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HUNGRY HORSE MITIGATION: AQUATIC MODELING OF THE SELECTIVE WITHDRAWAL SYSTEM -- HUNGRY HORSE DAM, MONTANA

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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The Hungry Horse Mitigation Consultation' Committee provided support to bring this important mitigation strategy to the forefront of public interest and helped make this project a reality. We would like to thank Sharon Sarver for her word processing skills.

EXECUTIVE SUMMARY

Program measure 903(h)(6) of the Columbia Basin Fish and Wildlife Program directed Bonneville Power Administration and the U.S. Bureau of Reclamation to ". . . immediately begin actions to result in installation of a selective withdrawal structure at Hungry Horse Dam to allow for temperature control to benefit resident fish."

Hungry Horse -Dam presently releases frigid water from the bottom of the reservoir (at about 4° C or 39-41° F) year long. Cold water effects insect production and fish growth downstream. Rapid temperature changes of up to 8.3° C (14" F) have been measured in the Flathead River downstream of the South Fork confluence, controlled by dam discharges. Thermal effects from Hungry Horse Dam are detectable for over 64 Km (40 river miles) downstream to Flathead Lake. These short-term temperature fluctuations and long-term cooling effects during summer and fall impair biological productivity in the Flathead river and also reduce recreational potential.

The installation of a selective withdrawal structure on each of the dam's discharge penstocks was determined to be the most cost-effective means to provide constant, permanent temperature control without impacting power production and flexibility in dam operation. The thermal model presented herein revealed that fish growth potential in the river would increase two to five times through selective withdrawal, temperature control. Temperature control is possible over the entire range of turbine discharge capacity, with very little effect on power production. Findings indicate that angling would improve through higher catch rates and larger fish.

Model results indicate an increased incidence of zooplankton washout from the reservoir with selective withdrawal. Field measurements of the vertical distribution of zooplankton in the pool and washout rates in the discharge were used to predict the significance of reservoir effects. An engineering modification to the mechanical structure was made to greatly reduce the downstream loss of zooplankton. The downstream benefits far outweigh the minor loss in reservoir food availability.

Temperature control will solve the most serious impact to river health. However, flow fluctuations will continue to effect insect production and usable fishery habitat in the Flathead River. A natural thermal regime combined with moderated flow fluctuation would further enhance riverine food production, trout growth and recreation potential.

INTRODUCTION

Man-caused temperature fluctuations have been linked to biological changes in the Flathead River Basin. Hungry Horse Dam was completed by the U.S. Bureau of Reclamation (Bureau) in 1952, impounding the South Fork of the Flathead River. The dam was designed with four turbine penstocks located 73 m (241 feet) below full pool elevation. Water discharged from this depth into the South Fork remains about 4° C (39 to 41” F) year round. Surface water as warm as 20° C is occasionally released as spill. Unnatural thermal and flow conditions have significantly changed the invertebrate fauna and fisheries dynamics in the 8 km (5 miles) of the South Fork downstream of the dam. Altered flows and water temperatures also effect the main stem Flathead River from the South Fork confluence, downstream for more than 64 km (40 miles) to Flathead Lake.

Thermal effects were detected in short duration fluctuations up to 8.3” C (15° F) and gross reductions in the annual accumulation of degree days. Rapid thermal spikes correspond with sudden changes in discharge volume. Seasonal perturbations were typified by summer cooling and winter warming.

In an attempt to remedy the thermal problem in the South Fork and main stem Flathead River, a multi-level outlet system (now called Selective Withdrawal) was proposed for further study in 1976 by the Pacific Northwest River Basin Commission. Researchers from the Montana Department of Fish, Wildlife and Parks (MDFWP) and U.S. Bureau of Reclamation (Bureau) assessed the feasibility of releasing water from selected layers in the reservoir to mimic natural river temperatures downstream. Fraley and Graham (1982) estimated that trout growth in the South Fork could be increased by a factor of ten with the addition of selective withdrawal. They also noted that trout growth in the main stem Flathead River could be almost doubled. No further actions were taken after resource managers predicted that warm water withdrawals would negatively impact fish populations in Hungry Horse Reservoir.

The concept of selective withdrawal was reassessed beginning in 1990. A computer model to simulate selective withdrawal was appended to the quantitative biological model of Hungry Horse Reservoir (HRMOD) developed by MDFWP and Montana State University. Simulation of the daily changes in reservoir hydrology, thermal structure and discharge depth provided accurate estimates of the effects of differing operational strategies on downstream water temperatures. Biological measures in HRMOD allowed researchers to assess benefits or tradeoffs upstream and downstream of the dam.

Alternative methods to moderate thermal effects were also assessed. Our goal was to achieve maximum thermal control with the least expensive mechanical alteration, yet maintain flexibility in electrical generation operations. Seven alternative actions were assessed, including structural modifications and operational measures to achieve functional thermal control. Selective withdrawal capability on all four penstocks was determined the most effective alternative to achieve permanent and constant control of discharge temperatures.

In March 1991, **MDFWP** and the Confederated Salish and Kootenai Tribe (Tribes) jointly submitted a "Fisheries Mitigation Plan for losses Attributable to the Construction and **Operation** of Hungry Horse Dam" (Plan) (**Fraley** et al. 1991). During the l&month public scoping period which culminated in the Plan, selective withdrawal gained great support by an advisory group representing 24 agencies, business or special interest groups. The Northwest Power Planning Council (Council) conducted a public scoping period regarding the Plan and in November 1991, amended the Columbia Basin Fish and Wildlife Program (Council 1987). **One** of the program amendments **903(h)(6),** directed Bonneville Power Administration (Bonneville) and the Bureau to". . . Immediately begin actions to result in installation of a selective witbdrawal structure at Hungry Horse Dam to allow for [downstream] temperature control to benefit resident fish." As an interim measure, the Bureau instituted limits on discharge change rates to moderate instantaneous temperature spikes. This action reduced the rapidity of temperature change and the threat of thermal shock in aquatic organisms. However, long-term cooling and radical thermal fluctuations continued. The intent to immediately construct selective withdrawal was reaffirmed by the Council on March 10, 1993.

During March 1993, Bonneville provided funding to the Bureau for engineering and **final** design of the structure. Biological analyses included herein were incorporated in the planning and design of the structure. Computer simulations and field sampling will aid in future operation of the device when it becomes functional.

STUDY AREA

Hungry Horse Dam impounds the South Fork of the **Flathead** River approximately 8 km upstream from the confluence with the main stem **Flathead** River (Figure 1). The North and Middle forks are unregulated and run at natural flows and river temperatures throughout the year. Thermal influence from Hungry Horse Dam effects the South Fork below the dam and the main stem **Flathead** River from the South Fork confluence downstream to **Flathead** Lake. Temperature recorders were installed in the South Fork below the dam; in the Middle Fork near West Glacier; and in the main stem **Flathead** at Columbia Falls, Spruce Park and Holt Bridge. The West Glacier site, located upstream of the thermal influence of the dam, served as the control. Site selection at Columbia Falls was defined as the point where convergent flows thoroughly mixed, resulting in constant temperature bank to bank. The Spruce Park thermograph, 29 km (18 miles) downstream from the South Fork confluence, monitors water temperature just upstream of the Stillwater River confluence. Inflowing waters from the Whitefish and Stillwater rivers moderate temperature effects in the downstream river reach. The Spruce Park recorder was positioned to detect atmospheric moderation between the two sites. The Holt Bridge site monitors water temperatures at the mouth of the **Flathead** River near **Flathead** Lake.

Hungry Horse Dam has four fixed outlet ports at the turbine penstocks (Figure 2). Water can be spilled, bypassing the turbines through three hollow jet valves and the '"glory hole." Jet valves release hypolimnetic waters 110 m (360 feet) below full **pool** (at elevation 3,200

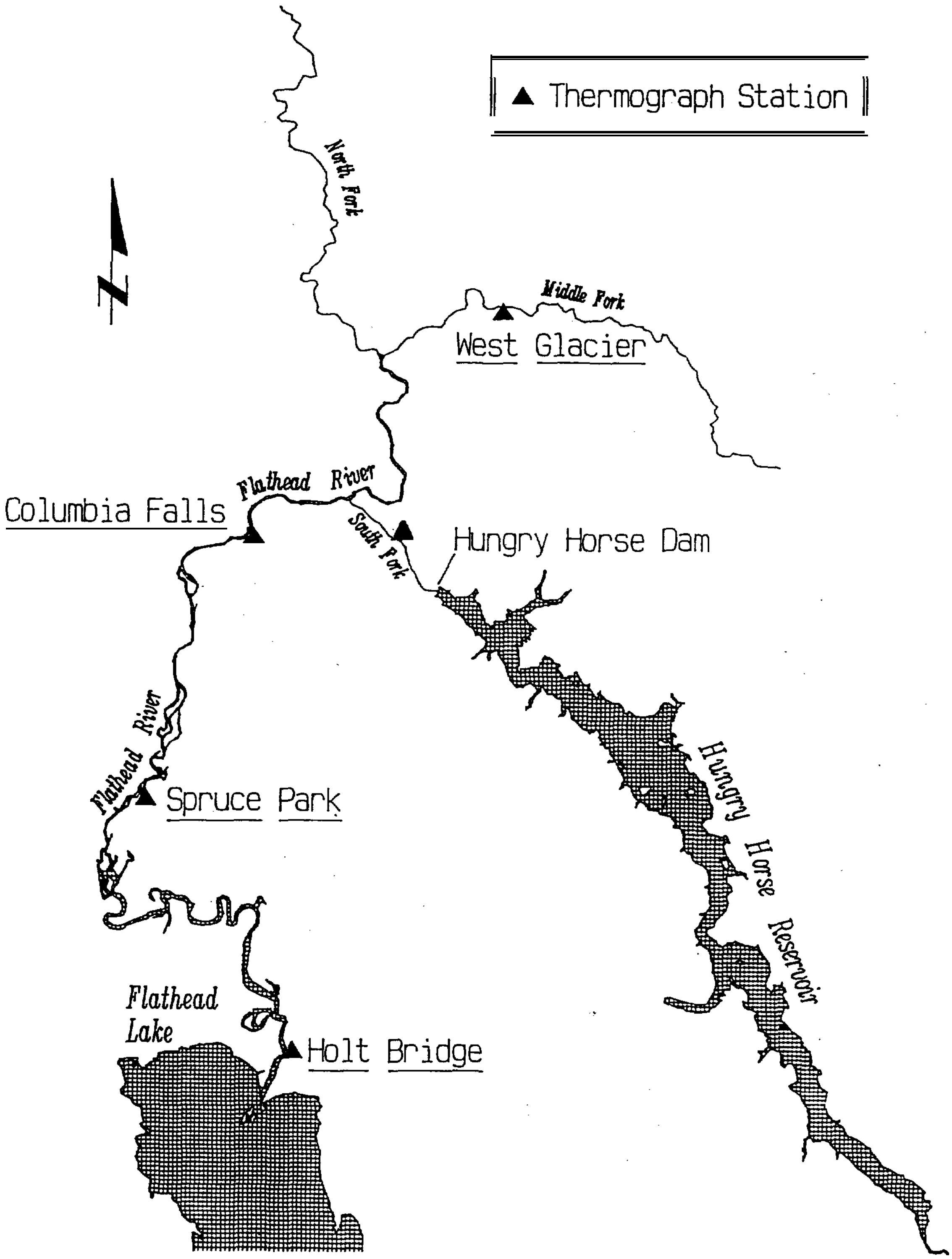


Figure 1. Locations of temperature recorders in the study area during 1991 and 1992. The West Glacier site provided the unregulated control. The U.S. Geological Survey monitors discharge temperatures in the South Fork below Hungry Horse Dam. Temperatures from the three forks are thoroughly mixed at the Columbia Falls site. 'The Spruce Park thermograph was positioned just upstream of the inflow from the Stillwater and Whitefish rivers which dilute thermal effects from the dam. River temperature at the inflow to Flathead Lake were monitored at the Holt Bridge site.

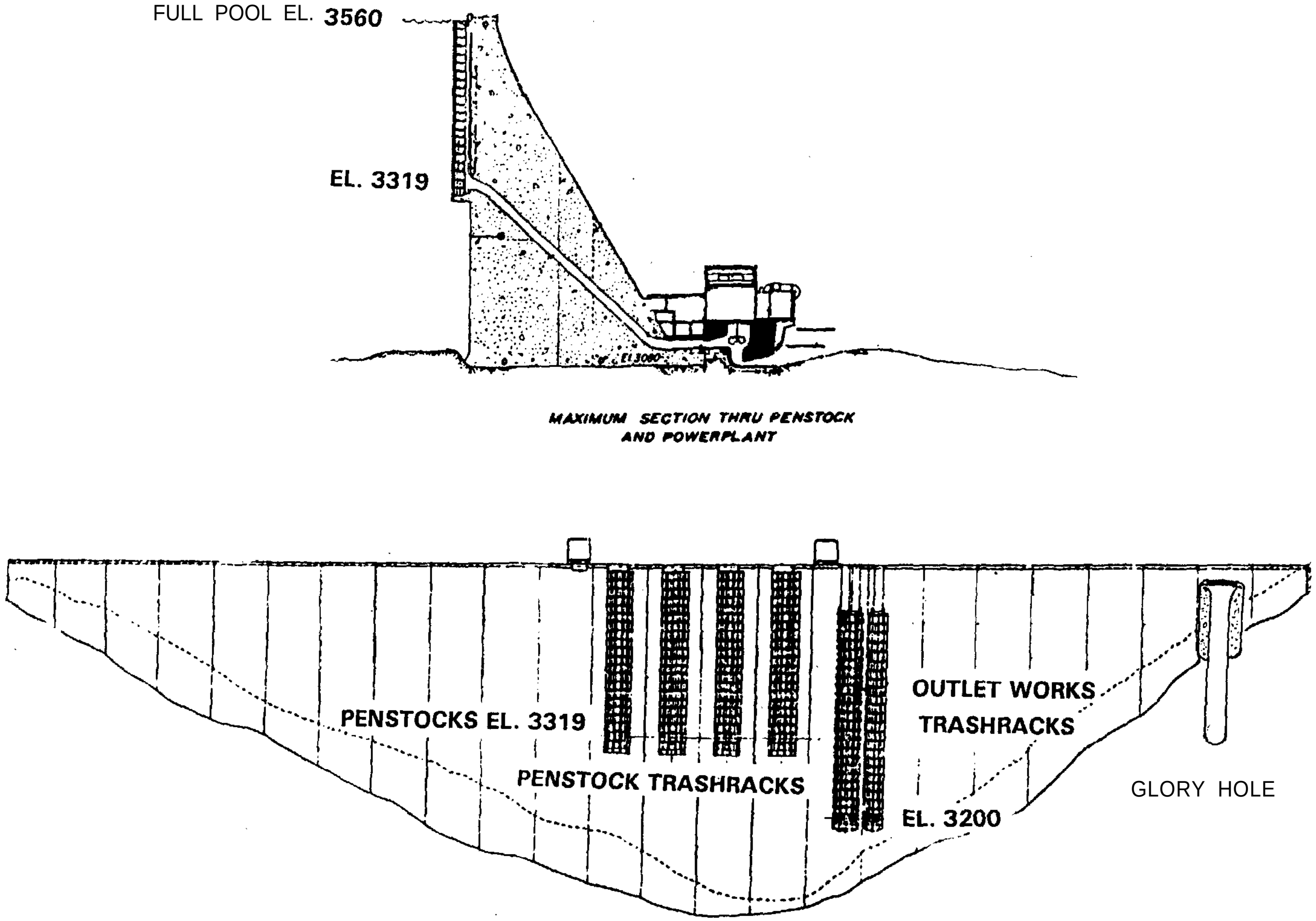


Figure 2. A scematic of Hungry Horse Dam as viewed from the side (top) and upstream face (bottom), shows the location of the four turbine penstock apertures (center), the outlet works to the hollow jet valves (right) and glory hole (far right). Trashracks extend from the apertures upward toward full pool elevation. Jet valves and glory hole spill water, bypassing the turbines. The selective withdrawal structure will be retrofitted into the turbine trashracks.

feet msl). The glory hole is only functional when the reservoir fills to within 3 meters (10 feet) of full pool elevation (3,560 feet msl). Consequently, the glory hole passes warm surface waters. The selective withdrawal system will be installed inside the existing trash racks on all four turbine penstocks.

METHODS

Taylor chart recorders were installed to monitor instantaneous temperature change at various points along the river. Thermographs were maintained monthly. Start and end times were recorded on the chart to detect and correct timer error. Continuous recordings were manually read on an hourly basis, verified for accuracy, then recorded on computer. Instantaneous temperature change appeared as a vertical line on the continuous thermal trace. The U.S. Geological Survey monitors the volume and temperature of Hungry Horse discharges in the South Fork. Hourly measurements were used to relate temperature effects to discharge fluctuations.

The reservoir thermal model was developed by MDFWP and MSU as part of a biological model (HRMOD). Thermal profiles were measured twice monthly at intervals along the reservoir from April through November 1983 through 1991. Sampling was terminated during ice formation. The model assumes a constant 4° C at the penstock depth during the ice cover period, until spring melt and lake turnover. Data describing the reservoir thermal structure was used to calibrate a modified version of a predictive mathematical model for the behavior of thermal stratification in Hungry Horse Reservoir (Ferreira et al. 1992). Their modeling strategy was based on the original Flaming Gorge Reservoir thermodynamics model developed by (Adams 1974).

Thermal predictions were calibrated to 11 years of daily climatological records (U.S. Weather Service, Kalispell, Montana), corrected to measured atmospheric conditions at Hungry Horse Dam; long-term inflowing tributary temperatures; the physical properties of water and a digitized three dimensional basin topography. Annual schedules of meteorological variables input to the model, including: relative humidity, solar aspect, air temperature, cloud cover and wind speed were smoothed to long-term trends. This is done using the parameters indicated in Table 1 obtained by nonlinear least-squares (Marquardt method) regression to data from Kalispell, Montana.

The model assumes horizontal homogeneity, and thus generates a single thermal profile for each day of the year. The model accounts for the measured absorption and transmission of solar radiation, solar aspect, surface convection due to cooling and advection due to inflow and outflow. Time lags between inflow and outflow were also accounted for.

Table 1. The mean, amplitude and phase shift establish 5 meteorological schedules needed by the thermal model.

	Mean	AMP	SHIFT
Inflow Temperature	6.664	9.137	155.19
Air Temperature	7.822	12.090	168.46
Humidity	0.702	0.105	4.18
Wind Speed	2.074	0.596	209.82
Cloud Cover	0.654	0.204	-20.24

The thermal model begins on January 1, works with a calendar year and starts after the ice is off the reservoir. The top part of each daily thermal profile (21 values representing a depth of 45 m) is stored for use later. Several modeling techniques were used to estimate the discharge water temperature based on the reservoir thermal structure at the dam. Based on a comparison of model estimates and observed field measurements, the **outflow** temperature was assumed to be equivalent to the temperature at the depth of withdrawal.

A difficult modeling problem arises when the surface elevation schedule for a water year does not begin and end near the same elevation. When an unbalanced schedule is converted from a calendar year to a water year (October 1 through September 30) by the thermal model, an abrupt break in elevation occurs where the two data files join. The problem was corrected by shifting the thermal structure of the reservoir up or down as needed so that the corresponding depth zones align. This allows the thermal model to continue in a reasonable manner. This solution, however, is not ideal; a thermal model able to predict the formation of ice and ice melt would be far superior. However, after weighing the cost of calibrating an ice cover model, we chose the former option since thermal adjustments effect only the period of limited biological productivity.

Only a few support programs were retained from the original thermal model (Adams 1974). Their basic function is described **here.** Function FLXOUT calculates surface losses due to evaporation, conduction and radiation. Subroutine SPEED calculates vertical, source and sink velocities as well as the water withdrawal thickness. Subroutine AVER performs convective mixing of the surface layers. Function PROB approximates the area under a normal distribution, Function FLXIN calculates incoming solar radiation.

The Hungry Horse model predicts discharge from unregulated North and Middle forks of the **Flathead** River based on a regression between daily inflows to Hungry Horse Reservoir and flows in the other two forks. The wild flow in the **Flathead** River at Columbia Falls **(FHF)** was estimated using the previously established inflow to Hungry Horse **(HRI)** by: FHF, = 1.5695 * $\mathbf{HRI}_{(i-1)}$ + 442.28 cfs, explaining over 96 percent of the variance in 12,409 observations.

Outflow limits for Hungry Horse Reservoir were then constructed so that when the outflow of Hungry Horse Reservoir is added to the discharge from the two unregulated river forks, the resulting flow is limited by immediate downstream flood constraints in the main stem of the **Flathead** River at Columbia Falls. If the combined flows exceed flood stage (44,810 cfs), Hungry Horse Dam discharge is reduced accordingly toward the absolute minimum release of **145 cfs. The user may override the outflow limits or design an annual schedule of daily outflow** values by designating a few points and interpolating the rest. Any user input outside the range of the physical discharge limits of the dam is reset to the limits automatically.

The selective withdrawal component allows user specification of an annual withdrawal depth schedule based on the thermal structure in the reservoir, or automatic depth selection to meet a pre-programmed temperature target at Columbia Falls (combined North, Middle and South Fork temperatures). The user may input a tile containing 365 daily values, or designate a **few** points and interpolate the rest. In either case, **values** below the physical minimum outflow depth (3,319 feet at Hungry Horse) are reset to the minimum. Similarly, all input values within 21 feet of the existing surface elevation are reset to 21 feet below the surface. This is **a physical** limit at the dam to avoid turbine cavitation.

The temperature in the unregulated forks of the **Flathead** River was established as a fixed schedule. This schedule closely approximates the observed temperature in the North Fork of the **Flathead** River for water years 19761988 (Figure **3),** explaining 94.8 percent of the total variation. The temperature of the South Fork was provided by the thermal model as the outflow . temperature. The first approximation of the temperature in the combined flows at Columbia Falls was calculated as the average temperature in the forks, weighted by flow volume. This approximation was somewhat lower than the observed temperature at Columbia Falls, so the residual was correlated with discharge. The positive residuals may reflect warming of the water between the measurement locations, or it may indicate that the Middle Fork of the **Flathead** River, for which no simultaneous data were available, was somewhat warmer than the North Fork. In either case, a simple regression largely corrected the problem explaining **89.6** percent of the variation in 3,374 observations. The equation is: $\mathbf{T_{new}} = 0.29 + 1.1328 * \mathbf{T_{old}} - 0.04636 * FLOW$, **where FLOW** is the discharge at Columbia Falls in K-cfs.

Evaluation of selective withdrawal required duplicate simulations comparing thermal influences with selective withdrawal to, equivalent simulations with fixed hypolixnnetic withdrawal. Simulations utilized historic daily inflow data from 1928 through 1992. Real data simulations incorporated actual daily elevations **from** 1954, when Hungry Horse first filled, through 1992. Hypothetical surface elevations based on current Rower and flood constraints were used for the period 1928 through 1952, when the dam began to regulate flows. Results of the comparisons were **evaluated** for temperature unit accumulation in the South Fork and in the combined flows of the **Flathead** River at Columbia Falls. Biological influences focused on trout growth . efficiency in the **Flathead** River and **trophic** level responses in the reservoir. The reservoir model **(HRMOD)** is beyond the scope of this manuscript, only summary results will be presented here.

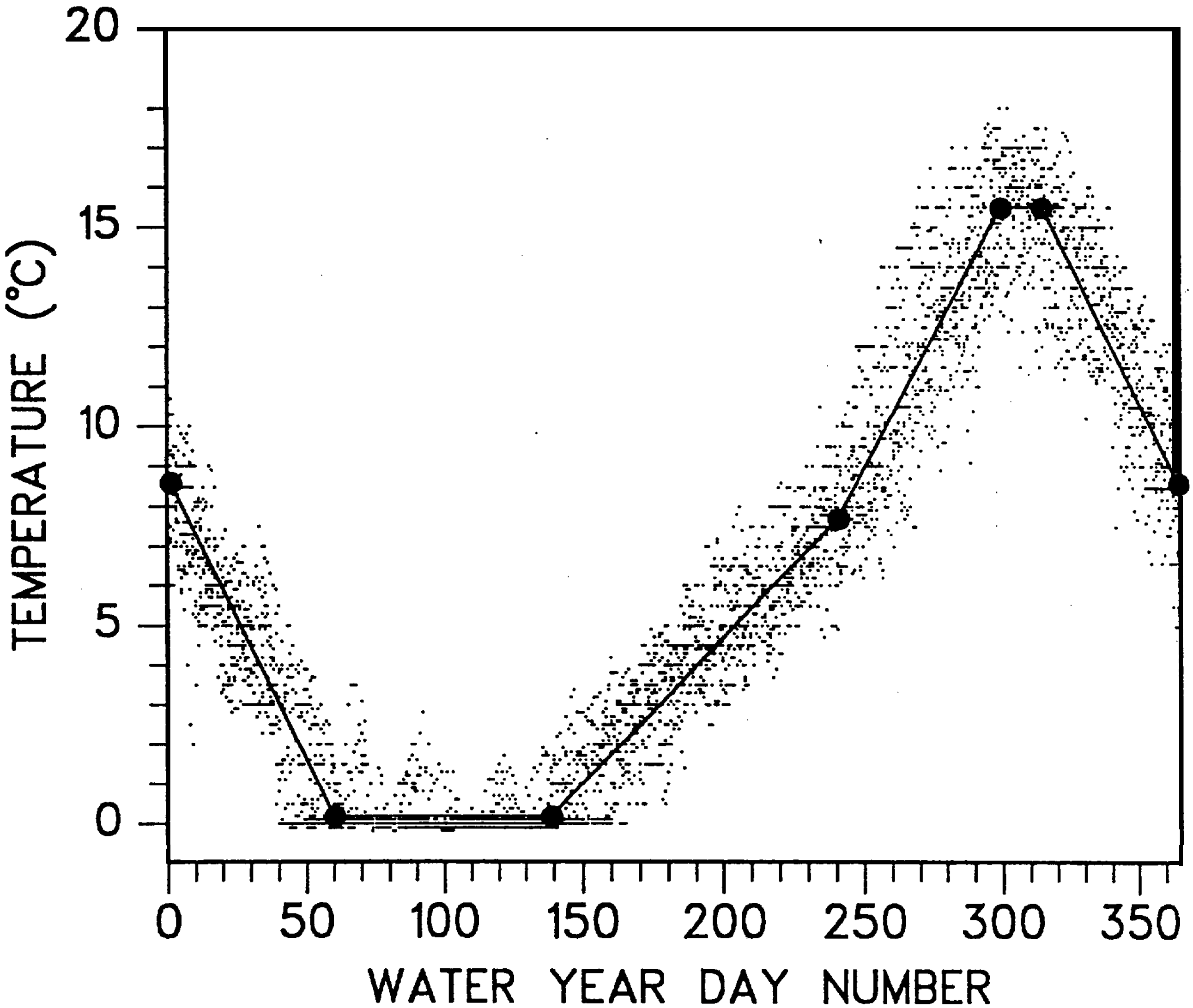


Figure 3. The fixed annual temperature schedule used to estimate the thermal regime in the unregulated North and Middle forks of the Flathead River. The scatter plot represents daily mean temperatures recorded by the U.S. Geological Survey in the North Fork. for water years 1976 through 1988.

Trout growth potential was first calculated relative to temperature unit accumulation in the affected river reach, A simple linear, additive model was applied to enumerate the number of days above each temperature within the range of maximal trout growth, 6 to 17° C. An example of model output using the average inflow volume, with and without selective withdrawal, is provided in Table 2. Degree days within this temperature range were itemized by month, then summed to arrive at the annual total of trout growth units.. This was used to describe trout growth potential.

Trout growth efficiency was later **evaluated** by incorporating curvalinear **temperature/growth** relationships and food ration effects. The later increased the accuracy of our estimates and included, for the first time, thermal influences on riverine insect production. The growth efficiency model was based on laboratory observations of weight gains in relation to temperature and to food availability (Brett et al. 1969). The model calculates increments of growth relative to a pair of **curvalinear** equations with two different temperature optima for different levels of food ration. Two curves were required -because trout under conditions of reduced caloric intake have increased growth efficiency at lower temperatures. Without selective withdrawal, any reduction in production caused by summertime cooling is **partially** offset by this phenomenon, so the model was designed to compensate for this ‘effect by using two curves.

Curves showing specific growth rates **(%** chg. in wt./day) are given by Brett et al. **(1969),** but these are presented without defined mathematical relationships. To incorporate these results into the model, known values were taken from the plotted curves (Figure 4) and fitted by quadratic regressions **($R^2 > .99$).** An alternate set of equations presented by Iwama and **Tautz** (1981) was considered applicable, but these were deemed less appropriate for our specific purpose.

Although the growth efficiency curves were well supported by lab analyses, selecting the applicable curves based on differing food availability was problematic. Perry and Huston (1981) indicate summertime periphytic productivity is actually higher below the mouth of the South Fork than above it. Surprisingly, the same was true for benthic metabolism. These unexpected results may be due in part to increased nutrients entering the river below the South Fork. These nutrients may more than offset the temperature effects (Stanford 1980). Because of this confounding influence, thermal effects on productivity are not directly measurable. Also it is known that wintertime production is higher than expected because of the release of relatively warm water.

Several studies have shown that the cold water discharges from the dam retard the growth of insects and disrupt their emergence patterns (Stanford 1975, Hauer 1980, Appert and Graham 1982, Hauer and Stanford 1982). Yet, even if the general effects of temperature on the activity and metabolism of all of the species of the aquatic insects were known, it would still be almost impossible to assess the negative impacts due to sudden and unnatural inputs of cold water. The possibility of disrupting behavioral patterns may be as serious as the more easily measured physiological effects. The damages incurred from **altering** the natural species composition of the river is similarly difficult to assess.

Table 2. An example of output from the linear growth potential model. A duplicate simulation was performed to compare trout growth units between **6 and 16° C** with fixed hypolimnetic withdrawal and selective withdrawal. Withdrawal depth for temperature correction was automated to meet predetermined temperature targets at Columbia Falls under average water conditions.

		Without Selective Withdrawal											
		Trout Growth Units											
Temp. (° C)	**Duration (Days)**	**Ckt**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
20	0												
19	0												
18	0												
17	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	0	0	0	0	0	0	1	0	0
12	22	0	0	0	0	0	0	0	0	0	15	7	0
11	44	0	0	0	0	0	0	0	0	0	29	15	0
10	61	0	0	0	0	0	0	0	0	8	31	22	0
9	82	0	0	0	0	0	0	0	0	18	31	31	2
8	100	0	0	0	0	0	0	0	0	29	31	31	9
7	133	1	0	0	0	0	0	0	12	30	31	31	28
6	169												
5	195												
4	234												
3	334												
2	365												
1	365												
0	365												
Monthly Totals		1	0	0	0	0	0	0	12	85	169	137	39
Total Degree Days - 2287.05; Total Trout Growth Units = 526.14													

Table 2. continued on next page.

		With Selective Withdrawal											
		Trout Growth Units											
Temp. (° C)	Duration (Days)	Oct	Nov	Dec	Jaa	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
20	0												
19	0												
18	0												
17	0	0	0	0	0	0	0	0	0	0	0	0	0
16	25	0	0	0	0	0	0	0	0	0	11	14	0
15	41	0	0	0	0	0	0	0	0	0	18	23	0
14	54	0	0	0	0	0	0	0	0	0	24	30	0
13	69	0	0	0	0	0	0	0	0	0	31	31	7
12	86	0	0	0	0	0	0	0	0	5	31	31	19
11	101	1	0	0	0	0	0	0	0	11	31	31	27
10	117	8	0	0	0	0	0	0	0	17	31	31	30
9	131	15	0	0	0	0	0	0	0	24	31	31	30
8	146	23	0	0	0	0	0	0	1	30	31	31	30
7	170	31	1	0	0	0	0	0	16	30	31	31	30
6	186												
5	205												
4	240												
3	338												
2	365												
1	365												
0	365												
Monthly Totals		78	1	0	0	0	0	0	17	117	270	284	173

Total Degree Days - 2818.96; Total Trout Growth Units = 1028.71

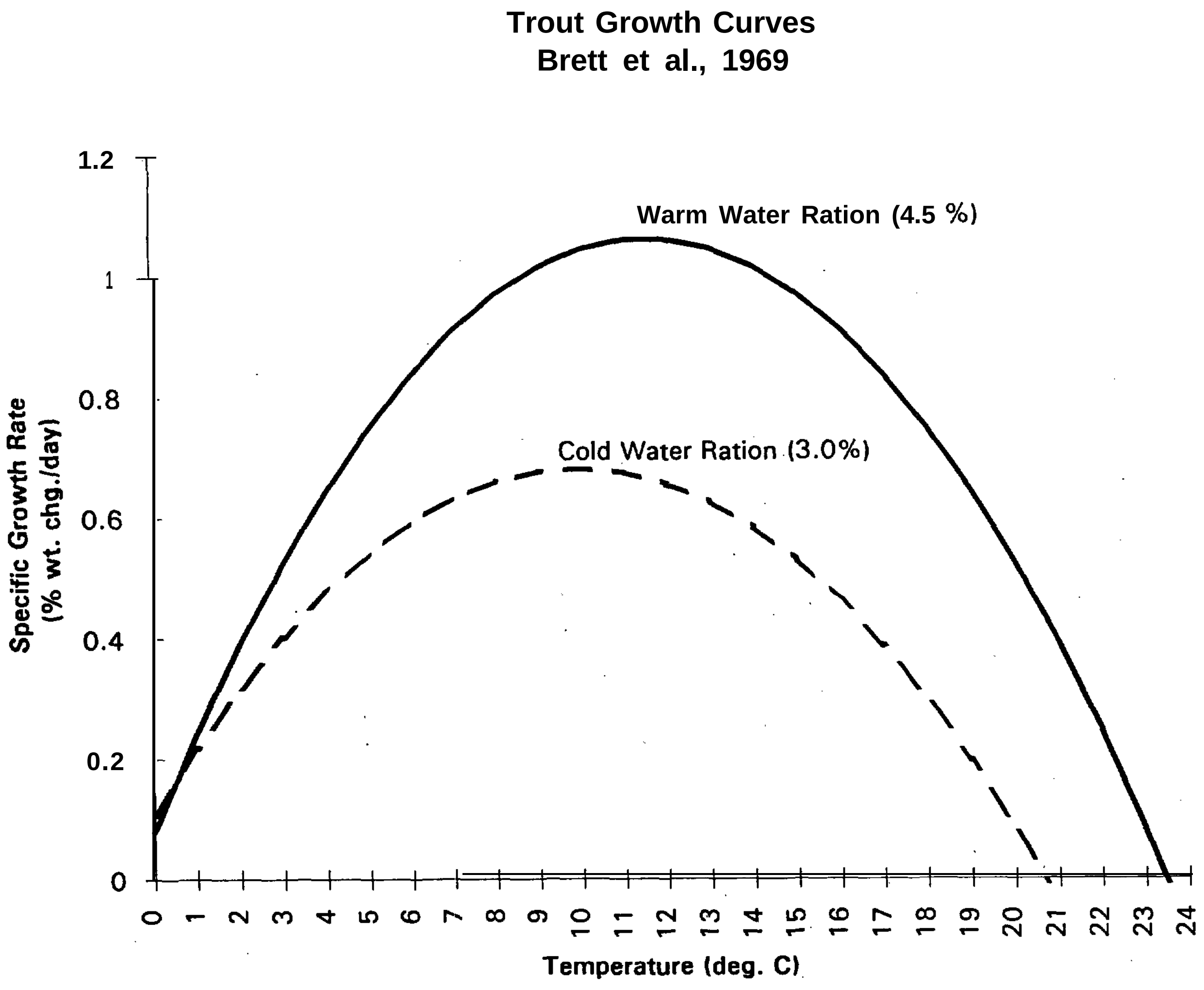


Figure 4. Growth efficiency curves relating specific growth rate to water temperature and food availability. Paired curves were selected from laboratory results presented by Brett et al. (1969). The curves approximate changes in the insect community structure, and thus food availability, when rapid thermal fluctuations and long-term cooling effects caused by hypolimnetic withdrawal are corrected through selective withdrawal.

All of the species making up the invertebrate fauna probably display a growth-temperature relationship similar to that of trout. Namely, an optimum temperature range beyond which growth diminishes as temperature deviates in either direction.

A standard equation for estimating metabolic changes in poikilotherms ("coldblooded" organisms) is: $Q_{10} = (k_1/k_2)^{10/(t-t)}$,
where Q_{10} equals the relative change in metabolism due to a 10° C temperature change. Numerous studies have shown this value to be typically between 2.0 and 3.0. "k_n" and "t_n" represent the measured rates (e.g. respiration) and temperatures, respectfully. Mid-summer temperature fluctuations due to cold water releases are typically about six or seven degrees. A, six degree drop with a Q_{10} of 2.5 represents a reduction in metabolism of 42 percent. However, these temperature fluctuations are intermittent (which may be worse than a constant reduction) and some aquatic insect species tolerate wider temperature fluctuations than others. Presumably the insect community structure has altered to favor such species, for better or worse, under the current thermal regime. To be conservative, we selected the growth curve with a 33 percent reduction of food availability for use in the model for test runs without selective withdrawal. Because of compensatory changes in the metabolism of the fish, this amounted to a maximum reduction of about 29 percent in the specific daily growth rate during the summer. During the winter no difference in growth rates occurs because no growth occurs if water temperatures are less than 6° C.

Although the fish growth model was founded numerical values derived from controlled laboratory experiments, the model output needed to be verified with field data so that the numerical coefficients could be adjusted to site-specific growth estimates. A number of studies have examined trout growth in the Flathead River system, but no data were available prior to dam construction (Johnson 1961, McMullin and Graham 1981, Liknes and Graham 1988). The most applicable data pertaining to the growth of westslope cutthroat trout (_Salmo clarkii_) in the main stem of the Flathead River were reported by McMullin and Graham (1981). The average length increase was 85 mm for age III+ westslope cutthroat trout based on back-calculated lengths at age III and IV. The beginning and ending lengths were 157 mm and 242 mm. Age III+ fish were selected because this represents a major year class for migrant fluvial and adfluvial trout (Leathe and Graham 1982). Approximately 60 percent of cutthroat and bull trout (_Salvelinus confluentus_) emigrate to the river from their natal tributaries at age III+, thus this estimate includes fish from several migrant classes. Estimates of actual river growth was difficult because some fish may have resided in Flathead Lake or their natal tributary during portions of their third year of growth. Nonetheless, these figures provided the basis for model calibration to better simulate site-specific growth conditions.

RESULTS

Natural Diel Cycling

Thermal fluctuation in the river headwaters, caused by naturally heating and cooling air temperatures, are most pronounced during summer and fall. In the unaffected portion of the Upper Flathead Drainage, diel temperature change is gradual. Daily variation seldom exceeds 5 ° C (9 ° F) during a 24 hour period, and typically fluctuates 3° C (5.4° F) due to atmospheric heating during the day and cooling at night. The slow rate of temperature change allows aquatic organisms to adjust to new conditions (Figure 5).

Unnatural Thermal Pulsing

As hypolimnetic waters are released through the dam turbines, the South Fork discharge contributes a larger percentage of the main stem Flathead River flow relative to the unregulated North and Middle forks. Sudden increases in discharge translate into very rapid thermal depressions (Figure 6). Conversely, sudden reductions in turbine discharge coincide with sudden warming in the Flathead River, as temperatures return toward ambient. This is especially apparent when converging flows from North and Middle forks reduce to basal conditions after spring runoff (mid May through mid June). Thermal spikes continue through October when natural tempera- decline toward 4° C (39” F).

Thermal pulses were observed on many occasions during the sampling period (Table 3). Rapid temperature changes were moderated somewhat during 1992 when ramping rates were instituted by the Bureau. Long-term cooling effects continued to reduce trout growth potential in the Flathead River.

Atmospheric Moderation of Downstream Temperatures

Little atmospheric moderation of water temperature occurs from the South Fork confluence downstream to the Spruce Park site. A comparison of temperatures recorded near Columbia Falls and thermograph measurements from 29 km (18 miles) downstream at Spruce Park shows a nearly identical thermal trace. The nearly simultaneous temperature spike at both sites often reveals a puzzling lack of the lag effect (Figure 7). The unregulated inflow of the Stillwater River moderates the thermal influence below the confluence. Temperature change at Holt Bridge, 72 km (45 miles) below the South Fork confluence is muted, although full recovery to ambient temperature was seldom observed.

Thermal influences on the river fishery are most significant in the upstream half of the affected river reach. The most productive habitat for fish species of special concern (westslope cutthroat trout and bull trout) occurs in the highly affected portion of the Flathead River upstream of the Stillwater River confluence. Habitat in the lower reach has been degraded due to impoundment by Kerr Dam at the outlet from Flathead Lake. When the lake is held at full pool, the lake influences the river 35 km (22 miles) upstream from the mouth. Higher river stage and

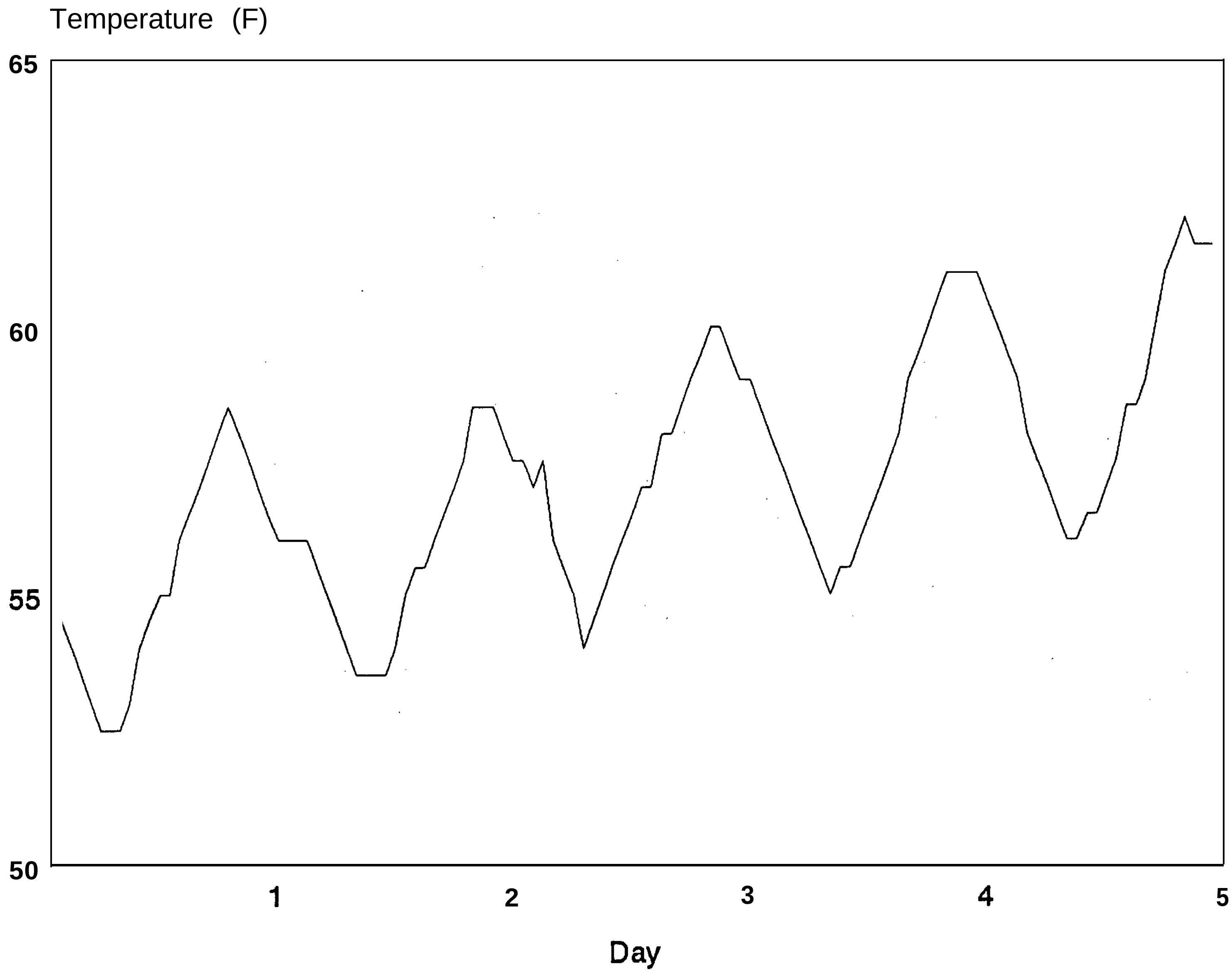


Figure 5. An example of typical'diel thermal fluctuation due to atmospheric heating during the day and cooling at night. This segment represents observed values during June 19 through 25, 1992.

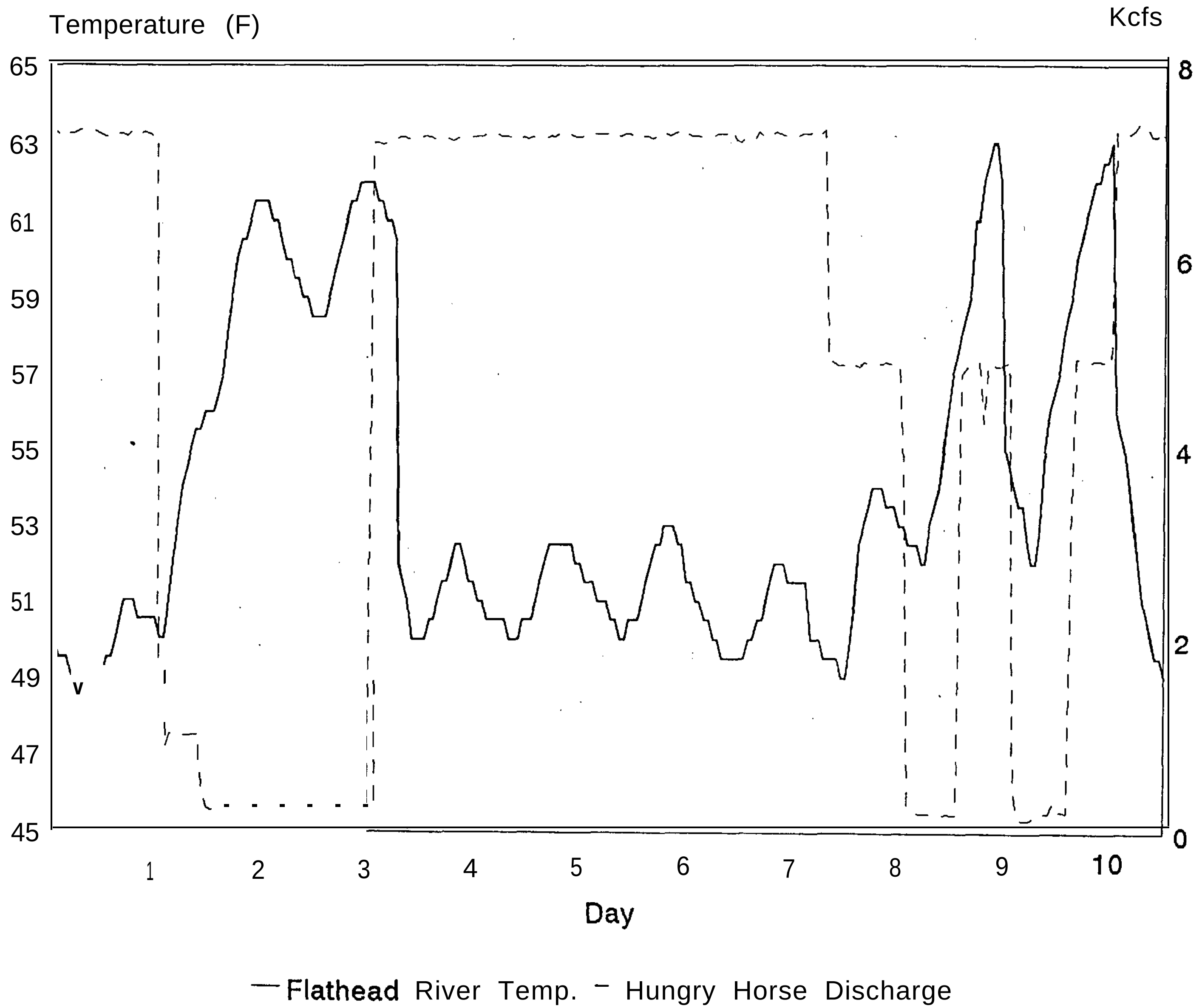


Figure 6. An example of thermal effects of hypolimnetic discharge from Hungry Horse Reservoir measured at Columbia Falls, June 19-24, 1992. The solid line represents hourly temperatures (°F). Dam discharges are represented by the dashed line.

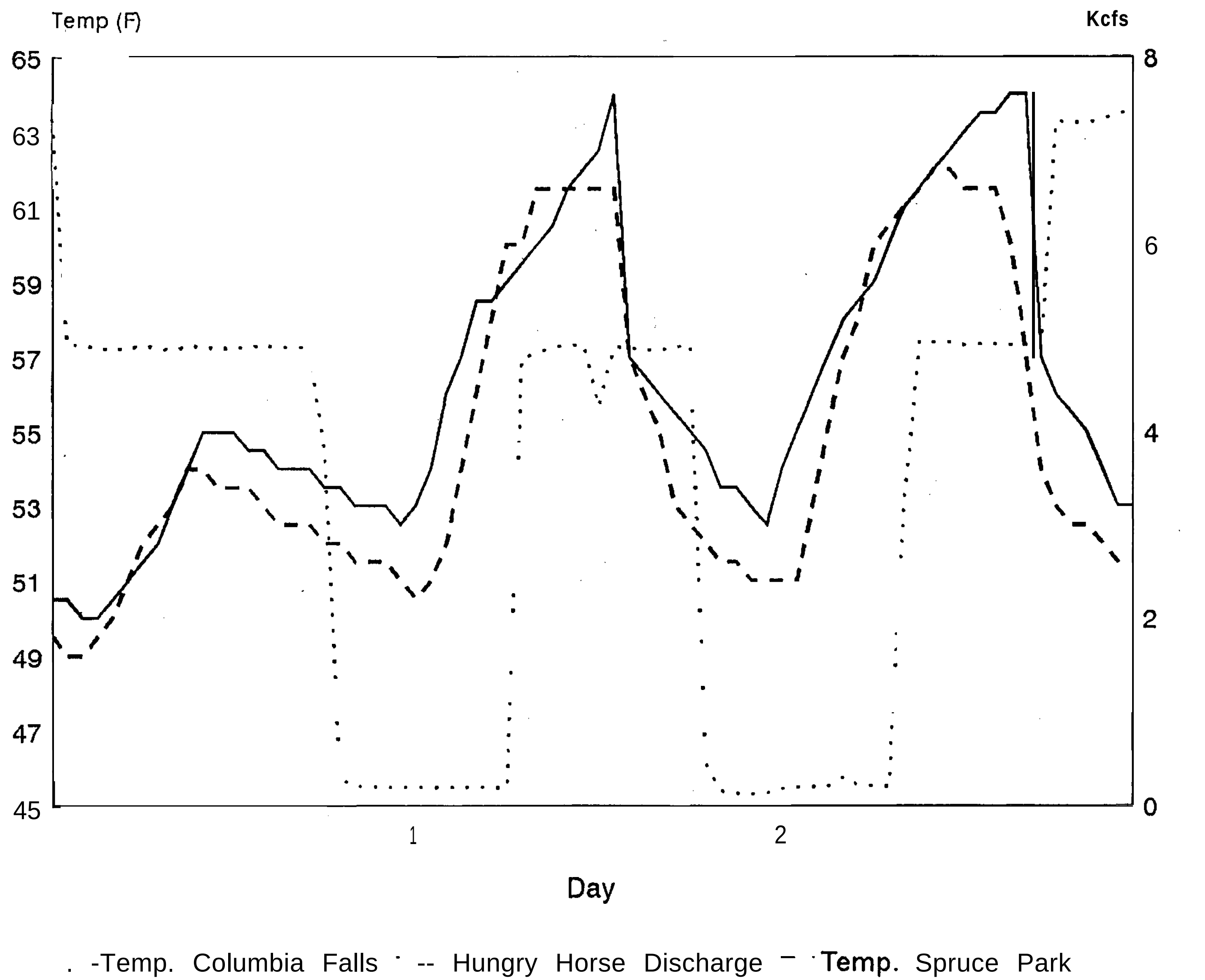


Figure 7. A comparison of hourly water temperatures recorded simultaneously at Columbia Falls (solid. line) and Spruce Park (dashed line) as compared to Hungry Horse Dam discharges (dotted line) during June, 1992.

Table 3. Instantaneous thermal fluctuations caused by hypolimnetic releases **from** Hungry Horse **(° F).** Arrows **denote** sudden warming (t) and cooling **(↓)** events. Multiple instantaneous thermal events during a single day are noted.

	Site Location			Site Location	
Date	Columbia Falls	Spruce Park	Date	Columbia Falls	Spruce Park
7/24/91	t 4, ↓ 5	t 3, ↓ 4	6/2/92	↓ 8	↓ 5, ↓ 5
7/25/91	t 5, ↓ 5	t 5, ↓ 5	6/3/92	t 2, ↓ 2, t 4	--
7/26/91	t 4	t 4	6/5/92	--	t 3
7/29/91	↓ 3	--[1]	6/6/92	--	t 3
7/30/91	t 4 ↑ 3, ↓ 4		6/8/92	↓ 5	↓ 5
7/31/91	↑ 5	t 8	6/15/92	↓ 4	--
8/1/91	↓ 5	t 3, ↓ 5	6/20/92	t 4, t 4	t 4
8/2/91	t 3, ↓ 6	t 9, ↓ 7	6/22/92	↓ 8	↓ 6
8/3/91	↑ 5	t 6	6/27/92	↓ 8	t 5, ↓ 7
8/5/91	↓ 5	↓ 5	6/28/92	t 3	t 8, ↓ 6
8/6/91	t 6	t 5, ↓ 5	6/29/92	↓ 7	X[2]
8/8/91	↓ 14	t 9, ↓ 10	7/1/92	t 3, ↓ 4	X
8/9/91	↑ 7, ↓ 10	t 9, ↓ 10	7/2/92	↓ 8	X
8/10/91	t 6, ↓ 11	t 10	7/5/92	↓ 8	X
8/12/91	↓ 6, t 6, ↓ 8	↓ 3, t 7	7/6/92	t 2	X
8/13/91	↓ 10	↓ 9	7/7/92-7/22/92	X	X
8/16/91	↓ 9	t 4, ↓ 7	7/27/92	↓ 8	↓ 6, t 6, ↓ 4
8/17/91	↓ 12	t 8, ↓ 9	8/1/92	--	↑ 9
8/18/91	--	t 8	8/3/92	↓ 8	--
8/19/91	↓ 7	↓ 5	8/8/92	--	↑ 15, ↓ 7
8/20/91	↓ 11	t 12, ↓ 15	8/10/92	--	t 3, ↓ 5
8/22/91	↓ 10	↓ 10	8/15/92	--	t 11
8/23/91	↓ 8	↓ 5	8/16/92	--	t 4

	Site Location			Site Location	
Date	Columbia Falls	Spruce Park	Date	Columbia Falls	Spruce Park
8/24/91	**--**	C *6*, ↑ *7*	**8/17/92**	***5 6***	↑ *4*, ↓ *4*
8/26/91	↓ **8**	↓ **5**, ↓ 5			
8/29/91	**--**	↑ **5**			
8/30/91	**--**	↑ *6*, ↓ 5			
8/31/91	**--**	↑ **9**			
9/8/91	↓ **5**	↓ **3**			
9/13/91	↓ **6**	↓ **3**			

[1]/**Thermal** change was not **instantaneous** at this site **(--).**

[2]/**Data** were lost due to equipment malfunction **(X).**

decreased water velocities have resulted in increased sediment accumulation in the river substrate. Channel alterations have resulted from increased sediment input from unstable riverbanks. Hank instability has been accelerated by frequent wetting and &watering resulting from intermittent power operations. Full recovery of the system will, therefore, require thermal control and moderated flow fluctuations.

Lone-term Cooling Due to Hvpolimnetic Withdrawal

Hypolimnetic releases reduce the accumulation of temperature degree days in **the Flathead** River downstream of the South Fork confluence. Water temperatures during the season of peak biological production (June through October) are significantly lower than historic records in the unaltered portion of the river. Under natural conditions, river temperatures rose to within the range necessary for trout growth in May and remained suitable through October and a portion of November.

Hypolimnetic withdrawal shortened the growing season to the period June through September. The cooling effect is masked during spring runoff,' when high flows from the unregulated forks contribute a large percentage of the **Flathead** River discharge. Dam discharges are generally reduced toward the minimum (145 cfs) between mid April and late June for reservoir **refill** and flood control. Thus, during a typical operation schedule, thermal influence from Hungry Horse Dam first becomes important in June when spring runoff declines toward basal flow and cold releases constitute a larger percentage of the combined river flow. The cooling effect increases in importance after the reservoir **refills** to the annual maximum elevation in July and drafting resumes. By late November, ambient temperatures in the unregulated forks decline toward **4°** C, similar to South Fork discharges, and the cooling effect ends (Figure 8).

Over the last decade, releases for power generation during late summer and fall have increased in duration and frequency, exacerbating the thermal problem. Historically, the reservoir was maintained at or near full pool throughout the **fall.** Power drafting began during late fall to meet regional power loads during the cold months. At stable, full pool elevations, discharge matched reservoir inflows, at basal fall flow conditions. More recently, provisional drafting, prior to the first inflow forecast on January 1, and early sales of electricity have increased the impetus for high discharges during the critical growth period. The cooling effect is most severe when flows in the unregulated forks decline to the seasonal minima.

Advantages of Thermal Modification Through Selective Withdrawal

Model simulations have shown that selective withdrawal would return the South Fork and main stem **Flathead** River to nearly natural temperatures from June through November (Figure 9). Rapid temperature fluctuations and long-term cooling effects could be greatly reduced. The physical constraints inherent to the dam structure .**would** result in slightly cooler river temperatures during the summer. When selective withdrawal was discontinued during the winter period, hypolimnetic withdrawal would result in slightly warmer river temperatures than would be observed in an unregulated system. If deemed desirable, the structure **could be**

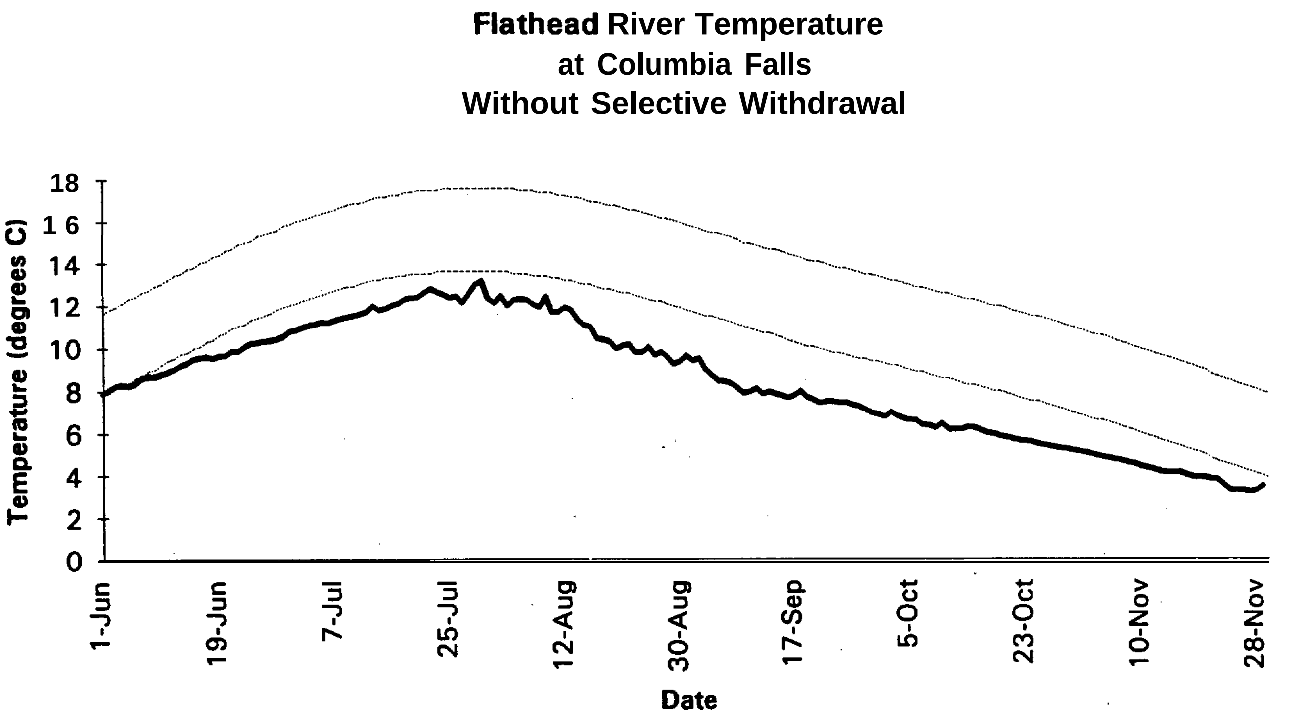


Figure 8. Long-term cooling of Flathead River temperatures caused by hypolimnetic withdrawal. Dashed lines bracket the natural temperature range during the peak growth season. These results are based on average long-tern conditions. This approach nulifies sudden temperature fluctuations that are evident in annual measurements.

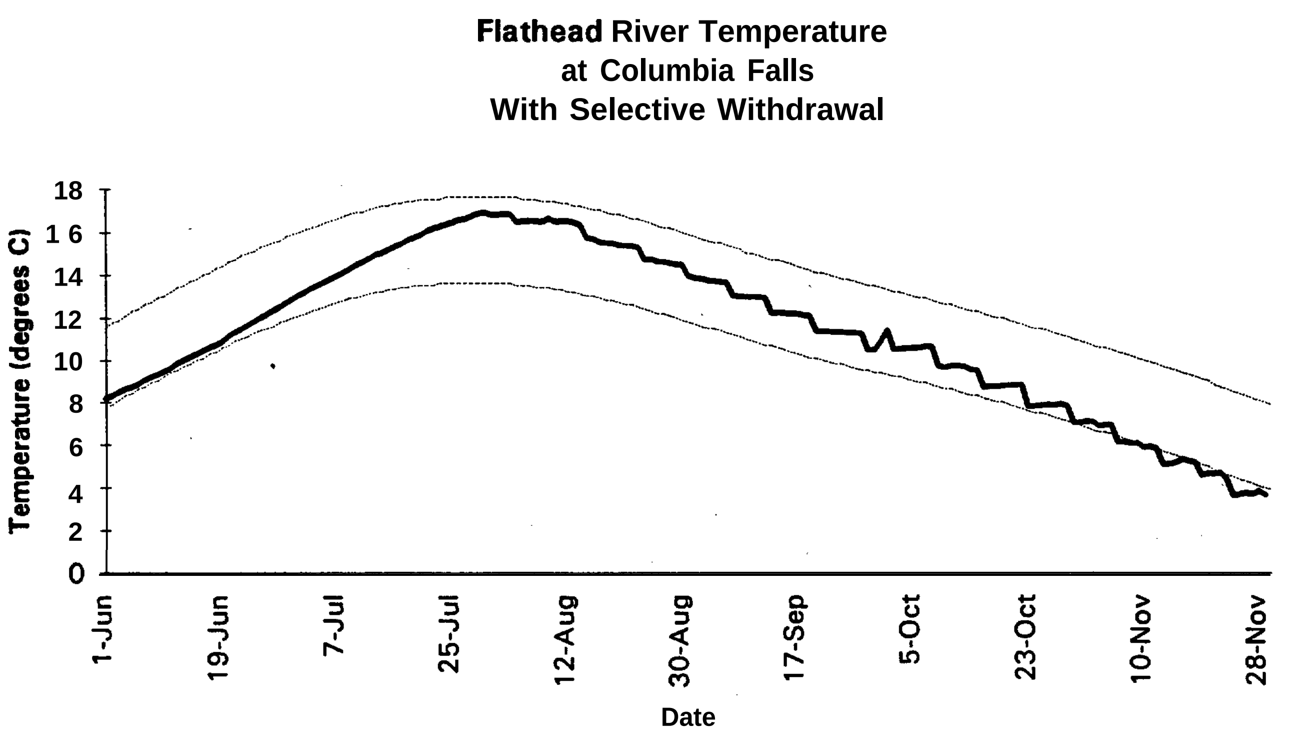


Figure 9. Thermal control resulting from selective withdrawal. Dashed lines bracket the natural temperature range during the peak growth period. These results are based on average long-term conditions. Complete control is possible under all water conditions observed historically, 1928 through present.

operated to extend the growing season well into November by releasing warmer than ambient water from the reservoir (Figure 10).

Temperature correction would aid the natural timing of adfluvial spawning migrations from **Flathead** Lake. Juvenile adfluvial species would experience favorable conditions in the river, upon emigration from their natal tributaries. Growth potential would also be improved for **fluvial** trout populations inhabiting the effected reach. Also, these temperatures would be more conducive to the natural timing of insect life cycle events and help restore the natural insect community structure. Flow fluctuations caused by power operations would continue to effect river stage and flow velocities, thus precluding a full recovery to the historic insect assemblage.

Increased production of aquatic organisms due to temperature alone will improve food availability for riverine fish species. Food availability in the dam tailwater will also be enhanced as zooplankton from the reservoir are entrained by the withdrawal device.

Results from paired simulations using the thermal model indicate that trout growth potential in the **Flathead** River would increase by two to five times, depending on annual water conditions. The growth efficiency model estimated that juvenile emigrants would grow 2.2 to 3.3 times faster if selective withdrawal was installed. Increased juvenile growth has been linked to increased survival in the river system.

Table 4 shows the results of simulations with and without selective withdrawal. The selected years were specifically chosen to provide test cases for an extremely high water year, a moderately high water year, an average water year, a moderately low water year and finally an extremely low water year.

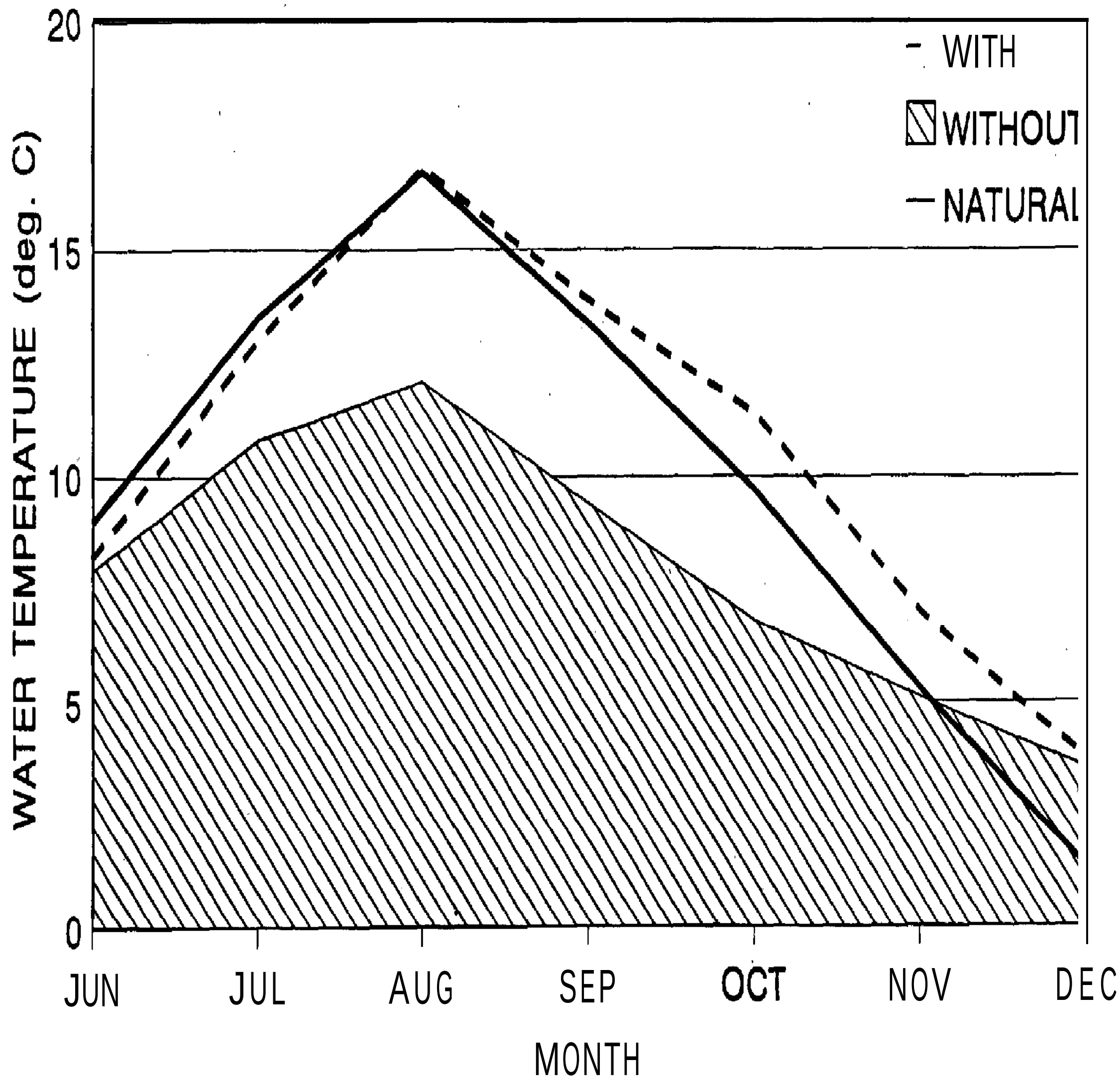
Table 4. Comparison of trout growth with and without selective withdrawal.

		Annual Weight Gain (Age Class **III+,** grams)'		
Year	**Percent Deviation from Normal Inflow**	**Without Selective Withdrawal**	**With Selective Withdrawal**	**Increase in Growth Rate**
1974	**+37.5**	**76**	**166**	**2.2x**
1976	**+ 14.6**	**64**	**163**	**2.5x**
1969	**+0.8**	**64**	**162**	**2.5x**
1957	**-13.6**	**59**	**171**	**2.9x**
1988	**-38.3**	**60**	**197**	**3.3x**

Without selective withdrawal, the highest and lowest weight gains correspond to increases in length of 76.0 and 63.4 mm. With selective withdrawal, the corresponding range in **linear** growth is 141.5 and 125.4 mm.

INFLUENCE OF SELECTIVE WITHDRAWAL

Average Conditions at Columbia Falls



Data for the 1 st of each month

Figure 10. A comparison of natural temperatures in the Flatheacl River at Columbia Falls, to average temperatures resulting from hypolimnetic withdrawal (shaded area) and temperatures achieved through selective withdrawal. Optimal trout growth occurs between 10 and 15" C. Cold water withdrawals reduce the duration of optimal water temperatures. Note that selective withdrawal can extend the growing season by releasing water temperatures warmer than ambient during fall,

Unnatural temperatures may influence predator prey interactions within the effected river reach. Prior to 1989, increasing numbers of lake trout, Salvelinus namaycush began to invade the Flathead River System from Flathead Lake. Lake trout are predaceous. Juvenile westslope cutthroat and bull trout have been identified in stomach contents obtained from the Flathead River (MDFWP unpublished file data). It remains uncertain how predation by lake trout has influenced the population dynamics of these native species of special concern. However, annual surveys of bull trout redds have shown an alarming reduction in spawning adults in the contiguous Flathead System. The declining trend coincided with year classes that emigrated from their natal tributaries when lake trout were present in the river. Adfluvial populations of westslope cutthroat trout have simultaneously undergone a decline, based on angler creel reports. Although other factors may have contributed to the decline cutthroat and bull trout populations, such as drought, habitat degradation or unknown species interactions, it is known that predation of juvenile migrants by lake trout does occur.

Artificially cooled river temperatures caused by increasingly frequent power releases during late summer and early fall may have facilitated the invasion of lake trout into the river system. Although lake trout may make excursions into warmer waters, they generally prefer temperatures about 10° C (50° F) (Scott and Crossman 1973). Historically, water temperatures exceeded 10° C from mid June through mid to late September. Temperatures typically increased to 17° C (63° F) during portions of July and August. Cooling from hypolimnetic withdrawal has caused temperatures to remain within the favorable range for lake trout during all months except portions of July and August. Daily river temperatures in the effected reach have rarely exceeded 13° C (55° F) during the warmest months. Thermal refugia in groundwater influenced areas may now allow lake trout to reside in the river year round.

As a result of increased interactions with lake trout, juvenile cutthroat and bull trout may be more prone to predation. Juveniles of both species emigrate from their natal tributaries during late June and July in the Flathead System (Liknes and Graham 1988, Fraley and Shepard 1989). orientation to the riverine environment is not immediate, juveniles must locate suitable habitat and feeding stations. Residence in the river varies, although migratory juveniles are present throughout summer and fall.

Thermal control through selective withdrawal could reduce or eliminate the presence of predaceous lake trout during the period when juveniles are most vulnerable. Warm water releases mimicking the natural temperature regime should make river residence less desirable to lake trout. If this is true, lake trout may retreat to the lake, thus reducing interactions with juvenile trout. Increased growth rates should also aid juvenile survival.

Primary and secondary production in the reservoir may actually be enhanced by selective withdrawal. Evidence suggests that warm water withdrawal in the vicinity of the thermocline may weaken the thermal stability during stratification. If so, wind mixing will carry warm surface waters deeper into the euphotic zone. Nutrients rich waters from beneath would also mix. As the mixing layer thickens, the reservoir surface cools, thus allowing increased solar heating through convection. This may increase the total annual absorption of heat by the reservoir. Model results indicate a net increase of primary production and zooplankton biomass (Figures 11 and 12).

Temperature control can be accomplished with little or no effect on power production. Initial concerns surrounded a slight head loss (estimated as equivalent to 0.6 m (2 feet)) caused by hydraulic friction inside the trashrack structure as water fell from the withdrawal depth to the penstock aperture. Engineers later designed the structure to minimize hydraulic friction. Panels covering the penstocks can be raised, and water released normally at the original withdrawal depth, from late November through May, corresponding with the historic period of reservoir drawdown for power production. Thus, potential effects on power production have been further reduced.

The present design enables dam operators to achieve temperature control over the entire range of turbine discharge capacity. If spill becomes necessary, turbine discharge could be adjusted to compensate for cold water releases from the jet valves or warm water released from the glory hole so that temperatures remain nearly natural in the South fork below the dam. We predict that thermal effects caused by most emergency operations can be controlled through coordinated releases from the outlet works.

Free nutrient levels might actually decline in the river because of the shallower withdrawal depth; suspended organic carbon would probably increase (Dr. L. Bahls, Montana Water Quality Bureau; Dr. J. Stanford, UM Biological Station, pers. comm.). Stanford (1990) hypothesized that cold discharges of water into Flathead Lake during the summer disrupts natural production of plankton in the upper water layers of the lake. Thus, more natural temperatures in the Flathead River could also benefit Flathead Lake.

Disadvantages of Selective Withdrawal

Biological production in Hungry Horse Reservoir will be effected when warm water is withdrawn for temperature control. During the period of thermal stratification, phytoplankton and zooplankton concentrate in the upper 20 meters (66 feet) of the reservoir (May et al. 1985). When the selective withdrawal device is in use, withdrawal depths range from approximately 7 to 24 meters. Entrainment of some percentage of these organisms is inevitable. Whereas biomass lost from the reservoir supplements food availability in the tailwater, reservoir biota experience a corresponding loss (Figures 11 and 12).

Refinement of operation strategies for the withdrawal structure can offset some downstream losses. Five adjustable panels controlling discharge depth at each penstock will enable simultaneous withdrawal from different layers in the pool into a single turbine. This “stratified” selective withdrawal can mix warm and cool layers to achieve an intermediate target temperature, yet avoid the most productive layer containing the highest density of organisms. Stratified withdrawal can also be achieved when two or more turbines are in use, by withdrawing differing strata in adjacent penstocks for mixing in the tailrace.

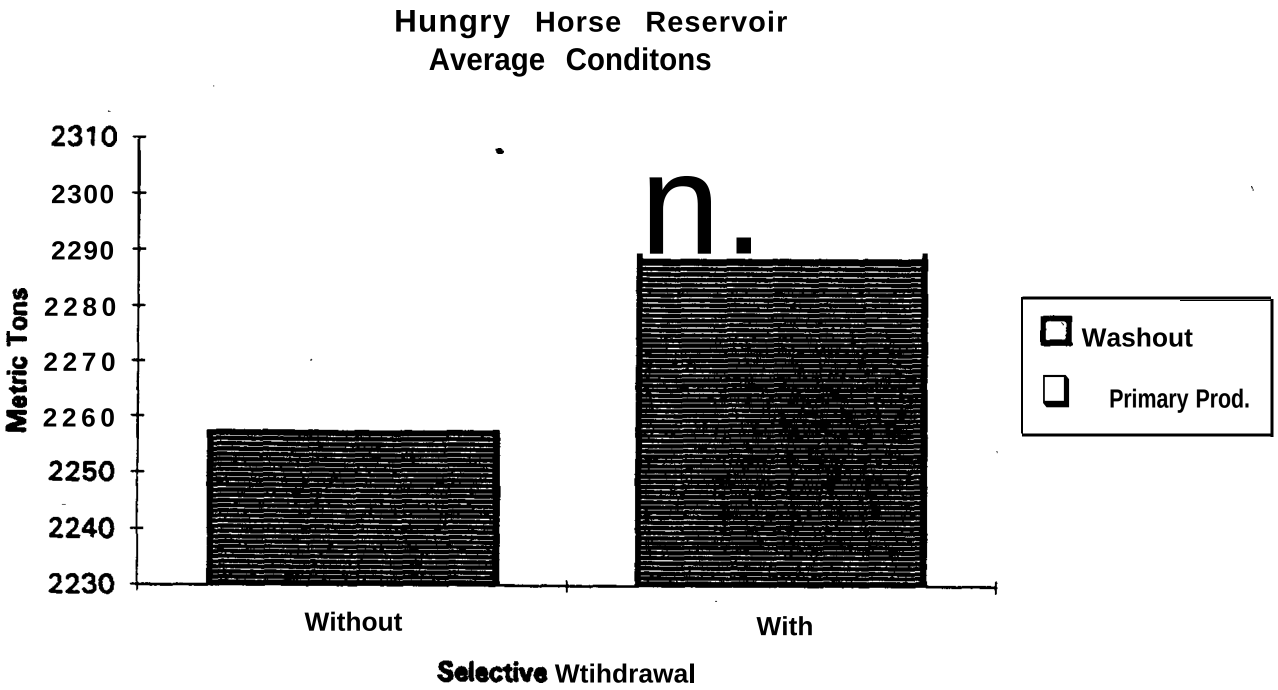


Figure 11. A comparison of annual primary production and washout through the dam turbines under fixed hypolimnetic discharge and selective withdrawal. Eownstreamloss is increasedwhenwamwater is withdrawn from the productive euphotic zone. The empirical model indicates that primary production my be enhanced by selective withdrawal when thermal stratification weakens, allowing the wind mixed zone to extend deeper within the euphotic zone.

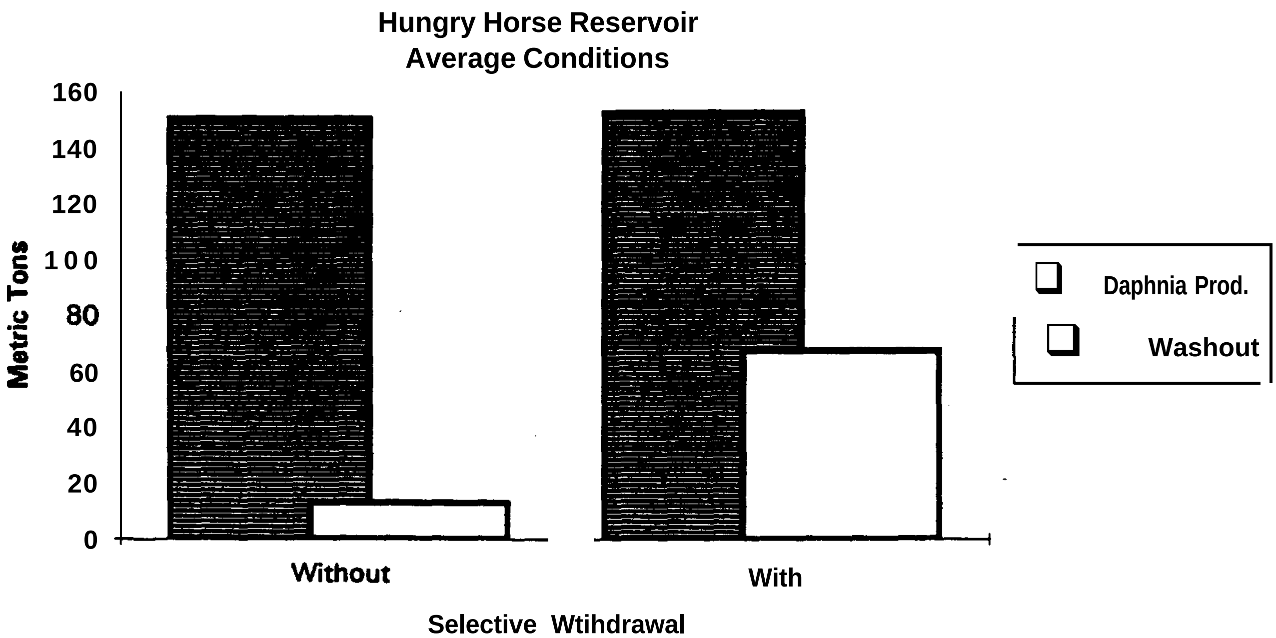


Figure 12. A comparison of daphnia production and washout from the dam under fixed hypolimnetic discharge and selective withdrawal. Downstream loss is increased when warm water is withdrawn from productive surface layers. Model simulation indicates that zooplankton production is somewhat higher under selective withdrawal.

Benthic insect production is influenced by water temperature and the accumulation of organic material deposited from the productive upper layers 'of the pool and allocthanous sources. Reservoir productivity lost through turbine penstocks could result in a slight reduction in benthic production. However, this could be offset by increased larval production at depth as warm water is mixed deeper in the water column and contacts the zone of high larval density.

The incidence of fish entrainment to the turbines may be increased by selective withdrawal. Under fixed hypolimnetic withdrawal entrainment has not been observed. Hydroacoustic surveys of Hungry Horse Reservoir have shown that nearly all fish are concentrated within the littoral zone and are oriented near the bottom or surface (MDFWP unpublished file data). Few hydroacoustic targets have been identified in pelagic areas or near the penstock apertures. The few targets recorded in the pelagic zone, however, were suspended near the mesolimnion and thus, could coincide with temperature layers targeted for release through selective withdrawal. If entrainment becomes significant, stratified withdrawal could be used to reduce this effect.

CONCLUSIONS

Considering the potential tradeoffs between reservoir effects and calculated growth benefits in the river downstream, we concluded that selective withdrawal should be constructed. This conclusion was supported by the direction provided by the Northwest Power Planning Council. Biological considerations reported herein should be incorporated in the design and operation of the structure to maximize the effectiveness of thermal control, yet minimize effects on reservoir productivity.

Installation of selective withdrawal on all four penstocks will result in complete and constant thermal control in the river downstream. Desired tailwater temperatures were achieved in all simulations using historic daily inflow and surface elevation data, 1954 through present.' River temperatures will continue to be slightly cooler than natural during summer and warmer during the winter because of the physical properties of the dam structure and basin configuration. Short-term temperature fluctuations and long-term cooling were reduced to near natural conditions, however, consistent with our goals to improve biological conditions below Hungry Horse Dam. Selective withdrawal could be used to extend the growing season by releasing warmer than ambient water during fall. Intentional deviations from the natural thermal regime should be done with care. The effects of unnatural thermal modifications on biological communities and species interactions are not fully understood.

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