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MODEL DEVELOPMENT TO ESTABLISH INTEGRATED OPERATIONAL RULE CURVES FOR HUNGRY HORSE AND LIBBY RESERVOIRS - MONTANA

FINAL REPORT 1996

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EXECUTIVE SUMMARY

Hungry Horse and Libby dams have profoundly affected the aquatic ecosystems in two major tributaries of the Columbia River by altering habitat and water quality, and by imposing barriers to fish migration. In 1980, the U.S. Congress passed the Pacific Northwest Electric Power Planning and Conservation Act, designed in part to balance hydropower development with other natural resources in the Columbia System. The Act formed the Northwest Power Planning Council (Council) who developed a program to protect, mitigate and enhance fish and wildlife on the Columbia River and its tributaries. Pursuant to the Council's Fish and Wildlife Program for the Columbia River System (1987), we constructed computer models to simulate the trophic dynamics of the reservoir biota as related to dam operation. Results were used to develop strategies to minimize impacts and enhance the reservoir and riverine fisheries, following program measures 903(a)(1-4) and 903(b)(1-5).

Two FORTRAN simulation models were developed for Hungry Horse and Libby reservoirs located in northwestern Montana. The models simulate the physical operation of the dams including the water budget and downstream flood concerns, and predict the resulting thermal structure of the reservoir and tailwater temperature. Biological responses include: primary production and washout, zooplankton production and washout, the deposition of terrestrial insects on the reservoir surface, benthic dipteran production and body growth of the major game fish. Input to the models is limited to the annual inflow hydrograph, monthly inflow forecasts beginning January 1, minimum and maximum outflow limits, and a proposal of either the annual surface elevation schedule or the annual schedule of dam discharges. The model user has the option to specify the depth at which water is withdrawn from the reservoir throughout the simulation. All other parameters and coefficients were fixed based on long-term source of empirical data (1983-1994). The models were designed to generate accurate, short-term predictions specific to two reservoirs and are not directly applicable to other waters. The modeling strategy, however, is portable to other reservoir systems where sufficient data are available.

Reservoir operation guidelines were developed to balance fisheries concerns in the headwaters with anadromous species recovery actions in the lower Columbia (Biological Rule Curves). These BRCs were then integrated with power production and flood control to reduce the economic impact of basin-wide fisheries recovery actions. These Integrated Rule Curves (IRCs) were developed simultaneously in the Columbia Basin System Operation Review (SOR), the Council's phase IV amendment process and recovery actions associated with endangered Columbia Basin fish species.

INTRODUCTION

Human demands on the Columbia River System are many and diverse. These demands frequently conflict with each other, and sometimes exceed the physical limitations of the basin. Operating guidelines have evolved at the reservoirs to achieve some balance between immediate concerns including hydroelectric power production, flood control, irrigation, navigation and recreation. The biological effects of hydropower operations became a priorlty for study as populations of several important fish species declined throughout the Columbia Basin. Operational guidelines were recommended by resource agencies to improve biological conditions. As additional demands are placed cm the system, or the priorities of these demands are shifted, the balance is upset. Computer simulation models can help identify and quantify the various tradeoffs and help avoid costly mistakes.

STUDY AREA

Hungry Horse and Libby reservoirs are large storage reservoirs on headwater rivers of the Columbia River Drainage in Montana (Figure 1 and 2). Hungry Horse Dam was constructed on the South Fork Flathead River in 1952. Libby Dam, on the Kootenai River, was completed in 1972.

Hungry Horse Dam was originally designed with a fixed withdrawal depth (3,319 feet msl) which released hypolimnetic water at 4 to 5° C year-round. A thermal control device called "selective withdrawal" was installed and began correcting tailwater temperatures in August 1995. Libby Dam was equipped with a similar selective withdrawal system during construction. Selective withdrawal enables dam operators to mix water from selected depths to mimic the natural thermal regime in the dam discharge. Neither dam is equipped with fish passage facilities.

Together, the study reservoirs provide 20 percent of the available storage in the Columbia River hydropower system. Water is stored from mid-April through the end of spring runoff, raising reservoir elevations toward maximum pool during July. Reservoir elevations then remain relatively constant until autumn when demands for electricity result in higher discharges. During spring, inflow forecasts and flood control criteria dictate how much water must be evacuated to accommodate flood waters. Minimum pool elevation usually occurs in mid-April; the range of annual fluctuation is dependent on inflow, drafting for power production and downstream flood control. Operational rule curves are set annually as dictated by a four-year critical drought plan and by hydrosystem coordination scheduling (Figure 3).

Dam operations influence biological factors upstream and downstream of the facility. Models were expanded to include the headwater hydrology and downstream flows and water temperatures in the discharge. The Hungry Horse model (HRMOD) includes natural flows in the North and Middle forks of the Flathead River, Flathead Lake elevations and discharges to the lower Flathead River from Kerr Dam. The Libby Reservoir model (LRMOD) extends downstream to Corra Linn Dam at the outlet from Kootenay Lake. Duncan Dam and reservoir were included as part of the flood control water balance. Inflows from tributary streams between Libby Dam and Bonners Ferry, Idaho. were included to examine recovery actions for river fish species including white sturgeon.

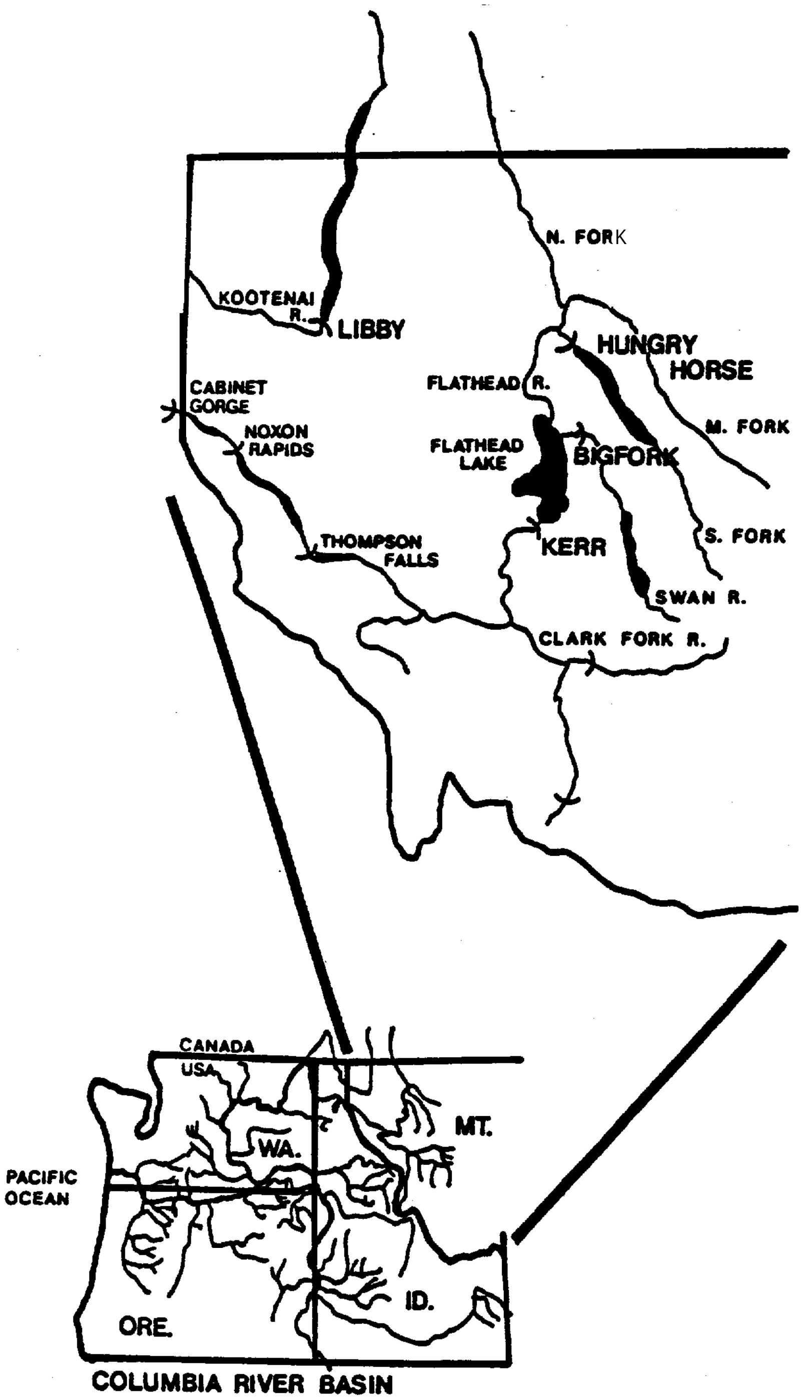

Figure 1. The location of Hungry Horse and Libby reservoirs in the headwaters of the Columbia River. The three forks of the Flathead River converge to form the main stem before entering Flathead Lake. The lake discharges through Kerr Dam and flows to its confluence with the Clark Fork River.

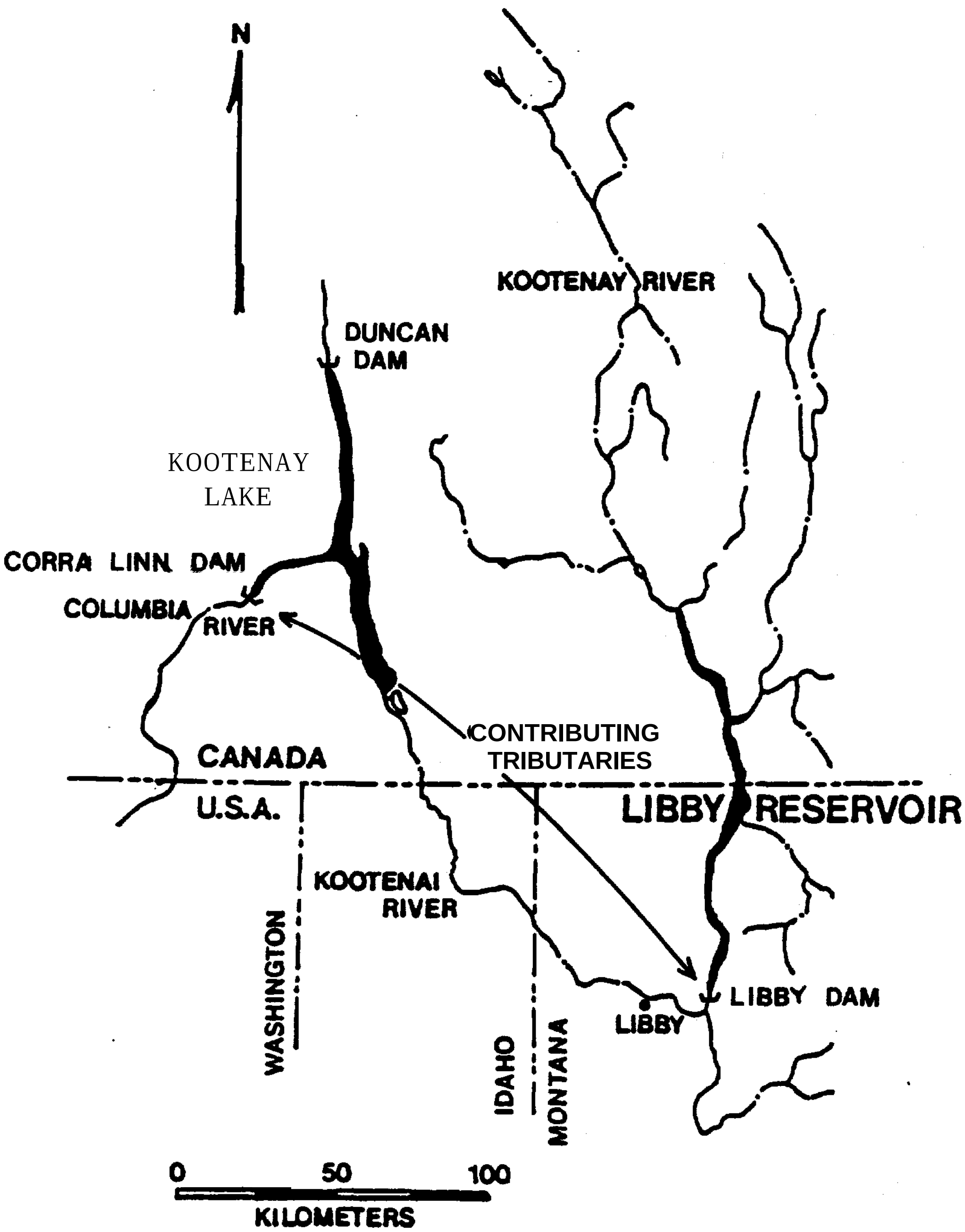

Figure 2. The hydrology of Libby Reservoir and the adjoining river drainage. Runoff from Canadian and U.S. tributaries forms Lake Koocanusa. Discharge from Libby Dam combines with flows from unregulated, wild streams in the Kootenai River before entering Kootenay Lake in British Columbia. Mowing waters from unregulated streams and Duncan Dam contribute to waters which exit through Corra Linn Dam enroute to the Columbia River.

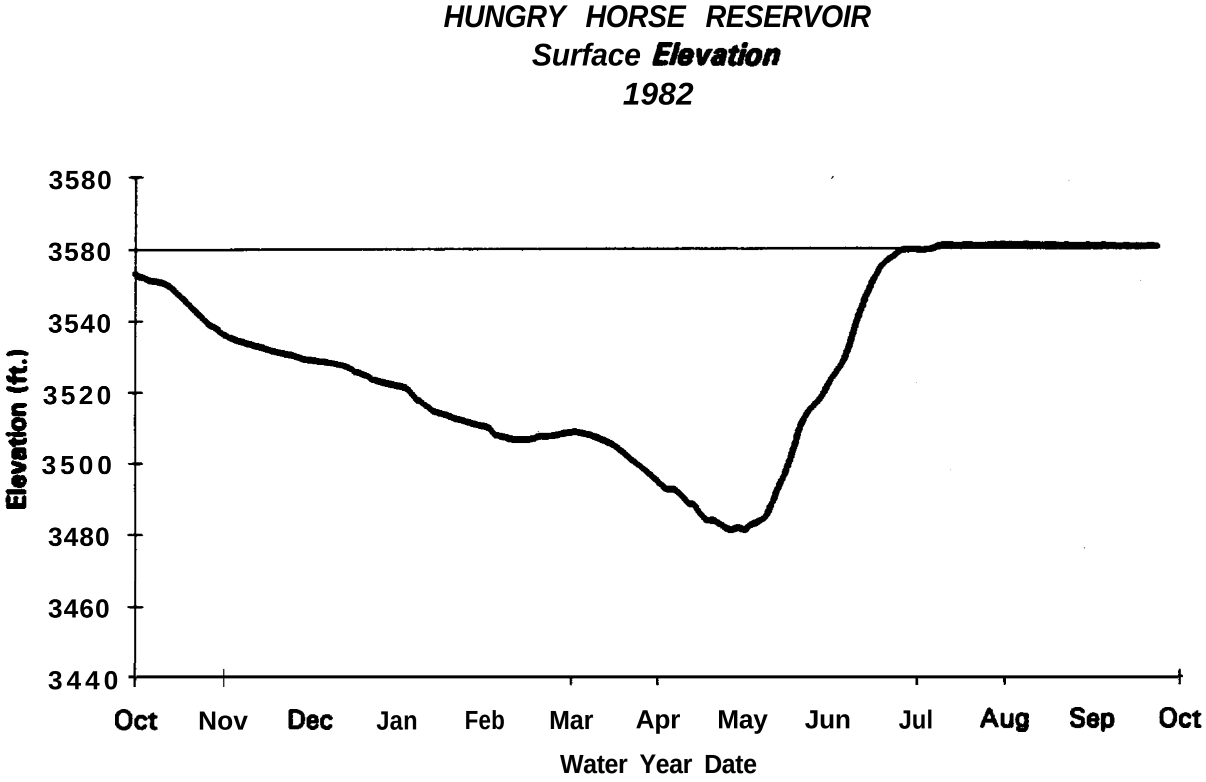

Figure 3. An example of the annual surface elevation change in Hungry Horse Reservoir. The axis represents a water year, beginning October 1 and ending September 30. The reservoir is typically drawn down starting in fall and reaches maximum draft in mid April. The pool recharge during spring runoff toward the full pool elevation (3,560 ft. msl) during July.

METHODS

The Data Base

Extensive historical data were available on the reservoir operations, river discharges and 'meteorological conditions in the area. Daily reservoir operation data for Hungry Horse Reservoir (eg. inflow, outflow and surface elevation) were available for water years 1953 through 1995. The daily elevation of **Flathead Lake** was available since 1929. Concurrent daily discharge data from the North Fork of the **Flathead** River and of the main stem **Flathead** River at Columbia Falls were available for water years 1955 through 1988. Daily discharges in the Middle Fork of the **Flathead** River, the Swan River and Kerr Dam were compiled for water years 1955 through 1981. The mean daily **temperature** of the North Fork of the **Flathead** River extended from water year 1976 through 1988. Daily temperature data were also available from the South Fork for water years 1965 through 1993 and for the main stem at Columbia Falls for water years 1980 through 1993.

For Libby Reservoir the basic daily operations data were **available** for water years 1976 through 1995. The oufflow elevation was known for 1981 through water year 1990. The daily elevation of Duncan Reservoir and Kootenay Lake, as **well** as the outflow of Kootenay Lake through Corra **Linn** Dam were available for 1969, 1972, 1974 and 1979 through 1986. The discharge of the Kootenai River at Porthill, Idaho was available for water years 1969 through 1995. The daily water temperature of the Libby Dam discharge was known for water years 1983 through 1995. **These** were used to calibrate a portion of the thermal model. The precipitation and temperature at Libby were available for water years 1976 through 1985.

Inflow forecasts for Hungry Horse, Libby and Duncan reservoirs were provided by ACOE. Data exist for each month January through July for the period of record 1928 through present. Physical and biological **characteristics** of Hungry Horse and Libby reservoirs were assessed by the Montana Department of Fish, Wildlife and Parks **(MFWP)** from 1983 through 1990. Field methodologies were **standardized** for continuity in data files (Chisholm et al. 1989, May et al. 1988). Field data through 1989 were used to construct the models (HRMOD and LRMOD) specific to each reservoir. Model components were validated after construction. Data from 1989 through 1995 were incorporated to **refine** model relationships.

The data include: vertical profiles of **temperature,** conductivity, **pH,** dissolved oxygen and light attenuation; chlorophyll concentrations and primary production; density of benthic larvae at depth; emergence of benthic insects; density, body **size,** relative biomass and vertical distribution of **zooplankton;** density of insects on the reservoir surface; fish stomach contents; relative abundance of fish species; fish lengths and weights; and fish age and growth from scales and otoliths. Most of these data were available from 1983 through 1992. The chlorophyll and primary production measurements began in 1986 and ended in 1989. Most of the above data were collected from three or four stations along the length of the reservoir, as well as from the outflow. Some inflow data **were** also collected.

Topographic maps of the reservoir basins provided an accurate three-dimensional representation of the reservoir bathymetry. Mapping provided volume and surface area relationships as a function of reservoir surface elevation.

Modeling Strategy

The basic modeling strategy is to make maximal use of extensive data gathered by MFWP and data compiled from other sources to develop empirical relationships which capture as much of the observed biological variation as possible. The model's equations which describe the relationships between dam operation and physical and biological factors were only as complex as the field data justified. The use of theoretical relationships was held to a minimum. These were used only to limit the scaling of coefficients, whose exact values have little or no effect on interpretation of the output.

The model has three main components: physical environment, thermal dynamics and biological dynamics (Figure 4). Calculations of the biological responses in higher trophic levels are based on the results of the lower trophic level submodels, much as energy is transferred through a biological system. The approach used in developing the models was the normally preferred one of "linear programming" with sequential modules. Each submodel was calibrated to field measurements and directly verified with empirical data to assure realistic predictions. This component approach helped field personnel focus on achievable goals, determine critical data needs and interrelate the diverse types of data that were collected. The strongest patterns in the biological data were associated with seasons, longitudinal sampling locations, surface areas, depths and temperatures. A variety of linear and non-linear relationships were established to portray these associations accurately.

Assumptions

1. Component models are more easily verified than are whole system, ecosystem models.

2. Empirically measured relationships are more reliable than are mechanistic relationships derived using unmeasurable coefficients.

3. Nutrient loading to the reservoirs will not be measurably changed by man's activities. If changes are detected, the model(s) must be recalibrated.

4. Water temperature of the dam discharge equals the temperature in the reservoir forebay at the depth of water withdrawal.

5. The thermal structure in the reservoir forebay, calculated by the thermal model was extrapolated throughout the reservoir. This assumption was supported by longitudinal thermal profile measurements.

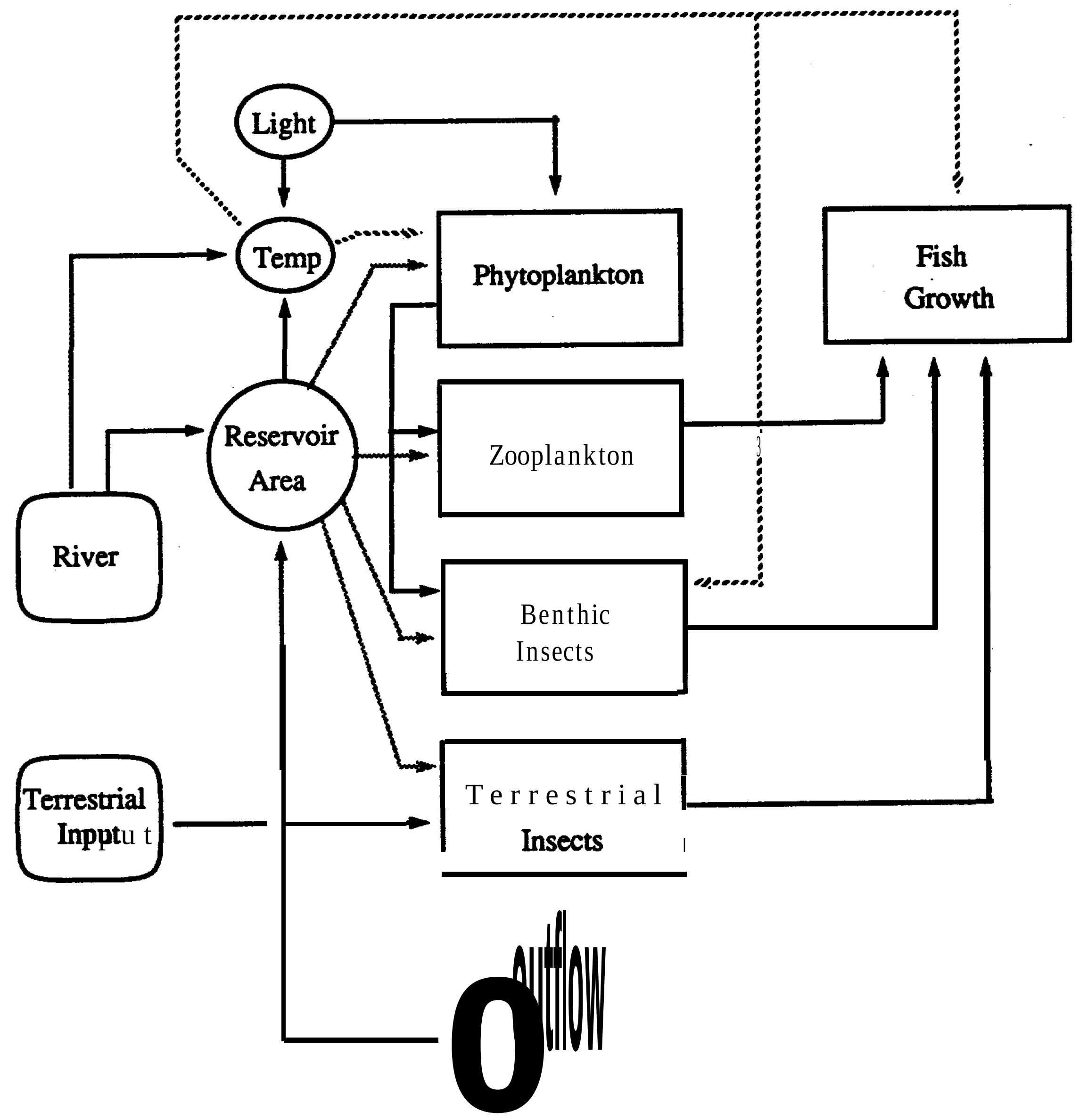

Figure 4. Compartmental diagram of model **interconnections.** The component structure facilitates evaluation and refinement of the model.

6. All discharged water must pass through the turbines (no spill) unless default specifications are superseded by the model user. Spill is allowed when historical discharge data are input to simulate a specific annual operation.

7. Local flood constraints are mandatory in all simulations. HRMOD protects Columbia Falls and the Flathead River downstream of Kerr Dam from excessive Hungry Horse discharge. LRMOD incorporates flood requirements for Bonners Ferry, Idaho; Kootenay Lake; Duncan Dam and Corra Linn Dam, B.C. Default specifications may be superseded by the model user when historic discharge data are used to simulate a specific annual operation.

8. Un-gauged, wild inflows can be predicted through regression on long-term flow data from a gauged, nearby stream.

9. Meteorological parameters were smoothed to long-term trends using 11 years of daily records, corrected to measurements at each dam.

10. Total zooplankton production is proportional to measured primary production, minus a loss function established for plankton communities in oligotrophic, temperate waters.

11. Total zooplankton production can be subdivided into estimates of reproduction within each zooplankton genera, based on the relative biomasses of zooplankton genera captured in monthly sampling series (1983-1991).

12. Estimated washout of zooplankton from Hungry Horse Dam, per discharge volume, through the proposed selective withdrawal structure (which became functional August 1995) was assumed to be proportional to the measured density at each withdrawal depth.

13. The vertical distribution of larval Chironomids is proportional to densities enumerated in triplicate dredge samples in each depth zone. This distribution is adjusted up or down to reflect elevational conditions at the beginning of each annual simulation.

14. Annual and daily estimates of benthic insect emergence, per unit biomass in a given year, assume identical reservoir operation for two years.

15. The seasonality and relative abundance of terrestrial insects were assumed to be proportional to captures in duplicate surface tow nets in nearshore <100 m and offshore zones.

16. Fish population size and species relative abundance were assumed to be static for all model simulations. The model design focused on the relative effects of various dam operation scenarios.

17. Fish growth estimates assumed identical dam operations during each year of the fishes life cycle. Westslope cutthroat at age IV+ and V+ assumed constant dam operation for 2 and 3 years, respectively. Kokanee at age I+ and II+ also assumed constant operation for 2 and 3 years.

Model Description

The models were written in FORTRAN using syntax allowed by Microsoft@ version 5.0. Screen graphics are produced using routines from Microsoft's@ Graphics library. The models emulate the graphics on any PC with VGA, EGA, CGA or Hercules graphics, a math co-processor and 300K of free memory. Table 1 provides the names and basic function of the files that are involved with the models.

The descriptions below are somewhat idealized for the sake of simplicity. In the actual model, many operations are accomplished in a piece-wise manner by separate subroutines. This is nearly always true where units of measurement vary. Units of measurement were reported in the units of choice by field personnel who compiled the information. The models operate on a water year basis. A water year begins on Cktober 1 of the preceding calendar year and ends on September 30. February 29 is removed from all daily time series data so that all years contained 365 days for each of comparison.

Physical Environment

The physical hydrology of the reservoir basin was descrii by daily values of inflow, surface elevation and discharge for the period of simulation. The physical framework calculates the water balance, the physical constraints of the dam structure and the geomorphology of the reservoir basin. Essentially all user input occurs in this part of the model.

Reservoir capacity relationships were based on three-dimensional mapping of the reservoir topography. The reservoir basins were digitized from large scale (1 in. = 400 ft.) topographic maps (Hungry Horse: U.S. Bureau of Reclamation Maps 447-105-211 to 238; Libby: USACOE File No. E53-1-154, Sheets l-37, 1972 and British Columbia Ministry of the Environment, Drawings M-247-C, Sheets l-63, 1969). For Hungry Horse Reservoir, contours were available for elevation 3,100 feet, from elevations 3,120 to 3,270 feet by 30 foot increments and from 3,300 to 3,560 feet by 10 foot increments. For Libby Reservoir, contours were available for elevations 2,120 to 2,160 feet by 20 foot increments and from 2,190 to 2,460 feet by 10 foot increments. The net impact of sedimentation and erosion on the result for these reservoirs was thought to be negligible. Elevation contours on individual maps were linked to derive the total volume and surface area at each reservoir elevation.

Minimum and maximum flow limits were modeled downstream through the nearest critical flood control center. HRMOD includes minimum and maximum flows for the South Fork Flathead River, flood constraints at Columbia Falls, Flathead Lake elevations and discharge through Kerr Dam. LRMOD mimics flood control procedures in the Kootenai River, Kootenay Lake, Duncan

Table **1.** The files involved with the reservoir models. Also listed are the basic functions of the contents of each file. A **"?"** indicates that the letter “H” or “L” should be substituted for the Hungry Horse or Libby version, **respectively.** A **"*"** indicates that the last two digits of the water year should be substituted.

File	Primary Function of File Contents
?RMOD.EXE	Main executable program.
?RMOD.FOR	Source code for the main program.
?RMOD.FON	Bit mapped fonts for use with the screen graphics.
?RMOD.HLP	Help frames for use during model execution.
?RSUPFL.FOR	Source code for basic graphics routines.
?RSUPO.FOR	Source code for basic operations.
?RSUPl .FOR	Source code for reservoir water balance routines.
?RSUP2.FOR	Source code for thermal model routines.
?RSUP3.FOR	Source code for biological assessment routines.
FLATHEAD.FOR	Source code for downstream flood concerns at Hungry Horse.
DUNCAN.FOR	Source code for downstream flood concerns at Libby.
?RDATA.FOR	Data initialization for some common variables.
LOELV*.DAT	Data files with historic outflow elevations for Libby.
?QIN*.DAT	Data files with historic inflows.
?QOUT*.DAT	Data files with historic outflows.
?SURF*.DAT	Data files with historic surface elevations.
REVIEW.EXE	Utility program to review model output files.
REVIEW.FOR	Source code for the above program.
REPORT.EXE	Utility program to produce hard copy output.
REPORT.FOR	Source code for the above program.
GRAPHICS.LIB	Microsoft@ library for screen graphics.
UTL.LIB	In-house library of screen and keyboard functions.
HPPLOT.LIB	In-house library of plotting routines.

Reservoir and **Corra Linn** Dam. **The models** solve the water budget, given a daily inflow schedule, plus **either** an annual schedule of daily discharges or surface elevations.

Inflow

During a model simulation, the user first **specifies** the annual inflow schedule. HRINQ and **LRINQ** are the main interactive routines that allow the user to establish or to modify this schedule. There are four main options. The first option is to input the total volume and then have the model partition it into daily values based on the long-term average shape of the inflow schedule. The shape of the average curve is stored as the slightly smoothed long-term average contribution of each day's inflow to the annual total (Figure 5). The inflow volume may be the total for the entire year or the total for any part of the **year** as defined by beginning and ending dates. The second option is to read all the daily **values** from a file provided by the user. This option is the most useful when using historical data. **Historical** inflow files are available for Hungry Horse Reservoir for water year 1929 through 1995 and for Libby Reservoir for water year 1911 through 1995.

An option was added to facilitate interaction with other models developed for power and flood control analyses by agencies in the lower Columbii River System. Files containing 14 monthly values (April and August were split into two W-month periods) can be input as a file. The model recognizes this input as a correct annual schedule and interprets the input as a histogram of average flows within each period.

The third option is to construct a fairly simple annual inflow shape by specifying a few points and having the model complete the annual schedule by linear interpolation. This option is most useful for varying the timing and shape of runoff events. **Once** the inflow curve is specified, the inflow volume is compared to the long-term average and descriptive statistics are reported. The inflow schedule can be examined **graphically.** The user can also calculate the inflow volume during a portion of the year by **specifying** the **beginning** and ending dates.

A fourth option was introduced to allow proposed reservoir elevation schedules to be established based on monthly inflow forecasts. The user initiates the run by entering an inflow schedule, usually from a historical inflow file or **from** a proposed inflow **file** for that year. The **drawdown** and refill schedule is then defined by the monthly inflow forecasts beginning on January 1, and **the** designated critical year value (1 through 4). This elevation schedule is guided by the **IRCs.** The rate of **drawdown** and refill is determined based on the magnitude of the forecasted inflow. Thresholds within the continuum of inflow volumes define each **IRC.** The seven monthly forecasts (January through July) **incrementally** adjust the basic **IRC** curve during each period of the water year. A proposed "target" curve is then generated, either by **interpolating** between adjacent curves or using the basic **IRC** elevation which corresponds with a given forecast volume.

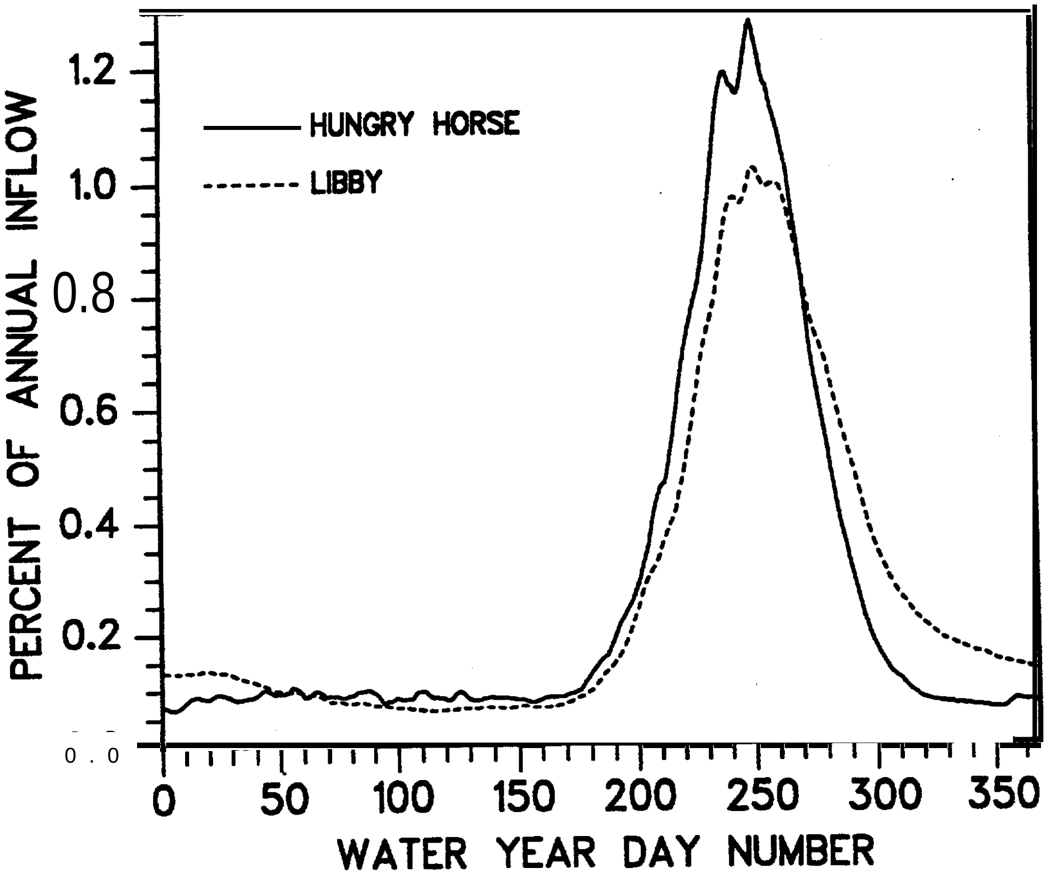

Figure 5. The long-term average shape of the inflow schedules for Hungry Horse and Libby reservoirs (1928-1990). The **water** year begins on October **1** and ends **September 30.** The shape defmes the percentage of the annual inflow that occurs on **each** day of the water year.

Outflow Limits

Default outflow limits are established automatically by subroutine QUOTMM based on the previously established inflow schedule. The range of dam discharges is restricted by-the physical limitations of the dam structure and downstream concerns. The model assumes that all water passes through the turbines and disallows spills, unless instructed by the user to override default limitations. Maximum turbine discharge is a measured function of hydraulic head and allowable generation capacity (Bureau of Reclamation 1954, Gibson test at Hungry Horse Reservoir, and empirically measured relationships developed by the U.S. Army Corps of Engineers for Libby). Total dam discharge is limited by the number of turbines in use and immediate downstream flood concerns.

The user may set minimum and maximum discharge limits throughout the year three different ways. First, the pm-programmed default limits may be used. Secondly, the values may be entered interactively by providing dates along with minimum or maximum values. The model then constructs the annual schedule by interpolating between dates. Finally, if a very complicated schedule is required, a customized ASCII file containing 365 paired values may be used. If the user specifies limits Which are outside the physical limits of the dam structure, the model automatically corrects the input error.

Flood control limits can be modified by the model user. The default outflow limits at both reservoirs are designed to prevent downstream flooding, but differ substantially in detail, so they are described separately below.

Hungry **Horse Reservoir:** The Hungry Horse model predicts discharge from the unregulated North and Middle forks of the Flathead River (FHR) based on a regression between daily inflows (day *i*) to Hungry Horse Reservoir (HRI) and the discharge from the other two forks. $\mathbf{FHR}_{(i)} = 1.5695 * \mathbf{HRI}_{(i-1)} + 442.28$ cfs. The relationship explains over 96 percent of the variance in 12,409 observations. Dam discharge is then added to the unregulated flows to estimate the total Flathead River discharge at Columbia Falls. The default flood control limits for Hungry Horse Reservoir are then constructed so that when the outflow of Hungry Horse Reservoir is added to the two unregulated river forks, the resulting flow falls within the established discharge limits for the main stem of the Flathead River. If the combined flows exceed flood stage (44,810 cfs), the simulated Hungry Horse Dam discharge is reduced accordingly toward the absolute minimum release of 145 cfs. The raw results are smoothed by subroutine RASMTH. The model reports the number of daily changes in the dam discharge necessary to accommodate the flood constraints at Columbia Falls. The user can then graphically examine the resulting outflow limits and modify the outflow limits in one of three ways. The minimum and/or maximum outflow limits can be removed for any number of days starting with the beginning of the water year. This is most useful for simulations in which no limitations on the outflow are desired, or when making predictions for the remainder of the present water year. This ensures that real data from the first part of the year remain unadjusted during the simulation, and that flood constraints are enforced for the period defined by projected data. The user may also design an annual schedule of outflow limits from scratch by designating a few points and interpolating the rest. And finally, an external file can be read. Any input outside the range of the physical limits is reset to the physical limits automatically.

Discharge limits were also incorporated to prevent kokanee salmon, *Oncorhynchus nerka*, (Walbaum), from spawning in areas that will probably be dewatered before hatching. If the subroutine CFALL is initiated, the maximum discharge at Columbia Falls is limited to 4,500 cfs. from October 15 through December 15. If a maximum discharge of 4,500 cfs is inadequate to meet the desired elevation schedule at current inflows, the year is automatically rerun, incrementing the maximum discharge by 1,000 cfs, until an adequate maximum discharge is obtained. At present, these limits for kokanee spawning are usually invoked unless specified otherwise by the model user.

Libby Reservoir: The default outflow limits for Libby Reservoir protect against flooding at Kootenay Lake in British Columbia as dictated by a treaty between USA and Canada (International Joint Commission). The downstream routines are invoked when the inflow to Libby is established or modified. They begin by balancing the water budget at Duncan Reservoir, the only other regulated tributary entering Kootenay Lake.

Historical Duncan Reservoir inflows are used from 1929 to 1978. If operating outside of this period, subroutine DRINQ e&mates the annual inflow schedule for Duncan Reservoir (DUNCANQ) based on the previously established inflow for Libby Reservoir (LQIN). The estimated daily inflow to Duncan is DUNCANQ = 0.151715 LQIN + 667.2778 smoothed by subroutine RASMTH. The relationship of the total daily inflows to the two reservoirs is based on 50 years of measured flows at the two sites ($P \leq 0.05$). Maximal cross-correlation between data from the two sites occurs when Libby Reservoir lags Duncan Reservoir by one day, but the effect was small and so it was ignored. The estimated inflow for the period of April through August is used to determine the drawdown schedule for Duncan Reservoir.

Subroutine DREVDD establishes the proposed surface elevation schedule for Duncan Reservoir based on flood control rule curves established by B.C. Hydro. The schedule is established using five fixed points and one adjustable point (Figure 6). The value for March 1 (water year day number 152) is determined by linear regression of the supplied rule curve data: $ELEV_{152} = 1954.3 - 72.85 * PRVL$. PRVL is the predicted inflow for the period of April through August in Mega acre-feet. The result was confined to fall between 1,800 and 1,868.6 feet. Subroutine DRQBAL balances the water budget for Duncan Reservoir in the same manner as will be described later fix Hungry Horse and Libby reservoirs when the surface elevation is proposed. Summary statistics and a graphical representation of the adjusted surface elevation, and the outflow schedules are reported to the user. The model was designed to abort if the physical discharge limits are exceeded or the spillway at Duncan Reservoir must be used. Most input data do not cause the model to abort. The user may override the spill limitation if necessaq. DRELVL is a supporting subroutine that calculates the volume of Duncan Reservoir given the surface elevation or vise versa. The relationship was provided by B.C. Hydro. The units are feet and cubic feet: $VOL = (ELEV - 1,790.7)^{1.2604}) * 2,123.928911 - 10,301.09375$.

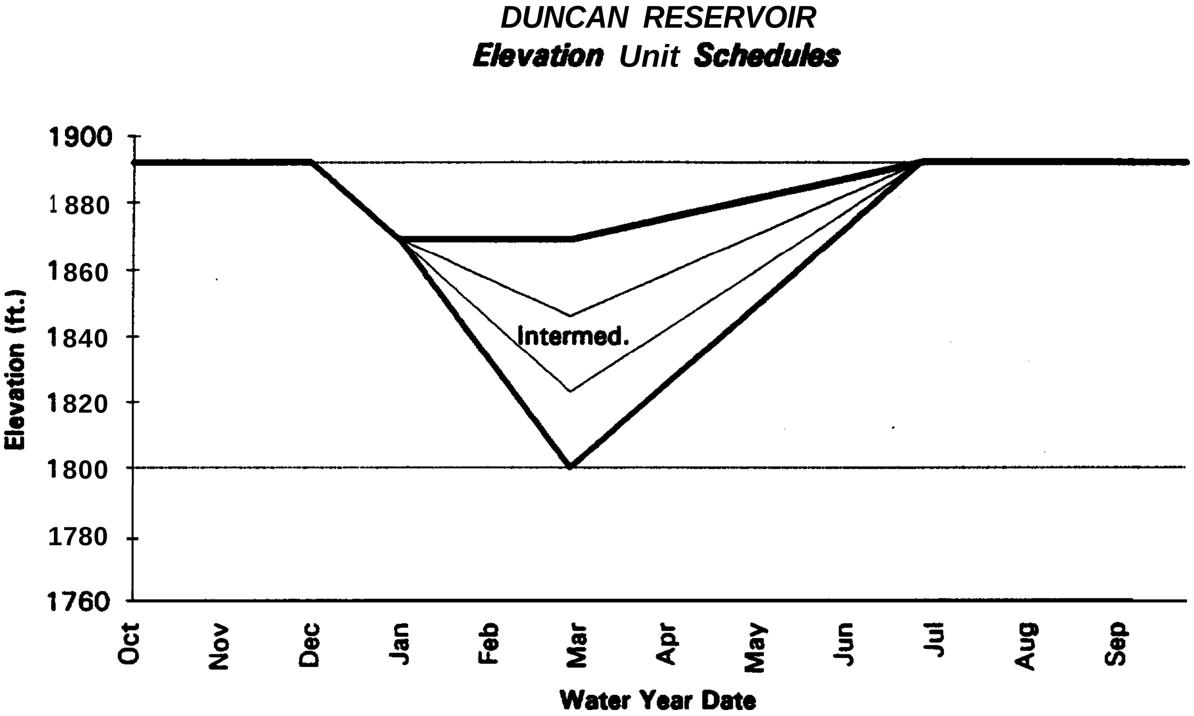

Figure 6. A schematic of the variable flood **control** requirements far Duncan Reservoir, B.C. The established **drawdown** for flood storage is adjusted based on the predicted inflow during the period of April through August.

Subroutine KLSURF establishes an initial surface elevation schedule for Kootenay Lake as a fixed schedule based on established rule curves and the historical data (Figure 7). KLEV is a supporting subroutine that calculates the volume of Kootenay Lake (above 1,735.867 feet) given the elevation or vise versa. The volume at 1,735.867 feet was arbitrarily set to .25 Mega acre-feet to prevent the occurrence of negative volumes during the calculations. The relationship for units in acre-feet is a simple linear regression: VOL = ELEV * 111,099.7 - 192,858,200.0, which explains 99.97 percent of the variation in the 1,259 supplied values.

Subroutine KLINQ estimates the total inflow to Kootenay Lake from all sources other than Libby Reservoir. The estimated inflow for each day of the water year is the estimated outflow from Duncan Reservoir plus 1.21 times the established inflow to Libby Reservoir. This was derived by regressing the inflow from sources other than Duncan and Libby on Libby inflow. The relationship was effected by the distance between drainages. The predictive capability'of the model improved as the time-step enlarged from daily to monthly values. The resulting schedule is smoothed by subroutine RASMTH.

Subroutine KLQBAL balances the preliminary water budget for Kootenay Lake in the same manner as described for Duncan Reservoir. Summary statistics and a graphical representation of the adjusted surface elevation and the outflow schedule are reported to the user. The model aborts if the surface elevation of Kootenay Lake falls below 1,733 feet. This can occur due to low inflow or because of severe drawdown to prevent flooding due to high inflow. KLQOMX is a supporting subroutine that calculates the physical maximum outflow (KLMO) for Kootenay Lake as a function of the surface elevation. The hydraulic control is Grohman Narrows just upstream of Corra Linn Dam. The equation for outflow in kcfs: KLMO = 6.0 + 0.683 * $(ELEV - 1,730.97)^{1.626}$, represents the present condition since the narrows was excavated in 1930. The regression equation was developed by digitizing points from a graph provided by B.C. Hydro then adjusted to better match the observed data (Figure 8). An elaborate algorithm also supplied by B.C. Hydro, defines the approximate elevation rule curves for Kootenay Lake throughout the year.

Once the model establishes the preliminary water budget for Kootenay Lake, subroutine QUOTMM establishes outflow limits for Libby Reservoir to avoid flooding Kootenay Lake and Bonners Ferry, Idaho. During a simulated flood event, calculated inflow to Duncan Reservoir is used to determine the appropriate flood control curve (amount of evacuated reservoir storage capacity) for Duncan Dam operation. Duncan Reservoir then receives flood waters and begins to fill toward the target refill date of July 1. If Duncan Reservoir storage is insufficient to maintain Kootenay Lake surface elevation within mandated levels, Libby Dam discharge is limited accordingly. The subroutine reports the number of days that the default outflow limits must be adjusted to accommodate flood control at Kootenay Lake. The resulting outflow limits are then graphically displayed.

The user may modify the outflow limits for Libby Dam in one of three ways as described for Hungry Horse Reservoir. Options were designed for examining flow restrictions for flood

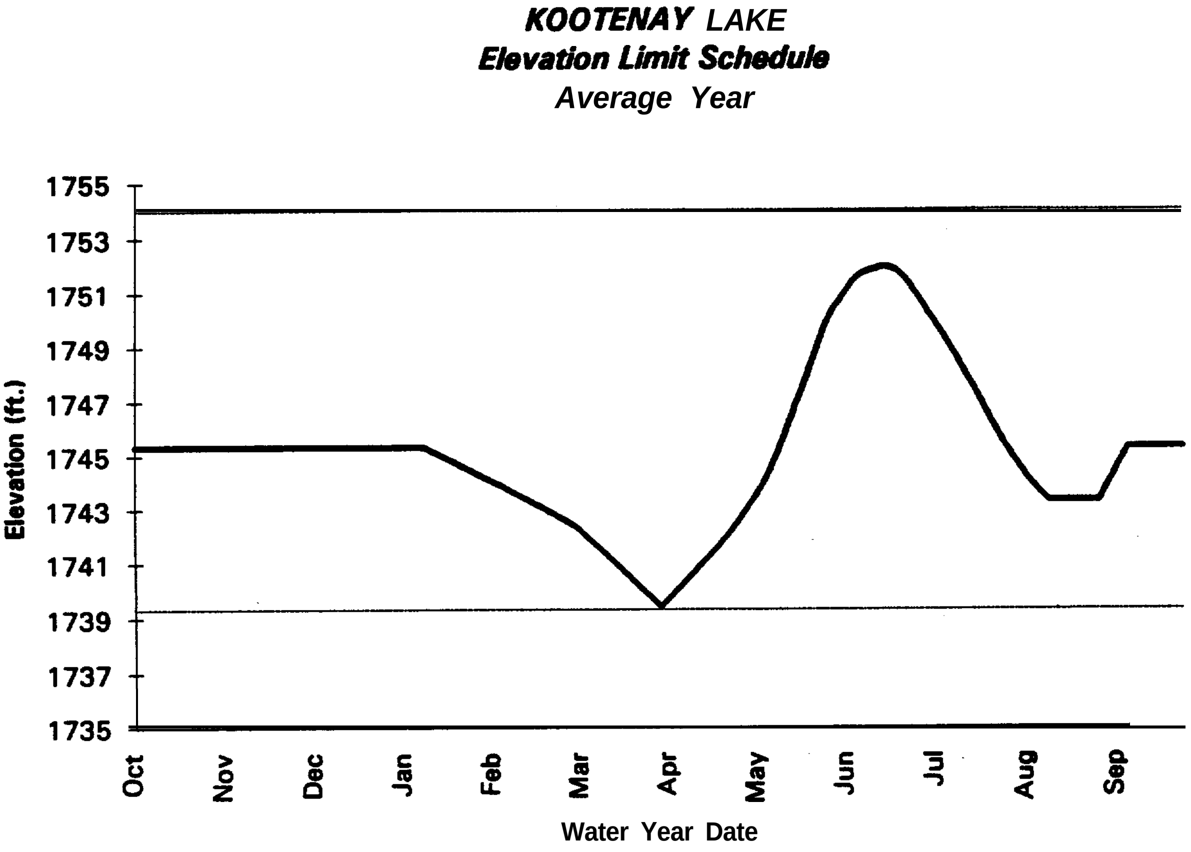

Figure 7. Resultant Kootenay Lake surface elevation schedule during an average water year. Elevational targets on specific dates are defines throughout the year by international treaty.

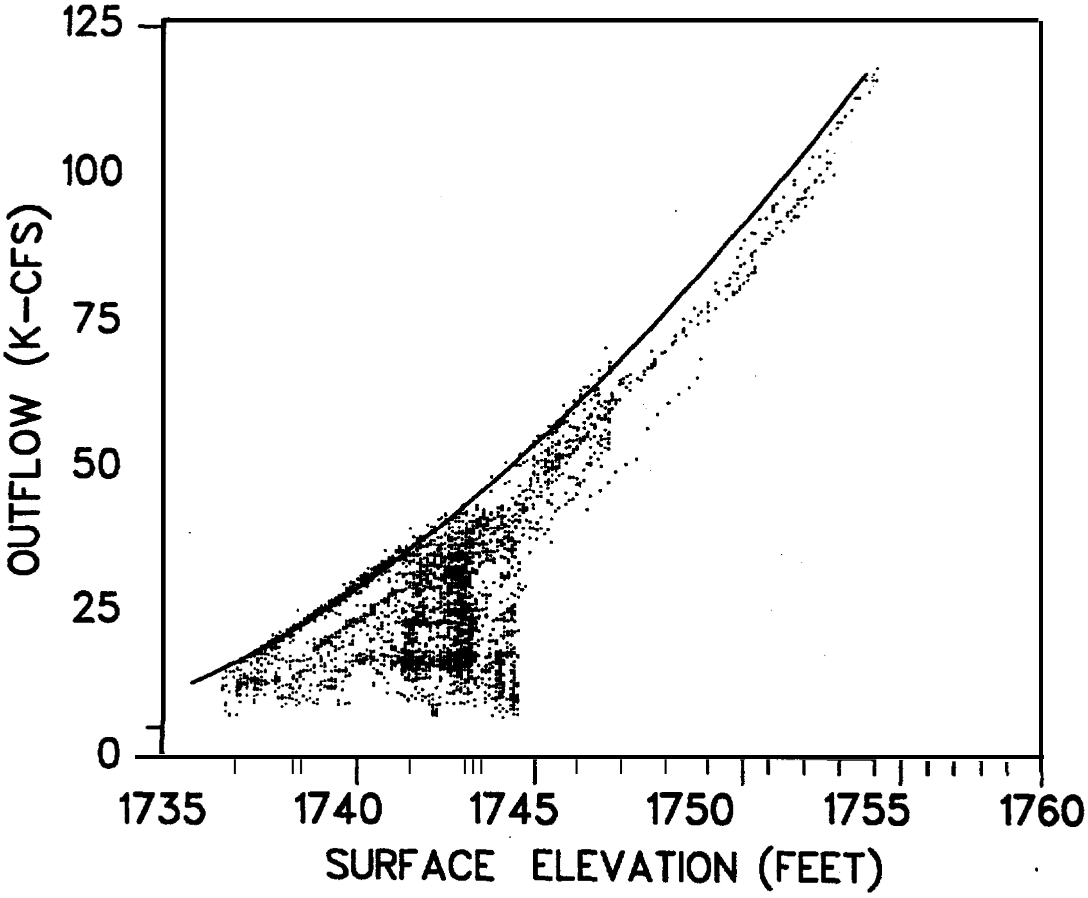

Figure 8. The relationship between outflow and surface elevation at Kootenay Lake. The curve represents the calculated maximal outflow rate. The points represent the observed results for 11 years between 1969 and 1986.

control, recreation and fisheries concerns. External ASCII files may be imported to create elaborate discharge hydrographs. Data files defining target flows at Bonners Ferry can also be used. In the latter case, the model reads a number of proposed schedules and then determines the appropriate one to achieve a selected flow regime on the basis of water availability (reservoir inflow volume). If the model is running of forecasted inflows the May forecast determines the Bonners Ferry regime for that year. This addition enables the user to examine flow enhancement to benefit white sturgeon (*Acipenser transmontanus*) spawning in the Kootenai River, and weight the resulting effects on reservoir pool elevations. The number of turbines in operation may be set by the user whenever the outflow limits are built from scratch. The model assumes that five turbines are in use unless a different number is specified.

Establishing the Annual Water Budget

After the inflow schedule and the outflow limits are in place, the user may propose either the surface elevation schedule or the outflow schedule. Those persons primarily concerned with the reservoir will normally propose the surface elevation schedule, while those who are primarily concerned with power generation or downstream concerns will normally propose the outflow schedule.

Subroutines HRINSUR and LRINSUR are interactive routines that establish or modify the annual surface elevation schedule. There are two options. The first is to build a schedule by specifying a few points and having the model interpolate the rest, and the second is to read the schedule from a file. The file may contain either all 365 daily values or 15 values consistent with the monthly Columbia System models (eg. SAM, HYDROSIM and HYSSR). Historical surface elevation files with 365 values are available for Hungry Horse Reservoir for water year 1953 through 1995 and for Libby Reservoir for water year 1974 through 1995. Leap day was removed from all data sets. When 15 values are read from a file, the model interprets the data as October 1, plus the end of each month for the remainder of the water year. April and August are divided into two half-month periods. The surface elevation schedule can be graphically displayed and saved in a file for use in later model runs.

Subroutines HROQ and LROQ are interactive routines that establish or modify the annual outflow schedule. Options and routines for establishing the outflow scheduled are similar to those used to create surface elevation schedules. An input file must contain 365 daily values. Historical outflow files are available for Hungry Horse for water years 1953 through 1995 and for Libby Reservoir for water years 1977 through 1995. For all input, the previously established outflow limits are automatically enforced. The proposed outflow schedule is changed if either the minimal or maximal outflow limit is exceeded. This routine graphically displays the annual outflow schedule. The user can examine the total outflow volume for any portion of the year. The proposed schedule, as adjusted for the current outflow limits, may be saved in a file for use in later model runs.

Two different methods for balancing the water budget are used depending on whether surface elevation schedule or the outflow schedule are specified by the model user. Subroutines

HRQBAL and LRQBAL balance the water budget when the surface elevation schedule is proposed by the user. The first attempt to calculate the outflow schedule is conducted chronologically using the difference between the inflow and the proposed change in reservoir volume designated by the surface elevation schedule. The surface elevation is subject to modification as required during these calculations. Additional water may be stored to prevent the outflow from exceeding the outflow maximum, and additional water may be released to prevent the outflow from falling below the outflow minimum. If the surface elevation reaches full pool and additional storage space is required, the forward approach has failed and a backwards approach begins. The backward approach uses the same calculations, but starts with the last day of the water year. With perfect hindsight, the surface elevation schedule can usually be adjusted to accommodate inflow and the outflow limits. On the backward pass, if the reservoir declines to minimal pool and additional storage must be released to meet the minimum flow requirement downstream, the backward approach also fails. Failure to balance the water budget indicates that the reservoir cannot accommodate the current input and that changes in one or mom of the input schedules must be made. Upon successful completion of the water balance calculations, if the beginning and ending elevation of the annual surface schedule differs by more than 5 feet, the model issues a warning that the annual water budget is not balanced and reports the amount of water lost or gained during the year. Simple statistics describing the drawdown and refill are reported and the surface elevation schedule is graphically displayed. The resultant outflow schedule can also be graphically examined.

A different approach for balancing the water budget at Libby is involked when using inflow forecasts (no foresight model). In this version the backward approach was removed, thus eliminating the perfect hindsight accommodation for inflows and oufflows throughout the water year. This version of **LRMOD** is allowed to look ahead five days only to determine coming inflow trends, thus determining all balances in a moving five-day window. A spill file is created for each year and if the resultant daily volume exceeds the capacity of the reservoir the amount of spill is calculated and noted for that day.

If the user designates the inflow and outflow schedules, subroutines HROBAL and LROBAL balance the water budget and calculate the resulting surface elevations. The user must specify the surface elevation on the first day of the water year (October 1). When historic operational data are used, the user may input the water year instead of the starting surface elevation. The model will automatically substitute the starting elevation far each year on record. The surface elevation schedule is calculated in a forward manner by adjusting the surface elevation each day for the net change in volume. The outflow schedule is modified, if necessary, to conform to the physical constraints of the dam and reservoir. For example, if the surface elevation reaches minimal pool, the minimum recommended flow may not be achieved. Likewise, if the surface elevation reaches full pool, the outflow may be increased. This approach allows the use of the spillway if the specified outflow exceeds the turbine capacity at the dam site. The physical limits of the downstream channel capacity can not be violated. Upon completion of the calculations, summary statistics, graphic output and warning messages similar to those produced by subroutines HRQBAL and LRQBAL are available.

Subroutine CQ2MFE used by both water budget balancing routines determines the maximum physical outflow rate as a function of the surface elevation. The version for Hungry Horse Reservoir is based on linear interpolation of results of the Bureau of Reclamation Gibson test conducted in 1954. The results were verified by comparing the relationship to the observed outflow (kcfs) and surface elevation data. The relationship was updated to reflect mechanical improvements in the Hungry Horse! Rower plant during 1988-1992. Maximum turbine discharge capacity increased to 3,125 cfs per unit. The version for Libby Reservoir, based on a second order polynomial regression supplied by the Army Corps of Engineers, calculates the maximum outflow using the number of turbines (NT) and the surface elevation in feet. The equation is $\mathrm{MAXOUT} = 5.3 * \mathrm{NT}\ (1.0 - 0.09098792 * (2{,}459 - \mathrm{ELEV}) - 0.00090117 * (2{,}459 - \mathrm{ELEV})^2)$. Figure 9 shows the relationship between maximal outflow and surface elevation at both reservoirs.

Subroutine *MSUM* produces a monthly summary of the inflow, outflow, surface elevation and volume as well as water retention and residence times. Annual averages are also provided in a tabular format. Water retention time is the volume divided by the inflow, whereas water residence time is the volume divided by the outflow. If water retention time and water residence time are about equal, the quantity becomes the better known water turnover time.

Evaluation of Downstream Concerns

Once the proposed water budget is balanced, downstream flows may be reexamined. The two reservoirs were modeled differently, so they are discussed separately. After evaluating the downstream concerns, the user may examine the biological consequences of the established reservoir operation, or alter the model input and recalculate the water budget. This way, the user may become quite familiar with the realities of running the reservoir.

Hungry Horse Reservoir: The established inflow, outflow and surface elevation at Hungry Horse influence the flow in the main stem of the Flathead River at the Columbia Falls critical flood control center, and the water budget of Flathead Lake. Subroutine FHFLOW calculates the Flathead River flow at Columbia Falls by adding the outflow of Hungry Horse Reservoir to the previously estimated natural flow at the South Fork confluence. The predicted discharge as well as the discharge limits may be graphically examined or stored for later use.
Subroutine FHLBAL calculates the water budget for Flathead Lake using the same procedures described for the storage reservoirs. All input is generated by the model. Subroutine FHLQLM establishes the outflow limits for Flathead Lake through Kerr Dam as defined by linear interpolation of the established criteria (Figure 10). Subroutine FHLSRF establishes the proposed surface elevation schedule for Flathead Lake. The initial elevations are produced by linear interpolation of data which approximate established rules for controlling lake levels and historical records (Figure 11). The total inflow to Flathead Lake, from all sources other than the Flathead River at Columbia Falls, was calculated as the difference between the measured outflow from the lake and the change in lake volume derived from the capacity at elevation relationship for Flathead Lake (see FHLVOL below). This component of the total inflow was highly variable on a daily basis because of time lags, but averaged 1.595 times the discharge of

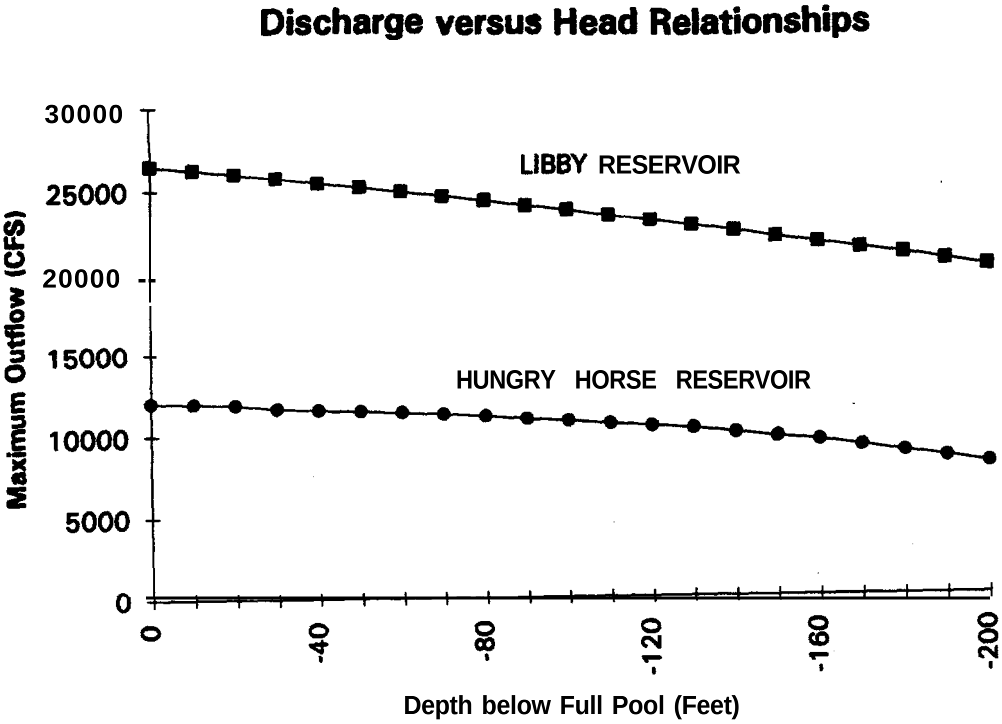

Figure 9. The turbine capacity at head (surface elevation) relationship at Hungry Horse and Libby dams. The curve for Hungry Horse reflects the recent rewrap **and uprate** of the power house.

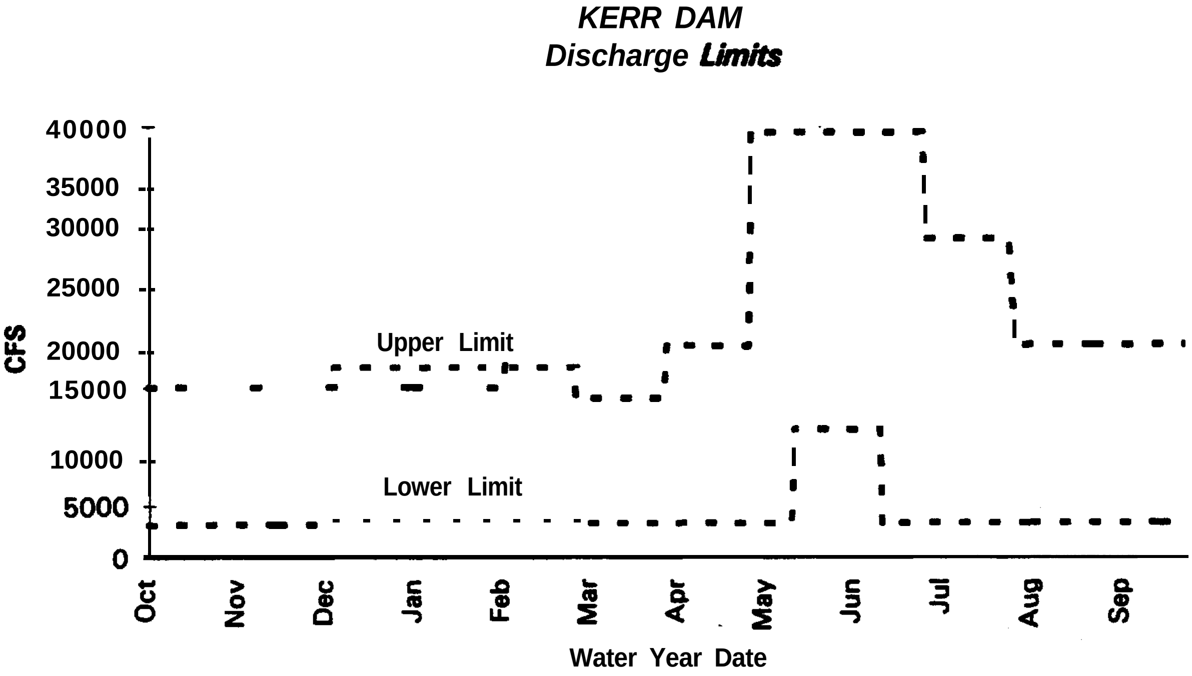

Figure 10. Minimum and maximum discharge limits at Kerr Dam on the outlet from Flathead Lake.

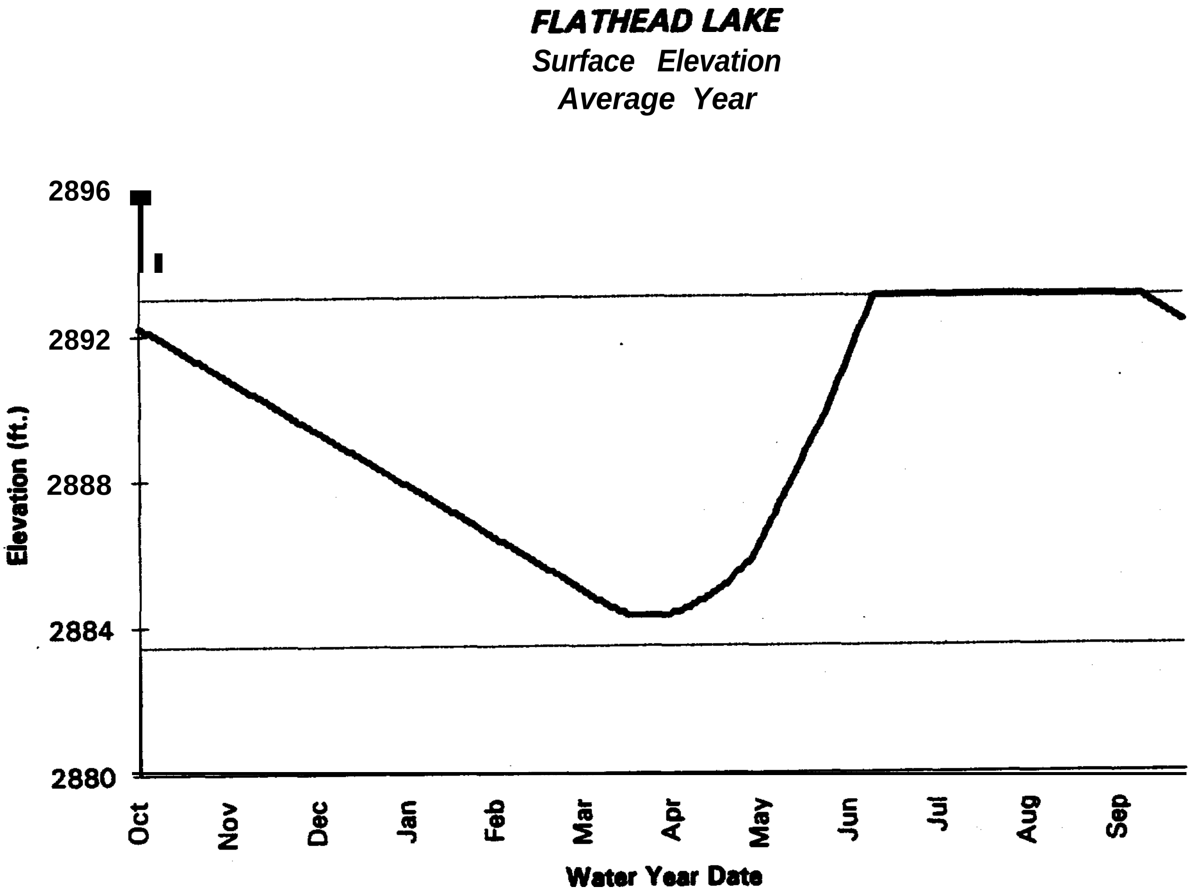

Figure 11. The annual surface elevation schedule at Flathead Lake during an average water year. Minimum elevations are defined by flood control requirements. Refill dates were established for recreation.

the Swan River. The discharge of the Swan River **(SWAN) was estimated** based on a regression using the inflow to Hungry Horse Reservoir (HER), allowing for a one day time lag. The equation is: $SWAN_i = 0.208 * HHR_{i-1} + 465.2$ cfs. The relationship explains over 87 percent of the variation in 9,854 daily observations. The total daily inflow to **Flathead** Lake is the sum of the **Flathead** River discharge at Columbia **Falls plus 1.595 times the estimated** discharge of the Swan River.

Two support subroutines are required to calculate the **Flathead** Lake water budget. Subroutine KERCAP calculates the channel capacity at Kerr Dam, (QMAX **(kcfs))** as a function of **Flathead** Lake **surface** elevation. The relationship is based on a second order polynomial regression of data provided by Montana Power Company. The equation is: $QMAX = 198.17 * ELEV^2 + 2{,}739.74 * ELEV + 1{,}712.29$, where ELEV is the elevation in feet coded by subtracting 2,882 feet. The equation explains over 99.9 percent of the variation in the supplied data and compared closely with historic lake elevations and Kerr Dam discharges (Figure 12). Subroutine **FHLVOL** calculates the volume of **Flathead** Lake above elevation 2,883 msl feet as a function of the surface elevation. This routine also performs the reverse calculation. The relationships are based on second order polynomial regressions of data supplied by Montana Power Company. The equation for the volume in acre-feet is: $VOL = 444.21 * ELEV^2 + 116{,}551.47 * ELEV - 115{,}847.35$, where the elevation is coded by subtracting 2,882 feet. The equation for the elevation is: $ELEV = 8.48 * VOL - 0.22733 * VOL^2 + 2{,}883.0$ feet, where the volume is expressed in **Mega** acre-feet. The relationships explain essentially all (over 99.99 percent) of the variation in the supplied data.

During years of extremely high river discharges, the maximum outflow limit must often be exceeded to balance the water budget for **Flathead** Lake. If the simulated runoff results in a forced spill, the model restarts prior to the runoff event. **Lake** storage is evacuated at maximum turbine capacity based on the previously established discharge at head relationship. If the runoff can not be contained within the established operation limits, the model reports that **Flathead** Lake must exceed its outflow limit, and it restarts the calculations. During the new calculations, any maximum outflow limit greater than **55,000** acre-feet per day is altered to 120,000 acre-feet per day. This procedure closely mimics the observed results for high water years.

Libby Reservoir: For the Libby model, the final water budget at Kootenay Lake is reexamined. Subroutine KLQBL2 balances the final water budget for Kootenay Lake exactly as described earlier in the flood control section. The only new aspect is that the outflow from Libby Reservoir is now known. The model calculates summary statistics and graphically displays the finalized surface elevation and oufflow schedules.

Thermal Model

After the model balances the basin hydrology, the thermal structure in the reservoir is calculated by the thermodynamics model. This component **is** a modified version of a predictive mathematical model for the behavior of thermal stratification in Flaming Gorge Reservoir (Adams 1974). An earlier version of this thermal model, calibrated to Hungry Horse and Libby reservoirs, was later published by the **U.S.** Geological Survey (Ferreira et al. 1992). The **site-**specific models were further refined using additional field measurements. Only a few support

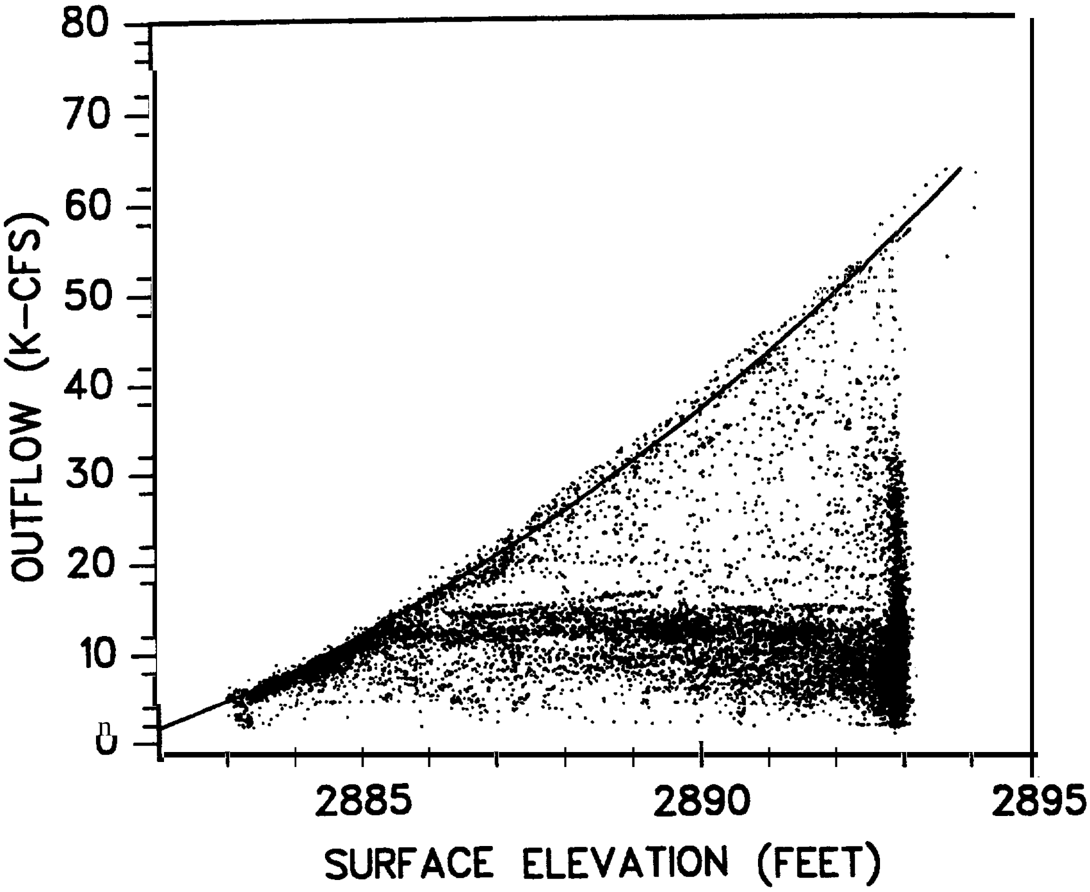

Figure 12.. The outflow of **Flathead** Lake at various lake stages. The curve represents the maximal outflow as calculated by the model. The data consists of 11,315 daily observations between 1954 and 1985.

programs were retained from the original thermal model. Function **FLXOUT** calculates surface losses due to evaporation, conduction and radiation. **Subroutine** SPEED calculates vertical, source and sink velocities as well as the 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.

Predictions were calibrated to 11 years of daily climatological records (U.S. Weather Service, Kalispell, Montana), adjusted to **measured** thermal conditions at the study reservoirs, long-term temperature data from inflowing tributaries, the physical properties of water and basin topography. Annual schedules of meteorological variables, input to the model, including relative humidity, solar aspect, air temperature, cloud cover and opacity, wind speed and direction and precipitation were smoothed to long-term trends.

Subroutine HRTHERM and LRTHERM establish most of the constants for the thermal model. They establish five meteorological schedules that **are** needed by the thermal model. This is done using subroutine CYCLE with the parameters indicated in Table 2. These parameters were obtained by nonlinear least-squares **(Marquardt** method) **regression** to data from Kalispell, Montana.

Table 2. The mean, amplitude and phase shift used by subroutine CYCLE to establish 5 meteorological schedules needed by the thermal model. The models for Hungry Horse Reservoir **(HHR)** and Libby Reservoir **(LR)** differ only in the mean for air temperature and humidity, adjusted to long-term site specific climatic data compiled in the vicinity of the dam site.

	Mean	**AMP**	**SHIFT**
Inflow temperature	6.664	9.137	155.19
Air temperature **(HHR)**	7.822	12.090	168.46
Air temperature **(LR)**	5.322	12.090	168.46
Humidity **(HHR)**	0.702	0.105	4.18
Humidity **(LR)**	0.602	0.105	4.18
Wind Speed	2.074	0.596	209.82
Cloud cover	0.654	0.204	-20.24

The model assumes horizontal homogeneity, and thus generates a single vertical temperature profile for each day of the year. **Thermal** profiles measured at intervals along the length of Hungry Horse and Libby **reservoirs** validate this assumption. The model accounts for the 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.

Subroutines HRTHERM and **LRTHERM** convert the previously established schedules to the units needed by thermal **model. The thermal** model begins on January 1, works with a calendar year (rather than **a** water year) and starts after the ice is off the reservoir (January 18 for Hungry Horse and December 29 for Libby). These routines shift the data sets to a water year schedule, then initiate the main thermal stratification subroutines **HTHERM** and LTHERM. The original thermal model was modified so that it no longer produces graphical or tabular output. Instead, the top part of each daily thermal **profile** is stored for use later. For Hungry Horse Reservoir 21 values are saved representing a depth of 45 **m** from the current surface elevation. For Libby Reservoir, 40 values are saved **representing** a depth of 62.4 m.

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 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 these thermal adjustments affect only the period of limited biological productivity.

Diie Temperatures

Libby Dam

The model simulates the temperature control **structure** (selective withdrawal) at Libby Dam. Thermal sensors on the dam face are used by dam operators to release water from the appropriate depth(s) to achieve a specified tailwater **temperature** (Figure 13). Several modeling techniques were used to estimate the discharge water temperature based on the thermal structure in the reservoir **forebay** near 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. Subroutine **SETOUT** establishes the daily outflow elevation based on user input. If the user specifies a schedule of outflow elevations during the simulation, the appropriate temperature water is released.

Subroutine LRINOE is an interactive routine allowing the user to establish the outflow elevation schedule. The user may input a file containing 365 daily values, or designate a few points and interpolate the rest. In either case, values below the physical minimum outflow (2,222 **feet** at Libby) 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. If no withdrawal depths are specified, a default withdrawal schedule releases water at 60 feet below the current surface elevation during the period that the control structure is in use.

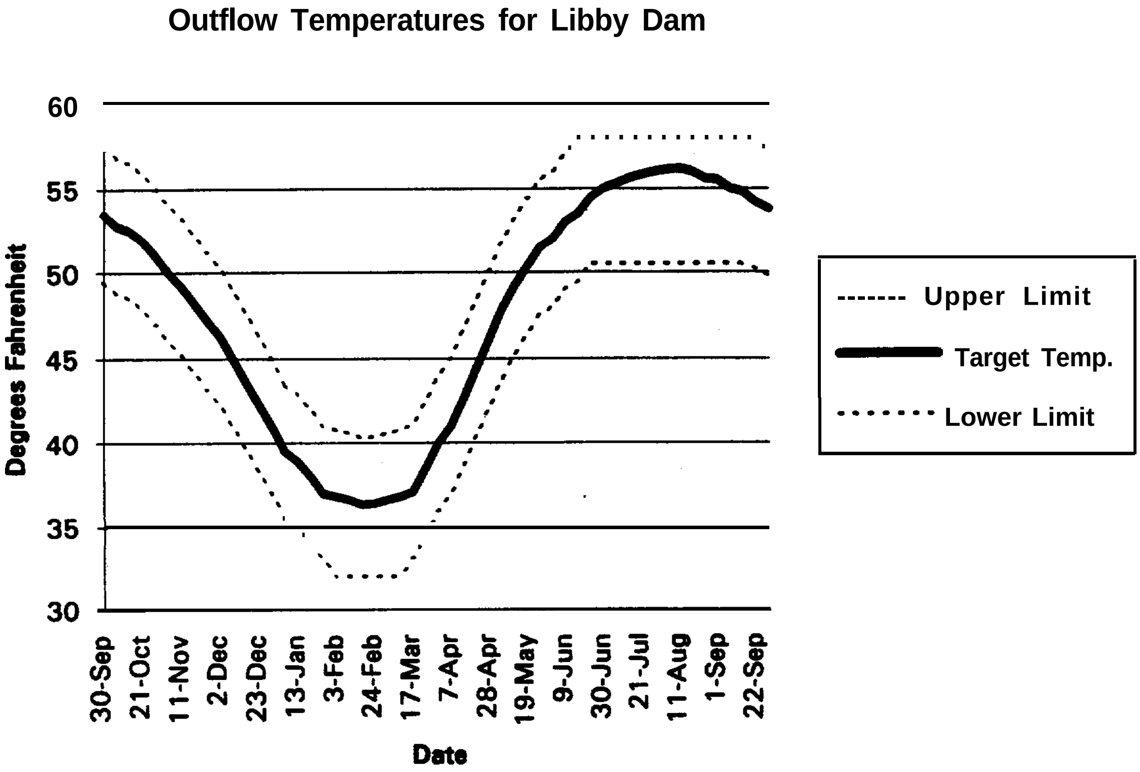

Figure 13. Minimum and maximum target temperatures for **the discharge** from Libby Dam.

Hungry Horse Dam

The Hungry Horse model was modified to evaluate the possible benefits of temperature control in the discharge from Hungry Horse Dam. The existing condition in the Flathead River was first examined to document the severity of rapid temperature fluctuations and long-term cooling effects. The model was then calibrated using long-term temperature measurements used to compare the effectiveness of various temperature control strategies.

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 record. A vertical trace on the chart represents a major change in water temperature in just a few minutes. The U.S. Geological Survey monitors the volume and temperature of Hungry Horse discharges in the South Fork. Hourly measurements were used to relate effects to discharge fluctuations.

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 withdrawal depth during the ice cover period, until spring melt and lake turnover.

The selective withdrawal component HRINOE 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, Figure 14). The user may input a file containing 365 daily outflow elevations 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. If no withdrawal strategy is specified, the withdraw depth defaults to the normal deep withdrawal elevation (3,319 feet).

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 1976-1988 (Figure 15), 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 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

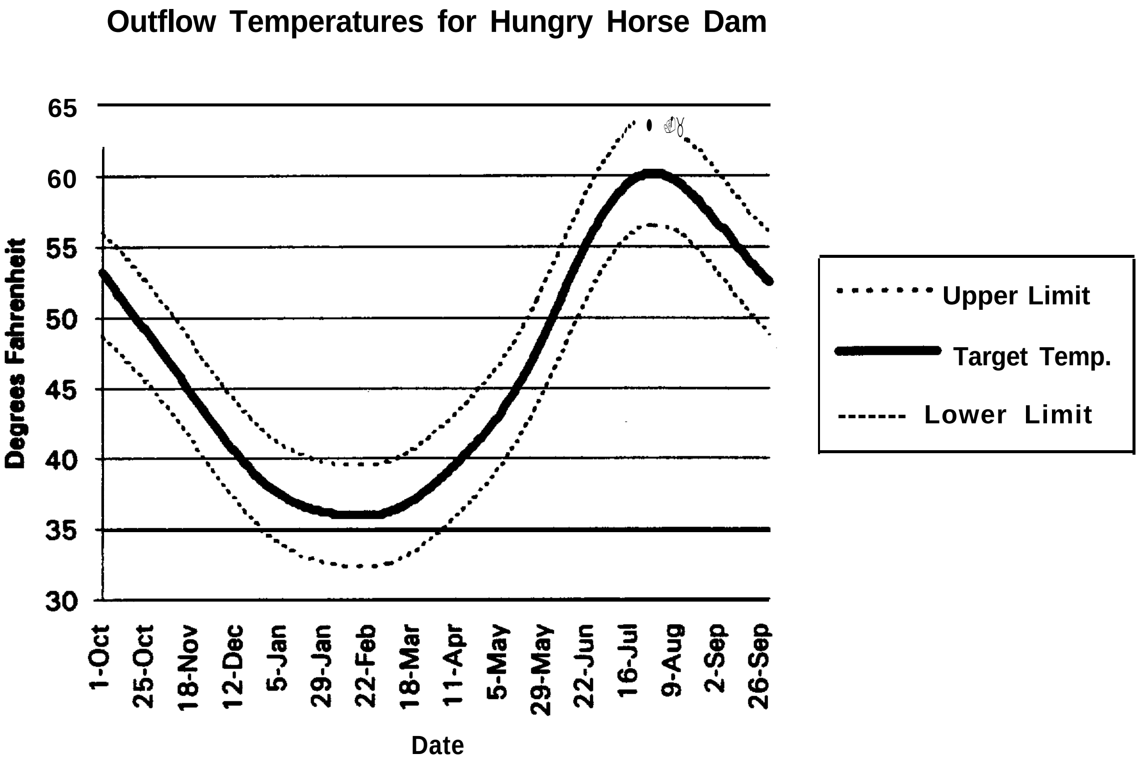

Figure 14. Minimum and maximum target temperatures for the **Flathead** River at Columbia Falls. These targets will become attainable when the proposed selective withdrawal structure becomes functional at Hungry Horse Dam.

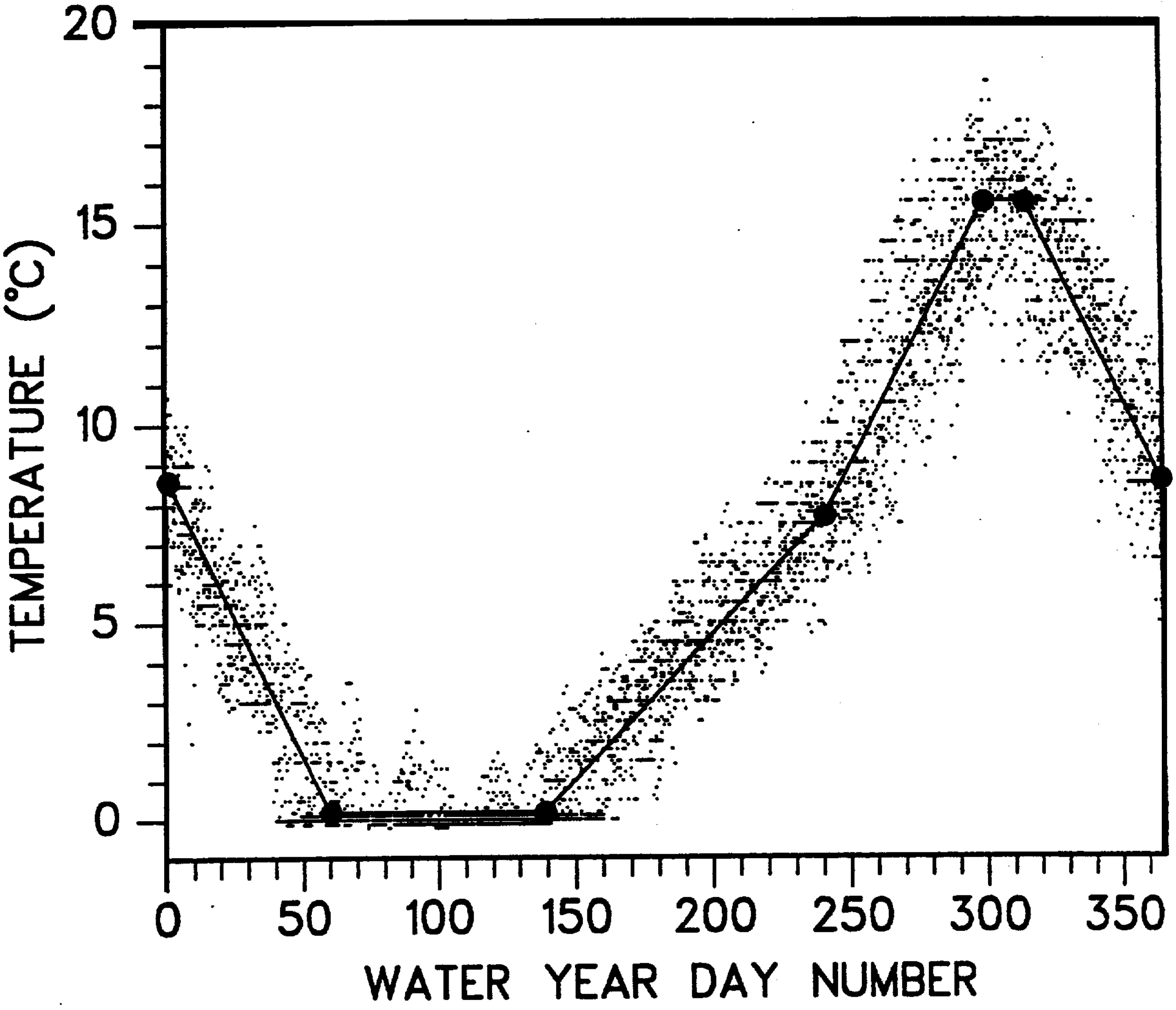

Figure 15. The fixed schedule used to estimate the temperature in the unregulated part of the Flathead River. The data cloud represents daily mean temperature of the North Fork for water years 1976 through 1988.

of the variation in 3,374 observations. The equation is: $T_{new} = 0.29 + 1.1328 * T_{old} - 0.04636 * FLOW$, where FLOW is the discharge at Columbia Falls in kcfs.

Evaluation of selective withdrawal required duplicate simulations comparing thermal influences with selective withdrawal to equivalent simulations with fixed hypolimnetic 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 integrated rule curves and local 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. Trout growth efficiency was also evaluated under different temperature conditions.

Additional subroutines allow examination of the results of the thermal stratification model. Subroutine XYOELV allows graphical display of the outflow elevation schedule. The surface elevation schedule and the minimal outflow elevation are displayed as dotted lines. Subroutine PLOTVD tabulates the duration and the volumedays at each temperature from 4 to 22° C in 1° C increments. Duration is reported in days and volumedays is reported in Mega acre-feet days. This routine also reports the total heat content duration of the reservoir in Mega acre-feet ° C days. Subroutine PLOTDD provides a graphical display of the degree days accumulated at each depth of the reservoir. Subroutine XYCONT allows graphical display of the annual temperature structure as thermal isopleths. Depths are represented as meters below the current surface. Isopleths start at 4° C and increment by 2° C. Subroutine P1TPRO provides a graphical display of the temperature profile for any day of the year as requested by the user. Subroutine XYOUTT allows graphical display of the outflow temperature schedule. Minimal and maximal desired outflow temperature limits are displayed as dotted lines.

Biological Assessments

Once the user has defined the hydrology and the thermal structure is calculated, the model begins the biological assessments if desired. The biological model uses the previously established operation schedules and the estimated annual thermal structure to estimate the impacts on biological processes of interest. User control is then limited to regulating the rate at which model analyses are executed, allowing time to view output graphs and tables pertaining to each trophic level. The biological component was subdivided into primary production, zooplankton production, benthic dipteran production, terrestrial insect deposition and fish growth. Target fish species were westslope cutthroat in Hungry Horse Reservoir and kokanee in Libby Reservoir.

Primary Production

Primary production was evaluated at Hungry Horse and Libby reservoirs using identical field sampling and lab techniques. Modeling strategies were identical. Throughout the sampling period, production rates were two to three times greater at Libby Reservoir than at Hungry Horse. Specific information on Hungry Horse is provided here.

Primary productivity and chlorophyll were measured at three-week intervals from May to November 1986, 1988 and 1989. Five surveys were also conducted in 1987. The vertical and longitudinal distribution of carbon fixation by phytoplankton was quantified with light- and dark-bottle C^{14} liquid scintillation techniques (Priscu and Goldman 1983). At each station, water samples were collected at discrete depths (0, 1, 3, 5, 10, 15, 20 and 25 m) and subsamples drawn off into one clear and one opaque bottle. These were inoculated with ^{14}C and then re-suspended at the depth of collection and incubated for three to seven hours near midday. The algae from each bottle was then collected by filtration for analysis of ^{14}C uptake by liquid scintillation counting. No size or taxonomic breakdown of phytoplankton were performed, so primary producers were considered as a community. We assumed that Primary production in the reservoirs would not change radically during the study due to unnatural nutrient loading from the atmosphere or human disturbance (Dodds et al. 1989).

Primary production was modeled as raw carbon fixation based on a linear regression of light and temperature to primary productivity.

One hundred and two primary production profiles were measured; 93 were usable due to nine missing light measurements. Production rates were estimated using the following general equation solving for "^{12}C uptake":

$$\frac{^{12}C \text{ uptake}}{^{12}C \text{ available}} = \frac{^{14}C \text{ uptake}}{^{14}C \text{ available}},$$

where "^{12}C available" was estimated from alkalinity measurements, "^{14}C available" was calculated from the specific activity of the $NaH^{14}CO_3$ stock solution and. "^{14}C uptake" was measured by liquid scintillation counting of the filtered algae.

The primary production component of the model accounts for the longitudinal pattern of production along the reservoir length and the seasonality of production as related to light and temperature. The dominant patterns in the data were incorporated so that area and time summations could be performed accurately.

Daily, volumetric production rates ($mgC/m^3/d$) at each station and depth were calculated from the hourly rates measured during the incubation period by normalization to light (total langleys/langleys during the incubation period). The volumetric rates for each depth sampled were then integrated to give a water-column, or areal, Productivity rate ($mgC/m^2/d$). Subroutine PRIMP estimates the daily primary production schedule and the annual total. It also estimates the amount of production that is washed out of the reservoir each day. The model estimates the water column total production (PP) in the dam forebay area by a linear regression on the product of surface light and the temperature at 1 meter. The equation is: $PP = 0.090942 * (LIGHT * TEMP) + 59.79$. Light was measured in Langleys or the units used in the thermal model (normally $Kcal/M^2$ day divided by 12) and the temperature is measured ° C. The conversion of the light units was based on empirical comparison of the model's output with the light meter results. The coefficients above were based on the observed temperature at 1 meter and the predicted light. The relationship using predicted values accounted for roughly half of the total variance. If field measurements of light were substituted for predicted values, the improvement was slight, explaining 57 percent of the raw variance. We determined that the model was adequate because it is not necessary to predict the light for any particular day. Instead, trophic responses are sensitive to longer-term trends and daily variation was absorbed into the regression coefficients so that weekly, monthly and annual totals were progressively more accurate.

The predictions of production in the upper areas of the reservoir were adjusted by using the grand means of all balanced observations (all stations measured on the same period) normalized so that the forebay area was 1.0. Production in the Graves Bay area of the reservoir was estimated by interpolation between adjacent segments in the reservoir. The discount factors are: Emery area (nearest the dam) 1.000, Murray area 0.826, Graves Bay area 0.736 and Sullivan area (at the headwaters) 0.646. The increasing trend in production toward the dam was presumably due to the accumulation of algae in the water. The accumulation of nutrients is not solely dependent on the length of. the reservoir, but also on the number and nature of tributaries entering the shoreline. The accumulation of algae is linked to reservoir length because individual cells multiply as they travel downstream. The accumulation of algae was supported by the chlorophyll data. An attempt to model the production residuals as a function of reservoir size (surface elevation or length) failed, but they were positively correlated.

The estimated water column total for each reservoir sampling location was extrapolated to the available surface area (acres converted to square meters), then converted from milligrams to metric tons (a combined multiplication factor of 4046.9E-9). The surface area at a depth of 5.37 meters below the current surface was used to expand the production totals. This depth was selected to correct for shoreline effects as the reservoir fluctuated. Based on the average vertical distribution of photosynthesis, half of the production in the water column total occurs above (or below) this depth. The total production is the sum of the production for the four reservoir areas. At Hungry Horse, the estimated total production was decreased by 99 percent for the period with predicted ice cover (and presumably snow cover). In the Libby model, production during the winter was modeled on empirical data. The total production of all days is summed to get the annual total.

The loss of primary production through the dam was calculated based on the vertical distribution of ^{14}C uptake in the reservoir area near the dam. The distance from-the surface to the outlet depth varies over time and from one simulation to another. To estimate downstream washout through the turbines, it was necessary to estimate the percentage of the total production figure that occurred within each vertical meter of the water column. This was accomplished with a negative exponential based on the data ($r^2 = 0.69$): $\%PP = e(2.57315 - 0.03459 * \mathrm{DEPTH})$. The result corresponding to the outlet elevation was applied to the estimated water column total and corresponding discharge volume on each date. The output representing the loss of new production (not biomass) was then subtracted from the reservoir production figure as a component in the Lp loss term. Lp represents the loss of phytoplankton to xooplankton, benthic rain, dissolved organic carbon and downstream loss. The predicted annual schedule of production, based on smoothed, annual schedules of light, temperature and reservoir volumes is also relatively smooth (Figure 16).

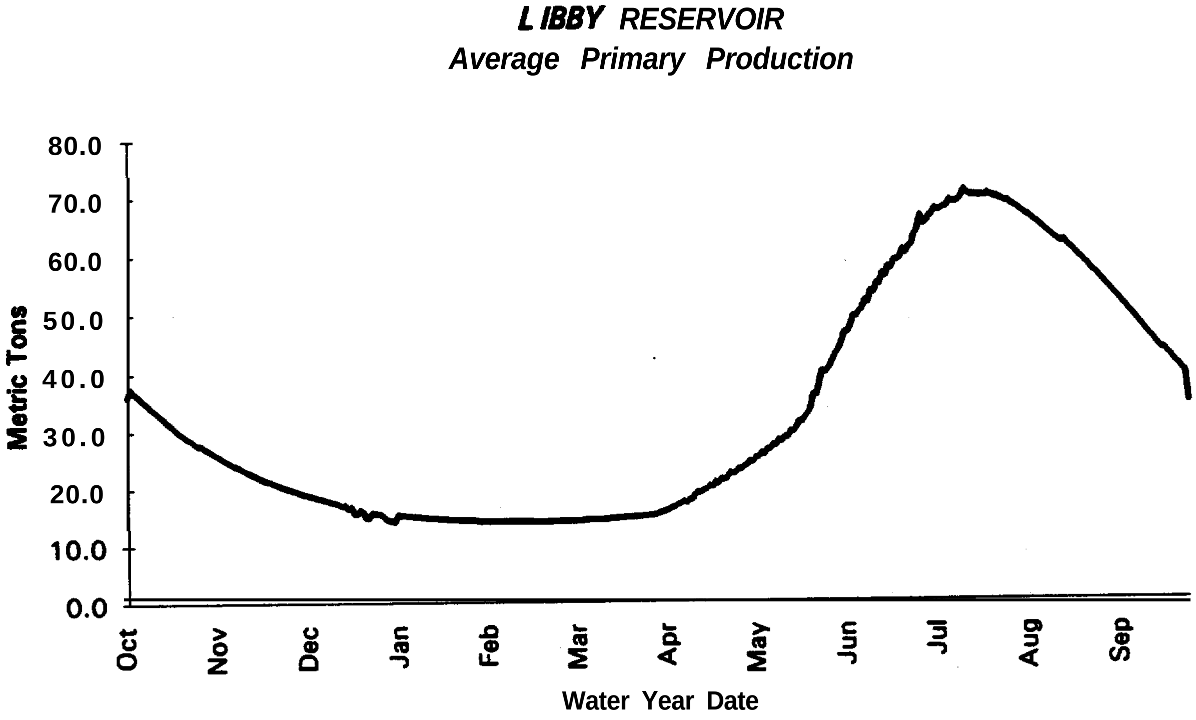

Figure 16. Daily calculations of primary production during 1982 at Libby Reservoir. The model calculates carbon fixation within sectors along the reservoir's length, then sums the results. Main influences include: reservoir volume, downstream flow and seasonal effects (solar aspect and attenuation and temperature).

Zooplankton Production

Longitudinal and seasonal zooplankton densities and community structure were assessed with triplicate 30-meter vertical tows. Vertical distribution was sampled with duplicate Schindler trap (Schindler 1969) series from the surface to 15 meters in 3 meter increments then 5 meter increments to 30 meters. Zooplankton genera and size fractions were examined in the lab using techniques described by May et al. (1987). Zooplankton biomass was calculated from dry weights following Bottrell et al. (1976).

Two techniques used to empirically quantify zooplankton production in the project reservoirs failed to produce usable results during model development. Cohort analyses using length frequency shifts over time were abandoned when it was determined that individual cohorts superimposed during the warm months and became indistinguishable. Birth rates of cladoceran species could ***not be estimated accurately based on*** female egg retention. Although preservative fluids were specifically designed to encourage egg retention, significant numbers of eggs were still discharged into the preservative. Isolated eggs could not be traced to the species of origin. Unknown mortality rates between samples also contributed error to empirical estimates of zooplankton production. Field evaluations showed evidence of size and species selective mortality (May et al. 1988, Chisholm et al. 1989). After our initial attempts to empirically calibrate a production model for each zooplankton genus, we concluded that the cost was too great relative to our needs. Instead, the model incorporates a theoretical relationship of energy transfer from the phytoplankton community to zooplankton (Ulanowics and Platts 1985). Total zooplankton production is a transformation of primary production minus washout loss, assuming a 15 percent net loss of the phytoplankton to dissolved organics, a 10 percent loss to detritus and a 15 percent growth efficiency in the zooplankton. Although this technique ignores known mechanisms controlling zooplankton population dynamics, any bias remains constant from one simulation to the next. This adequately achieves our goal of comparing one dam operational strategy to another without the need to conduct a more extensive investigation of zooplankton population dynamics. Our choice of modeling strategy, therefore, was based in part on cost-effectiveness.

Total zooplankton production is partitioned by genera based on the relative biomasses of each of the genera captured in the monthly zooplankton tows. The model calculates monthly and annual estimates of ***production*** of ***Daphnia, Bosmina, Diaptomus, Cyclops, Epischura*** and ***Leptodora.*** For each of these genera, the model describes zooplankton production (ZP) for each day (i) of the year as a linear function of primary production (PP): $ZP_i = A * PP_i * (b * SG_i * VOL_i + C)$. The coefficients a and b and the constant c were derived by regression from observed primary production values and zooplankton standing stock values. SG is a seasonality factor tailored for each of the genera and is based on the charted profiles of expected abundance for different times of the year. The variable V is the volume of the reservoir containing zooplankton, and is calculated over the upper 30 m of the reservoir water column.

Zooplankton Washout

Analyses of zooplankton entrainment through the selective withdrawal structure at Libby Dam were nearing completion in 1995. Our goal is to model the entrainment of zooplankton and fish under various operational strategies and water withdrawal depths. An understanding of the mechanisms controlling the entrainment of reservoir organisms will allow managers to influence the reservoir and river fishery.

Zooplankton washout at Hungry Horse Dam was measured by replicate drift net sampling in the dam discharge in two week intervals from 1987 through 1989 (May et al. 1988). The washout model describes the seasonality of downstream losses based on the previously estimated standing stocks in the reservoir by genera, and accounts for the increased rate of washout observed during periods of weak thermal stability.

Direct calibration of zooplankton washout from various withdrawal elevations was not possible at the time of this writing due to the fixed withdrawal structure at Hungry Horse Dam. HRMOD was modified to indirectly estimate xooplankton losses from various outlet depths to better evaluate the proposed selective withdrawal structure at Hungry Horse Dam. Estimates of downstream loss were based on the vertical distribution of xooplankton in the forebay as measured by Schindler trap sampling at standardized depths. The vertical distribution data were variable, yet clear patterns were discernable for each zooplankton genera. Trends in the depth distribution were expressed as a fraction of the water column total (similar to phytoplankton production). For each xooplankton taxon, a negative exponential curve was fit to the data. The shape of the vertical distribution was then scaled so that the Depth Density Factor (DDF) at. the original fixed withdrawal elevation was equal to one. The DDF is calculated by the model when the selective withdrawal component is invoked or when thermal stratification develops in the reservoir. The correct DDF value for each xooplankton genera is selected from the curve based on the current surface and withdrawal elevation. Results are then multiplied by the estimated xooplankton washout as calculated for the penstock depth, to estimate the loss at the withdrawal elevation. This component is calculated independently from zooplankton production, so may overestimate zooplankton loss when selective withdrawal is used. When the normal withdrawal elevation is chosen, however, the loss calculations are based entirely on empirical data. The BOR is presently funding an investigation of xooplankton entrainment through the recently installed selective withdrawal structure. Results are anticipated for comparison by spring 1997.

Benthic Dipteran Emergence

Benthic dipteran larvae were collected monthly from May through November 1985-1990 in each reservoir area with a Peterson dredge which sampled .092 m^2 of reservoir bottom. Three replicate samples were taken within each of the following depth intervals: (1) full pool elevation (3,560 ft) to 3,476 ft; (2) 3,477 ft to maximum drawdown on record prior to 1988 (3,432 ft), and; (3) below elevation 3,432 ft.

Benthos samples were sieved in the field through 5.6, 0.85 and 0.52 mm sieves and the material retained on the 0.52 mm sieve was preserved. This material, predominantly organic detritus, was stained with rose bengal to highlight larvae for easy removal. Larvae were enumerated and blotted wet weights obtained. Dipteran emergence was based on emergent insect capture in triplicate traps floating on the surface over the three depth zones (May and Weaver 1987).

Benthic production (insect emergence) was calculated from a linear regression of standing stock of dipteran larvae at each sampling depth, and dipteran emergence per unit biomass at each reservoir bottom elevation. Insect emergence is the preferred measure of production, because aquatic Diptera become available to fish as food upon emergence as pupae and adults. Larvae were only rarely observed in fish stomach contents. For each day of the water year, biomass and production were estimated by five foot increments from the current surface elevation to the bottom. Since benthic standing stocks at depth were dependent on the minimum pool elevation during the previous season, the model assumes that the input surface elevation schedule is repeated for two years. Calculated standing stock estimates were then corrected for elevation based on the minimum reservoir elevation for the year (SEMIN). The corrected elevation (E2M) is calculated from the current surface elevation (ELEV):

$$E2M = MAX[a_1, (ELEV - SEMIN + a_2)]$$

where a_1 = 3,430 for Hungry Horse and 2,270 for Libby,
and a_2 = 3,498 for Hungry Horse and 2,345 for Libby,
Note that A = MAX [B, C] means that A equals the greater of B or C.

The total standing stock (BD) in metric tons for the entire reservoir on the current day in the current depth zone is: $BD = MAX [O.O, DS * JO4046856 (a_1 - a_2 * E2M) * a_3]$, where DS = the surface area corresponding to that depth zone (that is, the surface area of the highest elevation in the depth zone, minus the surface area at the bottom of the depth zone).

a_1 = 7,519 at Hungry Horse and 7,444.3 at Libby,
a_2 = 2.0915 at Hungry Horse and 3.020 at Libby, and
a, = 0.001385 at Hungry Horse and .001264 at Libby.

Production (TBD) is proportional to the product of biomass (BD) and the bottom water temperature (T) squared, divided by a constant a_1. The constant brings the ratio of the calculated annual total production to the measured mean standing biomass into the range expected for reservoirs of this type based on Wetzel (1983) and supported by the emergence trap data.

a_1 = 3,336.887 for Hungry Horse and 4,333.45 for Libby.

Production within each depth zone is summed for each day. Daily values are summed to arrive at the annual total.

Terrestrial Insects

Terrestrial insect deposition was treated separately for nearshore (≤ 100 m) and offshore waters in each reservoir area. Capture rate was assumed to equal measured standing stocks for each species in triplicate, monthly surface tows in each of three reservoir areas. Coleoptera and Hemiptera tended to be more abundant in nearshore samples (where more were deposited, $p > 0.05$), whereas Hymenoptera and Homoptera were more randomly distributed. The seasonality of deposition was significantly different ($P \leq 0.05$) for the four main orders of terrestrial insects. The four orders, therefore, respond differently to reservoir operation and were modeled accordingly.

Since the rate of insect deposition could not be determined from surface tows (some individuals sink or are eaten by fish), we treated insect deposition as an unscaled seasonal index. Results represent the percent of maximum possible insect deposition that occurs when the reservoir is operated for power or flood control. Duplicate simulations can be compared to assess the relative effects of different operating strategies. Insect deposition rates were sampled in Hungry Horse Reservoir during 1991 and 1992 and are presently being analyzed. A quantitative insect deposition model can be constructed in the future.

Tow net data were fit with non-linear regression to define the seasonality of insect abundance as affected by changes in surface area and shoreline development. The seasonality of insect activity was modeled as a modified sine wave. A non-linear regression was used to fit the mean amplitude and phase shift to the observed densities:

$$\text{Density (number/hectare)} = \text{MAX}\,[0.0,\ \text{mean} + \text{AMP} * \sin(\text{period} + \text{phase shift})].$$

All values below zero were reset to zero. The Coleoptera model was post modified so that deposition was assumed to be zero during periods of ice. Each order had its own mean, amplitude and period based on the tow data (Figures 17 through 20).

Hungry Horse Reservoir Westslope Cutthroat 'hut Growth Model

Calculating fish body growth at both reservoirs was the most difficult task in the modelling effort. Our goal was to examine only the effects of dam operation on fish growth. Other factors that influence growth were isolated where possible, with differing degrees of success. The dependence of fish growth on many previously estimated values increased the uncertainty of the results. Therefore, the model is conservative and sensitive to only gross changes in reservoir conditions.

The growth of westslope cutthroat trout (*Oncorhynchus clarki lewisi*) was assumed to be directly proportional to the product of temperature and food availability. Only food items found in stomach content examinations were used in the analysis (May et al. 1988, Chisholm et al. 1989). The temperature term in the equation was the maximum value available in the reservoir up to the optimal temperature for growth. The model was used to predict the temperature structure

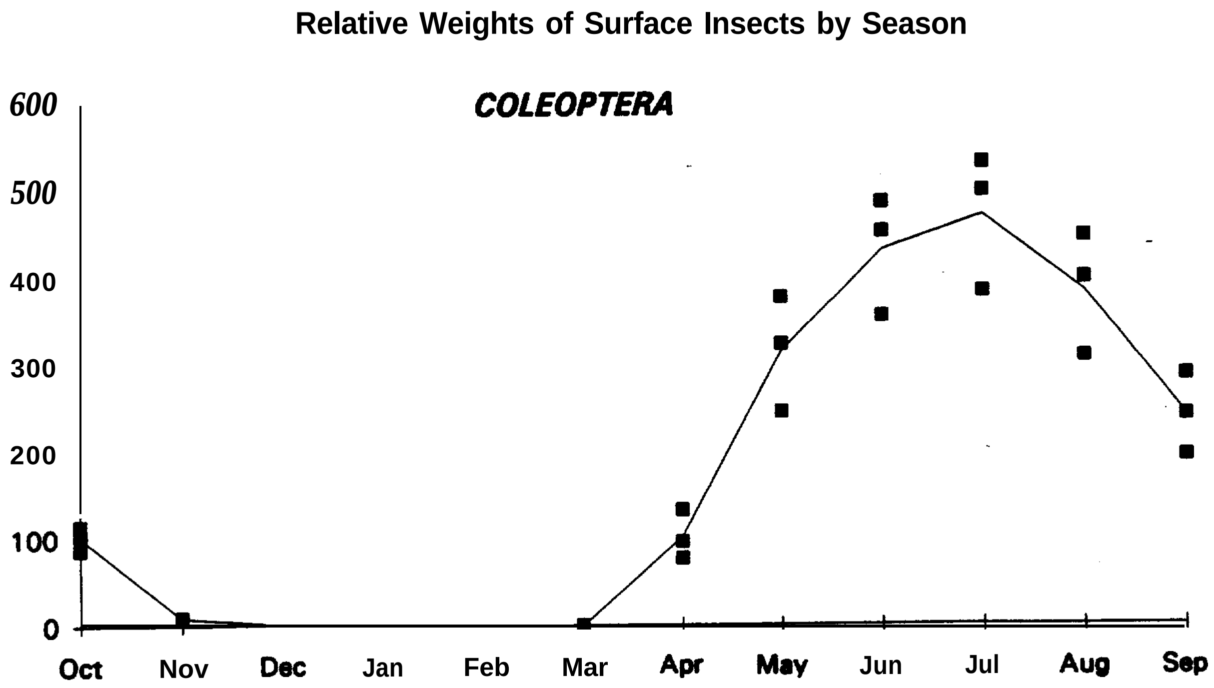

Figure 17. Seasonal distribution of *Coleoptera* deposited on the reservoir **surface** from the surrounding landscape. **Coleopteran** deposition was **measurably greater** in nearshore (< 100 m) areas at both reservoirs. The **line represents** average conditions; points **reveal** the range under normal **operating** conditions.

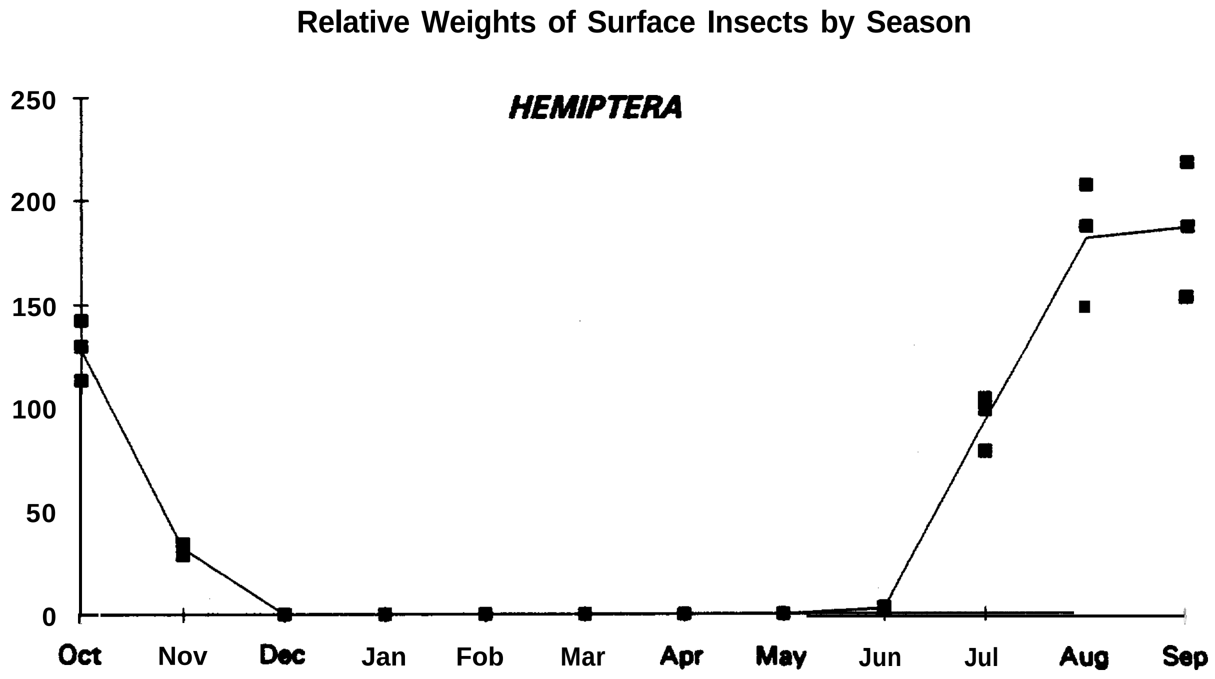

Figure 18. Seasonal distribution of *Hemiptera* **deposited** on the reservoir surface **from** the surrounding landscape. Hemipteran deposition was measurably greater in nearshore (<100 m) areas at both reservoirs. The line **represents** average conditions; points reveal the range under normal operating conditions.

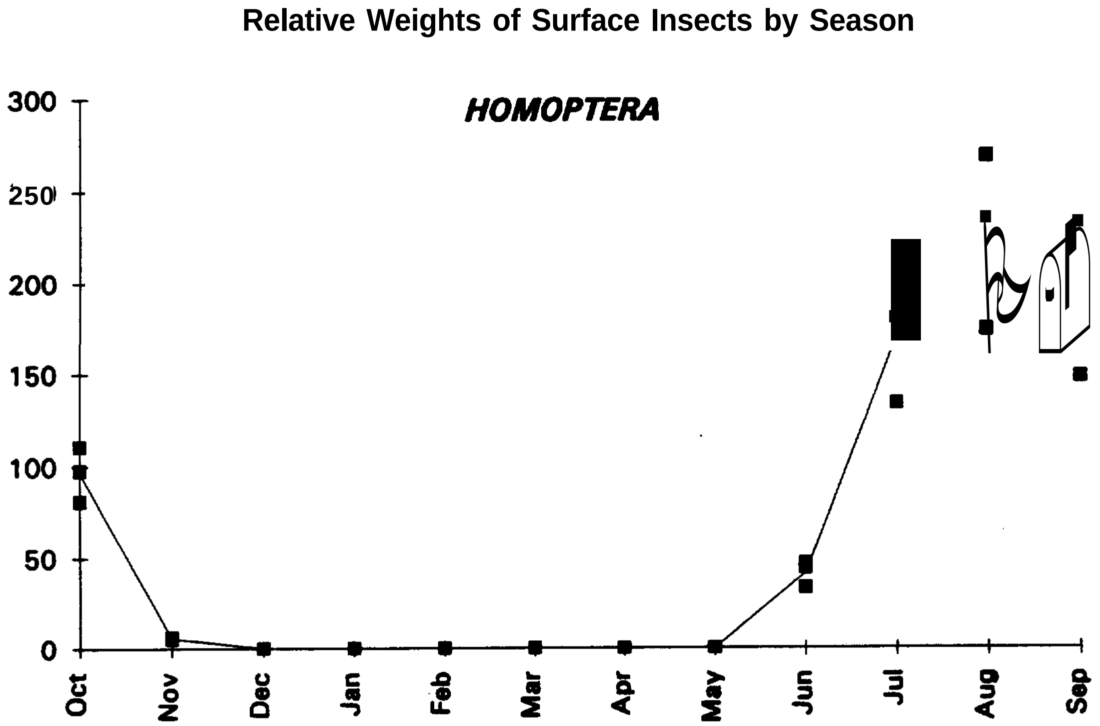

Figure 19. Seasonal distribution of ***Homoptera*** deposited on the **reservoir surface** from the surrounding landscape. Homopteran deposition was randomly distributed across the reservoir **surface.** The line represents average conditions; points reveal the range under normal operating conditions.

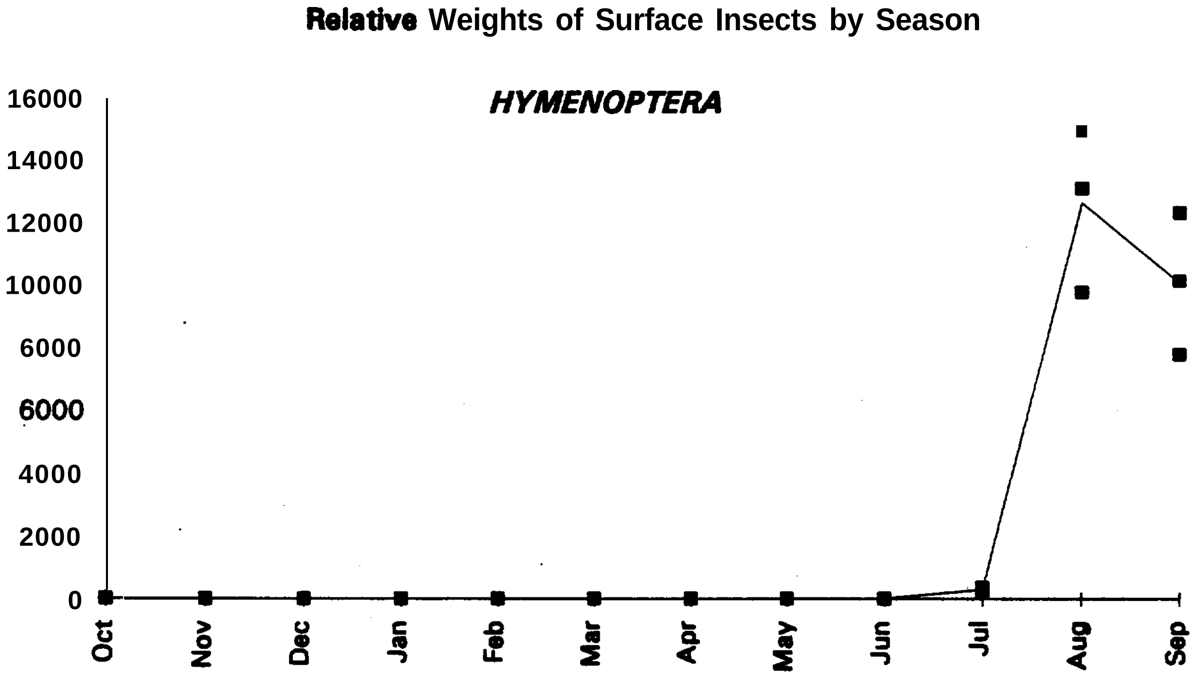

Figure 20. Seasonal distribution of ***Hymenoptera*** deposited on the **reservoir surface** from the surrounding landscape. Hymenopteran deposition was randomly distributed across the reservoir surface. The line represents average conditions; points reveal the range under normal operating conditions.

in the reservoir and food production for the entire period for which fish growth measurements were available. The product of the **temperature** and the species-specific food production schedules were summed during each growth increment. Weighing factors for the various food items were then related to observed changes in body **size** as determined by multiple regression. Because of the large number of highly correlated food production schedules, over-fitting may have been unavoidable. Coefficients should, therefore, not be interpreted literally. They represent the best model of the **available** data.

Fish population dynamics were not incorporated into the model. Several population models were tried during model development and later abandoned. Westslope cutthroat survival, growth and maximum size are strongly influenced by habitat conditions in their natal tributaries where they rear for one to five years before emigrating to the reservoir. Tributary conditions vary strongly with climatic variables and land management **practices,** but are nearly independent of dam operation. Because of cost and time constraints, we did not create a tributary model. Instead we assumed a static population size and focused only on fish growth in the reservoir. This strategy was adequate to meet our objective to compare the biological effects of one operational strategy to another.

Westslope cutthroat trout growth at Hungry Horse was modeled on monthly and annual growth increments from otoliths and scales, respectively. **Otoliths** and scales were extracted from a wide range of size categories and migrant classes. Tributary and reservoir cutthroat were aged from samples collected during the 1983 through 1992 field seasons. **Growth** increments on the otolith provided monthly growth rates during warm months and seasonal rates during winter, early spring and late **fall** (Brothers 1986, 1987 and 1988). Annual **growth** was obtained from **annulus** formation on scales (Weisberg 1986).

At Hungry Horse Reservoir, approximately 60 percent of juvenile cutthroat enter the reservoir during late June and early July of their third year of life or migrant class III. **Others** may emigrate at age I through V. Migrant class was identified by a rapid growth rate **immediately** upon emigration from their natal tributary to the reservoir, as recorded by scale **annulus** formation.

Model, validation was conducted using age information from 1983 through 1992. Validation of the model is confounded by factors other than dam operation that also influence growth. Cutthroat growth is apparently **influenced** by population density. Thus, if cutthroat numbers are high, growth may be reduced. Also, growth effects in the natal tributary may effect the maximum growth in the reservoir. Fish that emigrate at a larger **size** may grow more slowly upon entering the reservoir. The model is not capable of adjusting for growth effects in tributary streams and focuses only on growth effects in the reservoir. The technique described by Weisberg (1986) was used to compare actual growth observed during calendar years 1984 through 1990 with the grand **mean** of growth increments for all fish examined (expected growth). **Future** sampling will result in similar comparisons for calendar year 1991 and later. The technique assumes a common intercept for length calculations on individual fish. The intercept calculation involved the entire data set in a **regression** of natural log transformed measurements of scale diameter on total fish length. Total length at age for individual fish was then back-calculated at each annulus based on the following relationship:

$$LA_i = c + \log(A_i)/\mathrm{Log}\,(E_i) * (\mathrm{Log}\,L_c - c)$$

Where,

LA_i = length of individual fish at annulus A_i
A_i = increment from scale focus to annulus$_i$
E_i = radius from focus to scale distal edge
L_c = total length of individual fish at time of capture
c = common intercept of all fish in log regression of L_c on E_i

Results were separated by year class and the mean length at age and confidence intervals were calculated for each cohort. We modified the technique to reduce Lee's Phenomenon in older fish by back-calculating only the most recent annual growth increment in fish of age IV or older. The analysis was repeated using fish captured during spring only, and again with spring and fall captures. Since most growth is complete prior to our fall gill net series, we calculated growth during the season of capture. Spring samples permitted only back-calculation of growth during the previous year.

The cutthroat growth model CUTGROW is driven by all lower trophic components (zooplankton, benthic insects and terrestrial insects). Only fish that emigrated from their natal tributary at age III (migration class 3) were *represented in the* analysis. These fish are assumed to be 15 1.8 mm in total length on January 1 of the year they enter the reservoir then grow an additional 12.2 mm, on the average, before migrating to the reservoir. This growth is considered the beginning point in the reservoir model.

Daily growth of the fish is modeled through three years using the established temperature and food schedules. This assumes that the reservoir was operated in the same manner for three years. The equation for growth in millimeters for each day *i* is:

$$\mathrm{GROWTH}_i = \mathrm{FAC}_j * \mathrm{MIN}(\mathrm{TEMP}, 11.9) * (0.37 * \mathrm{DAPHNIA}_i + 15.34 * \mathrm{EPISHURA}_i + 0.060 * \mathrm{COLEOPTERA}_i + 0.00015 * \mathrm{HEMIPTERA}_i + 0.020 * \mathrm{HOMOPTERA}_i + 0.00011 * \mathrm{HYMENOPTERA}_i + 0.55 * \mathrm{BENTHIC}_i).$$

FAC_j is a scaling factor for each of the three ages', and 11.9" C represents the temperature of maximum growth efficiency. The scaling factors are 0.0405, 0.0155 and 0.005499 for ages 3, 4 and 5 respectively.

Growth in length (mm TL) is converted to weight (g) based on an equation derived from measurements of all 7,813 fish that were available at the time. The equation is WEIGHT = $0.00001146 * TL^{2.962}$. The relationship explains 98.9% of the total variation. Much of the unexplained variation is due to a few outliers that could represent measurement or recording errors. The output is a table representing the end of month growth (mm) and projected biomass of fish (ages III to IV).

Flathead River Trout Growth Models

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 3. 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 evaluated by incorporating curvalinear temperature/growth relationships and food ration effects. The latter increased the accuracy of our original linear model 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). Brett's curves, showing specific growth rates (% chg. in wt./day) were presented without defined mathematical relationships. To incorporate these results into the model, known values were taken from the plotted curves (Figure 21) and fitted by quadratic regressions. The curves were selected to represent a conservative increase in food availability as insects respond to temperature control. 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.

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 (198 1) indicate summertime periphytic productivity is actually higher below the mouth of the South Fork than above it. Surprisingly, the same was true for benthic insect metabolism. These unexpected results may be due in part to increased nutrients entering the main stem Flathead River from 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. It is also difficult to differentiate between the effects of rapid or intermittent flow changes and temperature fluctuations on the insect community below Hungry Horse Dam. Another important consideration is higher wintertime production because of the release of relatively warm water (≈ 4° C) from the reservoir. This later effect, however, would not be effected by the installation of a selective withdrawal device.

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. Thermal disruption of behavioral patterns may be as serious as the more easily measured physiological effects. The damages incurred from altering the natural species composition of

Table 3. An example of output fiom 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)	Oct	Nov	Dec	Jan	Fob	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 3 continued.

		With Selective Withdrawal											
		Trout Growth Units											
Temp. (° C)	Duration (Days)	Oct	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	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	a6	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

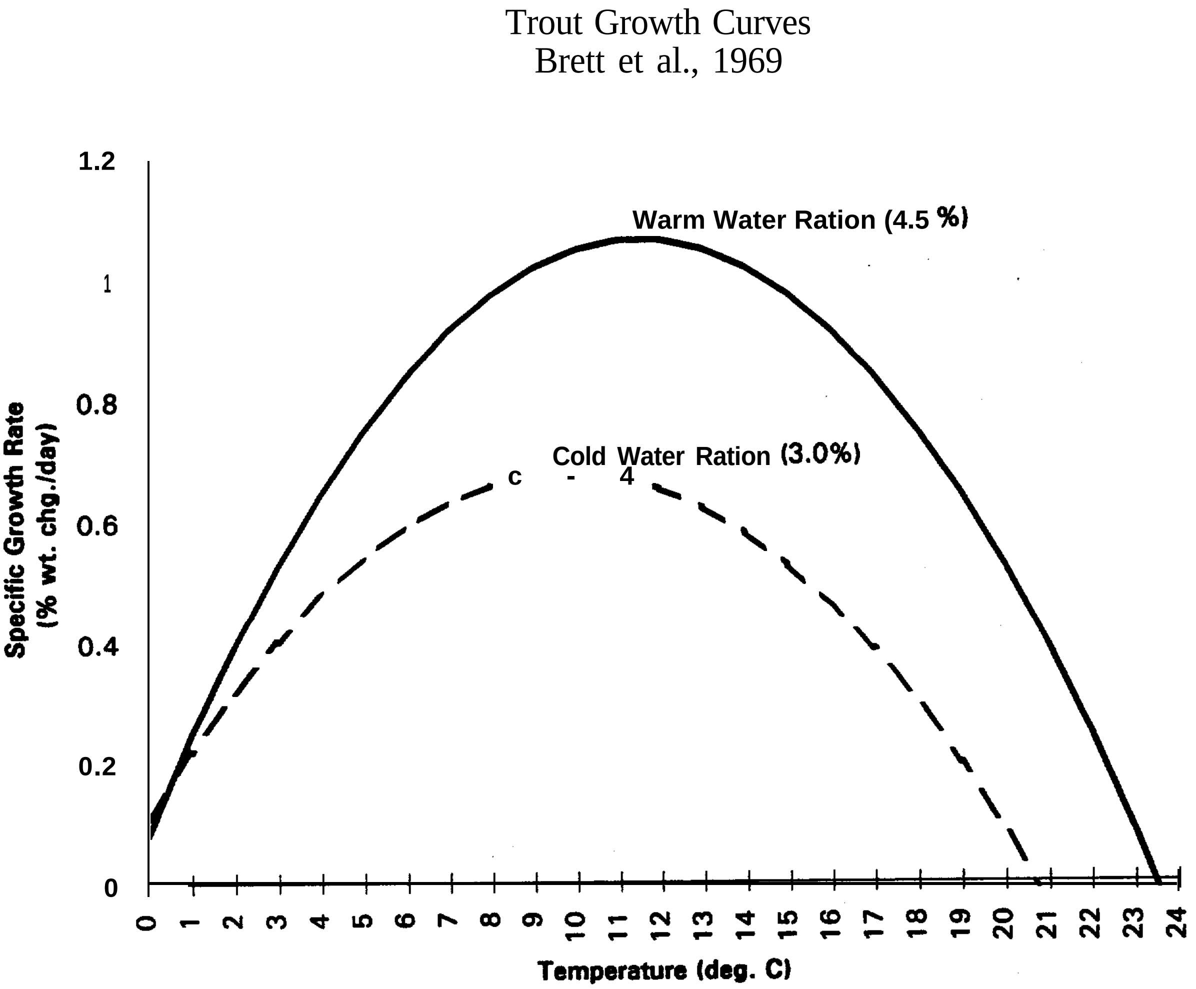

Figure 21. Growth efficiency curves relating specific growth rate to water temperature and food availability. Paired curves were selected from laboratory results presented by Brett et al. (1969). The curves approximate changes in the insect community structure, and thus food availability, when rapid thermal fluctuations and long-term cooling effects caused by hypolimnetic withdrawal are. corrected through selective withdrawal.

the river is similarly difficult to assess. We, therefore, attempted to capture the thermal influence on insect production as a community and developed conservative relationships relating temperature to growth efficiency.

All of the species making up the invertebrate fauna presumably 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: $Q_{10} = (k_1/k_2)^{10/(t_1-t_2)}$, 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. The values "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 on numerical values derived from controlled laboratory experiments, the model output was 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 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. 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. Age III+ fish were selected because this represents a major year class for migrant fluvial and adfluvial trout. 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.

The model was run on an annual basis, often in duplicate simulations to assess the effects of water availability or discharge temperature control (selective withdrawal) on trout growth. Temperature units and growth efficiency curves were used to calculate daily growth increments which were summed to provide monthly and annual growth trajectories. The model outputs growth in length (TL) and weight (g).

Libby Reservoir Kokanee Salmon Growth Model

Kokanee (*Oncorhynchus nerka*) growth at Libby Reservoir was modeled as individual body growth in length and weight of I+ and II+ age fish. The annual temperature regime and food production alone described the seasonal shape of kokanee growth. Growth varies with zooplankton availability and the volume of water at optimal temperatures for growth.

Growth information from monthly net sets was used to establish the relationships with temperature and food production derived from previously described model components, Although scale increments and otolith development were used to verify results, abundant catch data from monthly net surveys provided a larger data set for model calibration. Empirical growth was measured by comparing length distribution (mode) of each year class from one sampling period to the next (Figure 22). The growth trajectory of successive year classes could then be compared with corresponding environmental conditions.

Initially the kolcanee growth model incorporated an algorithm similar to the westslope cutthroat growth model developed for Hungry Horse Reservoir. Calculations were performed on a daily basis using surface water temperatures and xooplankton productivity. A static population was assumed so that dam operation strategies could be compared without the confounding influence of density effects caused by annual shifts in population structure. Fluctuating reservoir volume was considered an important influence on fish concentrations and, therefore, density dependent growth. Growth estimates resulting from the preliminary model were valuable for comparing dam operations, but predicted annual differences in growth were slight as compared to empirical growth data. This inconsistency between predicted and observed growth patterns necessitated the development of a new algorithm which incorporated more long-term effects.

Temperature profiles in the reservoir were determined to be the most important factor influenced by dam operation. In Libby Reservoir, xooplankton availability is directly coupled to phytoplankton availability, and phytoplankton productivity is controlled primarily by three factors: nutrients, and the volume of water having optimal light and temperature conditions. The nutrient profile reflects the nature of the watershed which has stabilized in recent years after a long history of artificial nutrient loading from a fertilizer plant in Canada (Woods 1982, Woods and Falter 1982). Of course, the total nutrient input varies annually in proportion to the runoff. Light is similarly "fixed externally" and is also fairly constant in the long-term sense from year to year. This leaves temperature and reservoir volume as the most important factors which can be influenced by different operational schemes of the reservoir. Temperature directly influences phytoplanlcton growth, xooplankton growth and kokanee growth. Because of this kokanee growth was correlated entirely with this pervasive factor.

The model now incorporates a long-term integration of temperature during the summer and takes into account the entire water column to a depth of 64 meters. Regressions show that the

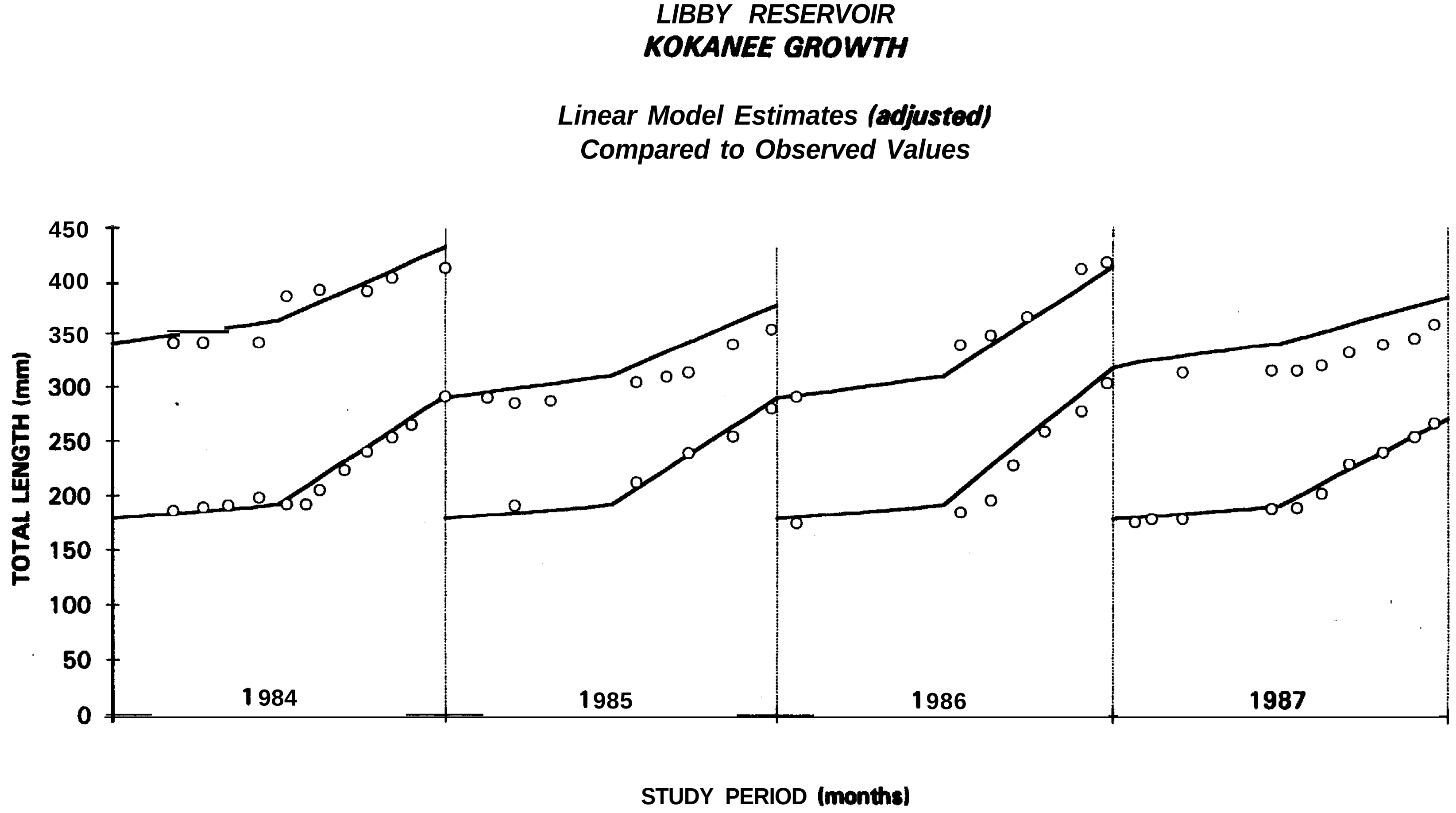

Figure 22. Empirical measurements of kokanee growth trajectories from monthly net samples in Libby Reservoir (1984- 1987) as compared to model predictions for the same study period. Open circles define the. mode in length distribution for each age class of kokanee. The solid lines represent the growth trajectory calculated by the model. The end point of age I growth in the first annual simulation defined the starting point for age II growth in this multiple year simulation.

predictability of the growth rates is higher for the I+ year class than for the II+ age class ($R^2 \cong 0.95$ and $R^2 \cong 0.88$, respectively). Growth rates during the winter are very small, so a long-term average was used. The conversion of lengths (mm TL) to weights (g) is performed with a regression equation specific to Libby Reservoir kokanee, WEIGHT = 3.16255 E-6 * $SIZE^{3.19262}$. The model calculates lengths and weights for both I+ and II+ fish for each month of the year. Equivalent output to a user named file is optional.

Thermal Modeling in the Flathead River Downstream of Hungry Home Dam

Man-caused temperature fluctuations have been linked to biological changes in the Flathead River Basin. Hungry Horse 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 MFWP 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 (Marotz et al. 1994). A subroutine to simulate selective withdrawal was appended to the Hungry Horse Reservoir model developed by MFWP 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 components in HRMOD were used to assess benefits or tradeoffs upstream and downstream of the dam.

Alternative methods to moderate the thermal effects of Hungry Horse Reservoir 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, MFWP 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 18-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 199 1, 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 withdrawal 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 rapid 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. In May 1994, the Bureau of Reclamation completed the final environmental assessment and found no significant impact caused by the installation and operation of selective withdrawal (Bureau 1994). Computer simulations and field sampling will aid in future operation of the device when it becomes functional.

Affected 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 23). 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.

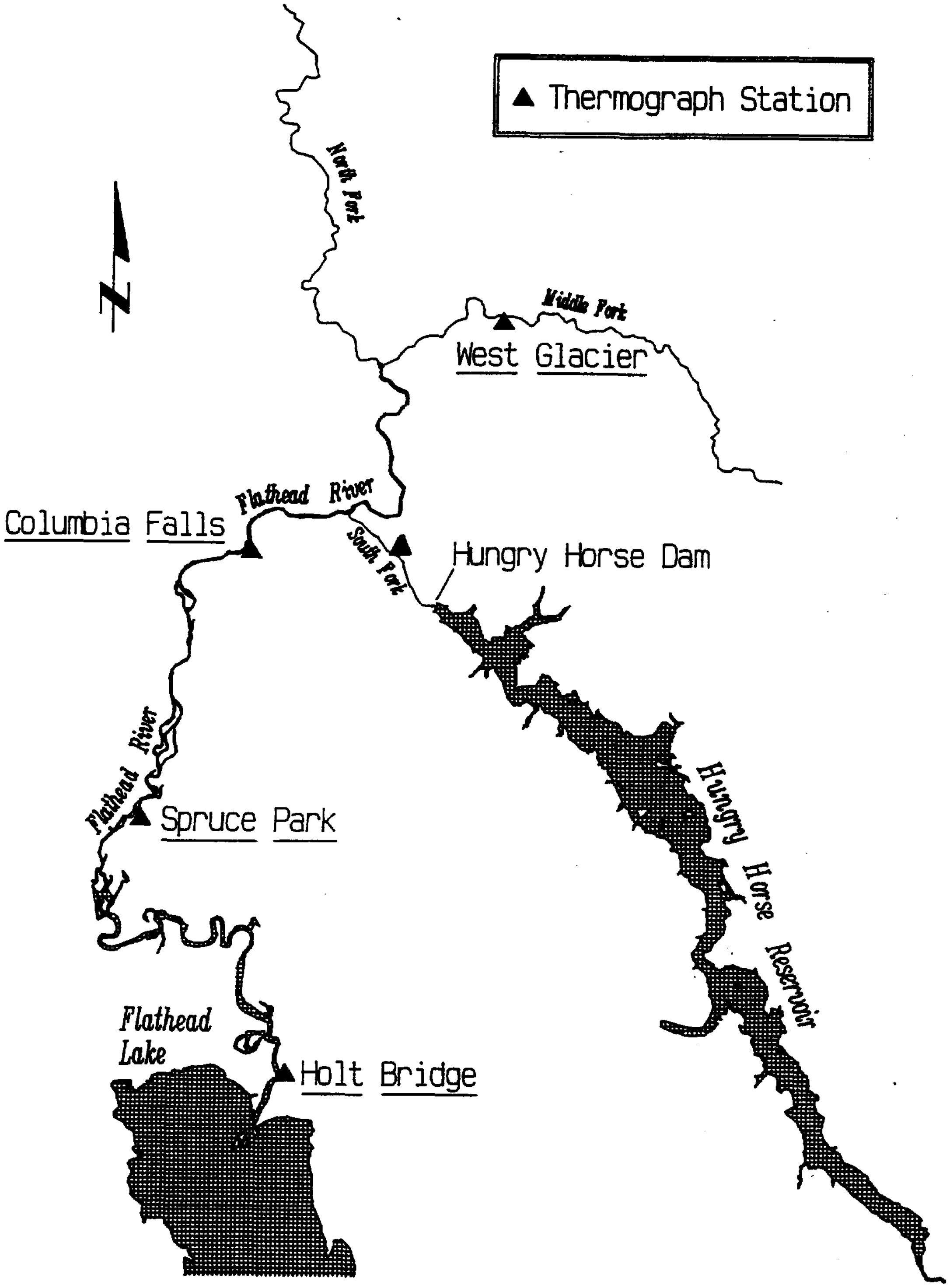

Figure 23. Locations of temperature recorders in the study area during 1991 and 1992. The West Glacier site provided the unregulated control. The U.S. Geological Survey monitors discharge temperatures in the South Fork below Hungry Horse Dam. Temperatures from the three forks are thoroughly mixed at 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 temperatures at the inflow to Flathead Lake were monitored at the Holt Bridge site.

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 24). 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 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.

Results of Thermal Modeling

Natural Did 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 25).

Unnatural Thermal Pulsing

As hypolimnetic waters are released through the darn 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 26). Conversely, sudden reductions in turbine discharge coincide with sudden warming in the **Flathead** River, as' temperatures return toward ambient. **In** both situations the effects are **especially** apparent when converging flows from North and Middle forks return to basal conditions after spring runoff (mid May through mid June). Thermal spikes continue through October when natural **temperatures** decline toward **4°** C **(39°** F).

Thermal pulses were observed on many occasions during the sampling period (Table 4). 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

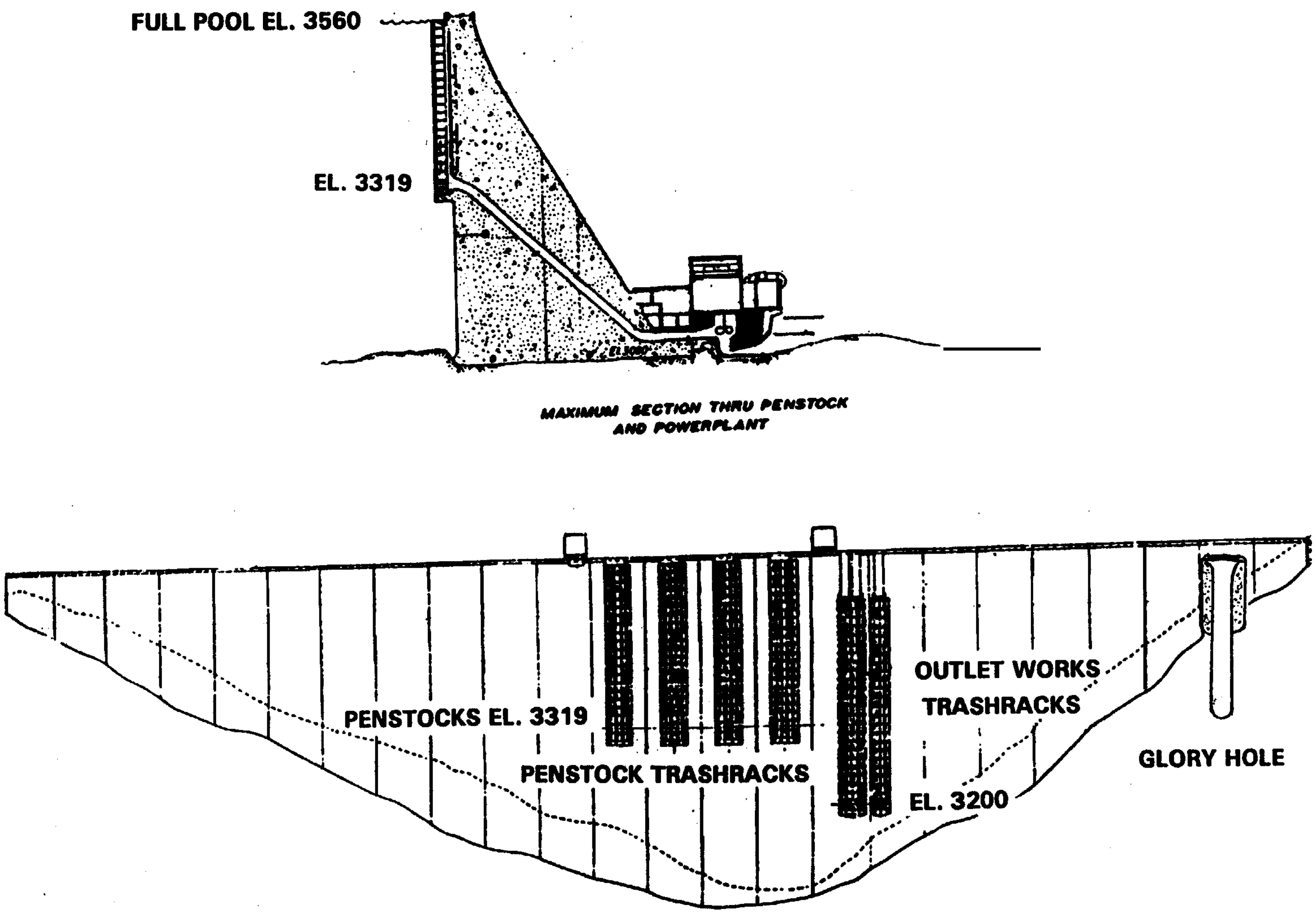

Figure 24. A schematic of Hungry Horse Dam as viewed from the side (top) and upstream face (bottom), shows the location of the four turbine penstock apertures (center), the outlet works to the hollow jet valves (right) and glory hole (far right). Trashracks extend from the apertures upward toward full pool elevation. Jet valves and glory hole spill water, bypassing the turbines. The selective withdrawal structure will be retrofitted into the turbine trashracks.

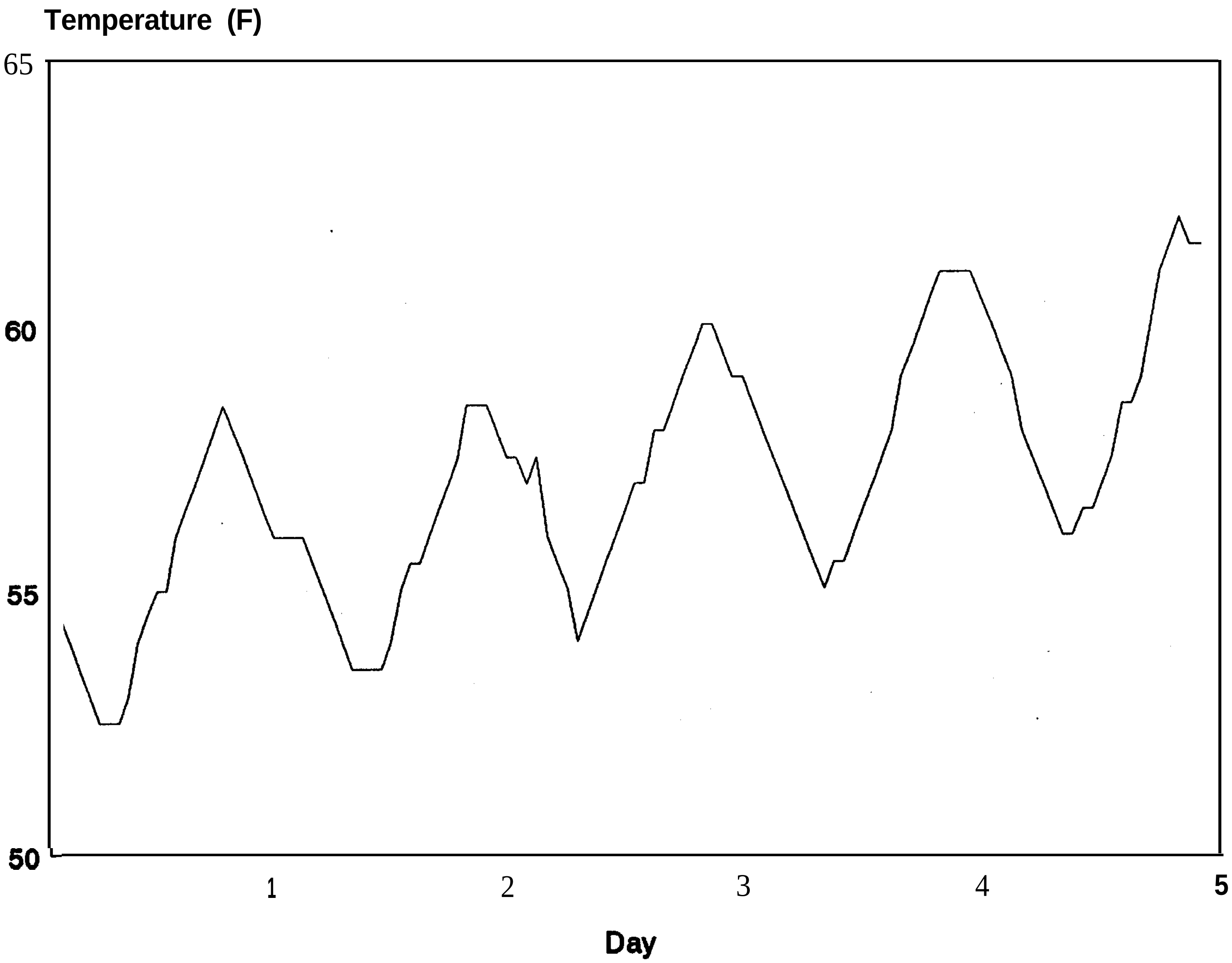

Figure 25. An example of typical diel thermal fluctuation due to atmospheric heating during the day and cooling at night. This segment represents observed values during June 19 through 25, 1992.

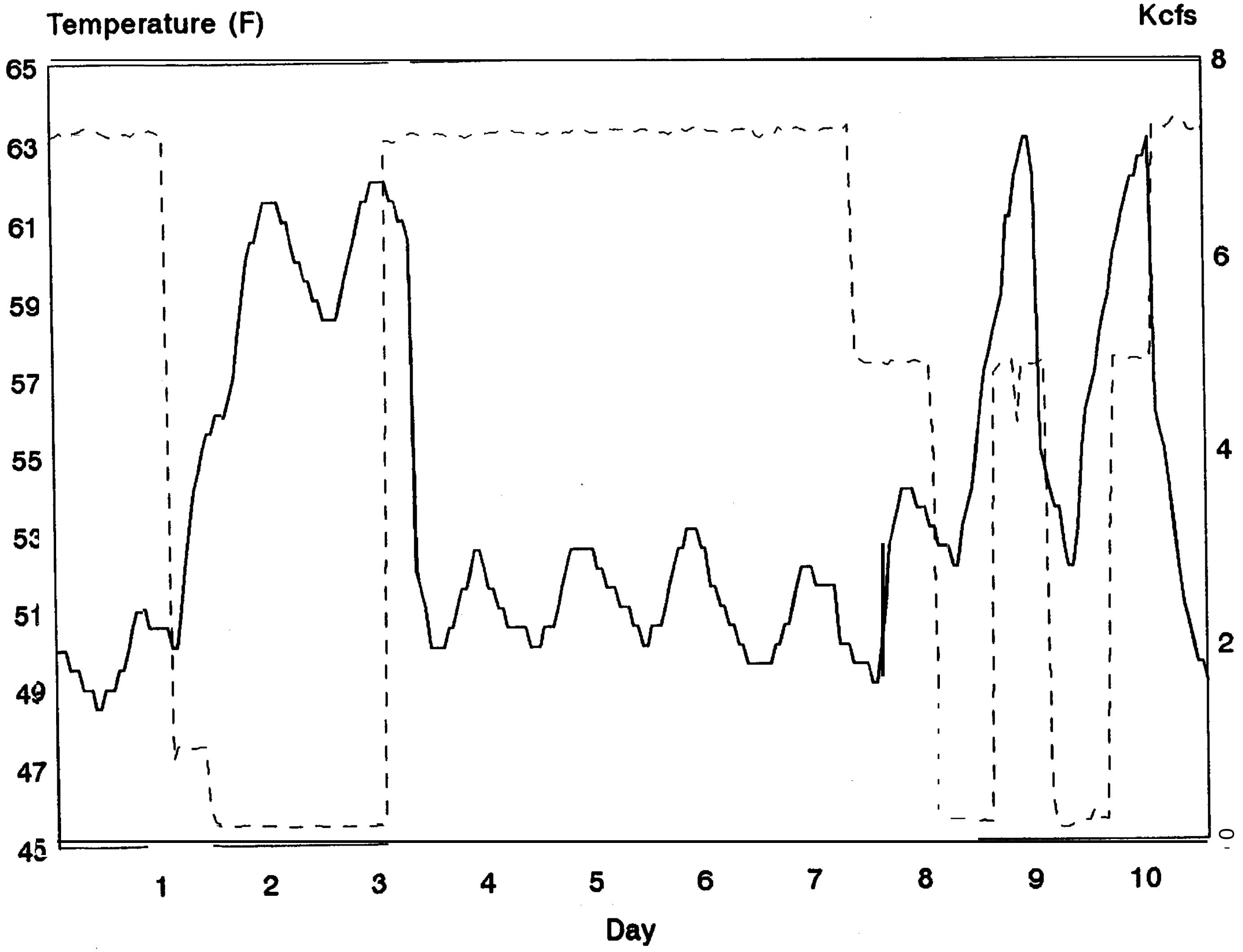

Figure 26. An example of thermal effects of hypolimnetic discharge from Hungry Horse Reservoir measured at Columbia Falls, June 19-24, 1992. The solid line represents hourly temperatures (°F). Dam discharges are represented by the dashed line.

Table 4. 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 t 3, ↓ 4		6/8/92	↓ 5	↓ 5
7/31/91	↑ 5	↑ 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	t 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	--	↑ 8	8/3/92	↓ 8	--
8/19/91	↓ 7	↓ 5	8/8/92		t 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
8/24/91	--	↓ 6, t 7	8/17/92	↓ 6	t 4, ↓ 4

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

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

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

reveals a puzzling lack of the lag effect (Figure 27). 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, but 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 as far as 35 km (22 miles) upstream from the mouth. Higher river stage and decreased water velocities have resulted in increased sediment accumulation in the river substrate. Channel alterations have resulted from increased sediment input from unstable riverbanks. Bank instability has been accelerated by frequent wetting and dewatering resulting from intermittent power operations. Full recovery of the system will, therefore, require thermal control and moderated flow fluctuations.

Long-term Cooling Due to Hypolimnetic 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 28).

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, which are basal flows under natural conditions in the fall. 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.

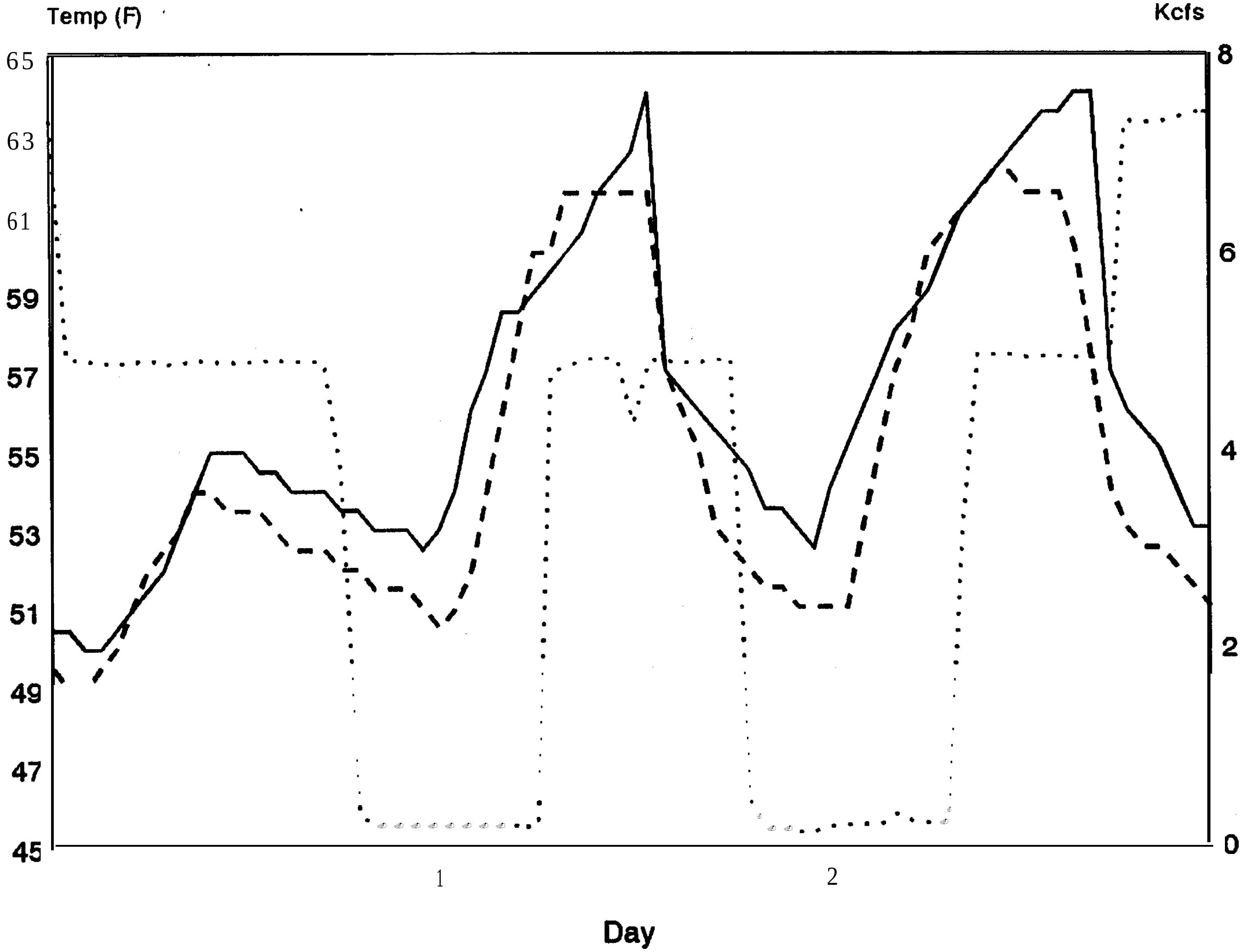


Figure 27. A comparison of hourly water temperatures recorded simultaneously at Columbia Falls (solid line) and Spruce Park (dashed line) as compared to Hungry Horse Dam discharges (dotted line) during June, 1992.

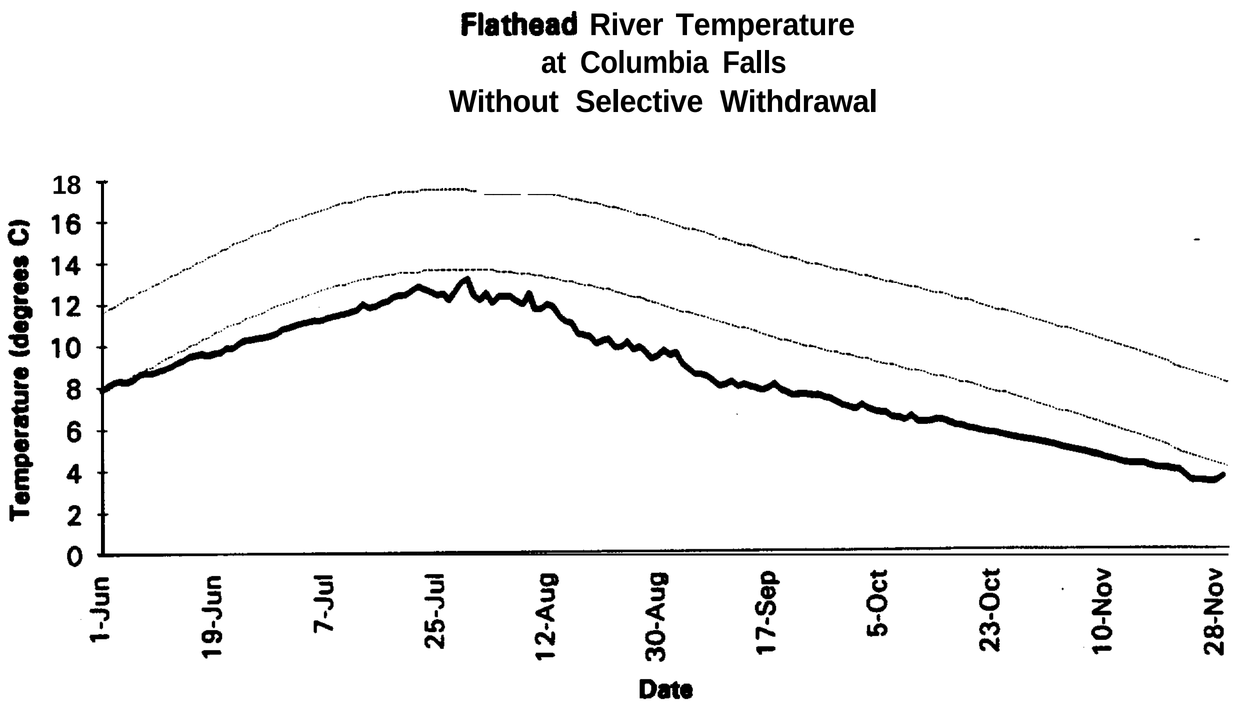


Figure 28. Long-term cooling of Flathead River temperatures caused by hypolimnetic withdrawal. Dashed lines bracket the natural temperature range during the peak growth season. These results are based on average long-term conditions. This approach nullifies sudden temperature fluctuations that are evident in annual measurements.

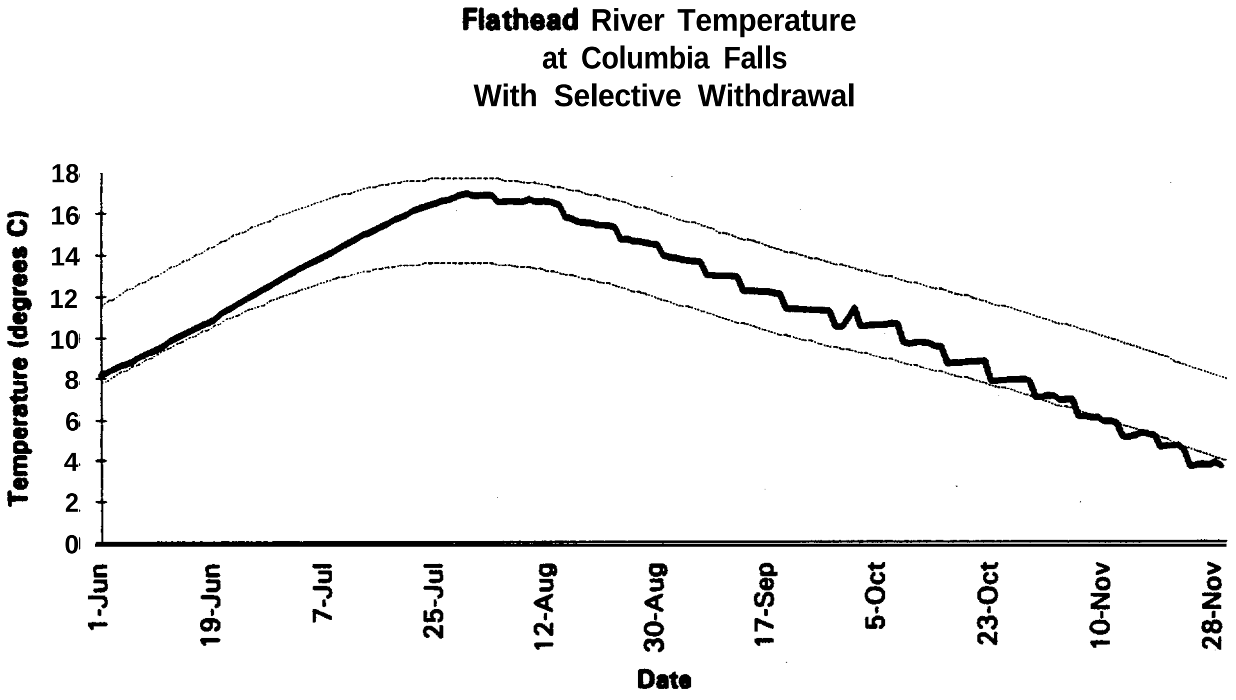


Figure 29. Thermal control resulting from selective withdrawal. Dashed line bracket the natural temperature range during the peak growth period. These results are based on average long-term conditions. Complete control is possible under all water conditions observed historically, 1928 through present.

Advantages of Thermal Modifiion 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 29). 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 operated to extend the growing season well into November by releasing warmer than ambient water from the reservoir (Figure 30).

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.

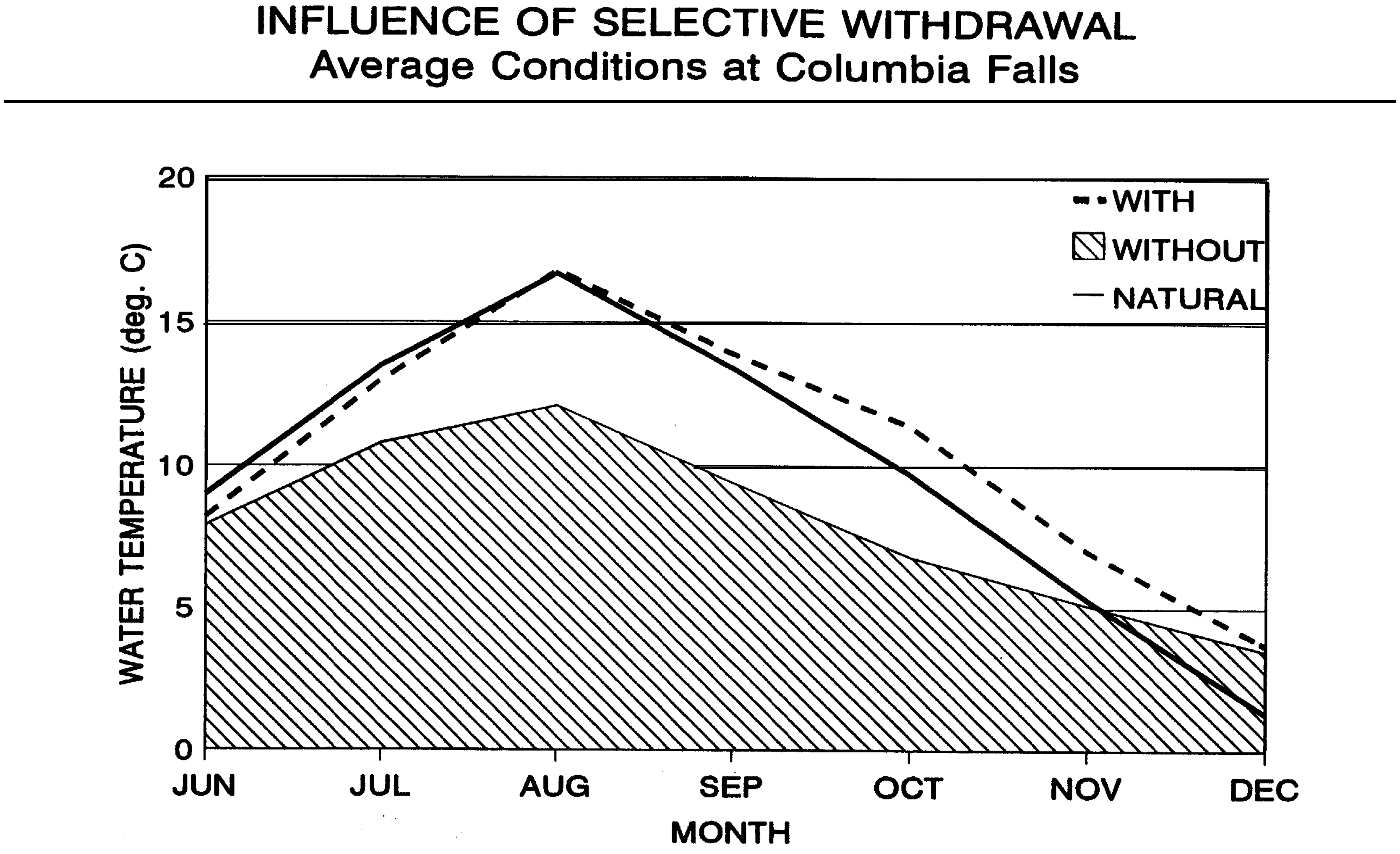
Increased production of aquatic organisms due to temperature alone will improve food availability for riverine fish species. Food availability in the dam tailwater will also be enhanced as zooplankton from the reservoir are entrained by the withdrawal device.

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 a selective withdrawal system were installed. Increased juvenile growth has been linked to increased survival in the river system.

Table 5 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.

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.

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 (MFWP unpublished file data). It remains uncertain if predation by lake trout has



Data for the 1st of each month

Figure 30. A comparison of natural temperatures in the Flathead 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.

Table 5. 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

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 makeexcursions 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, mixing by wind 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 heating through conduction (advection), reduced evaporation and decreased IR losses. 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 31 and 32).

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 falls 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

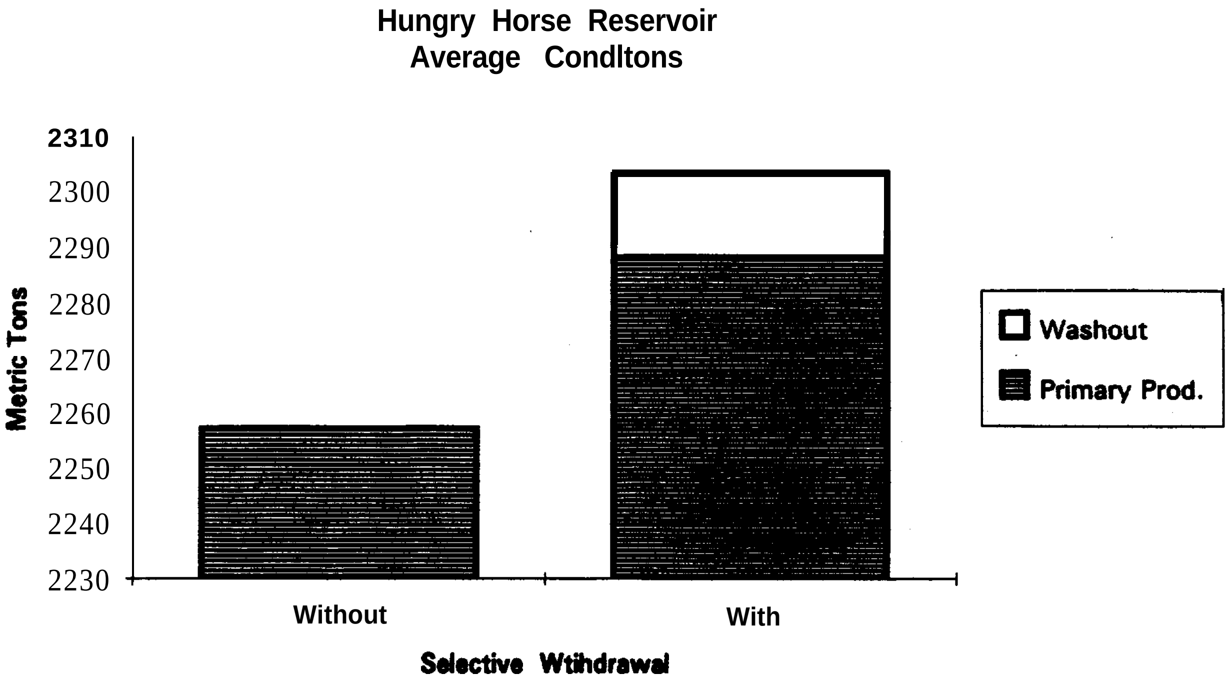


Figure 31. A comparison of annual primary production and washout through the dam turbines under fixed hypolimnetic discharge and selective withdrawal. Downstream loss is increased when warm water is withdrawn from the productive euphotic zone. The empirical model indicates that primary production may be enhanced by selective withdrawal when thermal stratification weakens, allowing the wind mixed zone to extend deeper within the euphotic zone.

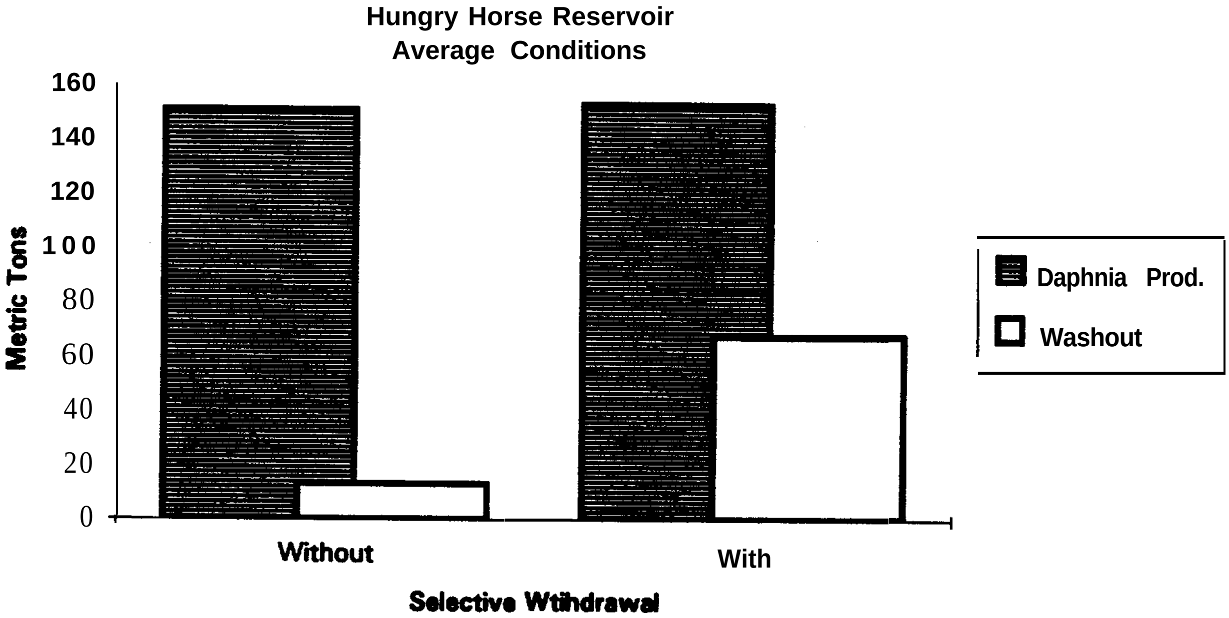


Figure 32. A comparison of daphnia production and washout from the dam under fixed hypolimnetic discharge and selective withdrawal. Downstream loss is increased when warm water is withdrawn from productive surface layers. Model simulation indicates that zooplankton production is somewhat higher under selective withdrawal.

experience a **corresponding loss (Figures** 31 and **32). It** should be noted, however, that the modeling methodology for zooplankton washout may have resulted in an overestimate of downstream loss (see methods section).

Refinement of operation strategies for the withdrawal **structure** can offset some downstream losses. The **final** design **specifications** include a movable control gate capable of selecting a desired layer of water for release through the **turbine** penstocks. Water flows over the top of the control gate **enroute** to the outlet works. The control gates also contain five adjustable panels controlling discharge 15 meters (50 ft.) below the top of the control gate. Two apertures in the control **structures** *enable simultaneous withdrawal* **from different** *layers in the pool into* a single turbine. This "strati&d" selective withdrawal can mix warm and cool layers to achieve an intermediate target temperauue, 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.**

Benthic insect production is influenced by water temperauue 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 **(MFWP** 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 of Thermal Modeling

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 Northwest Power Planning Council. Biological considerations reported herein were incorporated in the design **specifications** for the structure. **Zooplankton** entrainment and thermal control should be monitored to maximize benefits of selective withdrawal.

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 thermal structure in the basin. Short-term temperature fluctuations and long-term cooling were reduced to near natural conditions, 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.

Model Analyses to Determine Biological and Habitat Impacts in Hungry Home and Libby Reservoirs Caused by Dam Operations

Field research and model simulations have shown that deep drawdowns and refill failure are harmful to aquatic life in the reservoirs and rivers downstream. Reduced reservoir volume directly impacts the size of the aquatic environment for all organisms in the food web. The surface area of the reservoir dictates the amount of suspended algae (phytoplankton) that can grow, limiting the base of the food chain. Aquatic plants and insects are killed as water recedes from the vast expanses reservoir bottom. Fish are concentrated in a smaller pool and food availability is reduced.

The Hungry Horse and Libby models were used to calculate the biological impacts of various operational strategies.

Primary Productivity

Reservoir water fluctuations affect primary production by changing the volume of water of optimal temperatures, nutrient cycling and light transmittance. Primary production (carbon fixation) peaked between June and August and was two to three times greater at Libby than at Hungry Horse. Nutrient concentrations at Libby Reservoir were artificially elevated by effluent from a fertilizer plant in British Columbia, Canada. In 1987, mining was discontinued. Nutrient inputs gradually declined to stable levels when sampling began for model calibration. We assumed that nutrient input would vary only due to changes in inflow and that human disturbances would be minimal at both reservoirs for modeling purposes. Results specific to Hungry Horse Reservoir are presented here.

Seventy-eight chlorophyll profiles were compiled over four years, 1986 through 1989, at Hungry Horse Reservoir. The maximal concentration normally occurred at 15 meters from the surface. There was little seasonal pattern to the chlorophyll concentration in the upper 5 meters over the course of the year, although spring samples contained the highest values. No significant seasonal pattern was detected in the relative amount of chlorophyll occurring deep in the water column. There was also no statistically significant difference in chlorophyll concentrations among the four years, although during the extreme drawdown and refill failure of 1988 chlorophyll concentrated tended to be lower. Sampling locations nearest the dam exhibited higher chlorophyll concentrations ($p > 0.05$). This is believed to be a result of algal cells concentrating above the dam.

Primary production analyses were based on ninety-three light and dark bottle profiles, corresponding light attenuation profiles and continuous light recordings at Hungry Horse Dam. Correlation analysis indicated that dissolved inorganic carbon and light penetration were not related to total production in the water column. Total production was best correlated with the production at 5-10 meters depth, with chlorophyll at 10-20 meters and water temperature at O-5 meters. Total production increased with light and production per unit light remained constant throughout the year. When the data were balanced by sampling location, the stations nearest the dam had greater productivity. Total production was strongly seasonal and increased in the lower stations.

The existing model probably underestimates the impact of drawdown during the period of peak production. The model does not reflect the reduced time for algal production caused by more rapid replacement of the reservoir water when the reservoir fails to refill. The data indicate that this occurs, but the effect was small and not statistically significant ($p > 0.05$). Perhaps the increased circulation of nutrients in the smaller reservoir compensates for the reduced residence time of algal cells.

Model output of annual totals (metric tons of carbon fixed) was more sensitive to reservoir elevations during July and August than to the depth of maximum drawdown during late winter and early spring, provided that inflows were sufficient to refill. Failure to refill resulted in decreased primary productivity. Production decreased at an accelerated rate as surface elevation deviated from full pool (Figure 33).

Direct loss of phytoplankton production through the dam limits the available food for secondary producers such as zooplankton and benthic insect larvae. Downstream loss was greatest when surface elevation approached the depth of withdrawal and when discharge volume was maximized.

Zooplankton Production

Production of zooplankton, an important food for young trout and adult trout during the winter, responded to dam operation in the same manner as phytoplankton and the annual production schedule was nearly the same shape. Zooplankton production was reduced with increased withdrawals. This is a direct result of reduced algal production and smaller reservoir volume (Figure 34).

Washout of zooplankton through dam penstocks was measured at both reservoirs but lab results were only complete at Hungry Horse. Results showed that downstream loss of zooplankton slightly increased as drawdown approached the fixed withdrawal elevation. Loss of zooplankton biomass, measured in the tailwater, was significant when the-reservoir was isothermal and when surface elevation approached the outflow depth (May et al. 1988).

Zooplankton washout from Libby Reservoir can be inferred from field sampling and model simulations. Zooplankton are most abundant in the top 25 meters of Libby Reservoir during the

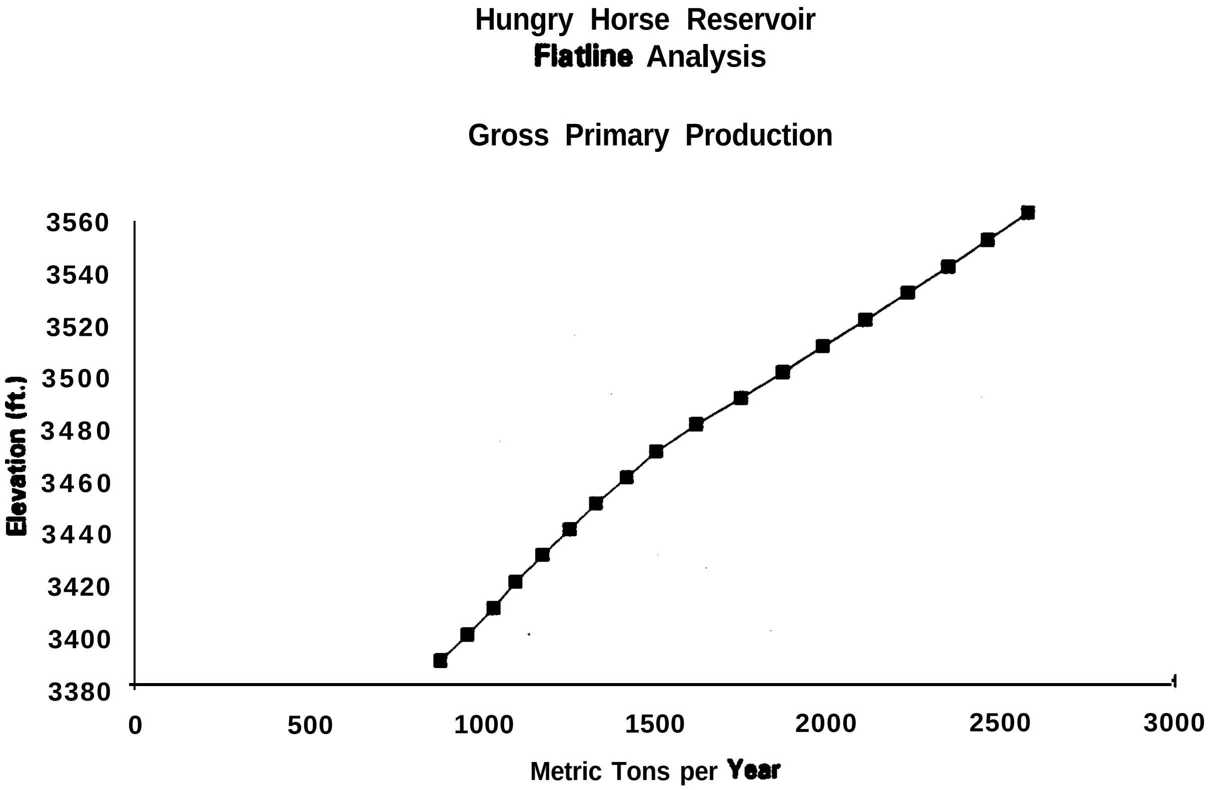


Figure 33. Generalized relationship between reservoir surface elevation and gross primary production in Hungry Horse Reservoir. Seasonal effects were removed to simplify the relationship.

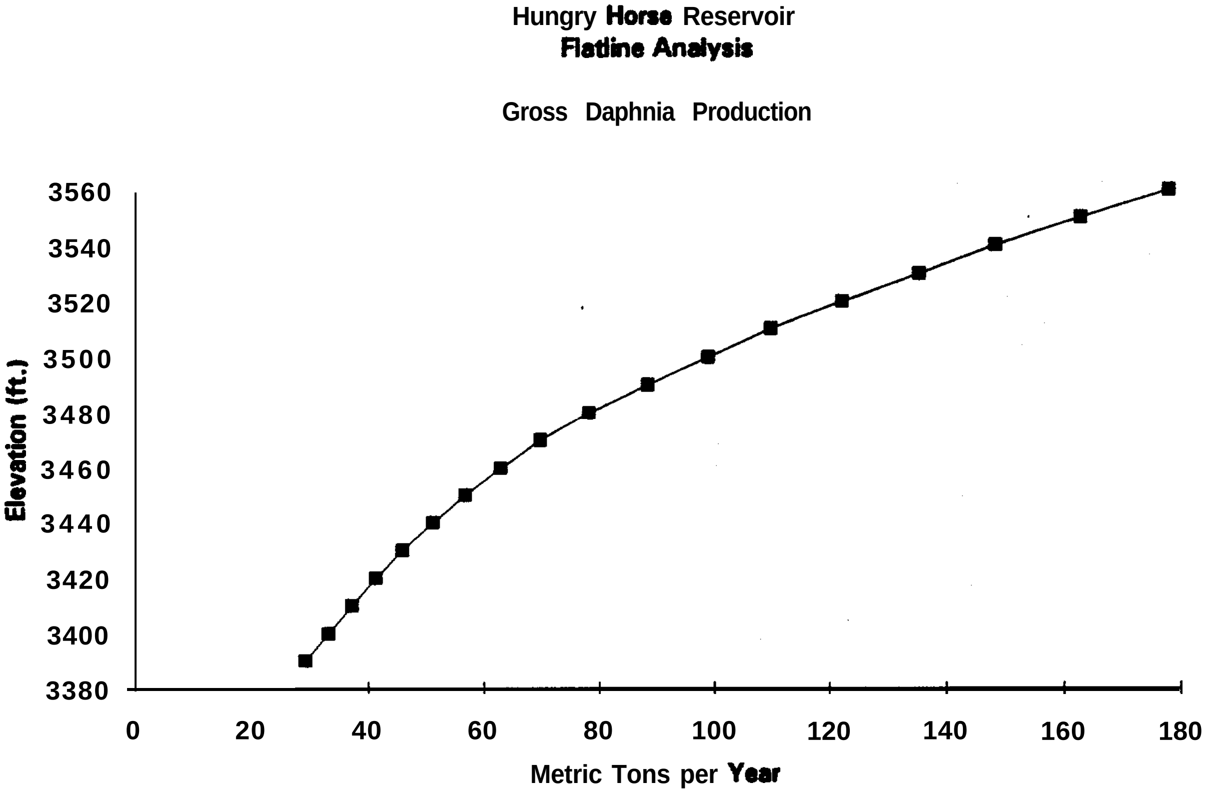


Figure 34. Generalized relationship between reservoir surface elevation and gross *Daphnia* production in Hungry Horse Reservoir. Seasonal effects were removed to simplify the relationship.

warm months. This depth corresponds with the water withdrawal depth when the selective withdrawal structure is in use. Thus, the most productive zone containing zooplankton is discharged through Libby Dam. Logically, this effect would be accelerated when the water exchange rate increases as the reservoir shrinks.

Benthic Insects

Insects that live in the bottom sediments for a portion of their life cycle are hardest hit by deep drawdown. Biomass of benthic insect larvae was least in the frequently dewatered layer of the reservoir and varied inversely with the frequency of dewatering. Conversely, captures of emergent insects, an important spring food supply for trout, indicated decreased emergence per unit biomass with increasing depth in both reservoirs, attesting to the importance of shallow areas for fish food production (Chisholm et al. 1989, May et al. 1988). These frequently dewatered shallow areas are severely affected by hydropower operations. As the reservoir surface declines below approximately 65 feet from full pool, benthic insect emergence declines rapidly. A reduced range of reservoir fluctuation can greatly enhance benthic production (Benson and Hudson 1975). Reservoir drawdown causes benthic insect mortality when dewatered substrate dries or freezes (Grimas 1961, Kaster and Jacobi 1978). Larval densities are also reduced in unprotected areas where wave action resorts the substrate (Cowell and Hudson 1968).

The general relationship between drawdown and benthic production is complicated by short-term temperature effects. During June through September, when the reservoir is thermally stratified, benthic production may be temporarily increased when surface elevation declines, bringing warm sunlit water in contact with substrate containing high densities of larvae. This is a short-term gain, however. When the reservoir refills, remaining larvae must recolonize the newly inundated substrate. Food availability is limited until the benthic community recovers. Complete recovery requires at least two years. Model simulations reveal a significant reduction in benthic insect production when drawdown exceeds the stated limits (Figure 35).

Terrestrial Insects

Surface insects make up the bulk of trout food items during summer and fall. Deposition of land insects onto the reservoir surface from the surrounding landscape is greatest in July, August and September. Average densities of nearshore (< 100 m) samples were greater than densities sampled offshore, but the difference was not statistically significant. Terrestrial deposition was proportional to the sire of the reservoir surface area. The activity period of the four major insect orders are significantly different and were modeled separately. When the reservoir remains at full pool during the months of insect activity, no loss of potential insect deposition occurs. Conversely, operation schedules that deviate from full pool result in lost potential; the loss increases with reduced surface area (Figure 36). Deep drawdowns prior to the first inflow forecast reduces operational flexibility and often results in poor refill probability. Refill failure impacts insect deposition and thus food availability for fish.

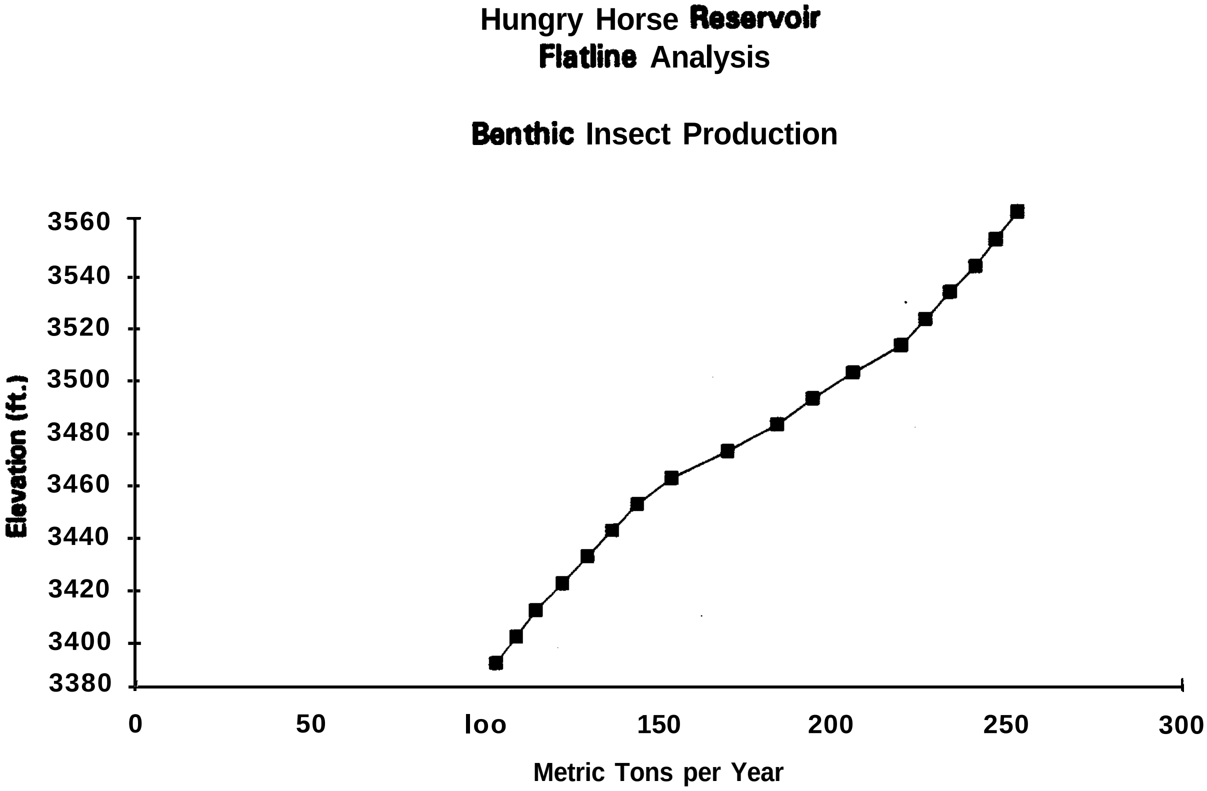


Figure **35.** Generalized relationship between reservoir surface **elevation** and benthic insect emergence in Hungry Horse Reservoir. Seasonal effects were removed to simplify the relationship.

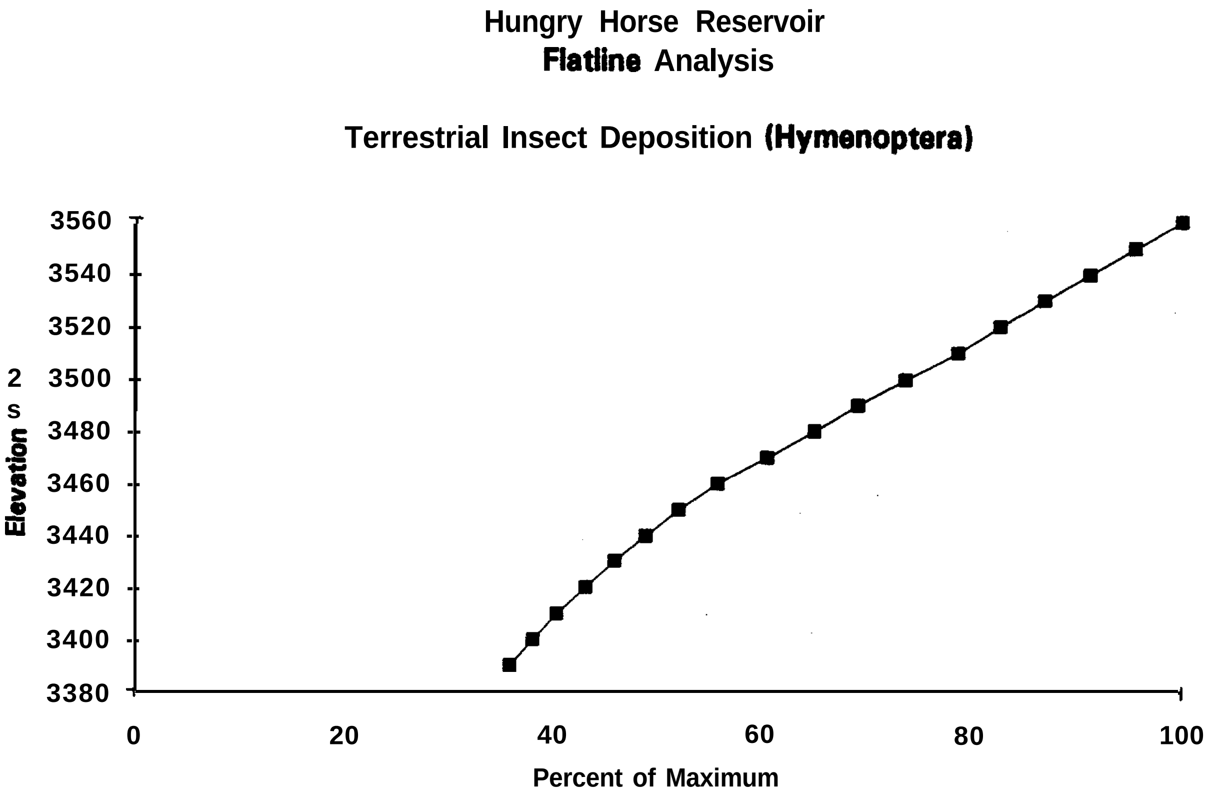


Figure 36. Generalized relationship between reservoir surface elevation and *Hymenopteran* deposition on the surface of Hungry Horse Reservoir. *Hymenoptera* were the most common terrestrial insect order represented in first stomach content analysis. Seasonal effects were removed to simplify the relationship.

Effects on Fish Species

Bull Trout

Hungry Horse Reservoir contains a population of bull trout (*Salvelinus confluentus*) considered "stable" based on annual gill net surveys conducted since 1983. Although netting data show annual variation, the long-term trend appears relatively stable. It is important to note that gill net results are tenuous because of fish migrations and movements. Also variable reservoir volumes and water temperatures affect sampling efficiency. Enumeration of spawning beds (redds) and juvenile population surveys have been recognized as a more accurate means to determine population size and range. Redd surveys were conducted in the South Fork Drainage for the first time in 1993, and continued in 1994 and 1995. Historical data for comparison are unavailable.

The reasons for the apparent stability of the Hungry Horse bull trout population are consistent with findings throughout the Flathead Basin. Most spawning tributaries occur in the Rob Marshall Wilderness and remain relatively undisturbed by human activity. Another important factor leading to a stable population in Hungry Horse Reservoir is the nearly natural species assemblage. The presence of the dam has precluded the upstream movement of non-native species. Species introduction to the upper South Fork basin, including rainbow and Yellowstone cutthroat trout and arctic grayling, have been observed only in small numbers. Rainbow trout, however, have been captured in significant numbers in a small portion of the South Fork headwaters. Only one eastern brook trout, known to hybridize with bull trout, has been reported from the area. Therefore, the fisheries community is almost exclusively composed of native species that co-evolved with bull trout in the system.

On October 27, 1992 bull trout were petitioned for listing under the Endangered Species Act (ESA) by three conservation organizations. The U.S. Fish and Wildlife Service (FWS) ruled that the petition had merit and prepared a status review. On June 7, 1994, the FWS determined that listing was warranted but precluded. Basin-wide surveys by MFWP during 1992 revealed that fewer than 2,000 spawning adults remain in the Flathead Lake population. MFWP responded with an emergency fishery closure for the species, with the exception of the two isolated populations in Hungry Horse Reservoir and nearby Swan Lake. The fishing ban became effective December 12, 1992. In 1993, Hungry Horse Reservoir was drawn down a record breaking 188 feet. Extreme drawdown to 174 feet below full pool occurred again in water year 1994. MFWP biologists became concerned that the stable bull trout population in Hungry Horse Reservoir may be damaged by the two consecutive, extreme drawdowns. The Fish, Wildlife and Parks Commission enacted an emergency fishing closure on the Hungry Horse Reservoir population in 1995.

Bull trout have also stabilized at low numbers in Libby Reservoir. Spawning and recruitment have been sustained by a few U.S. tributaries and the headwaters in Canada. Nearly all spawning in the U.S. occurs in the Graves Creek Drainage. The migration corridor to Graves Creek in the Tobacco River Drainage, near Eureka, Montana, has been affected by land disturbances (unpublished MFWP file data).

Eastern brook trout (*Salvelinus fontinalis*) have been commonly observed in Libby Reservoir tributaries. Pastern brook trout can hybridize with bull trout, posing a threat to bull trout genetic integrity. Most hybrids are unable to reproduce. In time, bull trout may disappear where brook trout become established. The threat of brook trout expansion has been the focus of management activities in the Kootenai basin since the 1970s. Fall spawning brook trout emerge from spawning gravels earlier than cutthroat and rainbow fry, and attain a competitive edge at an early age. The species has been known to displace native species where it becomes established.

Bull trout juveniles at both reservoirs supplement their diet with xooplankton and insects but soon depend almost exclusively on fish as they mature. Adults are opportunistic predators, eating small fish of any species. Stomach contents from Hungry Horse bull trout show that northern squawfish (*Ptychocheilus oregonensis*), longnose and largescale suckers (*Catostomus catostomus* and *Catostomus macrocheilus*) and mountain whitefish (*Prosopium williamsoni*) are important food items. Cutthroat and other gamefish, and aquatic dipteran pupae have been identified in their diet. At Libby, bull trout stomachs contained kokanee, Columbia River chub, largescale sucker and rainbow/cutthroat hybrids. Thus operations that harm prey species, ultimately impact the predators.

Westslope Cutthroat Trout

Trout growth is dependent on water temperature and food availability. Stomach content analyses obtained from westslope cutthroat trout revealed that terrestrial insects comprised most of the food eaten, on an annual basis, followed by benthic insects and zooplankton. Hymenoptera (flying ants, bees) were the most important terrestrial insect consumed and aquatic dipterans comprised nearly all of the aquatic insects ingested. At Hungry Horse, cutthroat selected *Daphnia pulex* almost exclusively when feeding on xooplankton, apparently due to its larger size. Cutthroat fed on *Daphnia* over 1.8 mm in length. The diet of cutthroat trout varied seasonally in response to food availability. In May, aquatic insects were the most important food item eaten, followed by terrestrial insects. From June through October, terrestrial insects dominated the diet. During this period, aquatic diptera were also an important component of the diet. When terrestrial insects were no longer available in November and December, the cutthroat switched to feeding primarily on *Daphnia pulex*.

Westslope cutthroat have been reduced to less than ten percent of their historic range. The decline has been attributed to hybridization with rainbow trout (*Oncorhynchus mykiss*), angling pressure and habitat losses. Spawning and rearing habitat has been lost (reservoir inundation or passage barriers or degradation by sediment input or dewatering). Deep drawdowns reduce biological production, food availability and the size that the aquatic environment, concentrating juveniles of the species with predators. Population fluctuations and growth regulation may compensate for some drawdown effects on the cutthroat food web. Although growth rates have been linked to adverse environmental conditions, individuals captured in annual surveys are in relatively good condition for their size. This implies that increased natural reproduction and modified reservoir operation to maintain biological production are the best tools to recover the populations.

Genetic sampling has shown that rainbow trout have greatly expanded in the **Kootenai** Drainage. **Pure** strain cutthroat and native inland **redband** trout are at risk of genetic introgression. Nearly **all** existing native populations inhabit only the headwaters of inflowing tributary streams.

The South Fork upstream of Hungry Horse Dam contains one of the largest self-sustaining populations of we&slope cutthroat in existence. The reservoir and tributary complex is an important genetic reserve for we&slope cutthroat trout. Two lakes in the Bob Marshall Wilderness (Woodward and Lena lakes) contain rainbow trout which are known to hybridize with cutthroat. Rainbows from these lakes have emigrated into the Upper South Fork Drainage, posing a threat to genetic integrity.

Kokanee in Libby Reservoir

In the Libby Reservoir model, the target species was kokanee **salmon. Kokanee** eat primarily **zooplankton** (98 percent). Based on gill net **captures** and scale and otolith analyses, growth rates of all fish species were highest in July and gradually **decreased** by late November (Chisholm et al. 1989; Brothers 1988). Biomass increase was **greatest from** July through September and weight continued to increase through November. Growth during late summer and fall is very important for juvenile salmon during their first year in the reservoir. Reservoir elevations at, or near, full pool from July through November encourages fish growth by increasing **food** production and enlarging the volume of water offering optimal temperatures for efficient biomass conversion. It is, therefore, important that the reservoirs remain at **full** pool at least through September 15 and decline only gradually through November.

A Comparison of Trophic Responses Under Actual Operations Reiative to Modifii Operations Adhering to Drawdown Limits

Drawdown and discharge limits were placed on Hungry Horse and Libby dams by measures 903(a) and **(b)** of the Columbia Basin Fish and Wildlife Program. **Drawdown** limits at Hungry Horse (85 feet) and Libby (90-110 feet), have been exceeded frequently during the last decade. Pertinent language in 903(b)(l)(D) states: "In years when the **drawdown** limit is exceeded for power purposes, Bonneville **[Power** Administration] shall fund the mitigation of fish losses to the extent those losses are caused by power operations."

Maximum **drawdown** at Hungry Horse and Libby dams is controlled by natural inflow volume, flood control criteria and water releases **for power** production. Extremely high inflow forecasts may necessitate exceeding the **drawdown** limits for flood control. Evacuation for flood control has not exceeded drawdowns required for power during the last decade. During 1990, however, local flood control required drafting Libby Reservoir to 117.6 feet below full pool. Since 1987, when the Program was published, the limits were exceeded at Libby Dam in 1988 (-144.3 feet), 1989 (-140.7 feet), 1990 (-133.5 feet) and 1991 (-153.7 feet). Hungry Horse limits were exceeded in 1988 (-178.1 feet), 1989 (137.7 feet) and 1991 (-99.3 feet). Maximum **drawdown** for power production during 1993 and 1994 have been extreme at both reservoirs. Hungry

Horse was drafted a recordbreaking 188 feet in 1993 and 174 feet in 1994. At Libby, **drawdown** exceeded 136 feet in 1993 and 94 **feet** in 1994.

To quantify the effect of exceeding the stated **drawdown** limits, we performed duplicate model simulations comparing historic annual operations with identical simulations differing only in the depth of maximum drawdown. In most cases, we simply **reconstructed** a balanced water budget and truncated the **drawdown** schedule to disallow drafting beneath the limit (85 feet at Hungry Horse and 110 feet at Libby) **(Marotz** and **DosSantos** 1993). Historic daily inflow data were used in both simulations of the paired analyses.

An exception was made to address operational year 1989 at Hungry Horse. In this case, the September 30, 1988 elevation resulting from the proposed operation (limiting **drawdown** to -85 feet during 1988) was used as the **beginning** elevation in the water year 1989 simulation. This was done because actual 1989 operations began at elevations below the 85 foot limit, making a paired simulation impossible. Given this proposed starting elevation, actual discharges were assumed until the **drawdown** limit was reached.

In all proposed simulations, we instructed the model to attempt to refill by July 1, yet maintain minimum flows in the river downstream (3,500 cfs at Columbia Falls and 4,000 cfs Libby discharge). Flood control limits were not exceeded at the immediate downstream critical flood control center. Spill was disallowed in all simulations.

Given the above hydrologic input, the biological responses were compared for all years **since** 1987 during which the **drawdown** limits were exceeded. Years selected at Hungry Horse included 1988, 1989, 1990 and 1993 (Table 6). Duplicate runs were performed on each year. The proposed elevation schedules arc denoted “prop. -85’” for each comparison with historic data. At Libby, we assessed 1988 through 1991 and 1993. The proposed schedules were denoted “prop. -110” (Table 7).

Hungry Horse Reservoir

Effects of deep **drawdown** and refill failure were especially damaging to the Hungry Horse Reservoir fishery during 1988, 1989 and 1993. Production (metric tons) of the most important genera of **zooplankton,** ***Daphnia, was*** reduced by 37 percent when **drawdown** exceeded 85 feet in 1988 and 1993. Stomach analyses have demonstrated that reservoir fish depend on **zooplankton** during the winter and early spring (May et al. 1988). Reduced winter food availability and pool volume may result in weight loss and **decreased survival** by spring. Although the latter **could not** be verified with the existing sampling program, based on best available data, populations of game fish in Hungry Horse Reservoir today arc no larger than were populations existing in the river prior to inundation by the dam. It is likely **that** the repeated deep drawdowns in recent years have reduced reservoir populations.

Compounding the winter reduction in food availability, the spring food supply is also reduced by drawdowns in excess of 85 feet. Benthic insects, the dominant spring food item, were

Table 6. Biological ***responses to historic operations*** of **Hungry** Horse Dam as compared to a paired simulation adhering to the **85** foot **drawdown** limit.

Water Year	Minimum Elevation	Refill Point	Net P. Prod.[b]	Gross Daphnia[c]	Hymenop. % Max.[d]	Benthic Prod.[e]	Wct III+ Wct. (g)[f]	Wct IV+ Wt. (g)	Wct V+ Wt. (g)
Prop. -85'	3475.5	3523.0	1924	110.7	81.5	131.6	190	303	352
1988	3381.9	3489.5	1580	80.8	63.6	59.5	125	184	209
	93.6								
Losses	63.9%[a]	33.5	344	30.0	17.9	72.1	65	119	143
as %			17.9%	27.1%	21.9%	54.8%	34.2%	39.3%	40.6%
					93.2				
Prop. -85'	3474.8	3545.4	2033	126.5	84.3	144.9	218	356	416
1989	3422.3	3545.3	1897	111.5		96.3	181	286	332
Losses	52.5	0.1	136	15.0	8.9	48.6	37	70	84
as %	40.0%		6.7%	11.8%	9.5%	33.5%	17.0%	19.7%	20.2%
Prop. -85'	3475.0	3560.0	2201	149.6	100.0	157.9	250	418	492
1991	3460.7	3560.9	2196	148.1	98.4	141.6	239	397	466
Losses	14.3	-0.9	5	1.4	1.6	16.3	11	21	26
as %	12.1%		0.2%	>0.1%	1.6%	10.3%	4.4%	5.0%	5.3%
				93.7	79.5				366
Prq1993-85'	3372.0	3513.7	1620	87.0	79.5	154.5	134	200	227
Losses	130.0	0.0	119.0	6.6	0.0	119.6	62	114	139
as %	59.9%		6.8%	7.0%	0.0%	68.7%	31.6%	36.3%	38.0

[a] Percent volume loss in reservoir storage.
[b] Metric tons of carbon fixed, light and dark bottle, C^{14} liquid scintillation technique.
[c] Daphnia biomass in metric tons.
[d] Percent of total possible deposition of Hymenopteras on the reservoir surface.
[e] Biomass of benthic diptera emergence per unit larval density, metric tom.
[f] Biomass accumulation by migrant class III westslope cutthroat trout, during their first year of reservoir life (Age III+), second (IV+) and third year (V+).

Table 7. Biological responses to historic operations at Libby Dam as compared to a paired simulation adhering to the **110** foot **drawdown** limit.

Water Year	Minimum Elevation	Refill Point	Net P. Prod.[a]	Gross Zoop.	Hymenop. % Max.[b]	Benthic Prod.[c]	Kok I+ Wt. (g)[d]	Kok II+ Wt. (g)
Prop. -110' 1988	2348.6 2314.7	2439.6 2435.4	11107 10740	1274.0 1232.0	90.3 88.6	307.2 223.0	213 208	551 531
Losses as %	19.3%	4.2	367 3.3%	3.3%	1.7 1.4%	27.4%	5 2.3%	20 3.6%
Prop. -110' 1989	2348.8 2318.3	2459.0 2450.7	11202 10895	1288.0 1250.0	99.4 94.0	259.3 201.1	212 212	547 547
Losses as %	30.5 17.7%	6.7	307 2.7%	38.0 3.0%	5.4 5.7%	58.2 28.9%	0 0.0%	0 0.0%
Prop. -110' 1990	2348.9 2325.5	2460.0 2459.5	11806 11742	1355.0 1347.0	100 99.7	360.1 237.6	229 227	615 606
Losses as %	23.4 14.0%	0.5	64 0.5%	8.0 0.6%	0.3 0.3%	122.5 34.0%	2 0.9%	9 1.5%
Prop1991110'	2305.3	2458.9	11432	1312.0	199.3	218.5	233 222	630 588
Losses as %	43.7 24.2%	0.1	481 4.0%	55.0 4.0%	0.7 0.7%	153.5 41.3%	11 4.7%	42 6.7%
Prop. -110' 1993	2348.9 2323.0	2448.2 2448.2	10870 10662	1247 1224	93.8 93.9	348.1 275.8	212 208	547 534
Losses as %	25.9	0.0	208 1.9%	23 1.8%	0.0 0.0%	72.3 20.8%	4 1.9%	13 2.4%

[a] Metric tons of carbon fixed, light and dark bottle, C^{14} liquid scintillation technique.
[b] Percent of total possible deposition of Hymenopteras on the reservoir surface.
[c] Biomass of benthic diptera emergence per unit larval density, metric tons.
[d] Biomass accumulation during the first year of reservoir growth (age I+) and second (II+).

reduced an estimated 55 percent in 1988 and 34 percent in 1989. As water temperatures begin to rise in late spring and early summer, fish must consume larger quantities of food just to maintain their weight. Thus spring growth is retarded by poor food availability. Life histories of benthic insect species in both reservoirs range from five weeks to three years and deep drawdowns can harm the spring food supply for at least two years. This effect is compounded when the benthic larvae are dewatered twice in two years killing larvae in huge quantities. Losses during 1993 were 68.7 percent, compounding and continuing the effects from previous years.

The summer and fall food of insectivorous species (e.g. westslope cutthroat trout) is dominated by terrestrial insects deposited on the waters surface. Deep drawdowns resulted in decreased refill elevation during the peak activity of terrestrial insects. Although the model calculates the deposition of four orders of terrestrial insects, we selected hymenoptera as an index organism because flying ants and bees make up the greatest biomass in fish stomachs. Insect deposition is proportional to reservoir surface area during the period of insect activity. The peak growth period in reservoir fish corresponds with the timing of terrestrial insect depositionand maximum volume of optimal water temperature. This is reflected in the growth estimates of the target species, westslope cutthroat trout (wct).

Growth increments observed for each year class were compared to the expected growth (Figures 37 and 38). If growth exceeded the grand mean, an upward arrow was drawn from the expected value to the observed length. Conversely, a downward arrow depicts growth increments less than the expected value. Arranged by calendar year, growth can be compared to environmental effects. Reservoir operation effects food availability and environmental factors influencing trout growth.

During the record breaking drawdown of 1988, trout growth in the reservoir was less than expected for fish in their first and second year of reservoir growth. Fall samples also revealed reduced third year growth. Second year reservoir growth was also reduced in 1989. Future scale sampling will allow for a more complete evaluation.

Model simulations comparing the actual 1991 operation, to the proposed schedule adhering to the 85 foot limit, shows trophic responses similar to 1988 and 1989, but to a lesser degree. It is important to note that growth and survival of fish under the proposed drawdown scenario is also suboptimal. If a comparison of the actual and modified operation shows only a minor reduction in reservoir productivity, the results do not imply a favorable response.

The 1993 simulation showed that trout growth was reduced by 32 to 38 percent. It is likely, however, that increased mortality will result in greater than predicted growth in survivors.

The long-term effects of dam operation on reservoir volume and food availability has reduced fish growth potential in Hungry Horse Reservoir. Results of a length back-calculation analysis using scale growth increments suggested a strong size selective mortality. Smaller emigrants from the index spawning tributary, Hungry Horse Creek, were less common in gill net samples

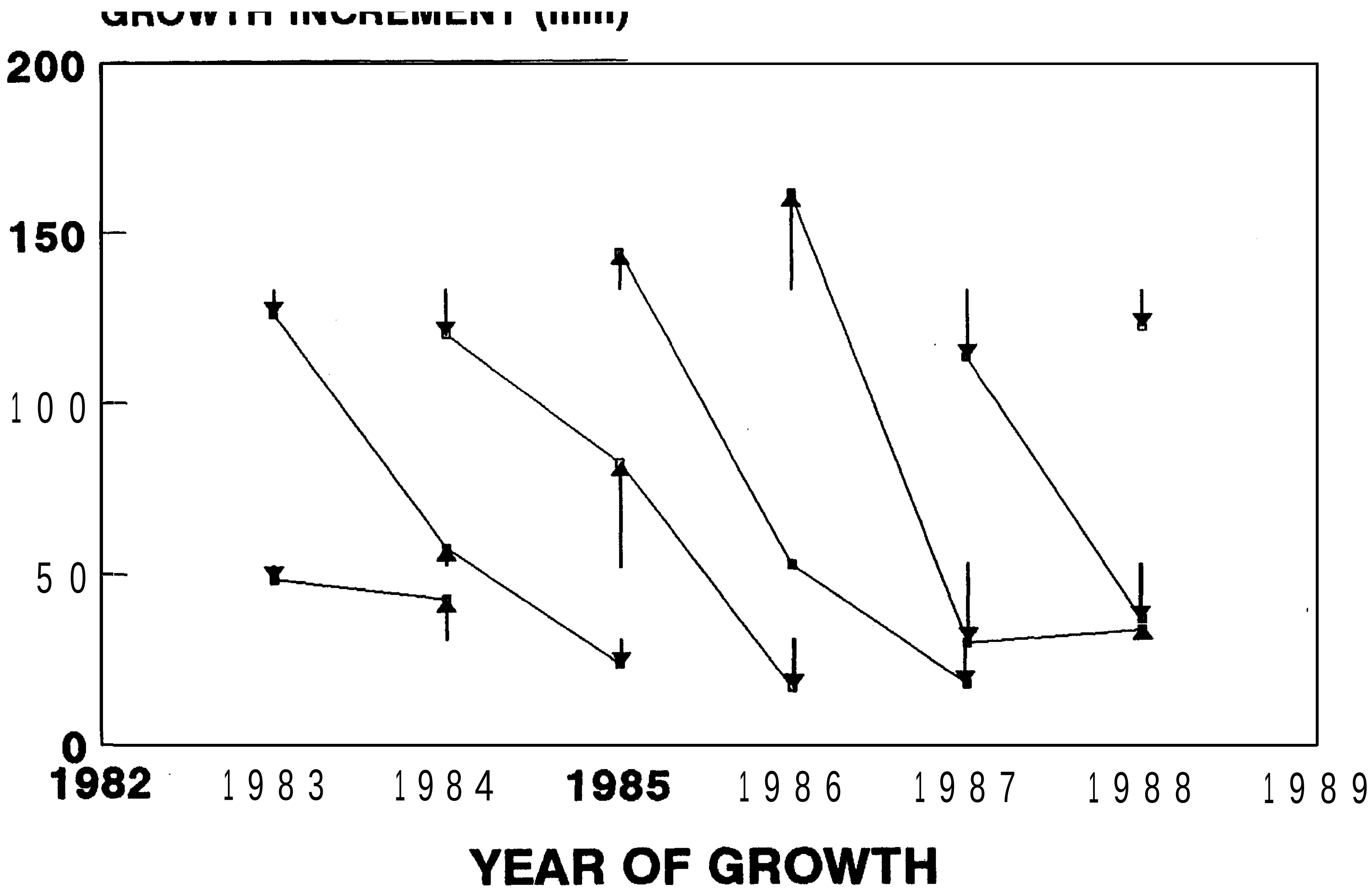


Figure 37. Annual growth increments of westslope cutthroat trout in Hungry Horse Reservoir. Lines connect first, second and third year reservoir growth for each year class (cohort) at ages III+, IV+ and V+, respectively. Arrows indicate the deviation between the expected growth, based on the grand mean of all fish, to the actual growth of each cohort. Upward arrows indicated good growth whereas downward arrows depict reduced growth. Only spring captured fish from migrant class III are represented.

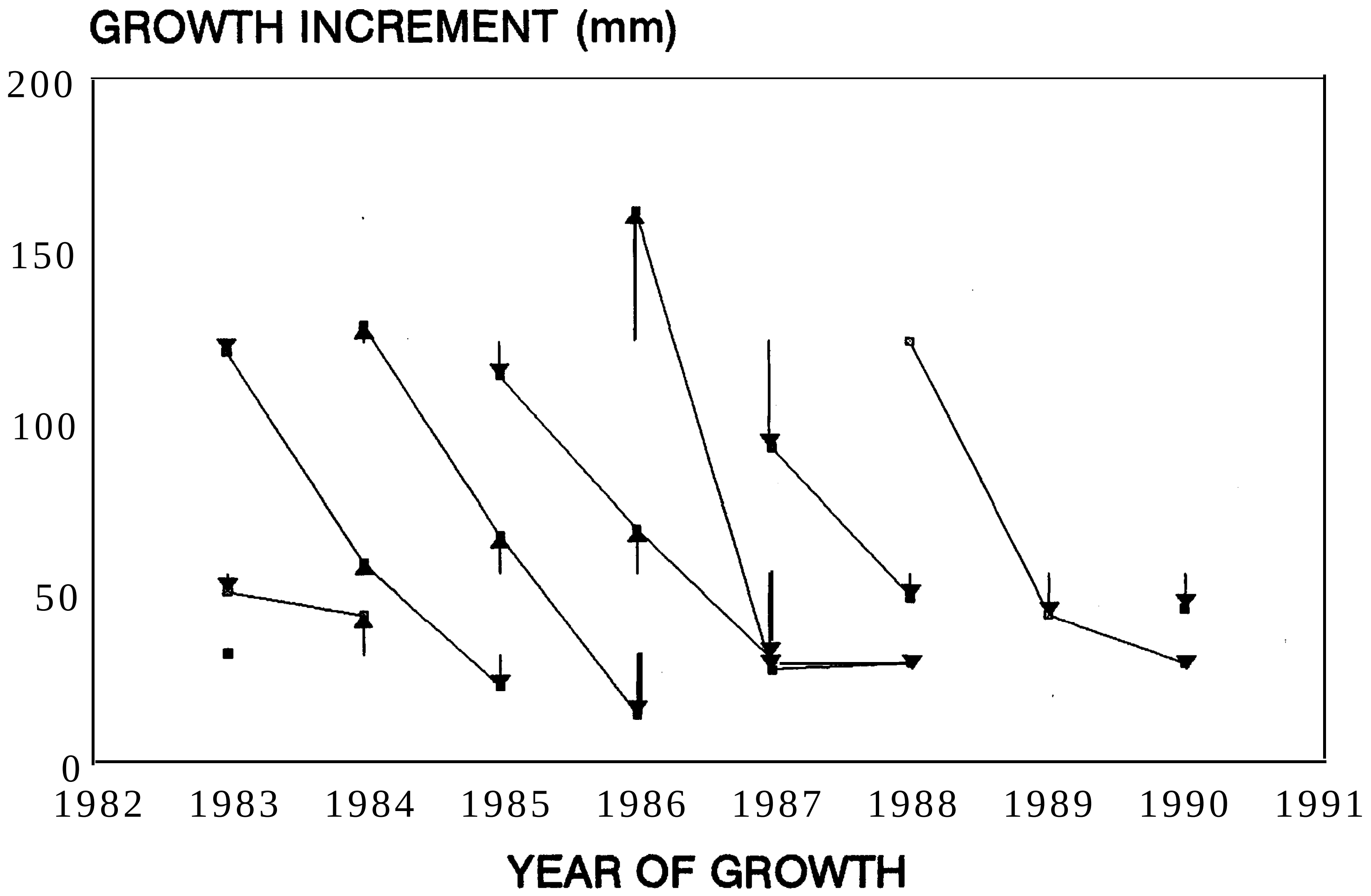


Figure 38. Annual growth increments of westslope cutthroat trout in Hungry Horse Reservoir. Lines connect first, second and third year reservoir growth for each year class (cohort) at ages III+, IV+ and V+, respectively. Arrows indicate the deviation between the expected growth, based on the grand mean of all fish, to the actual growth of each cohort. Upward arrows indicated good growth whereas downward arrows depict reduced growth. Spring and fall captures of migrant class III fish are represented. We assumed that fall captured fish had completed their annual growth increment by the time of capture.

taken one year after emigration than were larger fish that emigrated simultaneously (unpublished MFWP file data). Thus, reduced growth in tributaries apparently results in higher mortality in juveniles recruited to the reservoir. Poor first year reservoir growth can similarly result in decreased survival. Size-selective mortality is apparently caused by increased predation, especially when deep drawdown concentrates prey and predators in a smaller volume.

Recruitment of young fish into the reservoir population is also limited by blocked access to stream habitat by poorly installed road culverts. Approximately 16 percent of spawning and rearing habitat above full pool elevation was lost when roads swunding the reservoir were relocated to accommodate impoundment. Of the remaining spawning tributaries, access was blocked to two streams when passage barriers were exposed by deep drawdown in 1988 and 1993. One of these streams (Wounded Buck Creek) became accessible about half-way into the migration period when the reservoir inundated the barrier (at elevation 3,411 feet). The other (Lost Johnny Creek) remained inaccessible during the spring spawning period because of low reservoir elevations.

Reductions in growth and population size have diminished recreational opportunity. According to limited angler use statistics, Hungry Horse Reservoir only provides about 6,000 angler days annually. Angling pressure has remained relatively stable, even though the surrounding community has grown dramatically during the last decade. Angling pressure is correlated with angling opportunity. If fish populations increase to their maximum potential, it is expected that angling pressure would exceed present levels. Therefore, existing value estimates for the reservoir fishery of $60.00 per angling day (1990 dollars, Brooks 1993), grossly underestimate the potential for increased fisheries value if limiting factors were repaired.

Recreational impacts due to reservoir operation were quantified by the Bureau of Reclamation (Ben-Zvi et al. 1990). Ben-Zvi's evaluation includes estimates for number of recreational days lost due to low reservoir elevations. They estimated the value of a recreational day at Hungry Horse Reservoir ($27.24) in 1990 dollars (this includes all forms of recreation, including fishing). Ben-Zvi noted losses in recreation if reservoir elevations were below 3,550 during a 100-day recreation season (July - early September). Drawdowns below the 85' level increase the likelihood that the reservoir will fail to refill during the recreation season and will, therefore, result in losses in recreational benefits. The deep drawdowns and refill failures in 1988, 1989 and 1993 led to losses in recreation.

Additionally, the value of bull trout and westslope cutthroat inhabiting the reservoir has sharply increased as the species became less abundant. Genetically pure westslope cutthroat have been reduced to less than 10 percent of their historic range, making Hungry Horse populations an important genetic resource. Bull trout in the reservoir, which provide one of two relatively stable populations in Montana, are now threatened by the record breaking reservoir drawdowns in 1993 and 1994. The value of these Species of Special Concern to future generations can not be easily comprehended, nor quantified.

Libby Reservoir

At Libby Reservoir, kokanee salmon were selected as the target fish species because of their importance to the recreational fishery. Kokanee respond to reservoir volume and zooplankton production. Nmety-eight percent of the kokanee diet in Libby Reservoir consists of zooplankton. A few benthic insect pupae were also identified in kokanee stomach contents. By contrast, analysis of field samples shows that rainbow and westslope cutthroat trout respond to food availability (zooplankton, hymenoptera and benthos) similar to westslope in Hungry Horse. Model results indicate that the consequences of exceeding the drawdown limit at Libby is most important to insectivorous species (e.g. rainbow, cutthroat and mountain whitefish). Kokanee growth potential was also reduced during 1988, 1989, 1990, 1991 and 1993 when the 110 foot drawdown limit was exceeded.

Although the kokanee growth model was based on empirical field data from 1983 through 1986, model simulation of kokanee growth potential was not intended for verification through field measurement of kokanee growth. In reality, kokanee growth is strongly density dependent. Three year cycles of low to high population size have been identified in Libby Reservoir since kokanee first became established. Corresponding growth has similarly fluctuated, with highest annual growth associated with low population size and vice versa. For modeling purposes, we attempted to isolate operational effects from density effects by assuming a static population size. This technique allowed us to focus *on* operational effects for the purpose of comparing one operational strategy to another.

Regardless of the confounding effects of density dependent growth, field surveys have revealed reduced growth during the 1988 through 1991 period. The mode in the length distribution of age I+ kokanee, captured in annual vertical gill net series during August, show reduced size (unpublished MFWP file data). For comparison of environmental effects with first year reservoir growth, it is important to consider a one year time lag. For example, age I length in 1989 is attributable to growth conditions in 1988 and 1989. During 1987 and 1988 the majority of age I+ kokanee were grouped around 235 mm. By 1989 and 1990 the modal length had dropped to 195 mm. In 1991, the mode had increased to 255 mm, possibly due to reduced survival in previous years. The model length distribution of I+ kokanee from the 1992 field season had increased again to 275 mm.

Model estimates of kokanee growth potential and trophic dynamics show similar results (Table 7). A comparison of actual dam operation to the proposed drawdown schedule shows reduced kokanee growth potential in 1988, 1990, 1991 and 1993. Predicted growth of age I+ and II+ kokanee was reduced to between 0.9 and 6.7 percent over the period due to drawdowns exceeding 110 feet. The model did not detect a growth impact due to exceeding the 110 foot limit during 1989. This negative result is not insignificant. The program language actually reads W-110 feet" at Libby. Results of simulations which adhere to the 90 foot drawdown limit (where possible, within flood control requirements) show a favorable response in kokanee growth.

Commensurate with the effect on kokanee growth, trophic responses indicate a gross reduction in food availability for trout, whitefish and prey species. Benthic insect production was reduced between 27 and 41 percent during all years 1988-1991 due to exceeding the 110 foot limit. Losses in 1993 were 20.8 percent. The benthic insect community can not fully recover for at least two years following deep drawdown, impacting the spring food supply for insectivorous species. In addition, reductions in zooplankton production and terrestrial insect deposition severely limited food availability during the period. Reduced pool volume also influenced the growth potential of game and prey species. Thus, food web dynamics should also be unfavorable for the long-term maintenance of piscivorous species including bull trout and kamloop rainbow.

Effects on predators and insectivorous species may be most apparent in long-term population trends. Annual gill net surveys have shown that rainbow x cutthroat hybrids, whitefish, ***Prosopium williamsoni***, and bull trout have remained at low population levels since stabilizing after impoundment (Chisholm et al. 1989). Other species dependent on zooplankton, detritus (eg. ***peamouth, Mylocheilus caurinus***, and suckers, ***Catostomus catostomus and C. macrocheilus***) and fish prey (northern squawfish, ***Ptychocheilus oregonesis***) have substantially increased in numbers. Relative capture rates of reservoir species indicate that Columbia River chubs are the most numerous fish species in the reservoir. The expanded squawfish population has increased predation on juvenile fish of all species. Squawfish and bull trout inhabit the same reservoir depth only seasonally due to their differing temperature tolerances. This overlap brings the two species into direct competition for prey. Overlap of juvenile trout and adult squawfish apparently increases the likelihood of predation mortality. Thus, effects of insects and prey species are felt throughout the reservoir food web.

Shortly after inundation, Libby Reservoir provided a strong fishery for trout and whitefish. By 1983, however, the trout population had stabilized at low numbers. Shifts in the relative abundance of fish species became firmly established. Rebuilding the trout population has been difficult, due in part to operational impacts on reservoir volume and trophic dynamics. These long-term effects have not allowed the reservoir to reach its optimum fisheries potential.

Development of Integrated Rule Curves for the Operation of Hungry Horse and Libby Reservoirs, Montana and a System-wide Operation Strategy

The IRCs are a family of curves that represent trajectories for reservoir drawdown and refill based on the inflow forecast and critical year selection. The project-specific curves are selected based on the local inflow forecast to each reservoir. The critical year, however, is selected based on water levels in all the storage projects on the Columbia River during an extended drought.

Integrated Rule Curves for dam operation were designed to enhance biological production in Hungry Horse and Libby reservoirs and associated river basins within the context of the

Columbia River Basin. Operational strategies described by the curves were developed pursuant to measures 903(b)(1-3) of the Northwest Power Planning Council's (Council) Fish and Wildlife Program (NPPC 1987). The objectives were to maintain and enhance the fisheries resources and provide recommendations in the event a conflict occurs between river and reservoir operational requirements, measure 903(a)(6).

Preliminary Biological Rule Curves (BRCs) were calculated in 1989 using the quantitative biological models (HRMOD and LRMOD). Initial estimates of BRCs focused primarily on the reservoir biota (Fraley et al. 1989). In 1991 updated BRCs were developed to achieve balance between upstream and downstream concerns in both river basins. The BRCs successfully balanced the hydrology downstream to Kerr Dam at the outlet from Flathead Lake and Corra Linn Dam on the Kootenay River, B.C. System models (SAM and HYDROSIM) developed by BPA were required to examine corresponding effects in the lower Columbia River. This enabled researchers to find compromise between resident and anadromous fish requirements. The BRC concept included an alternative method of achieving system flood control. These modifications were evaluated using a model developed by the Army Corps of Engineers (HYSSR). During 1994, the BRCs were integrated with power production and system flood control. The resulting Integrated Rule Curves (IRCs) were developed to further reduce the economic impacts of Columbia Basin fisheries recovery actions.

The reservoir models facilitate the assessment of power and flood control operations under varying water conditions, drought to flood. Flood control was programmed as hard constraints in the models. If flood conditions developed at the nearest downstream critical flood control center (Columbia Falls on the Flathead or Bonners Ferry/Kootenay Lake on the Kootenai), the model automatically limited dam operation to control the flood. This facilitated the assessment of white sturgeon spawning requirements and regional flood control. Our intent was to work interactively with Columbia system hydroregulation models to strike a balance basin-wide. Although our analyses were based on daily operations, subroutines enable the models to input and output monthly data (with April and August split into two half-month intervals) required by the system models. Thus, the Hungry Horse and Libby models can readily interface with the system models.

The IRCs, developed in 1994 and amended in 1995, incorporate two incremental adjustments to allow for uncertainties in water availability (Figures 39 and 40, and Tables 8 and 9). These create flexibility during first year operations and progressively deeper reservoir drafting during the four-year critical period. The actual operation, then, is flexible and variable over time.

During a critical period (IRC2 through 4) the integrated curves allow progressively deeper drawdown each year. These curves were developed using the lowest historic inflow to each project for four consecutive years. The critical IRCs protect the fisheries resource from excessive drawdown. Modeling and field research indicate that reservoir productivity can, with time, rebound after infrequent deep drawdowns. However, even infrequent deep drafts have long lasting biological effects. These effects are especially evident in benthic insects, an important spring food supply for trout.

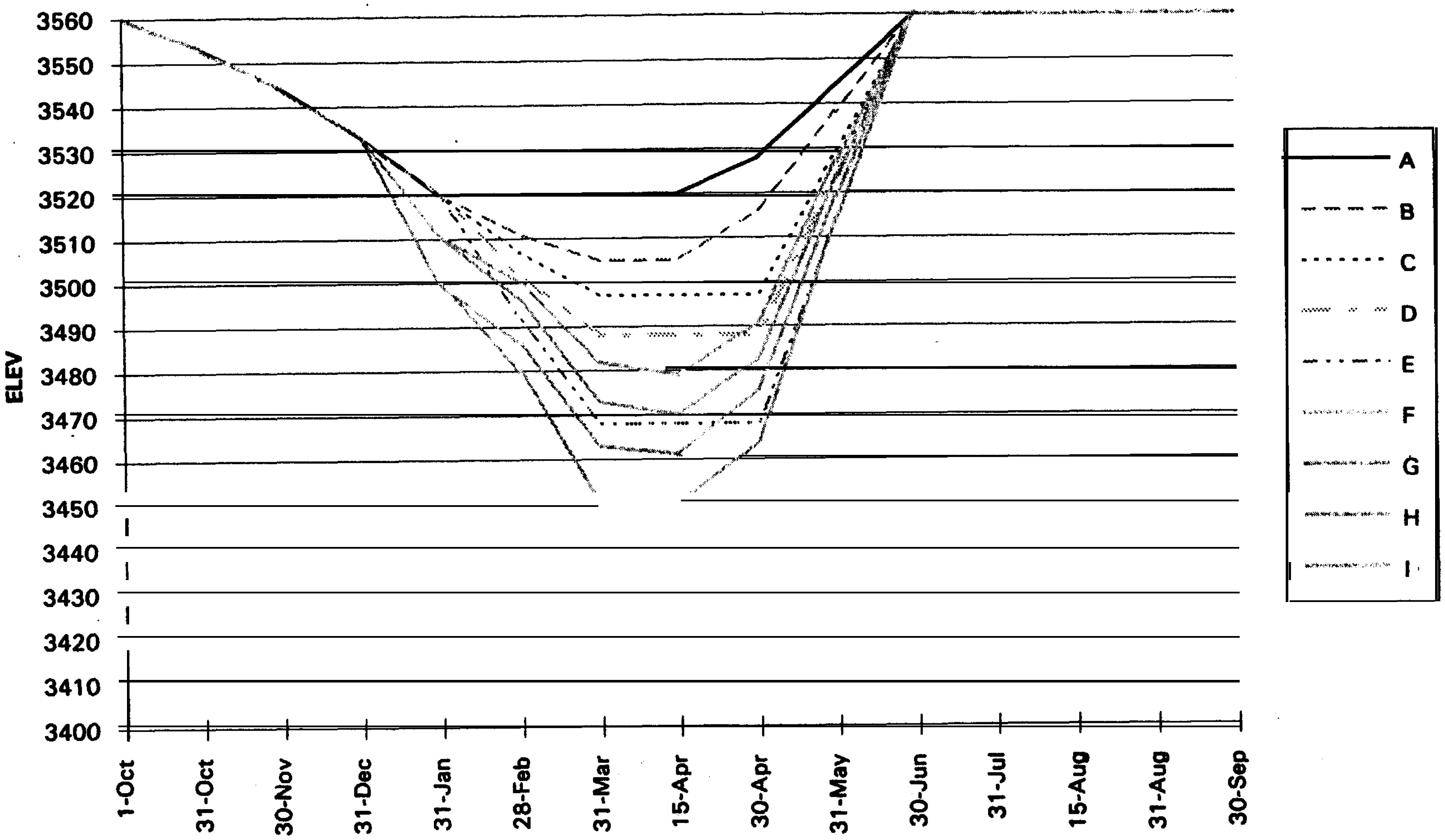


Figure 39. Integrated Rule Curves for operating Hungry Horse Reservoir. The family of curves represents two sliding scales corresponding with water availability. Curves A-E define operations during the first year of a critical period and allow for consecutively deeper drafts with increasing runoff forecasts. Curves C-I allow for consecutively deeper drafts during the second, third and fourth years of an extended drought.

Table 8. Numerical description of the Integrated **Rule Curves** for Hungry Horse Reservoir. Curves are selected dependent on the project inflow and critical year selection (Crit l-4 at bottom).

CURVE	C1	C2	C3	C4
A	00			
B	20	00		
C	40	20	00	
D	60	40	20	00
E	60	60	40	20
F		80	60	40
G			80	60
H				80
I				

RITICA L YEAR

W = DRIEST QUINTILE

0 = WETEST QUINTILE

STEP	A	B	C	D	E	F	G	H	I
1-Oct	3560	3560	3560	3560	3560	3560	3560	3560	3560
31-Oct	3553	3553	3553	3553	3553	3553	3553	3653	3553
30-Nov	3544	3544	3544	3544	3544	3544	3544	3544	3544
31-Dec	3533	3533	3533	3533	3533	3533	3533	3633	3533
31-Jan	3520	3520	3520	3520	3520	3511	3511	3500	3500
28-Feb	3520	3511	3507	3502	3492	3500	3496	3486	3480
31-Mar	3520	3505	3497	3488	3468	3482	3473	3463	3450
15-Apr	3520	3505	3497	3488	3468	3479	3470	3461	3450
30-Apr	3528	3516	3497	3488	3468	3491	3483	3476	3464
31-May	3544	3538	3529	3524	3514	3527	3523	3519	3514
303un	3560	3560	3560	3560	3560	3560	3560	3560	3560
31-Jul	3660	3560	3560	3560	3560	3560	3560	3560	3560
15-Aug	3560	3560	3560	3560	3560	3560	3560	3560	3560
31-Aug	3560	3560	3560	3560	3560	3560	3560	3560	3560
30-Sep	3560	3560	3560	3560	3560	3560	3560	3560	3560

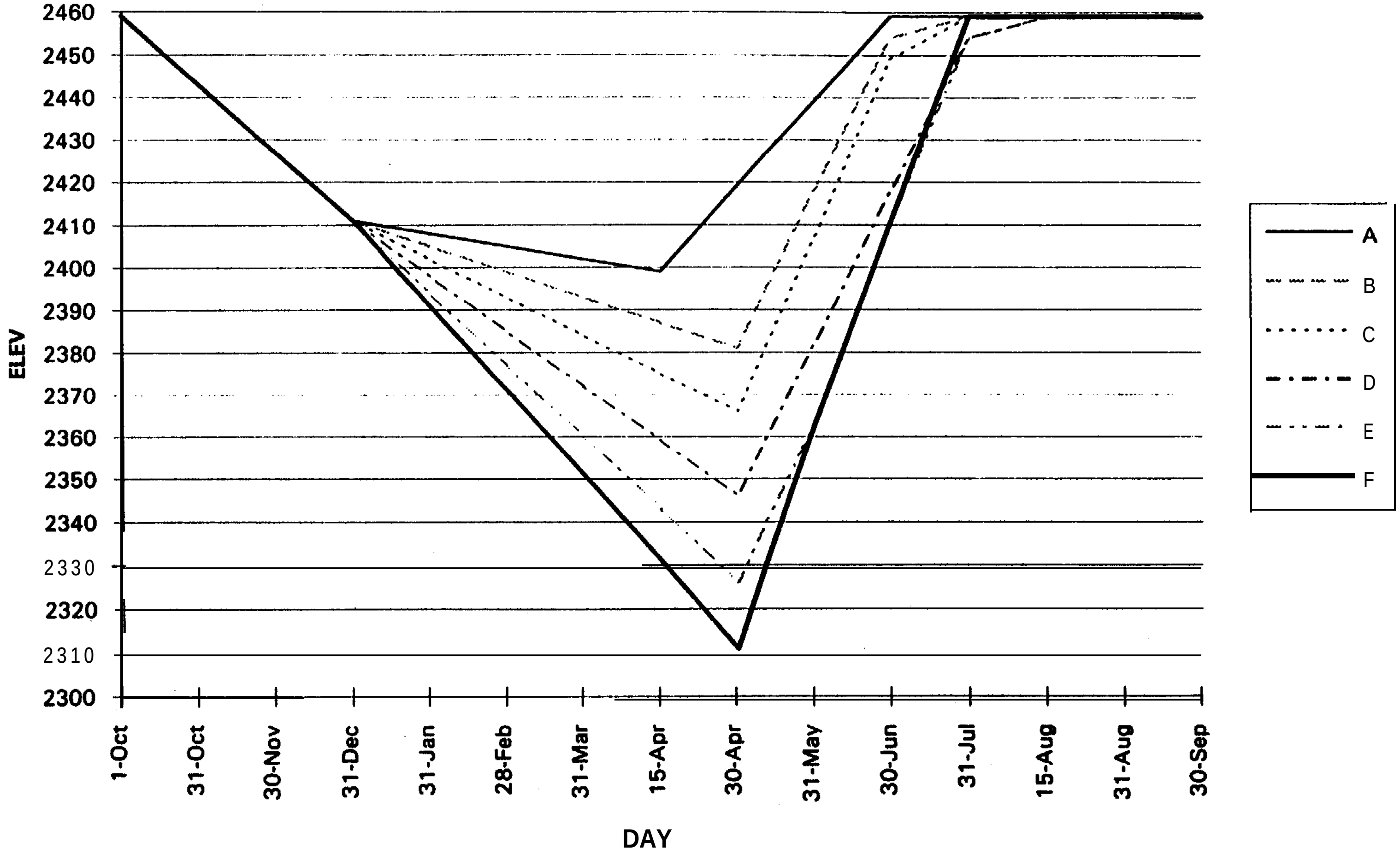


Figure 40. Integrated Rule Curves for operating Libby Reservoir. The family of curves represents two sliding scales corresponding with water availability. Curves A-B define operations during the first year of a critical period and allow for consecutively deeper drafts with increasing runoff forecasts. Curves **B-F** allow for consecutively deeper **drafts** during the second, third and fourth years of an extended drought.

Table 9. Numerical description of the **Integrated** Rule Curves for Libby Reservoir. Curves are selected **dependent** on the project **inflow** and critical year selection (Crit l-4 at bottom).

CURVE	C1	C2	C3	C4
A	00			
9	20	00		
c	40	20	00.20	
D	60	40	40	00,20,40
E	80	60	60	60
		80	80	80

CRITICAL YEAR

DO = DRIEST QUINTILE

8 0 = *WETEST QUINTILE*

STEP	A	B	c	D	E	F
1-Oct	2459	2459	2469	2459	2469	2459
31-Oct	2443	2443	2443	2443	2443	2443
30-Nov	2427	2427	2427	2427	2427	2427
31-Dec	2411	2411	2411	2411	2411	2411
31-Jan	2408	2405	2402	2398	2394	2391
28-Feb	2405	2399	2393	2385	2377	2371
31-Mar	2402	2393	2384	2372	2360	2351
15-Apr	2399	2387	2375	2359	2343	2331
30-Apr	2419	2381	2366	2346	2326	2311
31-May	2439	2418	2407	2382	2363	2363
30-Jun	2459	2454	2449	2418	2411	2411
31-Jul	2459	2459	2459	2454	2454	2459
15-Aug	2459	2459	2459	2459	2459	2459
31-Aug	2459	2459	2459	2459	2459	2469
30-Sep	2459	2459	2459	2459	2459	2469

Power analyses conducted by Bonneville Power Administration and the Council, using the System Analysis Model, showed that most impacts to firm power generation occur in the fourth year of the critical period (IRC4). The probability of extreme drawdowns necessitating the adoption of the fourth critical year is low. Also drafts exceeding the IRCs would seldom be required even under current operating practices. Thus, the calculated impact to firm power would only occur under extreme conditions. During normal and high water years, the IRCs will cause only minor impacts on firm power production. Wise marketing practices can mitigate impacts to revenue.

The Integrated Rule Curves are an improvement of SOS #4 included in the Columbia Basin System Operation Review Environmental Impact Statement. Unfortunately, the original intent of the operational strategy was lost in the system modeling process. A committee of technical modelers representing the primary agencies (ACOE, BOR, BPA, NPPC and MFWP) was convened on December 14, 1993 and has met several times during 1994 to model the system-wide intent of SOS #4. Power and system flood control were integrated in June 1994. During 1995, analyses continued to address system flood control and recovery actions for the endangered Snake River salmon. The following description provides the rationale for the resulting IRC design.

Local and System Flood Control

The original BRCs for Libby and Hungry Horse were designed using only local flood control. This was done intentionally so that we could differentiate between "local" and "system" flood control requirements. In most previous system-wide simulations, the BRCs were superseded by upper rule curves (URCs) during each month in which additional reservoir evacuation was required for system flood control. The difference between our BRCs and the URCs used by the system models, closely approximates the difference between local and system flood control. The BRCs for Hungry Horse apparently provided adequate flood protection because the two curves (the BRCs and URCs) converged. The Libby curves, however, were analyzed in detail by the Army corps of Engineers (Corps).

From the onset, we determined that we would not protect fish at the expense of local flood control. We did, however, commit to investigating new ways to control system floods. The IRC strategy for flood abatement is to re-regulate water released from storage reservoir, during spring and early summer, so that large peaks in the cumulative runoff are eliminated. Re-regulation of the flow at dams enroute downstream can be used to extend the duration and reduce the peak of the runoff event. The need for "system" flood control at Libby and Hungry Horse (storage reservoirs in general) can be reduced by the protracted water routing strategy which extends the spring runoff volume so that flows remain within flood stage limitations. At the time of this writing, the full potential for water routing had not been assessed. System models do not presently have sufficient spacial and temporal resolution to perform the analysis.

Our intent was to reduce the volume that must be evacuated from storage reservoirs for "system" floodcontrol. This would allow more water to be stored during the fall through spring period, thus reducing reservoir drawdown. At Libby Reservoir, this additional water can be released during late spring or early summer for anadromous salmon smolts and Kootenai white sturgeon without impacting reservoir refill during July. The volume of water to be stored prior to spring runoff need not be large and can be variable to compliment flood control. More water can be stored during low water years, of course, than could be safely retained during high water years. Water "earmarked" for release for sturgeon and salmon could be stored in increments beginning in Fall. Upon receipt of the first inflow forecast on January 1, the local flood constraints can be estimated, and the correct IRC curve selected. The amount of earmarked water that can be safely stored above the existing "system" flood curve can be adjusted with each successive inflow forecast. It is important to note that reservoir elevations can remain above the IRC if flood criteria are met.

Analyses using HRMOD and LRMOD have shown that the IRCs successfully protract the runoff for local and system flood constraints. Notable exceptions will continue to exist where maximum storage is insufficient to control floods caused by unregulated sources (eg. North and Middle forks of the Flathead River cause flooding even though Hungry Horse discharge is reduced to the minimum outflow of 145 cfs; or Kootenay Lake floods even though Duncan, Libby and Kootenay Lake adhere to maximum flood constraints). Uncontrollable flooding can occur now, and will not be exacerbated by implementing the IRC strategy. Our IRCs, of course, allow deep drafts when needed far local flood control.

We consulted with ACOE modelers to address flood control requirements. A new strategy for system-wide flood control developed by ACOE, called VARQ, is essentially the same as the strategy incorporated in the IRCs (Figure 41). The exceedence curves represent Libby Reservoir elevations in April that are necessary to control floods of varying magnitude. Symbols represent the standard "status quo" flood control URCs (base case) compared to two versions of VARQ and the IRCs. The URCs require extensive drafting for flood control relative to VARQ and the IRCs. Typically, the IRCs allow deeper drafts for power than are required for flood control in average to low water years and match VARQ in higher water conditions, The IRCs differ from VARQ only slightly in the highest water years.

ACOE reported that flood problems occur when the inflow forecasts at Libby Reservoir grossly underestimated the real inflow event. Using the system model HYSSR to compare the IRC targets with current flood control criteria, ACOE identified 1946, 1948, 1951, 1971, 1972 and 1976 as particularly problematic years at Libby Dam. We, therefore, agreed to investigate the problem years and, if necessary, amend the IRCs to provide the necessary flood protection. We determined that some of the flood events identified by ACOE resulted from a miscommunication regarding curve selection during the model simulations. The annual IRC drawdown schedules that we provided to the ACOE were end of month elevations for each year of the standard 50 year study (19281979). These year-specific IRCs were generated based on historic inflow schedules (with total foresight) rather than inflow forecasts (with inherent forecasting error). Problems occurred when the actual flows differed from the forecasts. When the actual reservoir

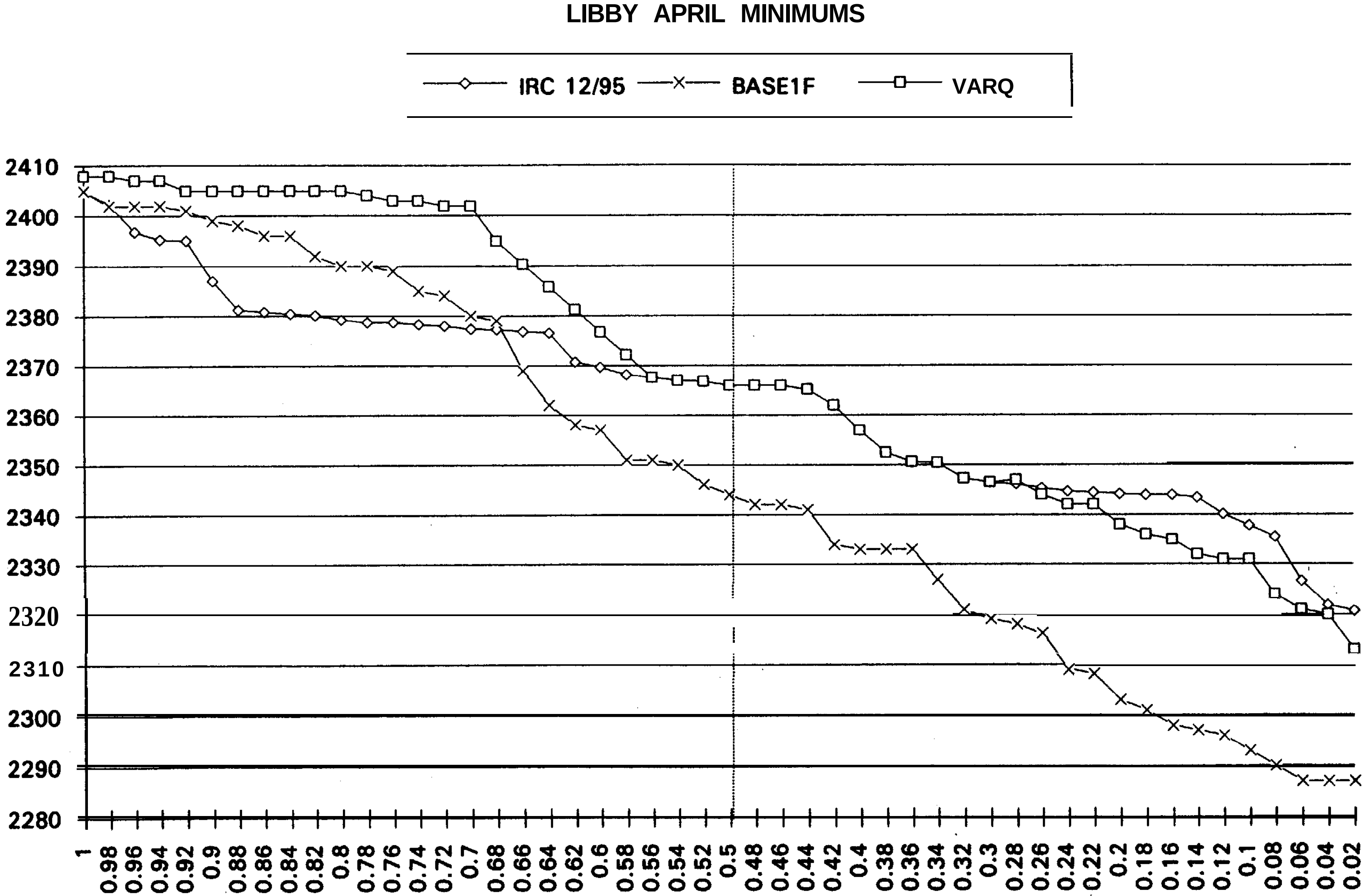


Figure 41. A comparison of April reservoir elevations needed to control floods of varying magnitude under the IRC, base case and VARQ. Adapted from original plot prepared by Pat McGrane ACOE.

inflows were less than forecasted, the IRCs dictated a shallower drawdown than would be required for flood control if the forecast& volume actually materialized. Since the ACOE must operate Libby Dam based on forecasts alone (with limited predictive capability) the IRCs based on total foresight did not provide adequate protection in certain years. Conversely, when actual flows exceeded the forecast, the IRCs often drafted the reservoir deeper than the forecast data would dictate. This error was corrected by reconfiguring the model to run on forecast data. Our intent has been to implement IRCs by selecting appropriate drawdown schedules based on water availability at the projects. The IRC targets are now selected and updated according to consecutive inflow forecasts.

Given this IRC selection technique, the risk of flood is restricted to years which the forecast grossly underestimates reality. As the accuracy of inflow forecasting improves, such occurrences should become less frequent, yet unpredicted floods can still occur. Recent floods (e.g. the 1964 flood) have been the result of rain on snow events. The localized, heavy rain event could not be predicted.. Typically, however, short-term runoff events result in extremely high river stage for only a short duration. The actual volume of the flood waters is relatively small compared to the vacated reservoir storage, and thus can be regulated. Consecutive forecasts become progressively more reliable as runoff approaches (variance diminishes because snow accumulation is nearly completed by the final forecasts and the accuracy of snow surveys improve). As the IRC targets are updated with each forecast, the amount of evacuated flood storage can be adjusted to an acceptable volume for flood control.

Fine tuning can be accomplished using short-term predictions of snow melt and precipitation. Model simulations using forecast data reveal that historic and simulated flood events are manageable under the IRC concept.

Hungry Horse Reservoir/F&head River

In the Flathead River, flow regulation is causing sediment accumulation, channel braiding and bank erosion. Short-term flow fluctuations from Hungry Horse Dam pulse water into the riverbanks. The water then returns to the river from the saturated banks carrying sediments and causing the banks. to collapse. Most sediment deposition is occuning in the lower 22 miles of river influenced by Flathead Lake elevations. These problems could be mitigated by high spring flows (below flood stage). A flushing flow would carry fine sediments out of the affected reach. Removal of fine sediments will decrease “embeddedness” of the substrate (increasing interstitial spaces) to provide insect habitat and hiding cover for juvenile salmonids (eg. bull trout). As the river travels downstream from the South Fork confluence to the mouth fine sediments accumulating in the lower 22 miles of the Flathead River shift the habitat type from a stonefly/mayfly/caddis assemblage to a midge dominated community, thereby affecting food availability (Dr. R. Hauer, pers. comm.).

Local flood constraints have reduced the frequency of channel maintenance flows. IRCs were constructed to disallow flooding at the immediate downstream critical flood control center at Columbia Falls, Montana. Discharges reduce to the absolute minimum (145 cfs) when the combined flows of the unregulated North and Middle forks approach flood stage (44,810 cfs). Channel maintenance flows can be enhanced through controlled releases during spring runoff. Spring discharges from Hungry Horse should be released during spring runoff (late May - early June) in a controlled volume to avoid conflicts with local flood control. Discharge should be less than the channel capacity of the South Fork below Hungry Horse Dam (20 kcfs), yet high enough to resort fine materials in the Flathead River bed (less than 5 mm diameter). Dam discharges would only augment natural discharges from the unregulated North and Middle forks.. A bank full flow for approximately 48 hours every 2.5 years would flush course substrate materials, resorting gravels and maintaining the channel. Channel maintenance will reduce river braiding that threatens adjacent lands.

Modifications to Albeni Falls Operations

The System Operation Review alternative SOS #4 proposed changes to the current operations of Albeni Falls Dam on Lake Pend Greille to better integrate flows throughout the system for resident fish, anadromous fish and system flood control.

The proposed elevations for Lake Pend Greille complement the proposed Integrated Rule Curves for Hungry Horse. As Lake Pend Oreille fills, it stores and reregulates much of the spring flows from the Clark Fork River. Then during July, the surface level of the lake is dropped about two feet. Releasing storage after the high spring flows extends the period of high discharge. Thus, Lake Pend Greille extends the runoff period, and reduces the peak flows into the Pend Greille River Drainage.

The lower elevation of the lake during July provides benefits to wetlands for waterfowl. The higher winter pool elevation (2,056 ft.) will provide dramatic increases in the amount of spawning gravels for kokanee. Kokanee harvest has dropped from an average of l,OOO,OOO fish in the 1950s and 1960s to only 100,000-200,000 in 1985-1991. In years between 1952 and 1966 high winter pool elevations lead to higher harvest of kokanee when those year classes entered the fishery. The Idaho Department of Fish and Game believes that increasing the winter pool elevation will again improve the kokanee population in Lake Pend Oreille (Melo Maiolie, Report to SOR DEIS).

Libby Reservoir/Kootenai River

Local flood control measures extend downstream to Corra Linn Dam at the outlet from Kootenay Lake. LRMOD calculates side flows to the Kootenai River (from inflowing water sources) between Libby Dam and Bonners Ferry. Kootenai River flow targets at Bonners Ferry and Kootenay Lake elevational targets were programmed as mandatory limits in the model to avoid flooding. Conversely, the dynamic side flow estimates can be added to Libby discharge to calculate the resultant-flow at Bonners Ferry. Inflows to Kootenay Lake, flood control storage at Duncan Reservoir and lake stage/discharge relationships for Corra Linn Dam were incorporated in the model to mimic coordinated flood control measures stated in the International Joint Commission treaty.

An understanding of flood control criteria at Bonners Ferry and Kootenay Lake was necessary to examine spring releases that enhance the river fisheries. Long-term simulations incorporating historic inflow forecasts and actual daily flow measurements revealed a range of acceptable water routing strategies. We then placed additional limits on dam discharge to achieve balance between fisheries concerns in the river and reservoir.

Kootenai White Sturgeon Recovery

Based on the currently available information, white sturgeon in the Kootenai River require a high spring river discharge and favorable water temperatures to assure successful recruitment. Research by Idaho Fish and Game and the Kootenai Tribe of Idaho revealed that few young white sturgeon have been recruited to the population since Libby Dam was installed (Apperson and Anders 1991). The failure to recruit juvenile sturgeon into the existing population has been linked to regulated flows below Libby Dam and habitat changes in the river margins and backwater areas (Giorgi 1994). The Idaho Conservation League proposed listing the Kootenai River white sturgeon under the Endangered Species Act. In September 1994, the U.S. Fish and Wildlife Service formalized their decision to list the Kootenai River white sturgeon as endangered under ESA.

Requirements for natural sturgeon spawning and recruitment remain largely unknown. Until thresholds for successful reproduction can be established, targets for flow augmentation and river stage can only be described in general terms. Thresholds can be identified by varying the volume, duration and shape of flows released for sturgeon, while assessing the effect on various life stages of the species. To this end, we have proposed a tiered approach for experimental sturgeon spawning flows (Figure 42 and Table 10). Annual variance in flows, resulting from this tiered approach will produce sufficient variance in the experimental design to quantify threshold conditions determining reproductive success and failure.

Experimental flow targets are selected based on the May 1 inflow forecast volume (reservoir inflow expected during the period April 1 through August 30 in MAF). These targets represent minimum flows at Bonners Ferry (Libby Dam discharge plus unregulated inflows between Libby Dam and Bonners Ferry). When the forecast underestimates the actual inflow volume, minimum sturgeon flow targets are exceeded as excess water is released to slow the rate of reservoir refill. Overestimation results in the release of stored water to achieve the minimum target. In both cases, flows can be shaped through inseason management to achieve the most desirable balance between discharge shape and reservoir refill trajectory.

The IRCs provide flexibility to assure that the runoff event corresponds with optimal water temperatures. A vertical array of thermometers on the upstream face of Libby Dam reveals the reservoir's thermal structure. As optimal water temperatures become available at the appropriate outlet depth, sturgeon releases can be shaped to achieve the optimal mix of flow and temperature. At present, the ACOE and MFWP have an agreement to release water no closer than 50 feet beneath the current surface elevation to reduce the entrainment of fish through the turbines. Recent sampling of entrainment (Skaar et al., MFWP, report in progress) may allow for greater balance between entrainment and thermal control, further refining inseason management for sturgeon recovery.

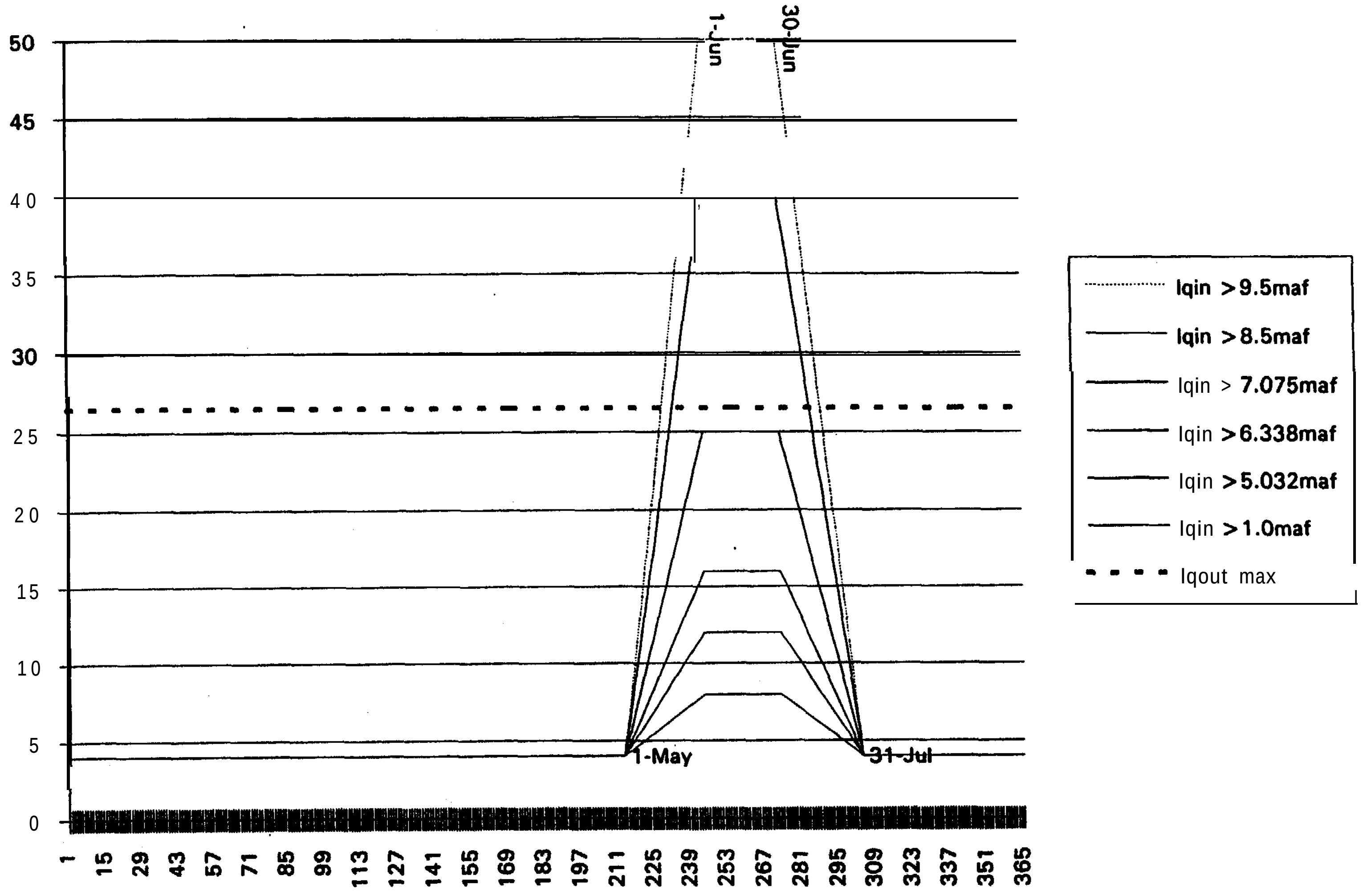


Figure 42. Tiered approach to sturgeon flow targets at Bonners Ferry, Idaho, as determined by water availability at Libby Reservoir. Volumes and shapes of the flow targets are preliminary, pending further research to identify thresholds between successful recruitment and reproductive failure.

Table 10. Numerical description of minimum sturgeon flows at Bonners Ferry under the tiered approach. Additional sideflows from unregulated streams may exceed the minimum requirements during a given year, if reservoir refill is not compromised. Combined flows are restrained by flood control criteria at Bonners Ferry, Idaho and Kootenay Lake, British Columbia, Canada.

Sturgeon ***Minimum Target*** *Row* ***Schedules***

Date	**WY DAY**	**> = 9.500 MAF 50 KCFS**	**> = 8.500 MAF 40 KCFS**	**> = 7.075 MAF 25 KCFS**	**> = 6.338 MAF 16 KCFS**	**> = 5.032 MAF 12 KCFS**	**> = 1.000 MAF 8 KCFS**
1-Oct	1	4.00	4.00	4.00	4.00	4.00	4.00
1-Apr	183	4.00	4.00	4.00	4.00	4.00	4.00
1**5-May**	227	24.77	20.26	13.48	9.42	7.61	5.81
31-May	243	48.52	38.84	24.32	15.81	11.74	7.87
1 **-Jun**	244	50.00	40.00	25.00	16.00	12.00	8.00
30-Jun	273	50.00	40.00	25.00	16.00	12.00	8.00
15-Jul	288	27.74	22.58	14.84	10.19	8.13	6.06
31 **-Jul**	304	4.00	4.00	4.00	4.00	4.00	4.00
31-Aug	335	4.00	4.00	4.00	4.00	4.00	4.00
30-Sep	365	4.00	4.00	4.00	4.00	4.00	4.00

The Libby Reservoir model was configured to automate the selection of flow targets and to shape unexpected flow events resulting from forecasting error within flood constraints. Analysis of the 50-year period of record (19291978) revealed that sturgeon targets can be met during critical years 1 and 2 without impacting reservoir productivity (Table 11). We do not recommend sturgeon releases in critical years 3 and 4 unless increased discharges are required for emergency flood control.

Two of the fifty years of record (1948 and 1974) would require inseason management (increased sturgeon flows) for flood control. Water year 1974 was classified as a critical year 3, so under the proposed tiered approach no sturgeon target would normally have been met. Inflows were sufficiently high, however, that by late May it became obvious that the inflow forecasts were too low and that water must be released to maintain flood storage capacity behind Libby Dam. The model was programmed to simulate inseason management by releasing the appropriate sturgeon target (corresponding to > 8.5 MAF in Figure 43) to control the flood. In reality, the 1974 flood was controlled in nearly the same manner, providing adequate conditions for sturgeon as evidenced by successful recruitment from the 1974 year class (Apperson and Anders 1991).

Similarly, in 1948 (designated critical year 1) the inflow forecast grossly underestimated the *actual runoff volume. If* Libby Dam had existed in 1948, the faulty inflow forecasts would not have warned the dam operators to evacuate sufficient storage volume to control the flood. The corresponding sturgeon flow target based on the underestimated May 1 forecast would likewise not have evacuated sufficient flood storage to reregulate the runoff. However, experienced operators would have been aware that the reservoir was refilling too rapidly and that a forced spill was imminent. We, therefore, programmed the model to release the maximum allowable sturgeon flow in response to the flood emergency.

Model evaluations reveled that impacts to the reservoir fishery can be reduced by storing water which was historically released during winter, for release during June to enhance sturgeon spawning. By explicitly storing water for sturgeon, reservoir elevations remain more favorable for biological production and refill probability is enhanced. Power marketing strategies make it possible to store water during fall and winter explicitly for release during June to provide the necessary spawning stimulus without compromising reservoir refill probability. Water releases for sturgeon then continue downstream to aid juvenile anadromous fish migration to the Pacific Ocean. Westslope cutthroat and rainbow trout also respond favorably to a spring discharge if timing of releases correspond with their life cycle requirements.

Although the model is capable of assessing an array of alternate volumes and shapes, more information on sturgeon requirements is needed to direct model development. The rapidly evolving science resulting from ongoing field surveys, and recent unprecedented findings, make the sturgeon flows a moving target. We must have definite biological evidence to make changes in LRMOD because of the model's complexity and time constraints. When additional evidence supporting model reconfiguration becomes available in the future, we will reconfigure the model as needed to assess the effects on other species.

Table 11. Results of a SO-year simulation examining flows at **Bonners** Ferry during May, June and July under the tiered flow **approach.**

BONNERS FERRY FLOWS				RC'S			DEC. 95		
	MAY			JUN			JULY		
YEAR	AVG	MAX	MIN	AVG	MAX	MIN	AVG	MAX	MIN
1929	11.63	21.94	7.32	23.16	41.67	14.66	20.46	28.75	14.11
1930	15.79	31.35	9.59	19.94	38.82	13.25	13.13	20.12	8.45
1931	11.41	17.86	7.99	12.88	14.70	10.73	8.78	10.55	7.57
1932	34.97	42.42	27.51	34.95	46.09	16.26	10.67	15.59	8.53
1933	20.77	43.09	10.23	43.55	54.37	38.11	24.62	40.40	9.80
1934	39.01	47.50	34.72	37.46	42.95	34.08	22.20	34.18	8.63
1935	15.13	23.65	9.16	32.16	41.48	24.32	16.04	25.00	10.12
1936	15.27	24.31	11.44	20.00	43.16	9.80	15.10	18.97	10.84
1937	12.01	17.79	7.60	14.77	18.00	12.11	12.44	19.42	9.26
18%	29.96	50.21	10.83	39.10	44.31	15.30	10.74	14.49	8.21
1939	16.44	29.69	11.01	13.16	17.58	11.19	14.45	23.20	11.54
1940	16.74	38.78	8.88	13.34	19.02	12.00	8.98	12.00	7.57
1941	10.66	12.89	8.28	11.32	13.49	9.38	8.00	9.48	7.03
1942	22.72	46.79	8.38	38.15	43.81	33.37	16.46	31.63	10.16
1943	25.25	31.14	15.52	26.55	39.21	25.00	17.91	30.85	10.37
1944	10.01	14.31	7.14	12.03	14.31	9.38	7.94	9.38	7.18
1945	11.46	20.38	6.40	16.07	22.33	12.11	12.17	18.56	8.17
1946	37.77	49.72	30.57	39.62	44.18	35.24	13.68	35.48	9.27
1647	31.10	49.18	14.70	27.28	42.09	16.00	17.89	27.17	8.79
1948	38.28	60.06	25.47	45.09	50.00	38.58	29.71	38.30	10.26
1949	26.09	45.51	9.41	16.03	26.23	12.00	9.33	12.00	8.06
1950	18.82	33.84	7.82	39.92	50.68	25.00	24.94	45.21	9.87
1951	38.64	46.42	23.41	38.86	48.63	33.56	21.28	37.90	11.58
1952	26.76	37.85	11.01	19.68	33.55	13.14	21.13	36.05	12.36
1662	14.43	29.16	8.84	32.69	49.90	16.00	27.92	39.31	10.71
1954	35.00	52.47	10.73	42.86	47.39	38.15	37.65	48.62	11.12
1955	11.33	19.31	6.36	33.84	50.06	13.71	35.00	39.41	21.46
1956	35.88	56.17	14.43	41.09	46.60	35.50	30.47	37.71	9.52
1957	37.75	43.61	14.38	21.55	36.01	12.00	12.56	16.41	9.23
1958	28.68	45.95	7.03	20.10	40.27	12.00	10.12	12.39	8.13
1959	33.07	41.30	19.22	44.79	50.24	34.05	22.49	40.65	9.87
1960	27.12	40.73	16.19	25.02	26.31	24.32	15.45	25.00	9.02
1961	30.03	55.37	8.95	41.97	47.43	34.69	24.76	34.06	8.88
1962	13.47	21.59	9.02	23.96	38.45	13.46	20.38	32.65	14.81
1963	13.36	22.83	8.53	32.07	42.12	13.53	25.85	40.39	10.37
1964	14.64	27.77	7.99	43.66	51.89	23.98	25.19	38.68	10.44
1965	23.03	43.71	9.52	41.97	49.41	36.77	17.26	38.26	9.34
1966	29.75	48.82	11.15	40.53	49.67	35.32	16.22	36.39	9.06
1967	20.43	47.62	6.50	48.31	51.55	44.61	33.68	42.70	9.91
1968	14.12	30.72	8.42	32.18	48.06	17.17	27.26	39.81	15.17
1969	38.55	46.68	30.57	42.29	49.54	36.65	26.94	40.95	9.23
1970	12.00	19.49	5.97	18.89	29.04	13.71	18.89	29.70	13.43
1971	35.98	48.54	11.61	42.00	47.99	36.59	18.55	36.66	10.80
1972	27.28	52.80	8.74	42.38	56.30	34.29	35.61	41.16	19.80
1973	12.66	21.94	7.00	15.95	24.28	12.36	20.01	30.00	11.23
1974	29.94	38.19	17.94	40.34	48.56	35.36	35.03	43.40	10.65
1976	14.62	23.65	7.39	24.98	25.00	24.32	15.41	25.00	8.95
1976	31.26	45.70	6.21	16.62	18.89	16.00	26.36	39.03	14.32
1977	10.14	13.10	8.67	11.89	19.24	8.95	7.97	8.70	6.93
1978	27.53	40.63	13.70	25.02	46.14	12.07	13.48	20.77	9.31

Anadromous Species Recovery

The ongoing salmon recovery program can cause important changes in storage reservoir operation. The National Marine Fisheries Service 1995 Biological Opinion states that anadromous fish require high water velocities in the Lower Columbia to aid in their migrations. This requires releases from storage reservoirs during May through August (often referred to as the "water budget"). Historically, the reservoirs refilled from mid April through early August and discharges were reduced to specified minimum limits. Thus, if storage projects are excessively drafted during April, increased releases during this period reduces the probability of refilling the reservoirs. Refill failures reduce biological production in the reservoir effect the ability of the system to supply anadromous fish migration flows and power production during the subsequent year. Also, a lack of stored water could compromise the system's ability to maintain minimum flows required to maintain resident fish species in critical river reaches. The 1995 Biological Opinion tailed to assess these tradeoffs incrementally with benefits to anadromous species recovery.

The IRCs were designed to balance the conflict between anadromous and resident fish requirements. This was accomplished by storing water during the fall through early spring period in the headwater reservoirs, for release during late May and June. Deep drafts and refill failures could then be minimixed while serving the needs of anadromous species. Spawning cues for river species such as the Kootenai white sturgeon and spring spawning trout are simultaneously provided.

The ability of IRCs to balance anadromous and resident fish requirements was tested using the system models. System model simulations indicate that the IRCs provide anadromous flow targets during the spring migration at McNary more frequently than the base case or "status quo" operation. Summer flow targets were not built into the IRCs, but results reveal improved conditions over past operating practices. The IRCs, can improve conditions for salmon migration, yet protect resident fish in the headwaters.

To reduce impacts to firm power, however, the IRCs were modified to allow greater flexibility during the cold months. This resulted in reduced releases during the smolt migration period. Flow augmentation can be improved by opera&g the projects above the IRCs to accumulate an earmarked block of water for spring/summer release.

Real Time Implementation of the Integrated Rule Curves

Historically, reservoir operations have been &fined by water availability throughout the Columbia River drainage and the region's need for power. The critical year (or critical rule curve, CRC1-4) is adopted by federal dam operators during July and may be amended as the water year develops. Critical year selection is based on the amount of water stored in all Columbia River hydropower projects. If the dams in the system refill to maximum capacity, CRC1 is selected. However, if the system fails to refill, CRC2-4 may be adopted based on the extent of refill failure, or percentage of maximum capacity remaining in system storage. Critical year planning (CRC selection) was devised by hydropower analysts to allow for consecutively deeper drafts during an extended drought, so that firm power could be guaranteed during the driest four year period on record (1928-1932). Current operating practices dictate that Hungry Horse and Libby reservoirs can be drafted to the bottom of active storage during the fourth year of a critical period (CRC4). Thus, Hungry Horse could be drawn down 224 feet and Libby-172 feet. Extreme drawdowns such as these would be an unacceptable risk to weak stocks of native species in the reservoirs.

The IRCs also allow for consecutively deeper drawdowns during an extended drought. Unlike CRC4, the IRCs define maximum drawdown during the fourth critical year as the elevation at which approximately 80 percent of the biological production in the reservoir has been lost. This strategy minimizes the severe biological impacts associated with excessive drawdown and enhances the ability of reservoir biota to recover more rapidly after an adverse event.

The reservoirs are operated from July through the following December with little information on accumulating snowpackand forthcoming runoff conditions. The first inflow forecast becomes available on January 1; forecasts are then updated monthly through July. Runoff estimates are based on winter snow surveys plus estimated precipitation defined as the average of long-term records.

The IRCs were designed for compatibility with annual operation planning. The IRCs were described on a water year basis (October 1 - September 30). The curves are consistent from July through January 1 and allow for conservative drafting prior to the first inflow forecasts. The IRCs maintain the maximum reservoir elevation until after September 15 to enhance the period of peak biological production in the reservoir (July through September). Storage is also released to maintain minimum flows in the river downstream. At Libby, the curves conform with the IJC Treaty between the U.S. and Canada which specify that two million acre feet must be evacuated by January 1. The Hungry Horse curves define a drawdown trajectory in excess of flood control requirements for provisional power drafting and system flexibility.

In real time, the dam operator would receive the first forecast for the project in early January and operate the dam as dictated by the IRC corresponding to the volume of each consecutive inflow forecast If the runoff is intermediate between two adjacent curves, the target elevation should be calculated by interpolation. Target elevations are sequentially amended as each forecast update becomes available. Thus, the annual operation targets differ in shape from one year to the next as adjustments are made in response to monthly runoff forecasts.

Forecasting error may result in a verifiable deviation from the operational targets. Typically, forecasting error is reduced with each successive forecast update. Minor errors can be corrected by scheduling storage or releases to regain the proper target elevation later in the same year. However, estimation errors have been significant in some years. An overestimate often results in refill failure, whereas underestimation of the inflow volume may require additional releases in response to the large inflow. The actual IRC operation is generally close to the IRC targets, yet flexible enough to respond to forecasting error and perturbations in local streamflows.

Refill probability was considered during IRC development. Our goal was to improve refill probability at the projects. When low flow conditions resulted in reservoir refill failure, we attempted to minimize the distance from full pool. Continuous simulation studies revealed that implementation of the IRCs can meet our stated goals, yet refill failures continue to occur. This effect is not readily apparent by viewing the target IRCs (Figures 39 and 40), which depict reservoir refill under all conditions. Again, the proposed targets differ from the resulting operation when forecast data are used. Forecasting error or precipitation events result in verifiable deviation from. the elevational targets.

The IRCs were designed using historic runoff forecasts and actual streamflow data. Our goal was to produce operational guidelines that were hydrologically at&able under varying flow conditions. In real time, project operators must rely on forecasts which introduce uncertainty. The models were, therefore, programmed with conservative stage and flow limits in the reach downstream. Spilling was disallowed to constrain discharges to within the maximum turbine capacity at each reservoir elevation (head). We also acknowledged the limited ability to correct for forecasting error. The resulting IRCs, when used with forecasts, incorporate a conservative buffer designed to absorb the forecast@ error. The family of curves and curve selection using forecasts were tested using the entire period of record 1929-1995. The IRCs for Hungry Horse performed within specifications with no forced spills. The IRCs for Libby Reservoir required inseason management for flood emergencies in 1948 and 1974 because of forecasting error. The 1974 simulation revealed that inseason management would be needed to respond to the higher than predicted runoff event. Under forecasted flows in 1948 a forced spill at Libby Dam would have resulted. These events would also occur under the base case (present) operating criteria. All other years were successfully regulated using IRCs.

Summary of Intent of Integrated Rule Curves

Problems occur for resident fish in reservoirs when reservoirs are drawn down beginning in late summer or early fall. The reduced volume and surface area limits the fall food supply and volume of optimal water temperatures during a critical trout growth period. Surface elevations continue to decline during winter, arriving at the lowest point in the annual cycle during April. Deep drafts reduce food production and concentrate young trout with predators like northern squawfish. Of greatest concern is the dewatering and desiccation of *chironomid* larvae in the bottom sediments. These insects provide the primary spring food supply for westslope cutthroat, a species of special concern in Montana, and other important game and forage species. Deep drawdowns also increase the probability that the reservoirs will fail to refill. Refill failure negatively impacts recreation, and reduces biological production which decreases fish survival and growth in the reservoirs.

Integrated Rule Curves were designed to limit the duration and frequencies of deep drawdowns and reservoir refill failure. Reduced drawdown protects aquatic insect larvae, assuring that a large percentage of insects will survive to emerge as pupae and adults which provide an important springtime food supply for fish. Increased refill frequency maximizes biological production during the warm months. **Refill** provides an ample volume of optimal **temperature water for fish growth and a large surface area for the deposition of terrestrial insects from the** surrounding landscape. Refill timing also assures **that passage** into spawning and rearing habitat in tributaries is maintained for species of special concern, including westslope cutthroat trout and the bull trout.

Integrated Rule Curves provide a solution to the apparent conflict between resident fish and anadromous salmon concerns, within the physical realities of flood control and power. This **operational strategy proposes the expansion of existing power sales to** and from the northwest region. Such sales would transfer surplus power out of the Columbii hydropower system during spring and return power to the system during fall and winter. This allows a portion of the northwest's peak power demand to be met by imported power. Reservoir storage which is normally released during the cold months for power purposes can then be "saved" for release during spring. Resident fish in **headwater** storage projects **benefit** from higher reservoir elevations during winter and early spring. **Stored** water is released (within mandated flood constraints) during June to augment **Kootenai** white sturgeon spawning. This water continues downstream to augment salmon migration flows. The result is shallower maximum drawdowns in **storage reservoirs** like Hungry Horse and **Libby** and improved reservoir refill probability. Recall that **refill failure** impairs biological productivity in the **reservoirs.** Even infrequent **deep** drafts cause long lasting biological impacts. The energy transfer strategy attempts to reduce these effects.

Although hydropower is relatively benign compared to other traditional generation techniques, environmental effects of hydropower **facilities** are well documented and costly in terms of lost recreation, food production and fisheries maintenance. Modified operations and wise power marketing strategies can lessen costs to the ratepayer, yet improve the quality of the aquatic environment. Model evaluations of the effects of **IRCs** on power production helped define the shape of the operational curves and integrate power **releases** with fisheries needs. Power demands continue to grow and the region's hydropower capacity is limited. Drought and an overall reduction in electrical generation relative to the demands on the system have necessitated increases in power rates. Revenue impacts can be reduced by **intra-regional** power transfers, but markets to transfer energy are young and must be fostered. Transmission **facilities** must be expanded to increase **intertie** access. Admittedly, adoption of the **IRCs** and proposed operational strategy will carry initial costs. Yet, it is important to include the hidden costs of ecosystem degradation, normally considered "externalities" in economic analysis. The costs of species recovery actions are significant. Mankind's ability to restore dwindling **species** to their former vitality is limited, despite the significant monetary investment. It is more **cost-effective** to maintain existing stocks at viable levels. Operations should be modified to avoid the loss of additional stocks in the future.

Future Targets

In SOS **#4** of the System ***Operation*** Review we proposed non-operational flood constraints, like levees, berms and dikes. We did not intend that the entire river be channelized or armored for flood control. Instead, we proposed protecting highly developed areas only. Undeveloped or sparsely populated floodplains should be zoned 'accordingly to restore or protect natural floodplain function. Floodplains, ifallowed to function naturally, absorb high flow events taking pressure off levees surrounding populated, critical flood control centers.

Flood control has arguably resulted in a net benefit to humans, yet there are hidden costs. Flood control creates a false sense of security that encourages development in low-lying areas. When a natural event overwhelms man's flood control devices, costs in property damage and human suffering can be exceedingly high. A case in point is the Mississippi drainage which represents one of mankind's greatest achievements in flood control and perhaps its most dismal failure. The colossal levees actually increased flood stage during the 1993 flood when water was confined within the extensively channelized drainage. As levees failed, previously protected developed areas were inundated, causing a national disaster. Floodplain development costs U.S. citizens who collectively finance flood control measures, disaster relief and flood insurance claims. Wetlands, now known to be extremely valuable ecological resources, have also been sacrificed to floodplain encroachment. Agricultural lands retain greater fertility when they are intermittently flooded by waters containing nutrient rich river sibs, whereas protected lands require fertilization and accumulate salts. The cost of intermittent crop damage in floodplain management areas must be weighed against soil depletion and compensation for structural damages when uncontrolled flood events occur in protected areas. The Columbia drainage offers an opportunity to protect floodplain function while the region remains, in most areas, lightly populated.

At present, some of the flow requests for anadromous recovery are not hydrologically possible because they pose a flood "risk" to low-lying areas. Likewise, optimal conditions for resident fish in storage projects can not be achieved when system flood control requirements greatly exceed local requirements. If existing flood constraints can be relaxed through floodplain zoning, levee improvement in developed areas and flow re-regulation during runoff, it will be possible to improve conditions simultaneously for resident and anadromous fish. We can also protect wetlands, improve agricultural production through intermittent flooding, and reduce unnecessary costs associated with flood damage on floodplains that should not be developed.

Conclusion of Integrated Rule Curve Development

-The IRC operational strategy was designed to improve conditions for all native fish species in the Columbia River System within the realities of flood control and power production. Flexible river flow and reservoir elevational targets allow for compromise among the often competing uses in the basin. System models have shown that flow augmentation for anadromous fish can be achieved, when hydrologically possible, without sacrificing native resident fish populations. Coordinated springtime releases from storage projects can achieve a protracted runoff, with peaks removed, to avoid flooding. Power produced during the springtime flow enhancement for sturgeon and salmon can be marketed through intra-regional exports to reduce the revenue impacts of this plan. Imported power during fall and winter allows headwater reservoirs to store water explicitly for release during spring. Resident fish benefit from high reservoir elevations, decreased drawdowns and improved refill probabiity. We recommend this integrated compromise for a balanced system operation in the Columbia Basin.

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APPENDIX A

Recommended Model Input for First-time Users

HUNGRY HORSE RESERVOIR MODEL

RECOMMENDED ENTRIES FOR FIRST TIME USERS --

The basic data files are HQIN??.DAT **& LQIN??.DAT** for historical inflows for the water years ?? (YR) for Hungry Horse & Libby. HSURF??.DAT **& LSURF??.DAT** are for the historical elevations for the water years.

See the enclosed sheet additional file structure information.

TYPE:	PURPOSE:
hrmod <enter>	.exe program
center>	when finished reading screen
center>	no input file
<enter>	no output file
<enter>	when finished reading screen
n	use file instead of avg.
f<enter>	use file
hqin88.dat<enter>	any **hqin8?.dat** file (caps. ok throughout)
<enter>	when finished reading screen
n	list input?
n	modify input?
n	integrate?
n	limit file?
y/n	plot?
n	modify limits?
y/n	plot?
<enter>	= zero days to ignore limits, max
<enter>	= zero days to ignore limits, min
n	modify limits
e<enter>	use elev. file
f<enter>	use elev. file
hsurf88.dat<enter>	**hsurf8?.dat**
n	list?
n	modify?
y/n	plot?
y/n	plot?
<enter>	when finished reading screen
y/n	plot?
y/n	plot?
y/n	plot?
n	junction
0<enter>	365 data only
<enter>	no file to save
<enter>	no file to save
<enter>	no file to save
<enter>	no file to save
center>	no file to save
3/(4)<enter>	continue/(stop)
Y	thermal
Y	selective withdrawal
Y	auto depth
<enter>	**when** finished reading screen
n	isopleths
n	profiles

n	temperature
y/n	plot q out elev
<enter>	when finished reading screen
<enter>	when finished reading screen = fish growth FHR
<enter>	fish file not needed
<enter>	no file needed
<enter>	no file needed
<enter>	no file needed
4/(5)<enter>	biol/(exit)
Y	biol?
center>	when finished reading screen = pp
<enter>	when finished reading screen
<enter>	when finished reading screen
<enter>	when finished reading screen
<enter>	when finished reading screen
<enter>	when finished reading screen
<enter>	when finished reading screen
<enter>	no file needed
5<enter>	exit

For LRMOD the procedure is comparable. One difference is in handling the data for Duncan Reservoir. You have a choice of using a default estimate or of using a file. We do not yet have Duncan Reservoir inflow files for the '80s, so a representative sample file is provided as DUNCAN.DAT if you want to use that option (self explanatory from menus).

```
Directory of B:\                                NOTES:

LRMOD        <DIR>     01-26-95 11:05p   Libby
HRMOD        <DIR>     01-26-95  11:03p   Hungry Horse

Directory of B:\HRMOD

HRSUP1A  FOR     44930 10-18-94   5:34p   Hydrology subroutines
HRMOD    FOR     16313 10-18-94   5:15p   Main
FLATHEAD FOR     18579 04-14-94   4:37p   Flathead Lake subroutines
HRSUP3A  FOR     15402 05-25-93   8:16p   Biology subroutines
HQIN80   DAT      2920 02-07-88  12:16p   Basic inflow data file
HRSUPFL  FOR     21376 08-03-92   3:23p   Utilities subroutines (graphics)
HQIN81   DAT      2920 02-07-88  12:17p
HRSUPO   FOR     28032 09-30-91  12:43p   Util. & conversion subroutines
HRSUP2   FOR     32512 07-31-91   4:11p   Thermal model subroutines
HRSUPEX  FOR      2816 05-07-91   8:19p   Util.  subroutines (graphics)
HRSUPHR  FOR      2816 05-07-91   8:18p   Util.  subroutines (graphics)
HRDATA   FOR     18560 11-21-91   4:44p   Data
HRMOD    EXE    205144 04-14-94   4:38p   Model
HQIN82   DAT      2920 02-07-88  12:17p
HQIN83   DAT      2920 02-07-88  12:17p
HQIN84  DAT       2920 02-07-88  12:17p
HQIN85   DAT      2920 02-07-88  12:17p
HQIN86   DAT      2920 02-07-88  12:17p   Basic inflow data files
HQIN89   DAT      2502 01-22-90   3:14p
HQIN87   DAT      2560 06-11-88   1:12p
HQIN88   DAT      2381 04-03-89  10:16a
HSURF87 DAT       2944 06-11-88   1:13p
HSURF80 DAT       3285 02-07-88  12:16p
HSURF81  DAT      3285 02-07-88  12:17p
HSURF82 DAT       3285 02-07-88  12:17p
HSURF8 3 DAT      3285 02-07-88  12:17p   Basic historical elevation files
```

```
HSURF84   DAT      3285  02-07-88  12:17p
HSURF85   DAT      3285  02-07-88  12:17p
HSURF86   DAT      3285  02-07-88  12:17p
HSURF88   DAT      3286   04-03-89  2:04p
HSURF89   DAT      3308   01-22-90  4:25p
HRMOD     HLP      2961   11-26-89  7:44p   Help screens
HRMOD     FON     50880  08-02-89  11:10a   Fonts
MSHERC    COM      6749   10-26-88  7:37p   Screen Util.
HRMOD     INC      1453   05-18-93  5:25p   Include file/ common storage-vbls.
       37 file(s)      528939 bytes

Directory of B:\LRMOD

LRMOD     EXE    205188  11-28-94   5:53p   Model
LQIN81    DAT      1956  10-28-91  10:26a
LQIN82    DAT      1940  10-28-91  10:27a
LQIN83    DAT      1945  10-28-91  10:27a        SAME AS ABOVE
LQIN85    DAT      1916  10-28-91  10:27a
LQIN86    DAT      1948  10-28-91  10:27a
LQIN87    DAT      1930  10-28-91  10:27a
LQIN89    DAT      1955  10-28-91  10:27a
LQIN80    DAT      1923  12-16-92   4:13p
LQIN84    DAT      1923  12-16-92   4:14p
LQIN88    DAT      1921  12-16-92   4:15p
LSURF80   DAT      2920  12-14-87  11:03p
LSURF81   DAT      2920  12-14-87  11:03p
LSURF82   DAT      2920  12-14-87  11:03p
LSURF83   DAT      2920  12-14-87  11:03p
LSURF84   DAT      2920  12-14-87  11:03p
LSURF85   DAT      2920  12-14-87  11:03p
LSURF86   DAT      2920  12-14-87  11:04p
LSURF88   DAT      3286  10-28-88  11:35a
LSURF87   DAT      3328  01-31-89   2:43p
LSURF89   DAT      2921  04-23-90   2:35p
LRSUP3A   FOR      9504  01-08-95   8:40p
MSHERC    COM      6749  10-26-88   7:37p
LRSUP0    FOR     24594  09-15-93   2:05p
LRMOD     FON     50880  08-02-89  11:10a
LRSUPEX   FOR      2688  05-07-91   5:23p
LRSUPFL   FOR     21213  11-06-92   2:34p
LRSUPHR   FOR      2816  05-07-91   5:22p
LRSUP2    FOR     31872  05-07-91   4:23p
LRSUP1A   FOR     41497  01-08-95   8:39p
DUNCAN    FOR     28563  09-14-94   4:32p   Duncan & Kootenay subroutines
LRDATA    FOR     29146  10-20-92   2:54p
LRMOD     INC      1389  02-01-93   4:42p
LRMOD     HLP      3328  11-24-89   6:36p
DUNCAN    DAT     2920   08-02-94  11:48a   Sample Duncan inflow data file
B                 19016  12-06-94   4:27p   Current Bonners Ferry limits file
R                  2920  01-06-95   9:16a   Current River (Libby) limits file
       39 file(s)      533615 bytes

Total files listed:
       79 file(s)     1062554 bytes
                       373248 bytes free
```