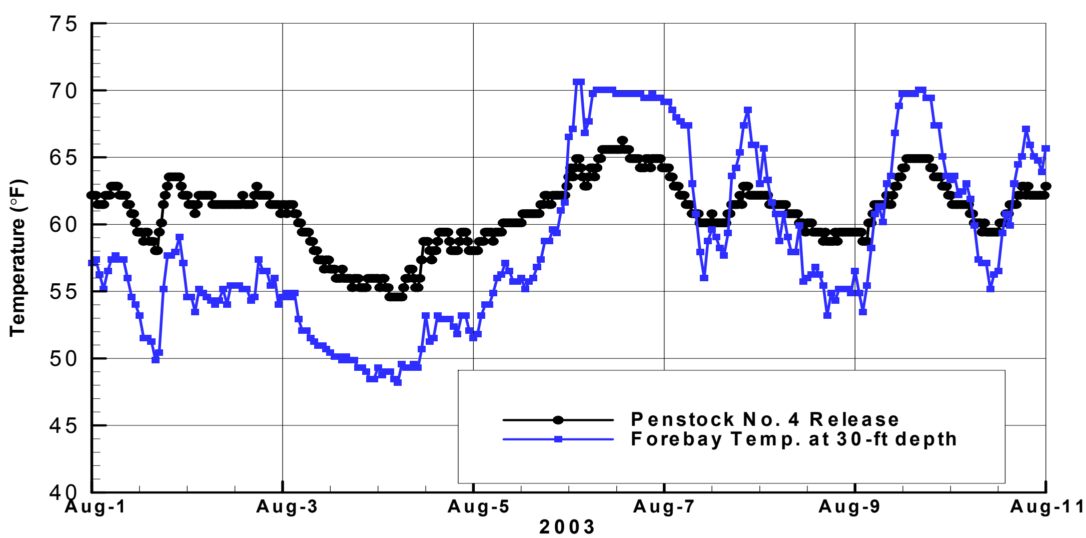


Figure 16. Comparison of 30-ft deep temperature logger and penstock No. 4 release temperature for the first ten days in August 2003. This plot illustrates the effect of diurnal and storm seiches on selective withdrawal release temperatures.

An analysis of pre- and post-selective withdrawal forebay temperatures showed that selective withdrawal operations caused a significant modification to thermocline characteristics. Post selective withdrawal temperature profiles during selective withdrawal operations showed larger temperature gradients in the thermocline for years 2000, 2001, and 2003.

A comparison of mid-August temperature profiles, shown in figure 17, illustrates the change in the thermocline shape and extent. It is apparent that surface withdrawal limits the deep mixing (or vertical stretching) of the thermocline when compared to deep-water withdrawals. For example, the lower limit of the thermocline changed from 170 feet to about 120 feet during selective withdrawal operations. Figure 17 also shows small differences in epilimnetic and hypolimnetic temperatures. However, it appears that selective withdrawal generates an epilimnion that was thinner than pre-selective withdrawal conditions. For the profiles shown in figure 17, the average pre-selective withdrawal epilimnion was 24.3 feet thick and the average post-selective withdrawal epilimnion was 18.0 feet thick. Comparing near-bottom temperatures for mid-August profiles showed the pre-selective withdrawal bottom temperatures were about 1.2 °F warmer than post-selective withdrawal temperatures. Again, this temperature difference is attributed to deep mixing that occurs during deep water withdrawals through the penstock intakes (elevation 3319 feet).

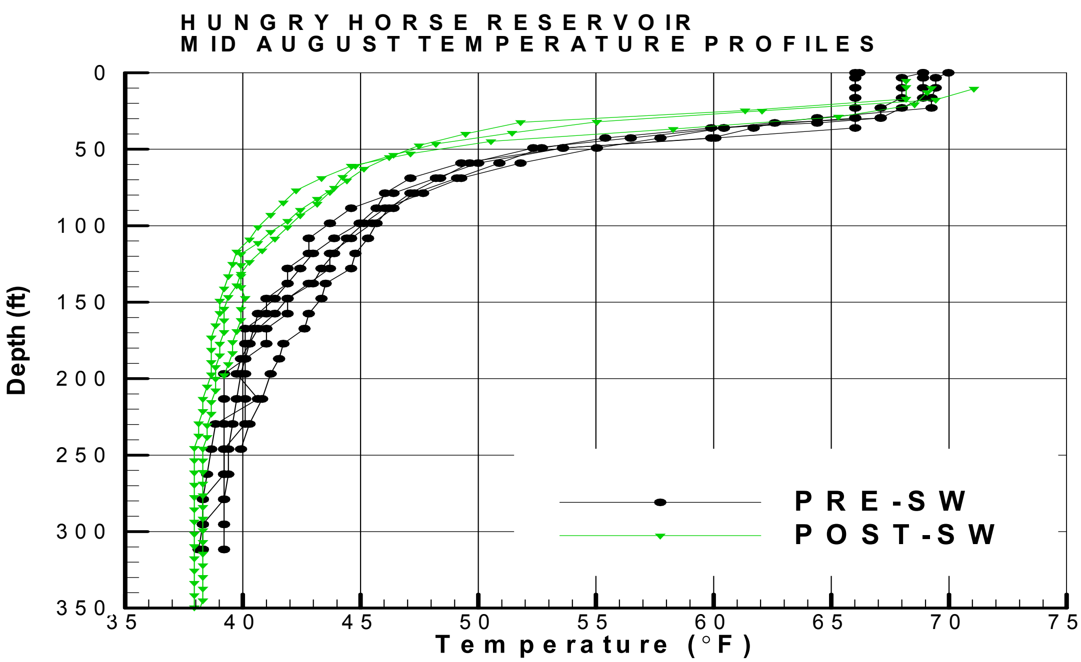


Figure 17. Comparison of Hungry Horse forebay temperature profiles for pre- and post-selective withdrawal conditions. The pre-selective withdrawal profiles were taken from mid-August profiles collected from 1983 to 1989. Likewise, post-selective withdrawal profiles were mid-August profiles from years 2000, 2001, and 2003.

Table 6 presents average surface temperatures for pre- and post-selective withdrawal operations for May through December. For this analysis, surface temperatures were defined as temperature measurements collected from just below the water surface to a depth of 5 feet. Pre-selective withdrawal temperatures were taken from MDFWP biweekly profile data collected from 1983 to 1989. Pre-selective withdrawal surface temperatures measured from day 15 ± 3 days of each month were averaged and used in the analysis. These days were chosen for analysis because most of the pre-selective withdrawal temperature profiles were collected around the middle of the month. In general, this analysis showed that surface temperatures during selective withdrawal operations increased every month until November and December when the surface temperatures decreased for post- selective withdrawal years. The maximum increase (4.5 °F) occurred in May 2000. However, May and June 2000 had abnormally high surface temperatures because of the dry and warm weather. Later in the summer, surface temperatures return to the normal range.

Table 6. Comparison of average surface temperatures for pre- and post-selective withdrawal periods.

	May	June	July	August	September	October	November	December
Pre-selective withdrawal (1983-1989)	44.2	54.9	65.3	67.6	60.4	51.8	46.0	42.4
Post-selective withdrawal								
2000	52.4	57.1	65.2	69.3	60.8	50.9	43.2	37.9
2001	45.4	54.4	69.0	69.2	63.2	60.6	n/a	n/a
2002	n/a	n/a	n/a	n/a	61.4	51.0	43.3	40.5
2003	n/a	n/a	68.5	69.4	59.8	n/a	n/a	n/a
Average for 2000 to 2003	48.9	55.8	67.5	69.3	61.3	54.2	43.2	39.2
Difference between pre- and post-selective withdrawal	4.6	0.9	2.2	1.7	0.9	2.4	-2.8	-3.3

An explanation for the apparent surface temperature warming may be a local thickening of the epilimnion associated with surface withdrawals that would not have occurred for pre-selective withdrawal operations. Or the temperature warming may result from comparing biweekly temperature profile data collected 3 miles upstream from the continuous monitoring site. It is possible that there is a surface temperature gradient between the two monitoring sites.

Comparing pre- and post-selective withdrawal surface temperatures for November and December revealed that selective withdrawal reduced the average mid-monthly surface temperature by 2.8 °F. Figure 18 presents a comparison of mid-November temperature profiles that illustrates the breakdown of the thermal stratification in Hungry Horse reservoir for pre- and post-selective withdrawal conditions. These data support the observation that fall turnover occurs a week or two earlier during selective withdrawal operations. For instance, fall turnover occurred on December 11, 2000 and December 14, 2002. Of the five mid-December profiles collected from 1983 to 1988 only one (collected on December 21, 1984 showed the reservoir had undergone fall turnover. It was not possible to determine the dates of fall turnover for pre-selective withdrawal profiles because no profiles were collected from mid December until mid April the following year because the reservoir was usually ice-covered.

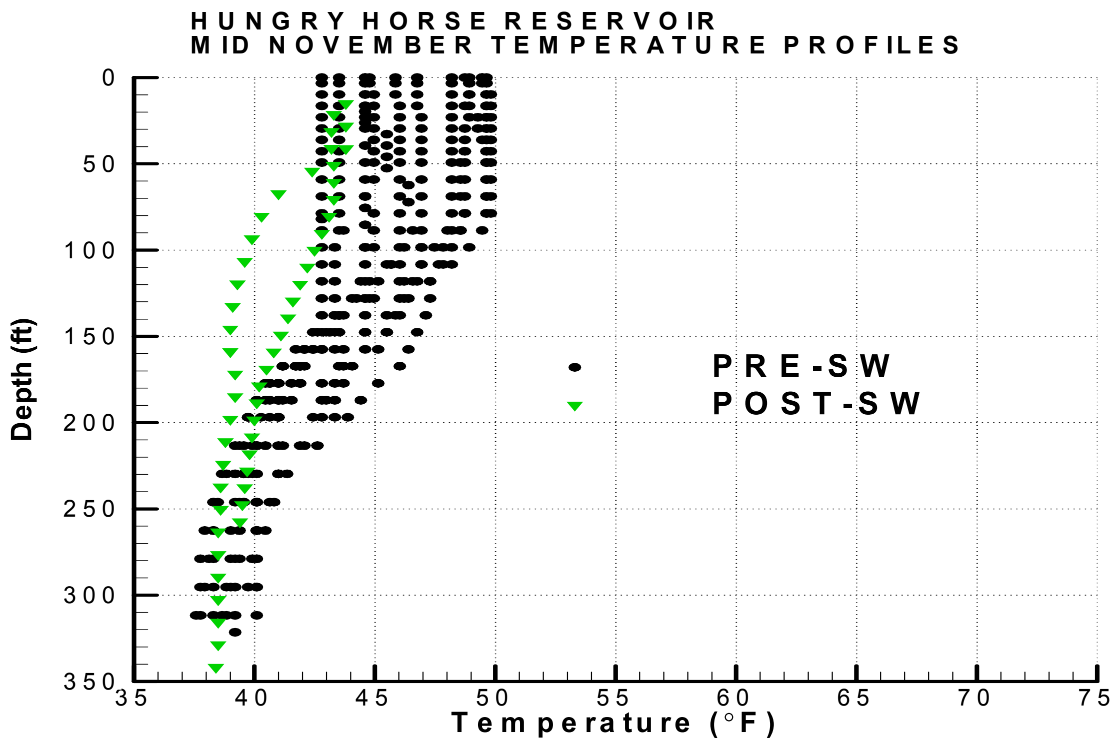


Figure 18. Comparison of Hungry Horse forebay temperature profiles for pre- and post-selective withdrawal conditions. The pre-selective withdrawal profiles were taken from mid-November profiles collected from 1983 to 1989. Likewise, post-selective withdrawal profiles were from years 2000 and 2002.

Selective Withdrawal Release Water Temperatures

Three data sources were available to assess changes in river temperature related to changes in control gate elevations, powerplant operations, and meteorological events:

- Turbine-bearing cooling water taken from each penstock
- Tidbit logger in the river ½ mile below the dam
- Reclamation's TDG monitoring station 1.7 miles downstream from Hungry Horse Dam

Turbine-bearing cooling water temperatures will be referred to as penstock water temperatures in this report. Selective withdrawal releases could be mixed with spillway or outlet works discharges. If so, then a river temperature would be best suited for temperature management. However, this situation did not occur during this evaluation.

In 2001, minimum flow releases (500 cfs) from late April to mid June left the temperature logger out of the water. This low water condition did not impact the evaluation because dam releases increased before selective withdrawal operations started.

Penstock Versus River Release Temperatures

An analysis of penstock water temperatures was conducted to determine if the MW-weighted release temperature agreed with the river temperatures measured ½-mile downstream. MW output was used as a surrogate for individual penstock flow rates in this analysis because there are no penstock flowmeters. The MW-weighted release temperature was computed by multiplying each penstock water temperature by the MW output for that particular unit. Each of these products were summed and divided by the total MW output for the power plant (see equation 1). If penstock flowmeters are installed at Hungry Horse, a similar computation can be performed by replacing MW with the flowrate.

$$Megawatt - weighted\ Temperature\,(^{\circ}\mathrm{F}) = \frac{\sum_{i=1}^{4}(Temp_i \times MW_i)}{\sum_{i=1}^{4} MW_i} \qquad (1)$$

Equation 1. Method used to compute the MW-weighted release temperature for the Hungry Horse Power Plant. Individual generator MW output was used as a surrogate for penstock flows.

Comparing MW-weighted penstock water temperatures shows that the difference between the two release temperatures was within the uncertainty of the temperature loggers used to monitoring the temperatures. Figure 19 contains a graph of flow weighted penstock release temperatures plotted against the Tidbit® river temperatures. A linear regression of the data set shows very good agreement between the two data sets, with a correlation coefficient (R^2) equal to 0.993. As a result, project operators can use either MW-weighted penstock water temperatures or river temperatures to monitor the selective withdrawal system's release temperature.

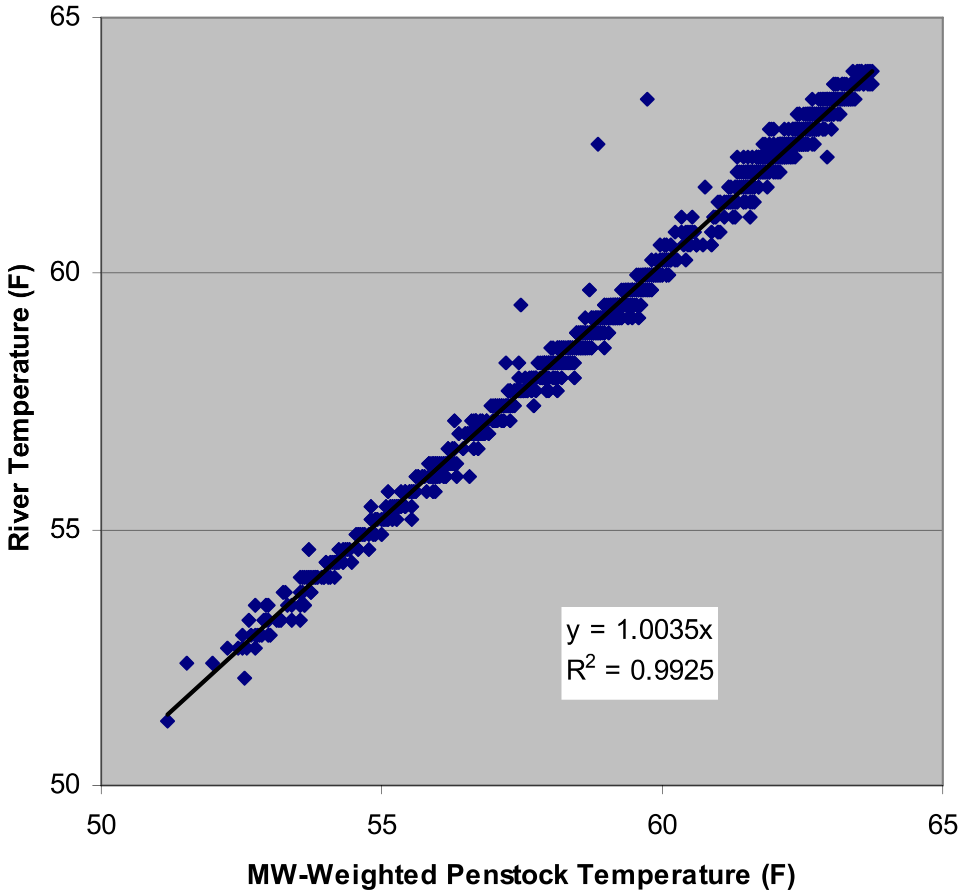


Figure 19. MW-weighted penstock release temperatures versus river temperatures and linear regression (best-fit) equation for data collected between June 12 and October 10, 2001. These data show that either the MW-weighted penstock temperatures or the river temperatures can be used with confidence to evaluate the selective withdrawal system. Note: The uncertainty of both the temperature loggers is ±0.4 °F.

Total Dissolved Gas Monitoring Site Versus River Temperatures

The difference between the total dissolved gas (TDG) and river temperatures was within the accuracy of the Tidbit logger used to monitoring the temperatures. This was determined by comparing water temperatures measured at the TDG monitoring site (Hydromet Station I.D.: HGHM) and the river logger site for 2003. A linear regression of the data set shows very good agreement between the two data sets, with a correlation coefficient equal to 0.996. Note: this linear regression analysis did not take into account travel time between the sites which adds a small source of uncertainty.

While the HGHM site could be used to monitor release temperatures, this analysis showed that there were extended periods where the monitoring equipment was out of service, so a back up system is recommended.

Temperature Differential across Powerplant Units

Comparing penstock water temperatures with each unit generating similar MW showed that there was a minor temperature differential between units No. 1 and No. 4. There were surprisingly few periods where power generation was evenly split between operating units. Typically, there were 3 or 4 periods per year when this condition occurred. Data from years 2001, 2002, and 2003 were analyzed, and the average temperature differential from unit No. 1 to unit No. 4 was 0.7 °F. In almost all cases unit No. 4 release temperatures were warmer that unit No. 1. The only time unit No. 4 releases were cooler (by 0.7 °F) than unit No. 1 was during a time when both units were generating 90 MW (the maximum generation for this data set).

Selective Withdrawal Performance

The Hungry Horse selective withdrawal system is operated to meet river temperature guidelines developed by MDFWP. A table of the MDFWP recommended daily temperatures from June 1 to September 30 is included in Appendix A. MDFWP guidelines include a ±3.6 °F tolerance band that allows for natural river temperature fluctuations. A comparison of average daily river temperatures from the TDG monitoring site to the temperature guidelines was used to evaluate selective withdrawal performance. Figures 20 through 23 compare the actual river temperature versus the MDFWP recommended release temperature. These plots show how control gate elevations were changed over the selective withdrawal seasons, how gate changes affected river temperatures, and how many gate changes were made in a given year. During the evaluation period, annual gate adjustments increased from 4 changes in 2000 to 14 changes in 2003.

For the selective withdrawal operations evaluation, the cumulative monthly temperature departures during the selective withdrawal operating season were a useful metric for describing how well project operators met the temperature guidelines for each month of the selective withdrawal season. The absolute values of daily temperature departures outside the temperature guidelines were summed for the months June, July, August, and September. Taking the absolute value of the temperature departure assigns equal weighting for releases being either too warm or too cold; this assumption may or may not be appropriate with respect to the fish growth criterion used to establish the guidelines. It is important to consider that this performance metric will be influenced by variations in the onset of reservoir stratification, when the selective withdrawal system went into service, operational constraints that may limit the frequency of gate adjustments, and control gate submergence limits.

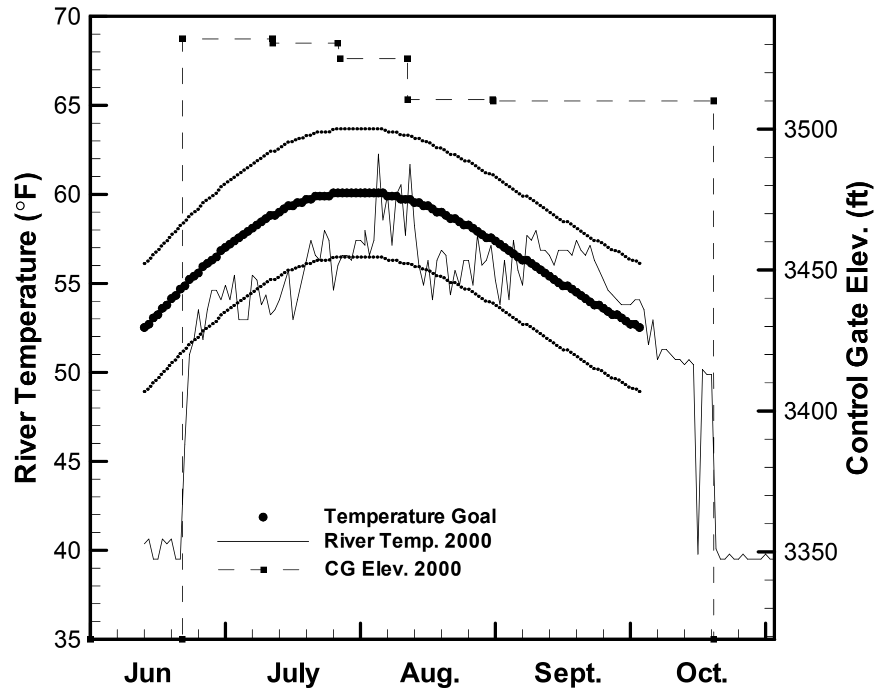


Figure 20. Comparison of actual versus recommended release water temperature for the south fork of the Flathead River, 2000. This plot also shows the control gate (CG) operations for the 2000 selective withdrawal season. The dotted lines represent the 3.6 °F allowable temperature variation.

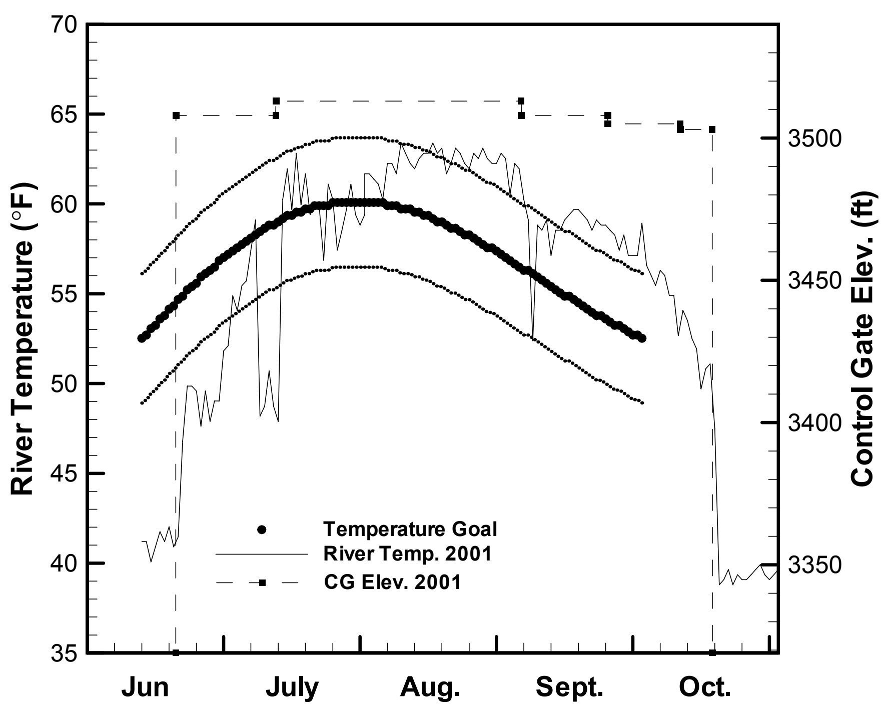


Figure 21. Comparison of actual versus recommended release water temperature for the south fork of the Flathead River, 2001. This plot also shows the control gate (CG) operations for the 2001 selective withdrawal season. The dotted lines represent the 3.6 °F allowable temperature variation.

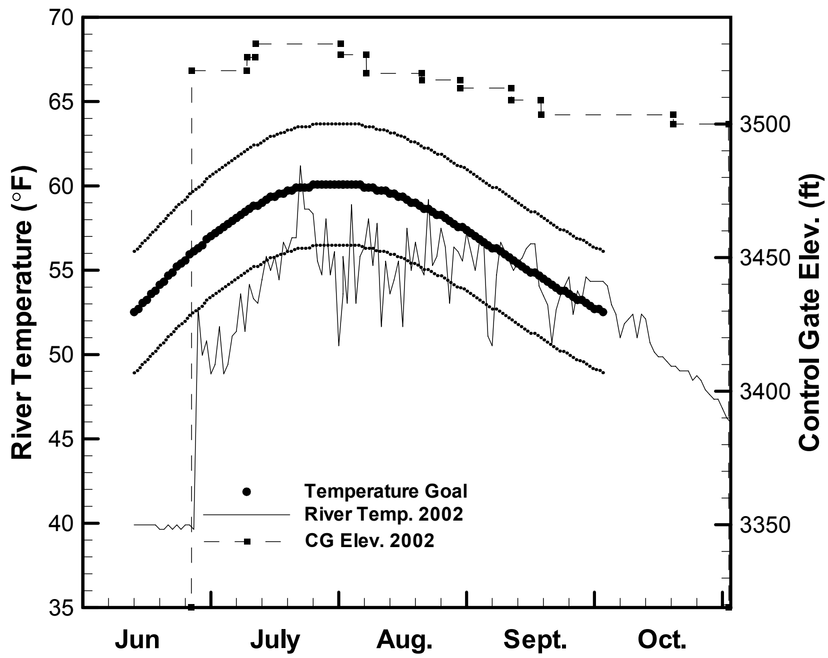


Figure 22. Comparison of actual versus recommended release water temperature for the south fork of the Flathead River, 2002. This plot also shows the control gate (CG) operations for the 2002 selective withdrawal season. The dotted lines represent the 3.6 °F allowable temperature variation.

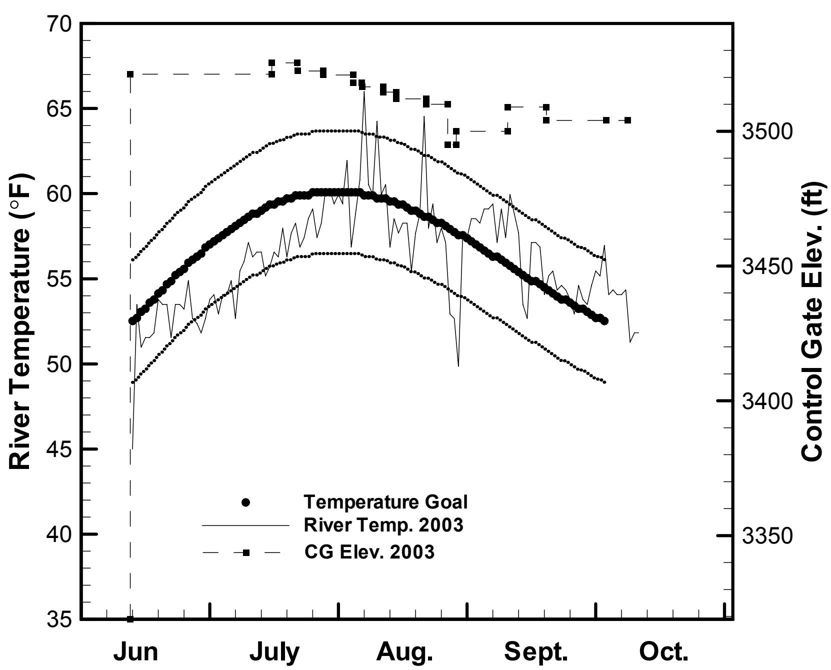


Figure 23. Comparison of actual versus recommended release water temperature for the south fork of the Flathead River, 2003. This plot also shows the control gate (CG) operations for the 2003 selective withdrawal season. The dotted lines represent the 3.6 °F allowable temperature variation.

Table 7 contains a summary of the cumulative monthly temperature departures outside the temperature guideline tolerance band. The data in table 7 are for days when the selective withdrawal system was fully operational. This distinction only applies to June data because the selective withdrawal system was normally deployed by mid-June and stayed in operation until mid-October. Hungry Horse personnel begin selective withdrawal system installation in early June, but they often experienced maintenance issues that delayed the installation from one to three weeks.

Table 7 also presents the total temperature departure for the season divided by the number of days the selective withdrawal system operated. The total days of selective withdrawal system operation were 101, 102, 96, and 111 for years 2000, 2001, 2002, and 2003, respectively. These data were used to compute the average daily temperature departure (**∑|ΔT|/**selective withdrawal days) for each month of the season by dividing the sum of the temperature departures by the total days of selective withdrawal operation. This analysis showed that June and July were further out of compliance than in August and September. June compliance is worse because there were periods when the surface water was too cold to meet the temperature guidelines. In July, the majority of departures occurred when the reservoir was filling and the submergence gradually increased to the point that selective withdrawal releases became too cold. Once the operators raised the gates the release temperatures were quickly brought into compliance. In late August and September 2001 there were several days where the release temperatures were higher than the guidelines. This condition was easily corrected by lowering the control gate (increasing submergence). This analysis showed that making timely control gate adjustments, except for in early June, will improve selective withdrawal performance with respect to meeting MDFWP temperature guidelines.

Table 7. Summary of cumulative monthly temperature departures for days with selective withdrawal operation (∑|ΔT|, °F).

	June	July	August	September	Total/season
2000	1.15	12.83	0.00	0.00	13.99
2001	5.13	6.50	8.51	23.99	44.14
2002	9.11	25.04	3.42	0.59	38.16
2003	1.40	2.52	4.21	1.48	9.61
∑|ΔT| (°F)	16.79	46.89	16.15	26.06	105.89
No. of selective withdrawal days	42	124	124	120	410
∑|ΔT| (°F) /selective withdrawal days	0.40	0.38	0.13	0.22	0.26

While average monthly data provide a basis for understanding selective withdrawal performance, evaluating daily data was also informative. Figure 24 shows daily temperature departures for 4 seasons of selective withdrawal operations. Contrary to the monthly data, the temperature departures shown in figure 24 retain their sign (i.e., they retain either a positive (+) or negative (-) value). Where negative temperature departures indicate selective withdrawal releases that were too cold. The plot shows that most of the negative departures occur early in the selective withdrawal season when reservoir surface temperatures were too cold or control gate submergence was too deep to satisfy the guidelines. Conversely, positive temperature departures occurred after mid July when release temperatures are too warm. During several consecutive days in August and September 2001, release temperatures were warmer than required and could have been brought into compliance by increasing control gate submergence. In 2002, control gate submergences were maintained at levels greater than 30 feet, which resulted in several periods when release temperatures were colder than the guidelines. For this case, selective withdrawal performance would have been improved if the 30 feet submergence criteria had been strictly observed. There are a few short duration spikes that are attributed to either storm or diurnal seiches which cannot be practically eliminated with control gate operations. In 2000 and 2003, the project operators did an excellent job operating the system and temperature departures were minimal.

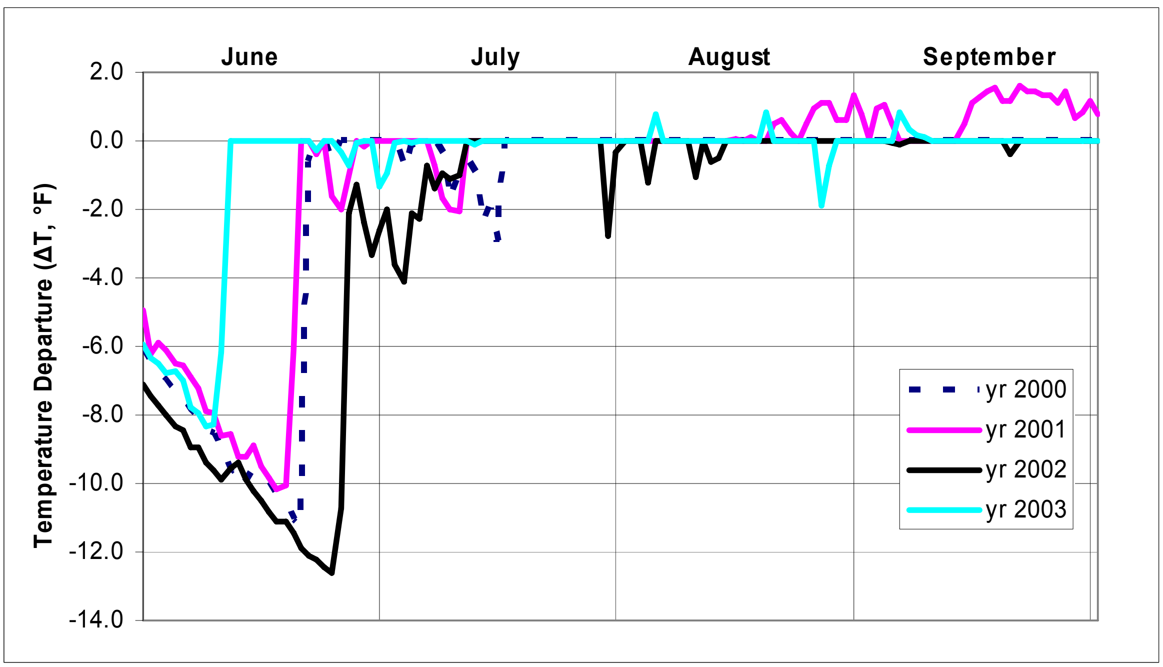


Figure 24. Plot of the daily temperature departures (ΔT) of selective withdrawal release temperatures for 2000 through 2003. This graph illustrates that selective withdrawal releases are too cold in June and July, but are too warm in August and September.

Control Gate Operations

Control gate elevation changes, while not difficult, take time and effort to change gate position and verify the new gate elevation. Over the first seven years of operation, system operators have found that control gate submergences of 30-32 feet are required to limit the accumulation of excessive floating debris. Eventually, floating debris (wood, leaves, pollen, etc.) becomes saturated, sinks and ends up fouling the bearing cooling water strainers or obstructing the wicket gates. Furthermore, a 30-foot submergence requirement was added to standard operating procedures (SOP) for unit start-up to protect relief gate shear pins, which effectively increases the minimum submergence from 20 to

30 feet because it is impractical to change the control gate submergence each time the unit is brought online. However, there are times early in selective withdrawal season when the required submergence is less than 30 feet to meet the temperature goals. Consequently, operators have to make a decision whether meeting the temperature goal is prudent given the submergence constraints. Typically, operators will follow the 30-ft submergence criteria to protect the power generating equipment.

System Head Loss

An analysis of historical records and recent field data was performed to describe the head loss characteristics of the selective withdrawal system at Hungry Horse Dam. This analysis included determining system head loss versus discharge relationships for pre- and post-selective withdrawal conditions. For this study, system head loss is defined as the total head loss from the forebay to the piezometer taps on the penstock upstream from the turbine scroll case.

1954 Turbine Performance Acceptance Tests

In January 1954, a turbine performance acceptance test was performed on unit No. 3 at the Hungry Horse Powerplant using the Gibson method (Gibson, 1954). Head losses measured from the forebay to the scroll case were analyzed to determine the system head loss characteristics prior to the installation of the selective withdrawal system. A total of 35 Gibson tests were performed. Over the course of testing, the flow ranged from 8 to 3004 cfs. During testing, the forebay water surface elevation was 3511.4 feet. The head loss and discharge data were used to develop a head loss relationship for unit No. 3. Figure 24 shows the data and best fit relationship for the system head loss.

1995 Field Installation Tests

After the selective withdrawal system was installed in 1995, Reclamation performed a set of field tests to insure that the selective withdrawal system components performed as designed. These tests were designed to evaluate the performance of mechanical equipment rather than selective withdrawal structures ability to control release temperature. The primary objectives were to document water hammer characteristics and make governor speed adjustments to control the closure rate of wicket gates as a means to reduce water hammer effects.

Field tests conducted the week of August 7, 1995, measured a maximum selective withdrawal system head loss for unit No. 4, for full power (107 MW), a 20-ft control gate submergence and with all slide gates closed. The selective withdrawal head loss (from forebay to penstock intake) was approximately 3.5 feet of head (Reclamation, 1996). The pressure transducers used for these tests were accurate to ±0.1 percent of 150 lb/in.^{2} (full scale) range or ± 0.35 feet of water. Original physical model testing had predicted that the head loss attributed to the selective withdrawal structure would be 3 to 5 feet (Kubitschek, 1994). Collecting a data set sufficient to develop a head loss versus discharge relationship was beyond the scope of these field tests.

The control gate performed well throughout the test. There were no noticeable vibrations, and the gate traveled smoothly up and down in the gate guides. At a control gate submergence of 20 feet, the wire ropes from the hoist were vibrating in the flow.

This vibration was considered undesirable and should be avoided by operating at a deeper submergence or reducing the flow in to the intake. During testing, some random temperature sampling was performed at the turbine and tail race. Temperatures greater than 57 °F were recorded. There was a strong indication that 20 feet of control gate submergence may not be needed to obtain the desired temperatures and that control gate submergences of 30 to 40 feet might be enough to meet temperature objectives.

According to the 1994 hydraulic model study conclusions (Kubitschek, 1994), air entraining vortices were predicted to present for operation at flows near the maximum passable (3070 cfs) in combination with low control gate submergence (20 feet or less). And that frequent operation under these conditions may require vortex suppression devices. It was also observed in the hydraulic model that air entraining vortices were not expected for discharges below 2300 cfs with a minimum submergence of 20 feet. Based on model observations of vortex conditions, the recommended minimum submergence was 20 feet for all discharges up to the maximum passable intake 3070 cfs. The 1995 field installation test results report contained no mention of observed vortices.

Throughout the field testing period, relief gate shear pins were failing even though the pressure transducer indicated that pressures were well within a safe range. Apparently prototype shear pins did not perform as they did in the bench tests. The pins were designed to shear at 2.6 lb/in^2, and the shear pins were failing at approximately 1.5 lb/in^2. Consequently, the size of the shear pins was increased and replaced.

2003 Selective Withdrawal Performance Tests

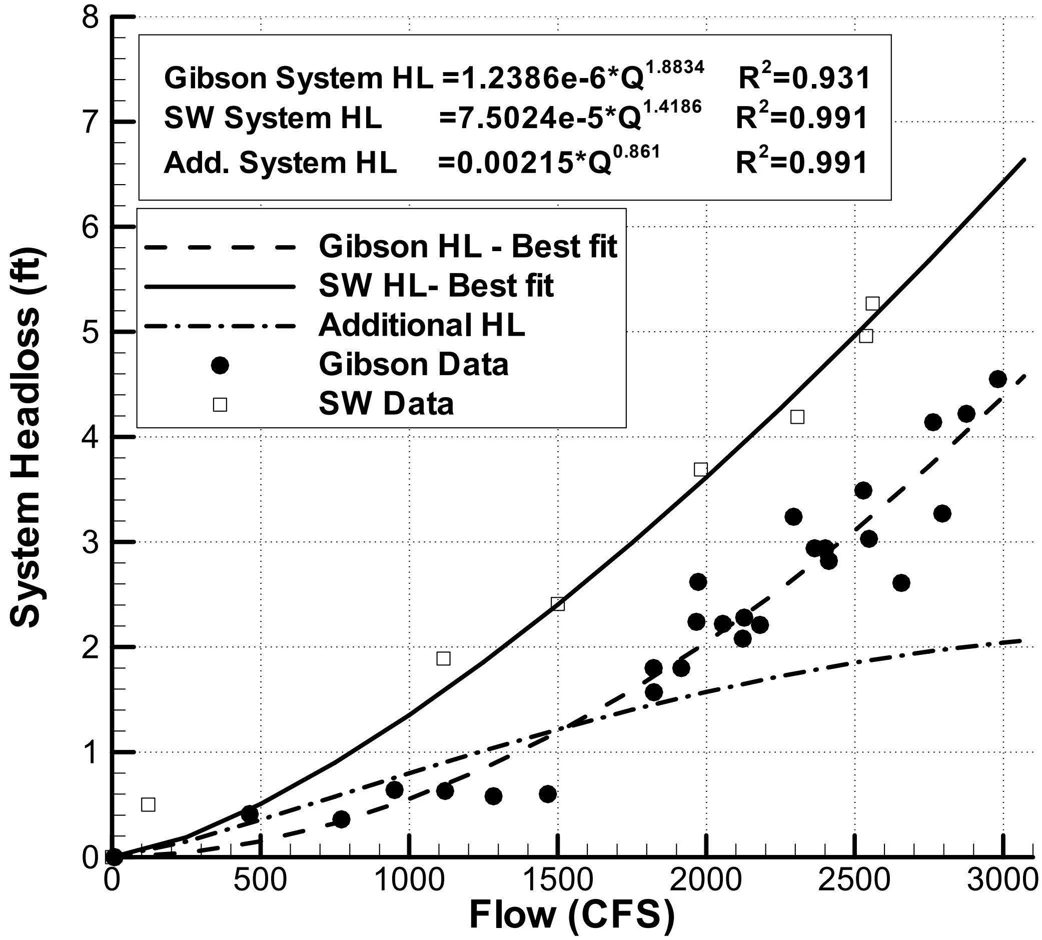
To develop a head loss versus discharge relationship for the selective withdrawal system, system head loss measurements were collected on unit No. 2, as described earlier in this report. During field tests conducted on July 16, 2003, unit No. 2 generation rates varied from 0 to 91 MW, control gate submergence was constant at 30 feet, all 5- by 7-foot slide gates were closed, and the reservoir elevation was 3555.3 feet (5 feet below the maximum water surface elevation). Scroll case pressures were measured using the same piezometer lines that Gibson used in 1954. Eight data points were collected (table 8) and analyzed using the same relationships for velocity head, floor elevation, and pressure conversions that were used by Gibson. Unlike the Gibson tests, a direct measurement of flowrate was not available for these tests. As a result, flows were estimated by prorating the river discharge by the ratio of individual MW output to the total plant MW output. Units No. 2 and No. 4 were the only units in operation during the tests. River discharges were obtained from a 1995 Field Installation Test Results (site I.D. 12362500) located about 1.7 miles downstream from Hungry Horse Dam. Using this data set, a best-fit power relationship between system head loss and discharge was developed as shown in figure 25.

Table 8. System head loss data for unit No. 2 collected on July 16, 2003.

Unit No. 2 Generation (MW)	Unit No.2 Estimated Flow (cfs)	System Headloss (ft)
0	0	0
4.6	121.7	0.50
40	1115.5	1.89
53	1500.7	2.41
71	1982.4	3.69
82	2306.9	4.19
89.8	2538.0	4.96
90.7	2560.4	5.27

To determine what additional head loss could be solely attributed to the selective withdrawal system, a Gibson test system head loss relationship was subtracted from the selective withdrawal system head loss relationship. This approach does not isolate the head loss attributed to 50 years of aging in the system components, such as the penstock, trash racks, inlet transitions, etc. Figure 25 shows the best-fit relationships developed to compute additional head loss. These relationships were used to estimate 6.6 feet of system head loss and 2.1 feet of additional head loss attributed to the selective withdrawal system for the maximum unit discharge of 3070 cfs. It is important to note that system head loss is a function of reservoir level (flow path length) and trash rack approach velocity (a function of submergence and debris accumulation on the trash rack). Both these factors can change the system head loss characteristics.

The uncertainty in the system head loss measurements was determined using error propagation analysis techniques described in a text on error analysis (Taylor, 1997). Uncertainties in pressure, discharge, and reservoir elevation were used in the head loss error analyses. For these analyses, it was assumed that the uncertainty in the penstock area was negligible. This analysis showed that the uncertainty in USGS discharge measurements (± 6 percent) was the primary error component. A conservative uncertainty estimate for additional head loss at a maximum flow of 3070 cfs was computed to be ±0.1 ft.



System head loss is measured from reservoir forebay to scroll case

Figure 25. System head loss data and best fit relationships for Gibson, selective withdrawal, and the additional head loss attributed to the Hungry Horse selective withdrawal system for 30 feet of submergence.

Control Gate Submergence Effects on System Head Loss

On September 11, 2002, a series of pressure measurements were collected for submergences ranging from 20 to 40 feet. The measurements were taken on unit No. 3 operating at a constant 66 MW (2000 cfs) at a reservoir head of 444 feet. Using 30 feet of submergence as a baseline, a relationship was developed for the differential head loss associated with a submergence departure from 30 feet. This analysis showed that there is very little change in system head loss over the range of submergences tested. For example, the differential head loss between 20 and 40 feet of submergence was 0.184 feet as shown in table 9.

Table 9. Differential head loss measured with control gate submergence ranging from 20 to 40 ft. Differential head loss is the change in head loss with respect to a typical control gate submergence of 30 ft.

Control Gate Submergence (ft)	System Head Loss (ft)	Differential Head Loss (ft)
20	3.09	0.15
25	3.01	0.07
30	2.94	0.00
32	2.94	0.00
35	2.94	0.00
40	2.91	-0.03

Equation 2 is the best fit equation for this relationship, where *S* is the control gate submergence in feet.

$$Differential\ head\ loss\ (ft) = -0.0914 + \left(98.594 / S^2\right) \quad (R^2 = 0.98) \qquad \textbf{(2)}$$

Equation 2. Best-fit relationship for computing differential head loss associated with control gate submergence.

SELECT Model Performance

To estimate release water quality parameters from stratified reservoirs, the U.S. Army Corps of Engineers created a one-dimensional selective withdrawal spreadsheet model, commonly known as the SELECT model. This modeling tool was developed to assist project operators in the day-to-day operations of a dam fitted with a selective withdrawal structure. Evaluating SELECT model performance for Hungry Horse Dam was based on its ability to predict release water temperatures when the reservoir temperature profile, reservoir elevation, control gate elevations, and individual control gate flow rates were input into the model. The model predictions were compared to actual release temperatures to determine the root mean square (RMS) uncertainty in the model output.

For this project, SELECT Version 4.0, A One-Dimensional Reservoir Selective Withdrawal Model Spreadsheet (Schneider et al., 1999) was used for all selective withdrawal modeling. In SELECT withdrawal ports (gates) can be described as a point sink, while spillways or submerged weirs are described as a line sink. Thus, there are two options to run the model: the port option and the weir option. The evaluation of Hungry Horse Dam used both options. The selective withdrawal system at Hungry Horse Dam contains control gates which draw water over the crest of the intake. Since the control gate configuration could be described as using either the port or weir options, data were input using both options for analysis. For the port option, a centerline elevation is specified to locate the port. The Hungry Horse selective withdrawal control gate has a horizontally-oriented port configuration as opposed to a vertical orientation. As a result, for both port and weir model runs, intake elevations were specified as control gate crest elevations. The port withdrawal angle was specified at 180^{o} and the weir length was the summation of the arc lengths for all operational semi-cylindrical control gates.

The SELECT model was used to predict release water temperatures for a variety of conditions in 2000, 2001, and 2003. Forebay temperature profiles were not collected in 2002. Since SELECT is a one-dimensional steady state model, it was important to pick data sets from periods with steady state conditions. Data sets were chosen based on steady state flow rates, release temperatures, and temperature profiles. Steady state conditions were defined as when model input values were nearly constant for 4 to 5 consecutive hours. However, model runs were also conducted before and after gate changes to examine how well the SELECT model predicts release temperatures for unsteady conditions. Release temperatures were analyzed before, during, and after storms where significant seiching occurred. In 2001, large changes in flow rate through control gate No. 4 were also analyzed. As expected, the SELECT model performance declined for unsteady conditions when compared to steady state model runs. For this report, only results for the steady state model runs are presented and discussed.

SELECT Modeling Results

The first round of SELECT modeling using year 2000 data included the evaluation of the weir and port withdrawal descriptions. A comparison of port and weir intake descriptions showed that the port option performed better based on the ability to predict the actual release temperatures. For example in 2000, release temperatures computed using the weir option were 2.8 °F colder when compared to release temperatures computed using the port option. Consequently, the port option was used for all remaining SELECT modeling.

Results for SELECT model runs for years 2000, 2001, and 2003 are summarized in Table 10. The root mean square (RMS) error between SELECT predictions and actual release temperatures are summarized as follows:

- For 2000, the RMS error for release temperature predictions was 1.3 °F
- For 2001, the RMS error for release temperature predictions was 1.3 °F
- For 2003, the RMS error for release temperature predictions was 1.5 °F

The model errors for all the model runs are shown in figure 26. Figure 26 illustrates that SELECT usually under predicts release temperatures during steady state conditions.

The model error was largest in July and August when stratification was strongest. In September when stratification began to breakdown, the epilimnion thickened and model predictions improved.

A series of SELECT model runs were performed to determine how much the control gate had to be raised to minimize the error in the SELECT model predictions. A gate adjustment offset was computed as the average gate elevation adjustment required to reduce the model errors to below 0.1 °F. For the data in table 10, SELECT model errors were minimized by raising the port elevation by an average of 2.3 feet.

Table 10. SELECT model runs for steady-state conditions for years 2000, 2001, and 2003.

Date / Time	Total Release (cfs)	SELECT Temp. (^oF)	Release Temp. (^oF)	Model Error* (^oF)	Temperature Goal (^oF)	Reservoir Elevation (ft)	Control Gate Submergence (ft)
2000 SELECT Model Runs							
6/23/2000 0:45	4644	49.5	49.6	-0.1	55.4	3556.9	24.9
6/26/2000 1:45	4669	49.7	51.3	-1.6	56.1	3557.8	25.8
7/6/2000 18:00	6109	57.9	55.5	2.4	58.1	3557.8	25.8
7/15/2000 16:15	5637	53.1	52.4	0.7	59.4	3555.7	25.2
8/5/2000 4:45	5287	63.9	61.7	2.2	59.9	3548.7	23.7
8/17/2000 8:00	4452	52.6	56.9	-4.3	59.0	3544.6	34.9
8/29/2000 2:45	2927	56.4	58.8	-2.4	57.4	3540.4	30.7
9/6/2000 19:00	1619	58.4	57.7	0.7	56.1	3539.0	29.3
9/15/2000 12:15	1627	55.1	56.9	-1.8	54.7	3538.1	28.4
2001 SELECT Model Runs							
6/26/2001 19:15	493	49.1	48.8	0.3	56.1	3540.1	32.1
7/3/2001 22:30	1015	52	55.2	-3.2	57.6	3542	34
7/7/2001 22:45	1037	56.6	59.4	-2.8	58.3	3542.4	34.4
7/21/2001 4:30	986	57.8	59.7	-1.9	59.9	3543.2	30.2
7/26/2001 17:00	1000	55.5	58.8	-3.3	60.1	3543.1	30.1
8/4/2001 15:15	1474	57.9	60.5	-2.6	60.1	3542.8	29.8
8/9/2001 8:00	1474	65	63.7	1.3	59.7	3542.5	29.5
8/16/2001 20:45	1822	63.2	63.7	-0.5	59.0	3541.7	28.7
8/28/2001 7:30	2168	60.1	62.5	-2.4	57.6	3540.1	27.1
9/1/2001 15:00	2214	63.4	62.5	0.8	56.8	3539.3	26.3
9/9/2001 17:30	2214	59.2	59.4	-0.2	55.6	3537.9	29.9
2003 SELECT Model Runs							
7/1/2003 0:00	3292	51.3	54.6	-3.3	57.2	3557.9	24.9
7/8/2003 0:00	5030	55.1	56.3	-1.2	58.5	3557.5	24.5
7/15/2003 15:00	5045	54.3	56.9	-2.6	59.4	3555.7	22.7
7/22/2003 15:00	5030	53.7	56.6	-2.9	59.9	3553.6	28.2
7/29/2003 15:00	5074	56	60.5	-4.5	60.1	3551.2	30.3
8/5/2003 15:00	5103	56.6	57.7	-1.1	59.9	3548.5	36.5
8/12/2003 15:00	5191	53.7	58	-4.3	59.5	3545.8	31.3
8/19/2003 15:00	4708	55.2	59.1	-3.9	58.6	3543	31
8/26/2003 15:00	2602	48.9	51.8	-2.9	57.7	3540.9	45.9
9/2/2003 15:00	1987	58.9	58.3	0.6	56.7	3539.7	39.7
9/9/2003 15:00	2049	60.2	60	0.2	55.6	3538.5	29.5
9/16/2003 15:00	1950	57.3	56.6	0.7	54.5	3537.7	28.7
9/23/2003 15:00	2096	53.1	53	0.1	53.4	3536.8	32.8
9/30/2003 15:00	2265	53.9	55.18	-1.3	52.5	3535.7	31.7

* Model Error = SELECT Release Temperature – River Temperature

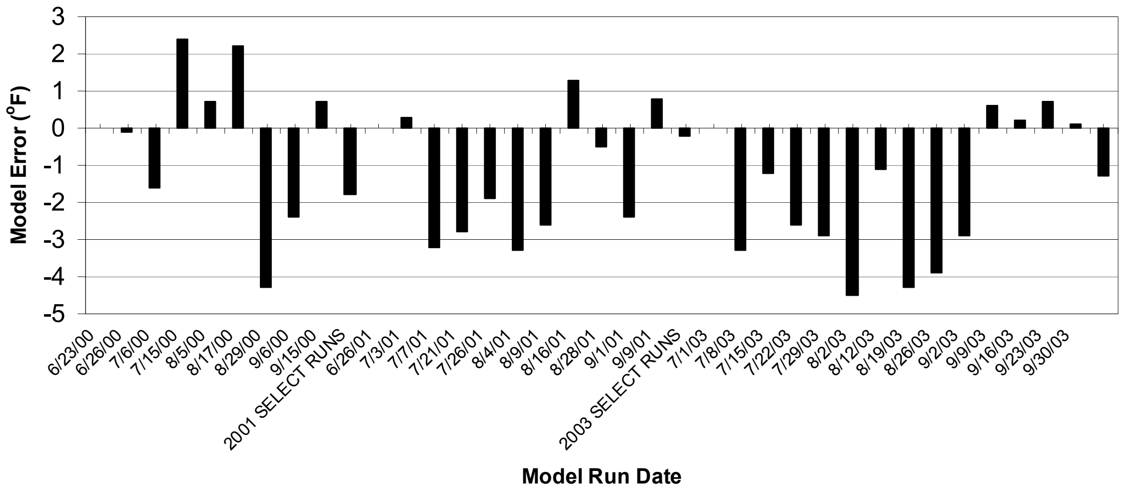


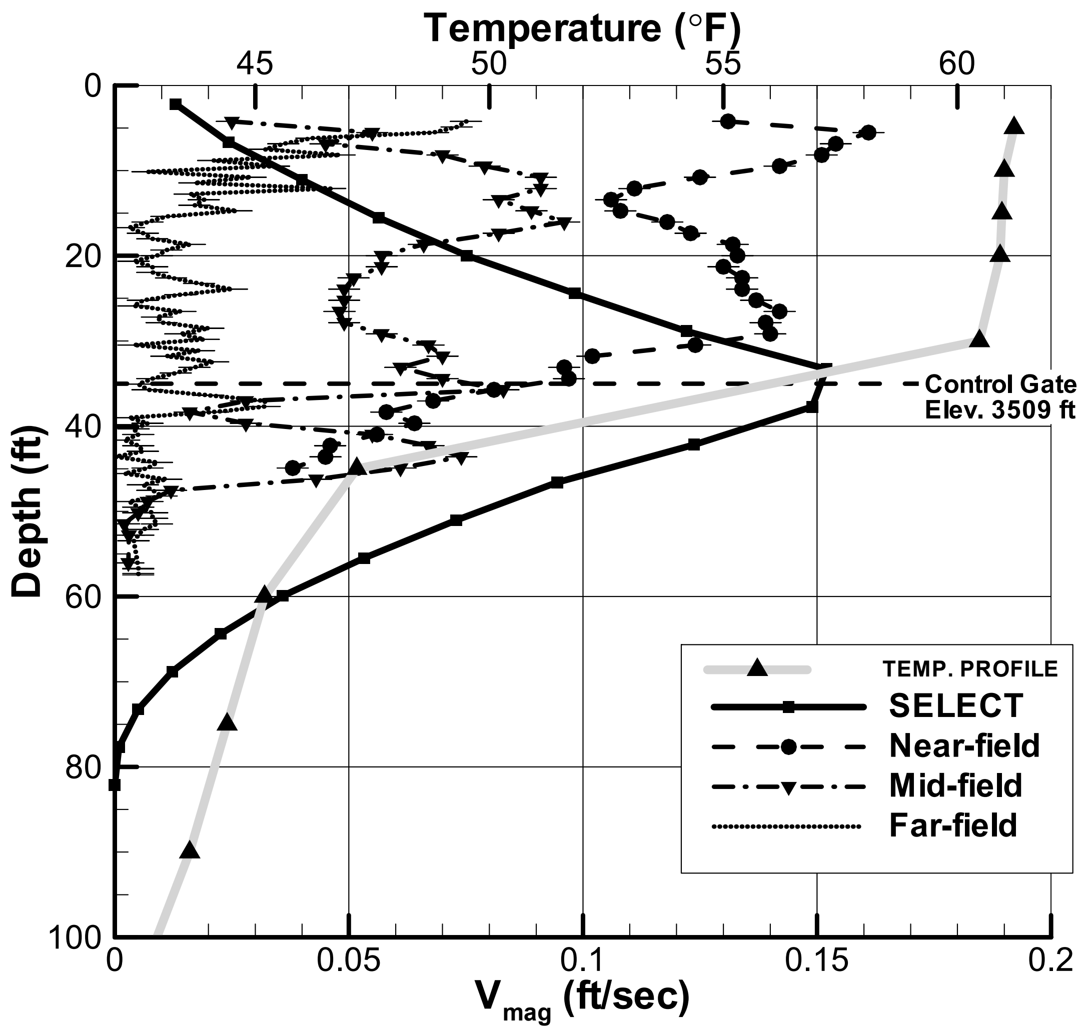
Figure 26. Plot of SELECT model errors for steady-state runs for years 2000, 2001, and 2003. This plot illustrates how using the SELECT model with the port option under predicts Hungry Horse release temperatures.

Comparison of SELECT Versus ADCP Velocity Profiles

ADCP profiles collected in the Hungry Horse forebay were used to compare field-measured velocity profiles with SELECT computed profiles. During ADCP data collection, the powerplant was releasing 2000 cfs per unit with 2 units operating. The reservoir elevation was 3543.9 feet and the control gates were at elevation 3509.

ADCP profiles were collected at three locations representing the near, mid, and far field withdrawal characteristics (figure 9). Figure 27 presents a comparison of the field and model velocity profiles for reservoir conditions on September 10, 2002. Velocity directions were not plotted, but they were in a northwesterly direction (305 degrees clockwise from north which is toward the intakes). A summary of the ADCP velocity profile data is included in appendix B.

The ADCP velocity data clearly show that SELECT does not accurately represent the actual withdrawal characteristics. SELECT under predicts upper withdrawal layer velocities and over predicts the lower withdrawal layer velocities (upper and lower layers are referenced with respect to the control gate crest). This result is consistent with SELECT under predicting the computed release water temperatures. There was an interesting dip in the ADCP velocity profiles at a depth of 13 feet that occurred in all three velocity profiles. The drop in velocity is likely attributed to ambient reservoir currents that SELECT is incapable of modeling.



Error bars represent the Standard Error of the ADCP Velocity Magnitude

Figure 27. Comparison between SELECT computed velocity profile and ADCP measured velocity magnitudes measured at three locations near the selective withdrawal structure. The ADCP velocities show that SELECT doesn't accurately represent the withdrawal characteristics of the Hungry Horse selective withdrawal control gates. Horizontal error bars on the plot represent the standard error of the ADCP velocity magnitudes. ADCP and forebay temperature profile data were collected September 10, 2002.

Discussion

Reservoir Operations

Variation in reservoir water levels can have a significant impact of selective withdrawal operations, especially for fixed-inlet intake structures. However, the Hungry Horse system was designed with a 160 vertical feet range of continuous operation. The system should perform satisfactorily from the maximum reservoir water surface elevation 3560 feet down to elevation 3400. In 2001, the driest year during this evaluation, the system operated at its lowest level when the control gate was used set at elevation 3502, with another 102 feet of operational range in reserve. The selective withdrawal system performed similarly for all reservoir elevations experienced during this evaluation. This result illustrates that variations in reservoir elevation, within the operational range, do not affect selective withdrawal performance. It is important for operators to be aware of increasing or decreasing water surface elevations and the affect on control gate submergence. There were several instances where the control gate submergence would drift away from 30 feet and the release water temperatures would fall out of compliance.

Release Temperature Monitoring

Three data sources were analyzed to determine the best location to monitor reservoir release temperatures, they were:

- Turbine-bearing cooling water taken from each penstock
- Tidbit logger in the river ½ mile below the dam
- Total Dissolved Gas monitoring station located 1.7 miles downstream from the dam (Reclamation HYDROMET station I.D. HGHM, or also available from the USGS gaging site 12362500)

An analysis of the three data sources showed there was no significant difference between the three locations. However, there is a 1 to 2 hour travel time from the dam to the HGHM site which makes this site a little less desirable from an operational standpoint. The HGHM site is convenient because its data are available from Reclamation's Hydromet website. However, equipment at the HGHM site was observed to be somewhat unreliable. If necessary, penstock water temperatures are also available from thermometers mounted in the cooling water supply lines.

A comparison of turbine-bearing cooling water temperatures when unit MW generation was equal showed that there was no appreciable temperature differential between units No. 1 and No. 4. In almost all cases, unit No. 4 temperatures were less than 0.7 °F warmer that unit No. 1 release temperatures. Based on the ± 0.4 °F uncertainty in the temperature loggers used for this study and the diurnal fluctuations in release temperatures, this modest differential should not be a concern to project operators when selecting which unit to operate.

Modification of Forebay Temperature Profiles

Reservoir Temperature Monitoring

Three years of high resolution temperature profiling in the forebay resulted in a very comprehensive database to study the thermal impacts on Hungry Horse reservoir. Likewise, a MDFWP database of biweekly reservoir temperature profiles from 1983 to 1989 was used to determine if selective withdrawal changed reservoir stratification. An analysis of pre- and post-selective withdrawal forebay temperatures showed that selective withdrawal operations modified the reservoir's thermal structure, both spatially and temporally.

Epilimnion

One common question that arises when surface withdrawal capability is added to a dam is: *Will the reservoir surface temperatures be reduced during selective withdrawal operations*? An analysis of pre- and post-selective withdrawal surface temperatures showed that forebay surface temperatures during selective withdrawal operations increased for each month of the selective withdrawal season. An explanation for this warming may be a local thickening of the epilimnion associated with surface withdrawal that wasn't present for pre-selective withdrawal operations. Diurnal seiches could also be a factor if the pre-selective withdrawal profiles were consistently collected in the morning. Or it may result from comparing biweekly temperature profile data with a continuous record. It would be interesting to know if diurnal seiches were present during pre-selective withdrawal operations or if they have increased in magnitude with the implementation of selective withdrawal?

Surface seiches are practically a daily occurrence at Hungry Horse reservoir. As a result, there can be hourly variations in selective withdrawal release temperatures. In some extreme cases, seiches can cause release temperatures to exceed the temperature guidelines. These temperature fluctuations are short-term and should not require adjustments to the control gate elevations.

Comparing pre- and post-selective withdrawal surface temperatures for November and December shows that selective withdrawal reduced the average monthly surface temperature by 3 °F. These data support the observation that fall turnover occurs a week or two earlier during selective withdrawal operation. However, there is a paucity of pre-selective withdrawal profile data to draw a firm conclusion on this observation.

Thermocline

An analysis of pre- and post-selective withdrawal forebay temperatures showed that selective withdrawal caused significant changes to the thermocline. Post selective withdrawal temperature profiles during selective withdrawal operations showed stronger thermoclines for years 2000, 2001, and 2003. Profiles showed that the lower limit of the thermocline changed from 170 feet to about 120 feet during selective withdrawal operations. These observations are contrary to what was reported by Marotz et al. (1994). Marotz' model results predicted that: "warm water withdrawal in the vicinity of the thermocline may weaken the thermal stability during stratification." A stronger thermocline has positive selective withdrawal performance implications because it will reduce the expansion of the lower limit of the withdrawal zone. A smaller withdrawal zone allows operators to increase the control gate submergence which reduces the system head loss.

Hypolimnion

Before installing the selective withdrawal system, hypolimnetic withdrawals caused little change in the water temperatures near the reservoir bottom (elevation 3100). A comparison of near-bottom temperatures showed a constant year-round temperature at 38 °F for pre- and post-selective withdrawal periods. The difference between average hypolimnetic temperatures for November and December for years 1983 through 1989 (pre-selective withdrawal) and years 2000 and 2002 were within the uncertainty in the temperature loggers thermistor (±0.4 °F) used for monitoring.

However, selective withdrawal operations creates more uniform hypolimnetic temperatures because the deep water mixing associated with pre-selective withdrawal operations no longer occurs. Likewise, water stored in the hypolimnion is more or less static during the selective withdrawal season and isn't released from the reservoir until early October when the selective withdrawal system is taken out of service.

Selective Withdrawal Operations

Meeting Flathead River temperature goals using selective withdrawal at Hungry Horse Dam is complicated by variable power operations, seiches, and control gate submergence requirements. Typically, there is a two-week delay in meeting June temperature criteria because control gate submergence is limited to 30 feet. This delay could be reduced if a 20 feet submergence were allowed during early June. A reservoir temperature model was used by MDFWP to develop the temperature guidelines using a 21 feet submergence criterion (Marotz et al., 1994). Reclamation's 30 feet submergence criteria is based on limiting debris entrainment into the penstocks that causes maintenance problems with broken wicket gate shear pins and excessive debris collecting in cooling water strainers. This problem is especially prevalent in the early summer when debris loads are heaviest. Furthermore, a change was made to the standard operating procedures (SOP) that requires 30 feet of control gate submergence during unit startup. This change to the SOP effectively increases the minimum submergence criterion at Hungry Horse by 10 feet. Control gates can be raised to less than 30 feet of submergence to achieve warmer release temperatures during periods of prolonged operation. However, the powerplant is remotely operated during evenings and weekends, and control gate positions are not available at the remote operations center. Furthermore, units at Hungry Horse often require remote or automatic restarting. Given this potential for misoperation, project operators do not like to operate at submergences less than 30 ft.

Control Gate Operations

Selective withdrawal operations in all years significantly improved downstream thermal conditions. Compliance with release temperature guidelines that MDFWP provided depends not only on operator-controlled gate elevations but also hydrologic and meteorologic conditions. The frequency of control gate adjustments varied from monthly in 2000 to weekly in 2003; increasing the frequency did not always translate into improved performance. For example in 2003, operators were using control gate increments of 1 to 3 feet to manage release temperatures. These small gate changes produced small changes in release temperatures which were masked by diurnal fluctuations. Selecting the proper control gate elevation was made difficult because of the 4 to 5 ^{o}F range of release temperatures caused by diurnal seiches. Consequently, it is recommended that a method be established to compute a mean daily release temperature to compare with the temperature goal so that appropriate gate changes can be selected. Average daily river temperatures are available on from the HGHM site on Reclamation's Hydromet system. It is also important to consider whether the reservoir is filling or drafting when deciding on the gate adjustment distance. In the late summer when reservoir elevations are dropping rapidly it may be appropriate to lower the gate an extra foot or two to reduce the number of gate changes required to meet the temperature guidelines.

The selective withdrawal system was designed with intermediate slide gates, located 50-ft below the top of the control gate, to reduce the withdrawal of plankton-enriched water from the reservoir. This feature was requested by MDFWP biologists based on reservoir modeling that showed a significant entrainment of zooplankton (Marotz et al., 1994). System operators reported that these gates were only used during the first two years of operation. Recent communications with MDFWP biologists revealed that results from post selective withdrawal reservoir/tailwater evaluation of zooplankton entrainment were not completed because of funding limitations.

During winter months the reservoir is isothermal and the selective withdrawal system is not used. Usually in early October the control gates are lowered to their lowest position and the relief gates are raised to the top of the trashrack structure to minimize system head loss and maximize power production. Reservoir modeling showed that selective withdrawal benefits for fish growth could be extended into November (Marotz et al., 1994). However, system operators prefer to take the system offline in early October because freezing air temperatures can create an unsafe work environment for maintenance staff during system shutdown.

System Head Losses

Physical model investigations were conducted in 1994 to evaluate the hydraulic characteristics of the Hungry Horse selective withdrawal system (Kubitschek, 1994). A 1:18 scale Froude model of a single power penstock intake and trashrack structure was constructed at Reclamation's Hydraulic Investigations and Laboratory Group in Denver, Colorado. Model tests were run to evaluate head loss and vortex formation potential. The predicted maximum additional prototype head loss associated with the selective withdrawal system was found to be 5.0 feet for the maximum intake discharge and a minimum submergence of 20.0 feet. The uncertainty in the model study head loss measurement was reported to be ± 40 percent or ±2.0 feet (Kubitschek, 1994).

Field measurements of system head loss indicated 6.6 feet of head loss for the maximum unit discharge of 3070 cfs and 30 feet of submergence. The selective withdrawal system was responsible for 2.1 feet of additional head loss. The additional head loss for the maximum unit discharge at 20 feet of submergence was about 2.3 feet. A conservative uncertainty estimate for this head loss was computed to be ±0.1 feet. It is important to note that system head loss is a function of reservoir level (flow path length) and trash rack approach velocity (a function of submergence) that can change with debris accumulation; both these factors can change the system head loss characteristics.

Field measurements showed that there is very little change in system head loss over the range of submergences tested. For example, the differential head loss between 20 and 40 feet of submergence was 0.18 feet. The difference between field and model study head loss measurements was likely caused by an undersized model head box, uncertainties in the pressure transducer used for the model study, and model scaling effects.

SELECT Modeling

The SELECT model was evaluated as a potential tool to assist project operators set control gate elevations to meet release temperature guidelines. The evaluation showed that SELECT does not accurately represent the withdrawal characteristics of the Hungry Horse selective withdrawal system. The horizontal orientation of the port is not suited for the port or weir intake descriptions in the model.

However, SELECT modeling results can be improved with a procedure developed using a “virtual” gate position. The procedure requires the user to populate the model with current temperature profile and operations data before a control gate change is made. Then the current port elevations are adjusted until the computed and actual release temperatures are equal. Next, the port elevations are changed to achieve the *target* release temperature. The elevation difference between the virtual and the new gate position is the distance the control gates should be adjusted from their current elevation(s).

For example, on July 13, 2001 a 5 feet gate change was made from control gate elevation 3508 to 3513. The purpose of the gate change was to reset the gate submergence to 30 feet. After the change, penstock release temperature increased from 56 to 59.5°F for a release equal to 1120 cfs. The river temperature goal for this day is 59.2 °F (Appendix A), so the operators overshot the goal by 0.3°F. To use SELECT to compute a gate change the operators would need to get a recent forebay temperature profile from the thermistor string on the face of the dam, powerplant releases, and the average daily river temperature for the previous day. It is important to use a daily average of release temperatures because it is common to have diurnal fluctuations up to 5 °F. For this example, data were taken from the forebay temperature string data collected for this study. The data describing the existing conditions were entered into the SELECT model. The model predicted a 52.1°F release temperature which is 3.9 °F lower than the actual value. The port elevations were adjusted until the SELECT release temperature equaled the actual value. The resulting port elevation was 3516.5 feet which is the "virtual" or calibrated control gate elevation. Next, port elevations were adjusted to elevation 3522.3 where SELECT release temperature equaled the temperature goal, 59.2 °F. The difference between this elevation and the virtual control gate elevation, 5.75 feet, is the estimated control gate change. Note: this estimate is 0.75 feet greater than the actual gate change. As a result, the computed gate change would have overshot the temperature goal by about 0.8°F which is within the ±3.6 °F tolerance band.

The projected penstock discharges are important operational considerations, because discharge plays an important role in selective withdrawal performance. For example, Hungry Horse powerplant releases were doubled to 2200 cfs at 17:00 on July 13, 2001 and the release temperature dropped 0.9°F. The effects of large flow changes can be modeled with SELECT by establishing a virtual control gate elevation and then changing the flowrate.

While this procedure may improve the operational efficiency in making control gate changes, it may be more practical to continue the practice of making gate adjustments based on operator experience and records of past operational changes. For the example above, we know that raising the control gate 5 feet resulted in a 3.5°F increase in outflow temperatures. It is reasonable to expect a similar response to a similar gate change in mid July for a different year—provided the gate submergence and unit discharges are similar. With this procedure, it is important for project operators to keep an accurate record of selective withdrawal operations as a resource for decision making.

Selective Withdrawal Operation and Maintenance Issues

In 2003, a survey was conducted to gather information on operational selective withdrawal systems throughout the United States (Vermeyen et al., 2003). Operators at Hungry Horse Dam submitted a response to the survey. Operation and maintenance issues they have encountered since the system went online in 1995 were:

- Governor speed of the wicket gates was set at 15 seconds to limit water hammer loading on the selective withdrawal structure.

- A 30-ft submergence requirement was added as a standard operation procedure for unit start-up. This change was implemented to protect relief gate shear pins during unit start-up and to minimize debris accumulation in the cooling water strainers. This requirement, combined with the 30-foot submergence operating requirement, effectively limits selective withdrawal operations to a minimum of 30 feet of submergence.

- On average, 1 or 2 pressure relief panels and approximately 6 relief panel shear pins need replacement during annual maintenance.
- On average, 12 wicket gate shear pins are replaced per year. Operators attribute shear pin failures to woody debris entrained through the selective withdrawal system

- Project operators reported that a submergence of 30-32 feet was found to limit debris accumulation in cooling water strainers.

- Total dissolved gas content in powerplant releases increased significantly when selective withdrawal was in-use and monitoring is now required to identify water quality conditions. Hungry Horse power plant releases in the summer are now close to exceeding Montana's Department of Environmental Quality's (MDEQ) water quality standards related to TDG levels.

- Surface withdrawals have increased debris loads, so larger secondary strainers on bearing cooling water supply lines were installed. The larger strainers were needed to filter out pollen and pine needles. Cooling water strainers now require daily inspection.

- Bearing cooling water alarm set points were raised. Higher temperature-rated bearings (No. 2 Babbitt) were installed during recent unit overhauls to accommodate higher release temperatures associated with selective withdrawal.

Conclusions

A review of the selective withdrawal release temperatures showed the majority of temperature guideline exceedences occurred during the first two weeks of June. For the rest of the temperature control season, only occasional exceedences occurred. The temperature control season is 122 days long and includes the months of June through September. The selective withdrawal system appears to have the operational flexibility to meet the temperature guidelines if operators closely monitor control gate submergence and average daily release temperatures.

Forebay temperature profile data revealed that selective withdrawal has increased surface temperatures by a seasonal average of 2.1 °F in Hungry Horse Reservoir. An explanation for the apparent surface temperature warming may be a local thickening of the epilimnion associated with surface withdrawals. Or it may result from comparing biweekly temperature profile data collected 3 miles upstream from the continuous monitoring site.

Forebay temperature profile data also showed that two types of seiches occur in the reservoir. Diurnal and storm seiches both impact the selective withdrawal performance. Diurnal seiches created 3 to 5 °F variations in release temperatures and would often double the thickness of the epilimnion in a few hours. Storm seiches modified forebay temperatures enough that temperature guidelines were exceeded for two to three days.

Collecting wind speed and direction data at the dam was not included in the study plan. This was unfortunate because local wind data would have been used to further describe the effects of seiching on selective withdrawal performance.

Forebay temperature profiles showed that the vertical extent of the thermocline was reduced during selective withdrawal, contrary to pre-project reservoir modeling results. Hypolimnetic temperatures were more uniform, but not significantly cooler during selective withdrawal operations. The overall volume of cold water stored in the hypolimnion was increased because of the reduced thermocline thickness.

An analysis of control gate operations showed that acceptable performance could be achieved with monthly to weekly gate adjustments. The frequency of gate adjustments will depend on surface water temperature, control gate submergence criterion, release flow rates, and debris accumulation near the intakes. There were periods in late summer when using submergences greater than 30 feet would have resulted in temperatures closer to the guidelines.

While investigating selective withdrawal impacts on total dissolved gas levels in Hungry Horse Dam releases was not included in this evaluation, it was observed that TDG levels increase significantly during surface withdrawals.

Measuring system head loss for a range of flows and submergences resulted in relationships that can be used to estimate additional head loss associated with this type of selective withdrawal system. The maximum system head loss measured was 6.6 feet for the maximum unit discharge of 3070 ft^3/sec at 30 feet of submergence. The selective withdrawal system was responsible for 2.1 feet of additional head loss. The additional head loss for the maximum unit discharge and 20 feet of submergence would be about 2.3 feet. This head loss information can be used to determine the economic impacts of adding selective withdrawal for future selective withdrawal installations.

The U.S. Army of Engineers' SELECT Model was evaluated for predicting release water temperatures from the Hungry Horse selective withdrawal system. This evaluation showed that SELECT does not have an outlet option that accurately describes the overdraw intake used at Hungry Horse. A procedure was developed which allows operators to estimate a control gate adjustment using a "virtual" port elevation.

For the Hungry Horse selective withdrawal system, a point sink assumption at the control gate elevations produced an under prediction of release temperatures. A 2 to 4 feet increase in the port centerline elevation produced the best results.

Selective withdrawal operations increased river temperatures during reservoir stratification, providing better habitat for endangered fish species. Additional control gate elevation changes throughout the summer and early fall will produce better compliance to river temperature guidelines.

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Appendices

Appendix A: Hungry Horse selective withdrawal release temperature guidelines

Table A-1: Hungry Horse selective withdrawal release temperature guidelines

JUNE			JULY			AUGUST			SEPTEMBER		
Day	Optimum Temp.ºC	Optimum Temp. ºF	Day	Optimum Temp. ºC	Optimum Temp. ºF	Day	Optimum Temp. ºC	Optimum Temp. ºF	Day	Optimum Temp. ºC	Optimum Temp. ºF
1-Jun	9.6	49.3	1-Jul	14.0	57.2	1-Aug	15.6	60.1	1-Sep	13.8	56.8
2-Jun	9.8	49.6	2-Jul	14.1	57.4	2-Aug	15.6	60.1	2-Sep	13.7	56.7
3-Jun	9.9	49.8	3-Jul	14.2	57.6	3-Aug	15.6	60.1	3-Sep	13.6	56.5
4-Jun	10.1	50.2	4-Jul	14.3	57.7	4-Aug	15.6	60.1	4-Sep	13.5	56.3
5-Jun	10.3	50.5	5-Jul	14.4	57.9	5-Aug	15.5	59.9	5-Sep	13.5	56.3
6-Jun	10.4	50.7	6-Jul	14.5	58.1	6-Aug	15.5	59.9	6-Sep	13.4	56.1
7-Jun	10.6	51.1	7-Jul	14.6	58.3	7-Aug	15.5	59.9	7-Sep	13.3	55.9
8-Jun	10.7	51.3	8-Jul	14.7	58.5	8-Aug	15.4	59.7	8-Sep	13.2	55.8
9-Jun	10.9	51.6	9-Jul	14.8	58.6	9-Aug	15.4	59.7	9-Sep	13.1	55.6
10-Jun	11.0	51.8	10-Jul	14.9	58.8	10-Aug	15.4	59.7	10-Sep	13.0	55.4
11-Jun	11.2	52.2	11-Jul	14.9	58.8	11-Aug	15.3	59.5	11-Sep	12.9	55.2
12-Jun	11.4	52.5	12-Jul	15.0	59.0	12-Aug	15.3	59.5	12-Sep	12.8	55.0
13-Jun	11.5	52.7	13-Jul	15.1	59.2	13-Aug	15.2	59.4	13-Sep	12.7	54.9
14-Jun	11.7	53.1	14-Jul	15.2	59.4	14-Aug	15.2	59.4	14-Sep	12.7	54.9
15-Jun	11.8	53.2	15-Jul	15.2	59.4	15-Aug	15.1	59.2	15-Sep	12.6	54.7
16-Jun	12.0	53.6	16-Jul	15.3	59.5	16-Aug	15.0	59.0	16-Sep	12.5	54.5
17-Jun	12.1	53.8	17-Jul	15.3	59.5	17-Aug	15.0	59.0	17-Sep	12.4	54.3
18-Jun	12.3	54.1	18-Jul	15.4	59.7	18-Aug	14.9	58.8	18-Sep	12.3	54.1
19-Jun	12.4	54.3	19-Jul	15.4	59.7	19-Aug	14.8	58.6	19-Sep	12.2	54.0
20-Jun	12.6	54.7	20-Jul	15.5	59.9	20-Aug	14.8	58.6	20-Sep	12.1	53.8
21-Jun	12.7	54.9	21-Jul	15.5	59.9	21-Aug	14.7	58.5	21-Sep	12.1	53.8
22-Jun	12.9	55.2	22-Jul	15.5	59.9	22-Aug	14.6	58.3	22-Sep	12.0	53.6
23-Jun	13.0	55.4	23-Jul	15.5	59.9	23-Aug	14.6	58.3	23-Sep	11.9	53.4
24-Jun	13.1	55.6	24-Jul	15.6	60.1	24-Aug	14.5	58.1	24-Sep	11.8	53.2
25-Jun	13.3	55.9	25-Jul	15.6	60.1	25-Aug	14.4	57.9	25-Sep	11.8	53.2
26-Jun	13.4	56.1	26-Jul	15.6	60.1	26-Aug	14.3	57.7	26-Sep	11.7	53.1
27-Jun	13.5	56.3	27-Jul	15.6	60.1	27-Aug	14.2	57.6	27-Sep	11.6	52.9
28-Jun	13.6	56.5	28-Jul	15.6	60.1	28-Aug	14.2	57.6	28-Sep	11.5	52.7
29-Jun	13.8	56.8	29-Jul	15.6	60.1	29-Aug	14.1	57.4	29-Sep	11.5	52.7
30-Jun	13.9	57.0	30-Jul	15.6	60.1	30-Aug	14.0	57.2	30-Sep	11.4	52.5
			31-Jul	15.6	60.1	31-Aug	13.9	57.0			

Appendix B: Averaged ADCP Data

Averaged ADCP data (data were averaged by software package WinRiver v.1.05)

Table B1. Far Field Velocity Profile WM 11 (Hi- Res) (HHDAM003R.000)

Depth		Velocity [ft/s] (Ref: Btm)			
(ft)	Magnitude	Direction[°]	Up	Error	% good
4.23	0.066	233.1	-0.031	-0.008	64
4.89	0.067	234.6	-0.005	-0.008	68
5.54	0.061	241	-0.004	-0.005	64
6.2	0.046	231.1	-0.003	0.003	45
6.86	0.034	244.5	-0.002	-0.002	35
7.51	0.035	242.4	-0.006	0.005	36
8.17	0.044	243.6	-0.002	0.002	28
8.82	0.023	235.4	-0.003	0.029	25
9.48	0.033	269.8	-0.014	0.028	24
10.14	0.007	43.6	-0.012	0.005	21
10.79	0.026	167.4	-0.007	0.011	18
11.45	0.01	209.4	-0.004	0.001	17
12.11	0.043	213.7	-0.011	-0.002	21
12.76	0.027	187.2	-0.013	-0.004	23
13.42	0.018	81.8	-0.014	-0.003	23
14.07	0.017	155.3	-0.012	0.002	32
14.73	0.023	187	-0.015	0.008	32
15.39	0.015	219.6	-0.012	0.007	36
16.04	0.002	234.1	-0.013	-0.002	41
16.7	0.003	292.9	-0.011	-0.013	43
17.36	0.013	179.1	-0.01	0.001	43
18.01	0.011	198.6	-0.015	0.011	40
18.67	0.015	185.3	-0.013	-0.006	38
19.32	0.011	207.7	-0.011	0.002	42
19.98	0.012	244.7	-0.009	-0.002	43
20.64	0.009	197.2	-0.011	0.004	45
21.29	0.015	212.3	-0.012	0.006	48
21.95	0.008	194.9	-0.013	0.01	48
22.6	0.006	332.6	-0.013	-0.005	44
23.26	0.025	237.3	-0.011	0.001	48
23.92	0.028	259.8	-0.011	0.001	57
24.57	0.014	208.4	-0.01	0.011	48
25.23	0.012	238.9	-0.011	0.001	45
25.89	0.009	222.5	-0.008	0.009	40
26.54	0.015	237.1	-0.011	0.022	49
27.2	0.01	137.2	-0.008	0.016	64
27.85	0.013	159.8	-0.009	0.009	65
28.51	0.025	155.7	-0.008	0.016	61
29.17	0.024	146.5	-0.01	0.003	61
29.82	0.02	164.8	-0.009	0.005	63
30.48	0.014	227.8	-0.007	0.011	60

Depth		Velocity [ft/s] (Ref: Btm)			
(ft)	Magnitude	Direction[°]	Up	Error	% good
31.14	0.026	236.6	-0.008	0.005	62
31.79	0.02	251	-0.011	0.002	62
32.45	0.022	271.2	-0.01	0.002	64
33.1	0.022	283.1	-0.011	-0.001	67
33.76	0.016	266.4	-0.009	0.002	67
34.42	0.012	284.4	-0.008	-0.001	67
35.07	0.013	233	-0.009	0.004	66
35.73	0.017	223.8	-0.007	-0.005	68
36.38	0.028	249.2	-0.004	-0.009	68
37.04	0.034	261.2	-0.006	-0.003	69
37.7	0.029	247.2	-0.007	0.002	67
38.35	0.016	264.8	-0.007	-0.001	71
39.01	0.012	238.7	-0.007	-0.001	71
39.67	0.007	231.6	-0.007	0.004	71
40.32	0.004	122.2	-0.009	-0.001	69
40.98	0.008	98.1	-0.009	0.001	70
41.63	0.006	90.9	-0.009	0.004	71
42.29	0.006	72.7	-0.008	0.005	70
42.95	0.016	83.6	-0.008	0.002	70
43.6	0.012	72.8	-0.009	0.005	71
44.26	0.013	68.4	-0.008	0	68
44.92	0.013	68.2	-0.005	0.001	67
45.57	0.005	34.1	-0.006	0.003	66
46.23	0.014	139.5	-0.006	0.005	69
46.88	0.009	112.2	-0.008	-0.001	69
47.54	0.008	91.6	-0.008	-0.002	70
48.2	0.008	103.9	-0.008	0	67
48.85	0.003	129.4	-0.009	-0.005	70
49.51	0.008	103.2	-0.008	-0.003	70
50.17	0.004	127.1	-0.007	0.001	71
50.82	0.002	120.1	-0.009	0	70
51.48	0.005	359.6	-0.009	-0.004	70
52.13	0.005	16.9	-0.007	0	70
52.79	0.006	43.4	-0.008	-0.002	71
53.45	0.006	28.2	-0.008	0	57
54.1	Bad*	Bad	Bad	Bad	0

*loss of data occurred below 54 feet because signal intensity dropped below the threshold value.

Table B2. Mid Field Velocity Profile - WM 11 (Hi- Res) fn=HHDAM007R.000

Depth		Velocity [ft/s] (Ref: Btm)			
[ft]	Magnitude	Direction[°]	Up	Error	% good
4.23	0.026	350.2	0.023	0.02	94
4.89	0.041	358.5	0.037	0.015	92
5.54	0.056	336.2	0.037	0.02	92
6.2	0.047	355.5	0.03	0.016	91
6.86	0.05	331.8	0.036	0.018	86
7.51	0.051	326.4	0.034	0.007	88
8.17	0.071	331.2	0.04	0.001	89
8.82	0.063	321.6	0.032	0.005	90
9.48	0.07	327.4	0.031	0.006	88
10.14	0.078	328	0.029	-0.003	87
10.79	0.089	321.5	0.032	-0.003	93
11.45	0.088	320.4	0.027	-0.003	95
12.11	0.089	325.8	0.026	-0.002	92
12.76	0.084	324.4	0.025	-0.008	94
13.42	0.08	325	0.026	-0.007	94
14.07	0.08	327.2	0.024	-0.004	95
14.73	0.083	330.6	0.023	-0.009	95
15.39	0.079	333.8	0.023	-0.01	93
16.04	0.079	333.5	0.023	-0.008	92
16.7	0.08	336.3	0.022	-0.01	92
17.36	0.072	338.6	0.021	-0.007	94
18.01	0.064	343.8	0.02	-0.011	96
18.67	0.056	347.8	0.019	-0.009	94
19.32	0.06	357.2	0.018	-0.013	95
19.98	0.053	1.6	0.018	-0.01	93
20.64	0.053	8.2	0.017	-0.012	92
21.29	0.055	17.1	0.015	-0.011	94
21.95	0.053	21.2	0.014	-0.009	95
22.6	0.052	27.2	0.013	-0.013	96
23.26	0.052	25.7	0.013	-0.014	96
23.92	0.05	28.1	0.012	-0.014	96
24.57	0.051	26.9	0.01	-0.014	96
25.23	0.049	27.3	0.009	-0.016	96
25.89	0.047	19.3	0.008	-0.014	96
26.54	0.043	16.3	0.007	-0.012	96
27.2	0.047	8.6	0.006	-0.011	96
27.85	0.044	7.5	0.005	-0.01	96
28.51	0.046	2.3	0.005	-0.012	96
29.17	0.049	354.6	0.004	-0.01	96
29.82	0.053	347	0.004	-0.006	96
30.48	0.055	346.2	0.002	-0.006	96
31.14	0.056	344.3	0.002	-0.01	96
31.79	0.054	354.5	0.002	-0.009	96
32.45	0.05	1.4	0.001	-0.002	96
33.1	0.049	357.9	0	0.002	96
33.76	0.047	352.4	0	0.006	96

Depth		Velocity [ft/s] (Ref: Btm)			
[ft]	Magnitude	Direction[°]	Up	Error	% good
34.42	0.056	348.8	-0.001	0.014	96
35.07	0.067	0.1	-0.003	0.011	96
35.73	0.066	3.9	-0.005	0.006	96
36.38	0.057	3.2	-0.006	0.002	96
37.04	0.041	358.8	-0.006	-0.001	96
37.7	0.028	350.5	-0.005	-0.004	96
38.35	0.029	340.3	-0.006	-0.006	96
39.01	0.031	336	-0.005	-0.007	96
39.67	0.037	338.3	-0.005	-0.006	96
40.32	0.046	344.6	-0.005	-0.007	96
40.98	0.054	351.8	-0.005	-0.005	96
41.63	0.057	358.7	-0.004	-0.006	96
42.29	0.058	2.2	-0.003	-0.006	96
42.95	0.06	6.4	-0.003	-0.004	96
43.6	0.061	7.2	-0.002	-0.003	96
44.26	0.06	9.1	-0.002	-0.002	96
44.92	0.055	8.5	-0.002	-0.004	96
45.57	0.047	25.3	0.002	0	94
46.23	0.048	28.3	0.001	-0.001	95
46.88	0.039	30.4	-0.001	0.001	96
47.54	0.036	33.8	0	0	96
48.2	0.034	33.7	0	-0.001	96
48.85	0.029	33.1	0	0.003	96
49.51	0.024	30.8	0	0	96
50.17	0.02	41.4	0	0.001	96
50.82	0.017	40.4	0	0.001	96
51.48	0.017	50.1	0	-0.001	96
52.13	0.015	55.4	0	0	96
52.79	0.015	61.3	0.001	-0.009	71
53.45	0.003	318.3	-0.016	-0.007	2

*loss of data occurred below 54 feet because signal intensity dropped below the threshold value.

Table B3. Near Field Velocity Profile - WM 11 (Hi- Res) fn=HHDAM010R.000

Depth		Velocity [ft/s] (Ref: Btm)			
[ft]	Magnitude	Direction[°]	Up	Error	% good
4.23	0.131	261.5	0.014	0.007	100
4.89	0.153	259.4	0.02	0.007	99
5.54	0.161	256.9	0.017	0.007	99
6.2	0.154	253.9	0.014	0.009	99
6.86	0.154	254.5	0.008	0.012	100
7.51	0.152	254.2	0.003	0.013	100
8.17	0.151	255.6	-0.001	0.009	100
8.82	0.145	256.6	-0.006	0.002	100
9.48	0.142	258.1	-0.011	0.007	100
10.14	0.131	261.7	-0.013	0.018	100
10.79	0.125	265.8	-0.015	0.018	99
11.45	0.116	273.9	-0.016	0.021	100
12.11	0.111	279.7	-0.017	0.028	100
12.76	0.104	286	-0.019	0.022	100
13.42	0.106	290.2	-0.02	0.019	100
14.07	0.108	298.6	-0.021	0.013	100
14.73	0.108	298.1	-0.02	0.012	100
15.39	0.109	302.3	-0.019	0.007	100
16.04	0.118	303.6	-0.018	0.002	100
16.7	0.118	302.9	-0.017	-0.001	100
17.36	0.123	306.4	-0.013	0	100
18.01	0.125	304.5	-0.011	-0.001	100
18.67	0.132	302.9	-0.011	0	100
19.32	0.133	302.4	-0.008	0	100
19.98	0.133	303.6	-0.008	0	100
20.64	0.13	303.5	-0.006	0.001	100
21.29	0.13	302.2	-0.006	-0.002	100
21.95	0.13	303.9	-0.005	0.004	100
22.6	0.134	306	-0.004	0.003	100
23.26	0.133	308.6	-0.002	0.004	100
23.92	0.134	310.5	-0.001	0.006	100
24.57	0.136	311.6	-0.001	0.002	100
25.23	0.137	314.2	-0.001	0	100
25.89	0.135	318.2	0	-0.001	100
26.54	0.142	319.8	-0.001	0.006	100
27.2	0.141	322.9	0	0.002	100
27.85	0.139	325.3	0	0.004	100
28.51	0.139	330.9	0.001	0.002	100
29.17	0.14	335.1	0.001	0.001	99
29.82	0.152	332.5	0.006	0.001	90
30.48	0.124	336.4	0.007	0.014	95
31.14	0.109	334.4	0.008	0.026	100
31.79	0.102	323.7	0.008	0.028	100
32.45	0.098	316.7	0.006	0.031	98
33.1	0.096	297	0.004	0.024	100
33.76	0.098	272.8	-0.002	0.016	100

Depth		Velocity [ft/s] (Ref: Btm)			
[ft]	Magnitude	Direction[°]	Up	Error	% good
34.42	0.097	263.6	-0.004	0.016	100
35.07	0.087	261.7	-0.007	0.003	99
35.73	0.081	272.2	-0.006	-0.008	99
36.38	0.089	284	-0.004	-0.018	98
37.04	0.068	300.5	-0.001	-0.007	98
37.7	0.055	323.9	0.001	-0.014	98
38.35	0.058	333.3	0.002	-0.007	96
39.01	0.063	338.7	0	0	100
39.67	0.064	338.5	0	0	100
40.32	0.061	337.1	0.003	0.006	98
40.98	0.056	333.1	0.003	0.007	99
41.63	0.047	321.9	0.003	0.01	94
42.29	0.046	328.5	0.004	0.007	96
42.95	0.052	323.6	0.003	0.001	94
43.6	0.045	319.3	0.005	0.011	95
44.26	0.047	310	0.004	0.021	94
44.92	0.038	300.8	0.005	0.021	91
45.57	0.036	295.4	0.006	0.021	51
46.23	0.033	312.9	0.008	-0.001	52
46.88	0.026	306.4	0.006	Bad	31
47.54	0.048	282.7	-0.002	Bad	36
48.2	0.043	306.6	-0.001	-0.023	32
48.85	0.049	305.8	0	0.003	43
49.51	0.019	308.8	0.003	0.03	51
50.17	0.026	280.6	-0.004	Bad	24
50.82	0.036	318	0.004	Bad	24
51.48	0.025	1.4	0.008	Bad	36
52.13	0.035	292	0	0.026	14

*loss of data occurred below 54 feet because signal intensity dropped below the threshold value.