APPENDIX D

Modeling of Biological Effects in Montana

Notice Sheet—
Upper Columbia Alternative Flood Control (VARQ) and Fish Operations EIS –
Biological responses to alternative flood control strategies at Hungry Horse and Libby dams, Montana

Nomenclature Corrections

To be consistent with the naming conventions for the different dam operations in the EIS, this report has been revised from the original that was submitted by the contractor. Other than the nomenclature revisions, the content and technical details have not been changed.

Biological Responses to Alternative Flood Control Strategies at Hungry Horse and Libby Dams, Montana.

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Contents

List of Figures

List of Tables

Executive Summary

The Biological Opinions recommended implementation of a variable discharge flood control strategy (VARQ) at the two northwestern Montana dams. The biological consequences of these alternative dam operation strategies were analyzed using computer models that were calibrated for each reservoir and river using field measurements. Hydrologic data provided by the U.S. Army Corps of Engineers (Corps) and Bureau of Reclamation (Reclamation) were used to assess six dam operating strategies at Libby Dam and two alternatives at Hungry Horse Dam. Nine years ranging from medium dry to medium wet (20^{th} to 80^{th} percentile water years) were selected for analysis at each dam.

Model analyses comparing Standard flood control (FC) to variable discharge (VARQ) FC strategies revealed that VARQ FC operations generally improved biological conditions in reservoirs compared to Standard FC operations. Benthic insect production increased when the annual reservoir drawdown was minimized and substrate containing benthic insect larvae remained continually inundated. Phytoplankton and zooplankton production, and the deposition of terrestrial insects, was greatest when the surface remained at or near full pool during the biologically productive warm months. Loss of plankton through the dam turbines was proportional to the vertical distribution of plankton production in the reservoir and sensitive to the volume and depth of water withdrawal. Environmental conditions under VARQ FC were more conducive for fish growth (kokanee at Libby and westslope cutthroat trout at Hungry Horse) than the Standard FC in most water years. Exceptions were examined.

Downstream of the dams, unnatural flow fluctuations caused by dam operations disrupt natural processes and reduce biological productivity. Impacts can be mitigated by restoring a more natural spring freshet and by stabilizing river flow during the productive summer and fall months. VARQ FC operations that provided specific flows for fish recovery generally increased benthic biomass production in the Flathead and Kootenai Rivers downstream. Biological benefits moderated with distance downstream due to inflows from unregulated streams. The productive portion of the river channel is limited by the lowest flow during the preceding 30 or 40 days. Benthic biomass does not recover until substrate has been continually inundated for a month or two, so short-term flow reductions should be avoided.

Implementing VARQ FC at Hungry Horse Dam had minimal effect on Flathead Lake operation over the range of flows modeled. Model simulations in the driest and wettest water years may reveal greater differences between the alternatives than were found during this study. Additional simulations could provide greater insight into the effect of VARQ FC operations during drought and flood conditions.

Introduction

Computer models developed by Montana Fish, Wildlife & Parks (MFWP) and Montana State University (MSU) for Hungry Horse Dam (HRMOD) and Libby Dam (LRMOD) were used to assess biological effects in the reservoirs. The reservoir models were designed in three components: hydrologic physical framework, temperature regime, and biological trophic levels (Marotz *et al.* 1996). Each component in the models was assessed for reliability by comparing results with observed empirical measurements. Additionally, the models were peer reviewed by independent scientists, including Dr. James Anderson and Dr. Gordie Swartzman of the Fisheries Research Institute, Seattle, Washington. The models were also critiqued and refined by the Independent Scientific Advisory Board (ISAB).

Natural Solutions developed a conceptual model to assess biological responses associated with alternative operational scenarios in the Flathead and Kootenai Rivers. The river model (RivBio) was calibrated using channel cross-section measurements collected by MFWP in the Kootenai and South Fork Flathead Rivers immediately downstream of Hungry Horse and Libby dams and the reach just upstream of Bonners Ferry, ID. Calibration data for the Flathead River at Columbia Falls, Montana were collected by Miller Ecological Consultants, Inc. using hydroacoustic survey techniques (Miller *et al.* 2003). RivBio calculates the amount of wetted perimeter each day during a simulation, and then tracks the duration each depth zone remains wet and productive. Alternatives were subsequently ranked based on time-series analyses of the growth and decay of benthic biomass.

Study Area

The Flathead and Kootenai Rivers are major headwater tributaries to the Columbia River. The Columbia River basin spans the Pacific Northwestern US and southwestern Canada (Figure 1).

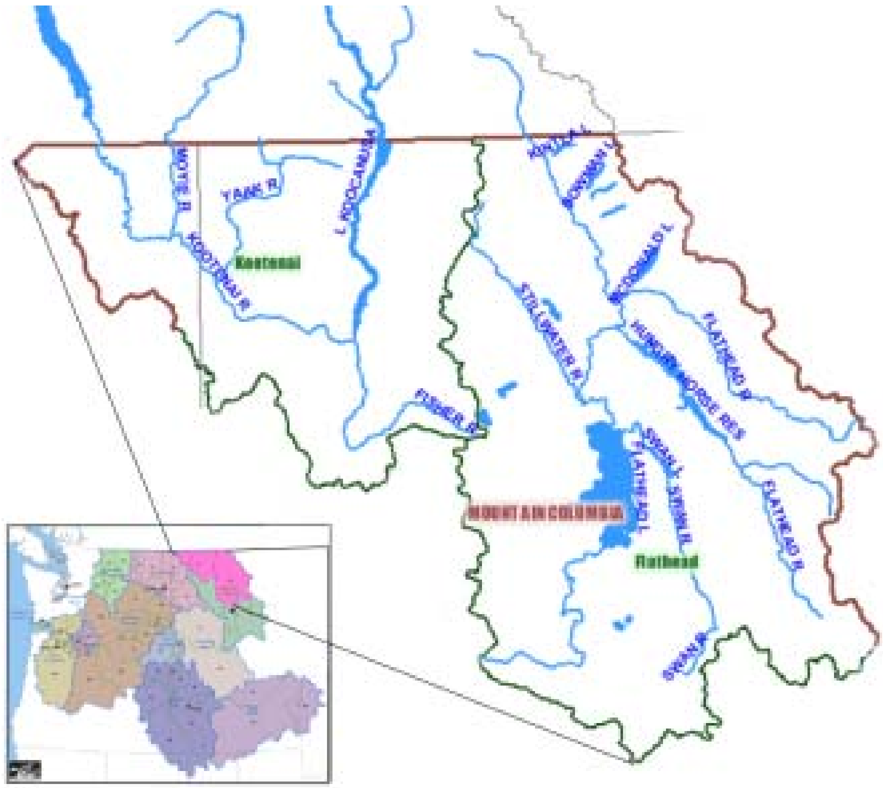


Figure 1. Location of the Flathead and Kootenai Watersheds in northwestern Montana. The Flathead River has three main headwaters. The South Fork flows into Hungry Horse Reservoir impounded by Hungry Horse Dam. The North and Middle forks form two borders of Glacier National Park and join the South Fork River downstream of Hungry Horse Dam to form the mainstem Flathead River, which flows into Flathead Lake, then into the Clark Fork of the Columbia River. The Kootenay River originates in British Columbia, Canada and flows south into Libby Reservoir (named Lake Koocanusa). Below Libby Dam, the Kootenai River joins the Fisher River, and then flows northwest through Idaho and into Kootenay Lake, BC, Canada. Both Rivers are headwater tributaries to the Columbia River (source: StreamNet and David Rockwell).

The Flathead River drainage, in northwestern Montana, is a 18,400 km^2 headwater drainage of the Columbia River basin, and includes Flathead Lake and the river system upstream (mainstem, North Fork, Middle Fork, and South Fork Flathead River). Hungry Horse Dam was completed in 1952 on the South Fork of the Flathead River near Hungry Horse, Montana. The South Fork flows from the Bob Marshall and Great Bear wildernesses into Hungry Horse Reservoir. Dam discharges merge with the North and

Middle Forks of the Flathead River to form the mainstem Flathead River that flows into Flathead Lake. Downstream of Kerr Dam, which regulates Flathead Lake, the Flathead River joins the Clark Fork of the Columbia River and flows west into Idaho.

The Kootenai River (spelled Kootenay in Canada) originates in British Columbia and flows south into Montana. Libby Dam, near Libby, Montana, was completed in 1972 forming Libby Reservoir (named Lake Koocanusa). Downstream of the dam, the Kootenai River flows south to Libby, west into Idaho, and then turns northwest into Kootenay Lake, British Columbia. The Kootenay River exits Kootenay Lake, BC through Corra Linn Dam and flows through several Canadian dam projects before joining the Columbia River.

Combined, Hungry Horse and Libby Reservoirs provide approximately 40 percent of the available U.S. water storage in the Columbia River basin power and flood control system. Both federal dams were retrofitted with selective withdrawal systems to control the water temperature of the dam discharge. Selective withdrawal enables dam operators to release water from selected depths and temperature strata in the reservoirs to mimic the natural thermal regime in the Flathead and Kootenai Rivers downstream. Both dams regulate river discharge, preclude upstream fish migration, and isolate fish populations upstream.

Hungry Horse and Libby Reservoirs follow an annual drawdown and refill cycle. The reservoirs fill during spring snowmelt toward full pool (3560 feet above mean sea level (msl) at Hungry Horse and 2459 feet msl at Libby) during July. Since 1995, the reservoirs have been drafted up to 20 feet during summer to augment flows for anadromous fish restoration in the lower Columbia River. Drafting continues during fall and winter as water is released to generate electricity to meet power demands during the cold months, and to evacuate reservoir storage to control floods during the following spring. Minimum pool is typically reached by mid-April each year, and the cycle repeats. Maximum drawdown at Hungry Horse Reservoir has reached 189 feet below full pool and Libby Reservoir has been drafted to 152 feet. Fluctuating surface elevations create vast expanses of denuded cobble, gravel and sand substrates along the shorelines, and sparse aquatic or terrestrial vegetation grows intermittently when substrate is wet or dry.

Natural river flows were highest during spring snowmelt (late May or early June) and decreased during late June or early July toward generally stable low flows from late summer through early spring. Regulated flows increase during peak energy demands from late fall through early spring, essentially reversing the annual hydrograph. Downstream of the dams, minimum river flows are normally maintained no less than 3.5 kcfs in the Flathead River at Columbia Falls and 4 kcfs in the Kootenai below Libby Dam. Channel morphology in the Flathead and Kootenai Rivers is predominantly C (meandering with flood plain development) and D (braded) stream types (Rosgen 1995).

Objectives

The specific objectives were to:

1. Simulate current dam operation strategies for Hungry Horse and Libby Reservoir models (HRMOD and LRMOD; Marotz *et al.* 1996), including VARQ flood control (FC), flow augmentation for fish restoration, and seasonal limits to dam discharge.

2. Establish the hydrologic mass balance for the different dam operations.

3. Calculate biological productivity in the reservoir biota under each dam operation alternative. Specifically, calculate primary productivity and loss through the dam turbines, zooplankton production and washout losses, benthic insect production, terrestrial insect deposition, and fish growth (kokanee at Libby; westslope cutthroat at Hungry Horse).

4. Perform model simulations for Hungry Horse and Libby Reservoirs to assess the biological responses to two alternative flood control scenarios that are being considered in the UCEIS (listed in 7 below).

5. Assess biological productivity in the Flathead and Kootenai Rivers using the Wetted Perimeter (WETP) technique for various dam operation scenarios in the Flathead and Kootenai Rivers, and rank the alternatives using existing wetted perimeter-discharge relationships and comparisons of the area of the zone of flow fluctuation, *varial zone.*

    a) Specific to the analysis of Libby Dam operations, use mass balance equations in LRMOD to simulate file data provided by the Corps for river flows at Bonners Ferry, Idaho. Reconfigure the model to simulate the tiered flow strategy for Kootenai white sturgeon and summertime flow augmentation for bull trout and anadromous fish in the lower Columbia River.

    b) Specific to the analysis of Hungry Horse Dam operations, assess biological productivity in Hungry Horse Reservoir using HRMOD, and reconfigure the model to mimic VARQ FC and summertime flow augmentation for bull trout and anadromous fish in the lower Columbia River.

    c) For Flathead Lake, update HRMOD to incorporate current operations of Kerr Dam using Reclamation data. Based on hydrological results, infer biological effects, if any, resulting from different Hungry Horse operations.

6. Evaluate biological results of each alternative flood control strategy (listed below). For each operation, analyze representative water years (as ranked by seasonal water supply or other representative parameter) as follows: three years from the 2nd quintile, three years from the 3rd (middle) quintile, and three years from the 4th quintile (Table 1).

Model simulations for Libby Dam included six different operations:

- Standard Flood Control (Benchmark LS);
- VARQ Flood Control (Benchmark LV);
- Standard Flood Control w/ fish flows, including sturgeon flows up to
- powerhouse capacity (Alternative LS1);
- VARQ Flood Control w/ fish flows, including sturgeon flows up to powerhouse capacity (Alternative LV1);
- Standard Flood Control w/ fish flows, including sturgeon flows up to 10,000 cfs over powerhouse capacity (Alternative LS2); and
- VARQ Flood Control w/ fish flows, including sturgeon flows up to 10,000 cfs over powerhouse capacity (Alternative LV2).

Libby Dam operations LS1, LS2, LV1 and LV2 are NEPA alternatives considered by the EIS; whereas benchmarks LS and LV (flood control only) are for comparison, to isolate the effects of the fish flows.

Model simulations for Hungry Horse Dam compared two alternative operations:

- Standard Flood Control w/ fish flows (HS); and
- VARQ Flood Control w/ fish flows (HV).

Both are NEPA alternatives; the effects of the flood-control-only operations were defined in the System Operations Review EIS finalized in 1995, and as with Libby, those are not being evaluated as NEPA alternatives for the UCEIS.

Table 1. Water year selection for phase 1 and 2 of the analysis.

Hungry Horse Dam	Phase 1			Phase 2		
	Tier[a]	Water year	Percentile[b]	Tier	Water year	Percentile
	2 Low	1937	20.50	2 Low	1980	30.10
	3 Average	1993	41.00	2 Low	1969	39.70
	3 Average	1981	58.90	3 Average	1979	50.60
	4 High	1943	79.40	4 High	1932	60.20
				4 High	1952	69.80
Libby Dam	Phase 1			Phase 2		
	Tier	Water year	Percentile[c]	Tier	Water year	Percentile
	2 Low	1983	29.40	2 Low	1989	23.50
	3 Average	1955	56.80	2 Low	1957	37.20
	4 High	1965	60.70	3 Average	1968	41.10
	4 High	1971	78.40	3 Average	1963	50.90
				4 High	1981	70.50

[a] Tiers represent quintiles of water availability from very low (Tier 1) through very High (Tier 5).
Tier 2 (low)=20<x≤40 percent, Tier 3(Average)=40<x≤60 percent, Tier 4(High)=60<x≤80 percent.
[b] Percentiles are based on historic inflow volumes (May through September) from 1929 through 2002.
[c] Percentiles are based on historic inflow volumes (April through August) from 1949 through 1999.

Methods

Reservoir Modeling

Hydrologic data (reservoir inflows, surface elevations and discharge) for Libby Dam were provided by the Corps (UCEIS Kootenai River Nov. 14, 2003) and Reclamation provided hydrologic data for Hungry Horse Dam and Flathead Lake (Reclamation VARQ FC Analysis March 8, 2004)

Trophic responses in Hungry Horse and Libby Reservoirs resulting from various dam operation strategies were analyzed using the quantitative biological models (HRMOD and LRMOD, respectively) developed by MFWP and MSU (Marotz *et al.* 1996). The reservoir models are public domain computer programs; however, the original models were updated and refined specifically for the current analyses. We updated the original models to simulate current dam operating practices, including VARQ FC, flow augmentation for fish restoration, seasonal minimum and maximum river flows, Flathead Lake operation and Kerr Dam discharge limits.

Model physical framework

The reservoir models solve the mass balance of reservoir inflow, surface elevation, and dam discharge based on the physical characteristics of each dam. Model input includes an annual (365 d) reservoir inflow schedule, plus either an annual schedule of daily reservoir elevations or daily dam discharges. Leap days were eliminated from all data sets. Daily simulations calculate reservoir surface elevations when the model user supplies inflow and discharge files. Discharges are calculated when inflows and surface elevations are input.

The mass balance of reservoir inflow, surface elevation change, and discharge was based on digitized three-dimensional mapping of each reservoir’s topography. Topographical maps (1 in. = 400 ft.) were digitized for each reservoir to calculate reservoir morphometry (Hungry Horse: BoR maps 447-105-211 to 238; Libby: Corps File No. E53-1-154, Sheets 1-37, 1972 and British Columbia Ministry of Environment, Drawings M-247-C, Sheets 1-63 1969). Reservoir volumes and surface area at each depth were calculated using the 3D maps and historic reservoir inflows, surface elevations and discharges, and corrected for bank storage. Once the models solved the hydrologic mass balance, the thermal model calculated daily vertical tthermal profiles and the volumes of water at each temperature in the reservoir pools (Marotz et al. 1996).

Dam Discharge

The BoR and Corps provided daily river discharge data for downstream locations. BoR provided flow data for Columbia Falls on the Flathead River and Flathead Lake elevations and discharge. Corps supplied Libby Dam discharge and Kootenai River flows at Bonners Ferry, Idaho. These data were used for all analyses in this report.

For comparison, LRMOD and HRMOD can also calculate these data using regression relationships based on concurrent historic river flow data. Daily discharge of the mainstem Flathead River at Columbia Falls can be calculated as the combined discharge from Hungry Horse Dam plus the unregulated flows from the Flathead River headwaters (North and Middle Forks). The combined flow from the unregulated North and Middle Forks was modeled using concurrent daily discharge measurements at Hungry Horse Dam and the Flathead River at Columbia Falls (USGS, 1954-1996). Daily flows from the North and Middle Forks were calculated as the flow at Columbia Falls minus Hungry Horse Dam discharge. Flow from the unregulated portion of the Flathead River headwaters was regressed on Hungry Horse Reservoir inflows to develop a predictive model used to estimate flows at Columbia Falls during simulations. The total inflow to Flathead Lake included Flathead River discharge at Columbia Falls plus inflows from the Stillwater and Swan Rivers and assorted small streams around the lake (pooled). Similarly, LRMOD can use a predictive model of unregulated local inflows to calculate the flow at Bonners Ferry, which includes Libby Dam discharge plus unregulated local inflows between Libby Dam and Bonners Ferry. For this analysis, however, the ACOE provided flows at Bonners Ferry. Alternatives (LS1, LS2, LV1 and LV2) provided fish flow requirements for Kootenai white sturgeon, bull trout and other species of special concern as called for in the 2000 Biological Opinions by USFWS and NOAA-Fisheries.

Flathead Lake Component

Hydrologic data for Flathead Lake were provided by Reclamation. For comparison, HRMOD was used to calculate Flathead Lake elevation and Kerr Dam discharge as a function of Hungry Horse Dam operation and Kerr Dam operational criteria (MPC and Corps 1962). The Memorandum of Understanding (MOU) states: "Conditions permitting, the [Flathead] lake will be drawn down to elevation 2883 feet...by April 15 and will be raised to elevation 2890 feet by Memorial Day (May 30th) and to elevation 2893 feet...by June 15th. When the lake reaches elevation 2886 feet, in moderate or major flood year, the Licensee will gradually open its spill gates to maintain free flow and will not close the gates until after the danger of exceeding elevation 2893 feet has passed." In reality, Flathead Lake seldom reaches the minimum elevation of 2883. The MOU also acknowledges that during "…natural floods in the past, unaffected by any regulation, [the surface elevations of Flathead Lake] have exceeded an elevation of 2893 feet."

The Flathead Lake component in HRMOD calculated the Flathead Lake volume and discharge capacity at each lake elevation. Two model subroutines in HRMOD calculated the Flathead Lake water budget. The first subroutine calculated the Kerr discharge capacity (kcfs) as a function of the lake surface elevation. The relationship is based on a second order polynomial regression of data provided by PPL Montana (Lance Elias, personal communication). The equation for maximum Kerr discharge 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 QMAX equation explained over 99.9 percent of the raw variation and compared closely with 11,315 daily values of historic discharges and corresponding lake elevations (Marotz et al. 1996). The second subroutine calculates the volume of Flathead Lake above elevation 2,883 feet msl 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 PPL Montana. The equation for the volume (VOL) in acrefeet is:

$$VOL=444.21 * Elev^2 + 116{,}551.47 * Elev - 115{,}847.35.$$

Where the elevation (Elev) is coded by subtracting 2,882 feet.

The equation for the elevation (Elev) is:

$$Elev = 8.48 * VOL^2 + 2{,}883.0 \text{ feet.}$$

Where the volume is expressed in million acre feet (MAF). The relationships explained over 99.99 percent of the variation in the available USGS data.

The Flathead Lake component did not include biological calculations, although some biological responses could be inferred from seasonal lake levels and Kerr Dam discharges. The Flathead River and Lake components were updated to include the most current operating requirements at Hungry Horse Dam and Kerr Dam.

Reservoir Trophic Responses

Once the hydrologic mass balance and reservoir thermal structure was established, the biological models calculated primary productivity, zooplankton biomass, aquatic insect emergence, terrestrial insect deposition, and fish growth (Marotz *et al.* 1996).

Primary Productivity

The biological response of primary producers (suspended algae or *phytoplankton*) in Hungry Horse and Libby Reservoirs was modeled using empirical data collected by MFWP and MSU from 1986 through 1989. Nutrient inputs to the reservoirs were assumed to have remained constant since the models were calibrated. Field and laboratory techniques were identical at both reservoirs. Primary productivity and chlorophyll a were measured longitudinally and at depth (0, 1, 3, 5, 10, 15, 20 and 25 m) using light and dark bottle arrays and carbon^{14} liquid scintillation techniques following Priscu and Goldman (1983). Samples were taken at buoyed sites in three locations along each reservoir. Production and seasonality of phytoplankton biomass was correlated with simultaneous measurements of solar input, light attenuation at each depth and water temperature at each depth (Marotz *et al.* 1996; May *et al.* 1988). Environmental variables including solar input, air temperature, and cloud cover and opacity exhibit short-term variability, but vary little between years. The reservoir heat budget, by comparison, responds gradually to the long-term climatic trends used to calibrate the thermal model. Similarly, the depth of the reservoir euphotic zone follows a predictable annual cycle associated with seasonal trends in river flow and turbidity. As a result, the model is sensitive mainly to reservoir surface area, volume and water temperature at each depth. The model calculates the longitudinal and vertical distribution of carbon fixation and relates these values to volumetric production rates ($mgC/m^3/d$) in each reservoir.

The loss of primary producers through the dams was calculated based on the monthly vertical distribution of C^{14} fixation in the forebay of each dam (Marotz *et al.* 1996). Since the distance from the reservoir surface to the outlet depth varies with dam operation, the estimated loss depends on surface elevation and depth of withdrawal. This relationship was simulated using a negative exponential, based on the data ($r^2 = 0.69$):

$$\%PP = {}_{exp}(2.57315 - 0.03459 * DEPTH).$$

Production within in each 3 m depth zone in the forebay was calculated as a percentage of the water column total on each day of the simulation. The result was applied to the daily discharge volume. For all simulations, the selective withdrawal thermal models were configured to withdraw water from the correct depth stratum to meet established seasonal temperature targets in the dam discharge.

Zooplankton Biomass

Monthly zooplankton densities were assessed along the length of Hungry Horse and Libby reservoirs using triplicate 30-meter vertical Wisconsin plankton net tows (May *et al.* 1987 and 1988; Chisholm *et al.* 1989). Seasonal shifts in zooplankton vertical distribution were estimated using duplicate Schindler trap (Schindler 1969) series from the water surface to 15 m in 3 m intervals, then 5 m intervals to 30 m. Zooplankton genera and size fractions were examined in the laboratory (May *et al.* 1987), and zooplankton biomass was calculated from dry weights (Bottrell *et al.* 1976).

The models calculated gross zooplankton production based on the relationship of energy transfer from the phytoplankton community to zooplankton (Ulanowics and Platts 1985). Bias introduced using this technique remains constant from one simulation to the next, which allowed us to compare alternative dam operations without the need to conduct further investigations of zooplankton population dynamics (Marotz *et al.* 1996).

HRMOD partitioned total zooplankton production by genera based on the relative biomasses of each genera captured in monthly zooplankton tows. The model calculated monthly and annual estimates of production of *Daphnia, Bosmina, Diaptomus, Cyclops, Epischura* and *Leptodora.* For each genus, 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 from regression from observed primary production values and zooplankton standing stock values. SG is a seasonality factor developed for the genera based on the observed abundance of the genera throughout the year. VOL is the volume of the reservoir containing zooplankton, and was calculated over the upper 30 m of the reservoir water column. LRMOD performs a similar calculation for zooplankton.

Loss of zooplankton through Hungry Horse Dam was calculated (by discharge volume) based on the vertical distribution of zooplankton and depth of water withdrawal (Cavigli *et al.* 1998). This function had limited effect on the results of this analysis, however, because the selective withdrawal depth was configured to achieve the optimal temperature in the dam discharge in all simulations.

Benthic Insect Production

Model calculations for benthic insect production in the reservoirs were calibrated by triplicate dredge samples from established reservoir depth zones. Larvae sieved from dredge samples and corresponding adults captured in surface insect emergence traps were collected monthly during the ice–free period from 1985 through 1990 (May and Weaver 1987; May *et al.* 1988; Chisholm *et al.* 1989; Marotz *et al.* 1996). Benthic production was calculated as insect emergence based on 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 was used as the measure of benthic production because aquatic Diptera become available as food for fish upon emergence as pupae or adults. Larvae were rarely observed in fish stomach contents. For each day of a simulation, biomass and emergence were calculated in five-foot depth increments from the water surface to the reservoir bottom.

The original models were modified for this analysis to allow for single year simulations. This was necessary because larval densities at depth are dependent on the minimum pool elevation during the previous season. During reservoir drawdown, desiccated substrate becomes devoid of aquatic insects within a few days, which essentially “resets” the vertical distribution of aquatic insect larvae from year to year. The empirically derived depth distribution of benthic larvae was, therefore, adjusted up or down based on the minimum reservoir elevation during the previous year. Standing stock estimates were then calculated based on the minimum pool elevation during the simulated water year (SEMIN). The corrected elevation (E2M) was calculated from the reservoir elevation (ELEV) on each day during the annual simulation:

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

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. Elevations in the equation denote depth zone boundaries used in dredge sampling (Chisholm et al. 1989; May et al. 1988).

The total standing stock (BD) in metric tons for the entire reservoir on the current day in each depth zone was calculated:

$$BD = MAX\ [0.0, DS * .004046856\ (b_1 - b_2 * E2M) * b_3]$$

Where DS = the surface area of each depth zone (the area of the top of the zone minus the area of the bottom of the zone), and

b_1 = 7,519 at Hungry Horse and 7,444.3 at Libby,
b_2 = 2.0915 at Hungry Horse and 3.020 at Libby, and
b_3 = 0.001385 at Hungry Horse and 0.001264 at Libby.

Benthic production (TBD) is proportional to the product of biomass (BD) and the bottom water temperature (T) squared, divided by a constant c_1 .

$$TBD = (BD*T^2)/ c_1$$

Where c_1 = 3,336.887 for Hungry Horse and 4,333.45 for Libby.

The constant adjusts the ratio of the calculated annual total production and the measured mean standing biomass, so that the ratio falls within the range expected for oligotrophic and mesooligothrophic reservoirs (Wetzel 1983). Results were corroborated by insect emergence trap data. Production within each depth zone was summed for each day. Daily values were then summed to derive the annual total for each alternative dam operation.

Terrestrial Insect Deposition

Insects from the landscape surrounding the reservoirs become available to fish as they are deposited on the water surface. Triplicate, monthly surface-tow data from nearshore (< 100 m) and offshore areas in both reservoirs showed that the four main orders of insects differed in distance from shore and seasonal abundance ($P \leq 0.05$) (Marotz *et al.* 1996). Coleoptera and Hemiptera have limited flight capability and were deposited near shore ($P \leq 0.05$), whereas Hymenoptera and Homoptera were more randomly dispersed throughout the reservoirs. The abundance of Coleoptera on the reservoir surfaces peaked in July (present April through October); Hemiptera in August and September (present July through October), Homoptera in August (present June through November) and Hymenoptera peaked in August (present July through September). The models calculated nearshore and offshore zones separately. Insects captured in surface tows do not provide a measure of insect deposition rates because insects deposited on the surface are eaten by fish or sink. Therefore, the abundance and seasonality of insect captured in surface tows was used to develop a seasonal index used to calculate the percentage of the maximum possible at full pool:

Density (number/acre) = MAX [0.0, mean + AMP* sin (period + phase shift)].

Where MAX[0.0, X] resets all values of X below zero to zero or greater.
AMP = amplitude of the sine wave. Shift = the sine wave was shifted temporally to correspond to the time period when each insects were active, as observed in surface tows and deposition traps. Each order was modeled on the mean date, AMP and phase shift of observed densities. The Coleoptera model was reset to zero during periods when ice forms on the reservoir surface.

Westslope Cutthroat Trout Growth – Hungry Horse Reservoir

During model development, factors unrelated to dam operation were isolated where possible. Dependence on previously described trophic models increases the uncertainty of fish growth calculations, resulting in a model that is conservative and sensitive only to gross changes in reservoir conditions. Bias introduced by the underlying model calculations was consistent in all simulations of the dam operation alternatives, so that the relative ranking of the various operations was not affected by compounded error (Marotz *et al.* 1996).

Westslope cutthroat growth was assumed to be proportional to the product of water temperature and food availability. The water temperature term in the calculation represents the maximum daily reservoir temperature up to the optimal temperature for trout growth. The empirically calibrated thermal model calculated the vertical thermal profile on each day of the simulation. This describes the annual development of the thermocline and fall turnover as stratification weakens. Only food items found in stomach content analyses were used in the analysis (May *et al.* 1988; Chisholm *et al.* 1989). Fish growth during model development was calculated based on fish scale annuli (Weisberg 1986) and seasonal increments in otolith growth (Brothers 1986), and growth models were verified using additional data (Brothers 1987 and 1988; see also Weisberg and Frie 1987).

The model did not address fish population dynamics because density dependent and independent factors that control fish populations in tributary streams could not be isolated. Population size and age structure were, therefore, held constant in the model to remove the effects of density dependant growth. Only fish that emigrate to the reservoir at age III (migrant class III) are represented in the model output. Daily growth was modeled for three years (age III through V) using established water temperatures and food schedules. This strategy was adequate to meet the goal of comparing dam operating strategies without the expense of further research. Coefficients represent the best model of available data. The equation for growth in mm/day is:

$$GROWTH_i = FAC_j * \mathrm{Min}(TEMP, 11.9° C) * (0.37 * \mathit{DAPHNIA}_i + 15.34\ \mathit{EPISHURA}_i + 0.060 * \mathit{COLEOPTERA}_i + 0.00015 * \mathit{HEMIPTERA}_i + 0.020 * \mathit{HOMOPTERA}_i + 0.00011 * \mathit{HYMENOPTERA}_i + 0.55\ \mathit{BENTHOS}).$$

Where, FAC_j is a scaling factor for each fish age, and 11.9° C represents the temperature of maximum trout growth efficiency. Scaling factors for each yearclass were calculated to scale the model to observed growth data (FAC = 0.0405, 0.0155 and 0.005449 for ages III, IV and V, respectively).

Growth in length (total length [TL] mm) was converted to weight (g) based on measurements from 7,813 westslope cutthroat trout used to calibrate the model:

$$WEIGHT = 0.00001146 * TL^{2.962}$$

The weight calculation solved 98.9 percent of the total variation. Model output included monthly growth (TL) and weight (g) of fish at age III through V.

Kokanee Growth – Libby Reservoir

Kokanee growth (age II and III) was described by the annual thermal regime in the reservoir and food availability. Empirical growth measurements varied with zooplankton availability and water temperature. Although growth increments, scale annuli and otoliths were available, catch data from monthly net surveys provided a larger data set of incremental kokanee growth for model calibration. Empirical growth was derived from the mode of kokanee lengths in each age class captured in monthly net samples (Chisholm *et al.* 1989; Marotz *et al.* 1996). Since zooplankton production is dependant on phytoplankton production, which varies directly with solar input and water temperature, the vertical thermal profile (thermocline) of the reservoir (to a depth of 64 m) was the most significant factor that influenced kokanee growth. Linear regression analyses showed that growth was higher for age I+ kokanee as compared to age II+ fish ($R^2 = 0.95$ and $R^2 = 0.88$, respectively).

Weight (g) calculations specific to kokanee in Libby Reservoir was based on the following relationship:

$$\text{WEIGHT(g)} = 3.16255\ E^{-6} * TL^{3.19262}$$ Where TL is the Total length (mm).

River Modeling

Hungry Horse Dam was retrofit with a selective withdrawal system in August 1996, which enables dam operators to control water temperatures in the tailrace and mimic pre-dam thermal conditions (Christenson *et al.* 1996; Marotz *et al.* 1996). MFWP quantified zooplankton vertical distribution in the reservoir forebay and entrainment through the turbine penstocks in 1995 and 1996 to provide recommendations for operating the system to minimize zooplankton entrainment (Cavigli *et al.* 1998). The selective withdrawal system can control water temperatures and zooplankton entrainment in the dam discharge regardless of which flood control strategy is implemented. Therefore, all model simulations were configured to optimize temperature targets in the dam discharge.

Researchers are currently developing empirical instream flow models for the Kootenai and Flathead Rivers that estimate bull trout and westslope cutthroat trout habitat availability at various operational flow regimes (Muhlfeld *et al.* 2003 and 2003b; Miller and Geise 2003; Hoffman *et al.* 2002). Although this research will provide a rigorous estimate of biological impacts associated with dam operations, results were not available for this project. Therefore, we used the wetted perimeter technique (WETP) to estimate biological productivity in the rivers because it was the most descriptive methodology available for this analysis (MFWP 1982; Leathe and Nelson 1986). WETP is a measure of the length of inundated river bottom across the river, similar to a chain draped over the substrate in the bottom of each channel cross-section.

RivBio

The WETP analysis was performed using the river model "RivBio" developed for this analysis. RivBio was programmed in Visual Basic (VB) using channel morphology data and river flows to calculate an index of benthic biomass for each alternative dam operation. Biological productivity in the Flathead and Kootenai Rivers was assessed using annual input files of daily dam discharge for each river reach. Daily discharges were used to calculate WETP on each date during an annual model simulation based on survey data specific to each river reach (Hoffman *et al.* 2002; Marotz and Muhlfeld 2000; Miller and Geise 2003). RivBio linked the daily river flow data to the WETP-discharge relationship for each river reach.

In the Kootenai River, WETP relationships were developed using 26 transects surveyed by MFWP in each of two river reaches (Hoffman *et al.* 2002). WETP results for each transect were averaged to derive a composite transect representing the channel morphology within each river reach. Reach 1 included transects located directly downstream of Libby Dam (Figure 2). Reach 2 included transects located immediately upstream of Bonners Ferry, Idaho, in the portion of the Kootenai River that is not influenced by the regulation of Kootenay Lake, British Columbia (Figure 3). The Kootenai River WETP relationship was calibrated at flows from 3 kcfs to 40 kcfs. Since the hydrologic data provided by the Corps contained daily flows slightly less than 3 kcfs and greater than 40 kcfs, survey results were inferred to lower and higher flows by extrapolating the tails of the WETP relationship. This relationship is linear below 3 kcfs, and data provided by the Corps seldom extended into this range. Error caused by flows greater than 40 kcfs had little effect on the model results because substrate in the highest portion of the river channel is not inundated long enough to become biologically productive.

RivBio analyzed benthic biomass growth and decay in two river reaches in the Flathead Watershed. Reach 1 includes the South Fork Flathead River immediately downstream of Hungry Horse dam (Figure 4). The WETP relationship for the South Fork Flathead River was developed using standard survey techniques (Leathe and Nelson 1986; Marotz and Muhlfeld 2000). Reach 2 is the mainstem Flathead River near Columbia Falls (Figure 5, Segment 1). Channel morphology data in reach 2 were obtained using a boat-mounted GPS hydroacoustic system (Miller *et al.* 2003).

The river model computes the size of the zone of water fluctuation, or "*varial zone*", for the various operating strategies. Depth zones varied in size depending upon the WETP relationship at various river flows.

The index of benthic biomass productivity or *"biomass units"* was computed in four steps. First, a "*status index*" was established to track wet and dry periods in the different depth zones. Beginning on the first day of a simulation, if the input flow datum was equal to or higher than the flow on the previous day, the "*status index*" was increased by one day.

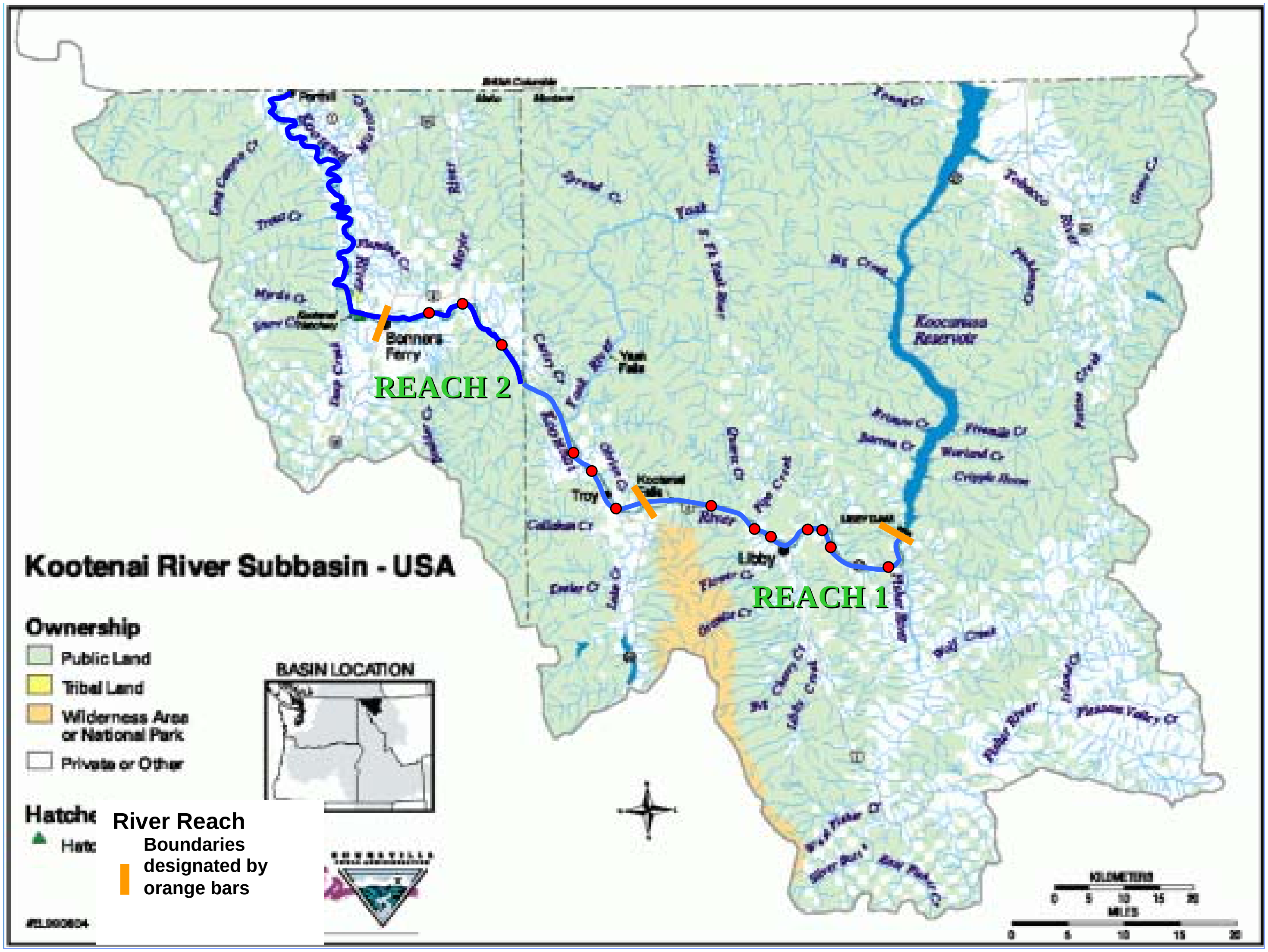


Figure 2. The Kootenai River immediately downstream of Libby Dam, Montana, was called “Reach 1” in this report. The reach just upstream of Bonners Ferry, Idaho, was “Reach 2” Sampling locations for channel cross-sections are indicated by red dots on the river channel (Source: BPA and MFWP Libby Area Office).

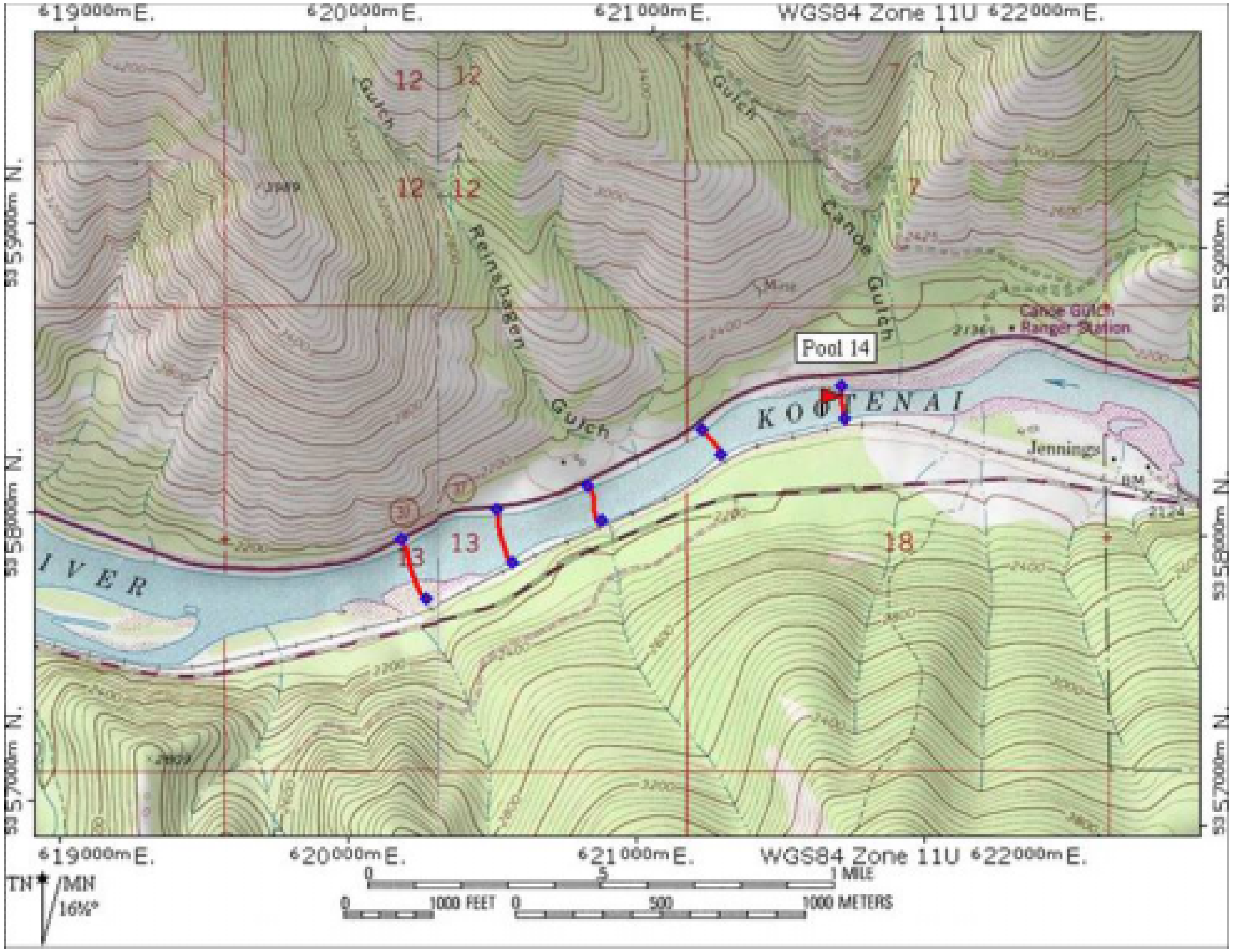


Figure 3. Each sampling location in Figure 2 represents a series of channel cross-sections that were used to calibrate RivBio. This example shows the location of transects near Jennings Rapids in Reach 1 (Source: MFWP Libby Area Office).

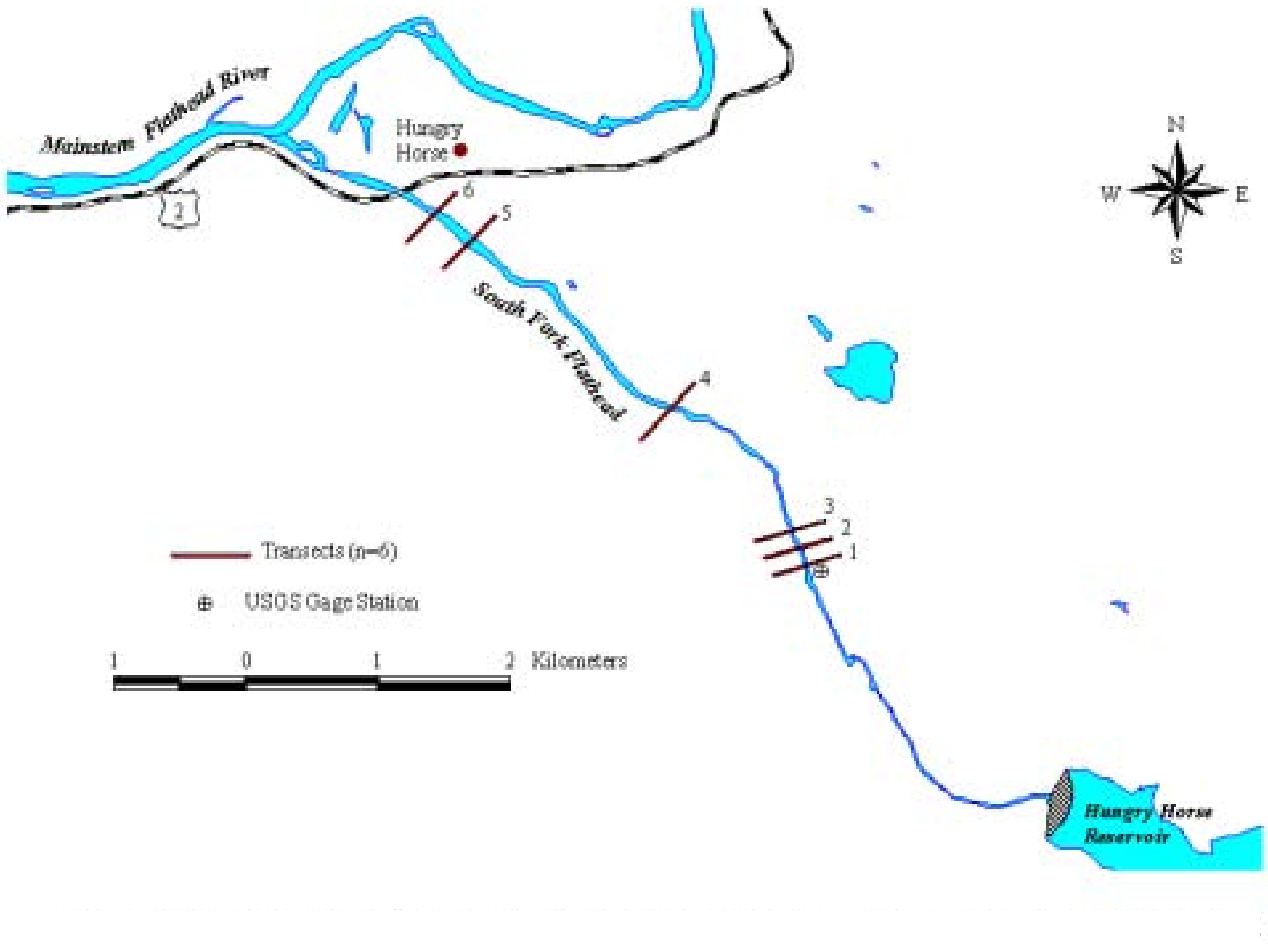


Figure 4. The South Fork Flathead River downstream of Hungry Horse Dam, Montana. The location of channel cross-sections that were used to calibrate RivBio are indicated on the map (Source: Marotz and Muhlfeld (2000) map by Steve Glutting MFWP).

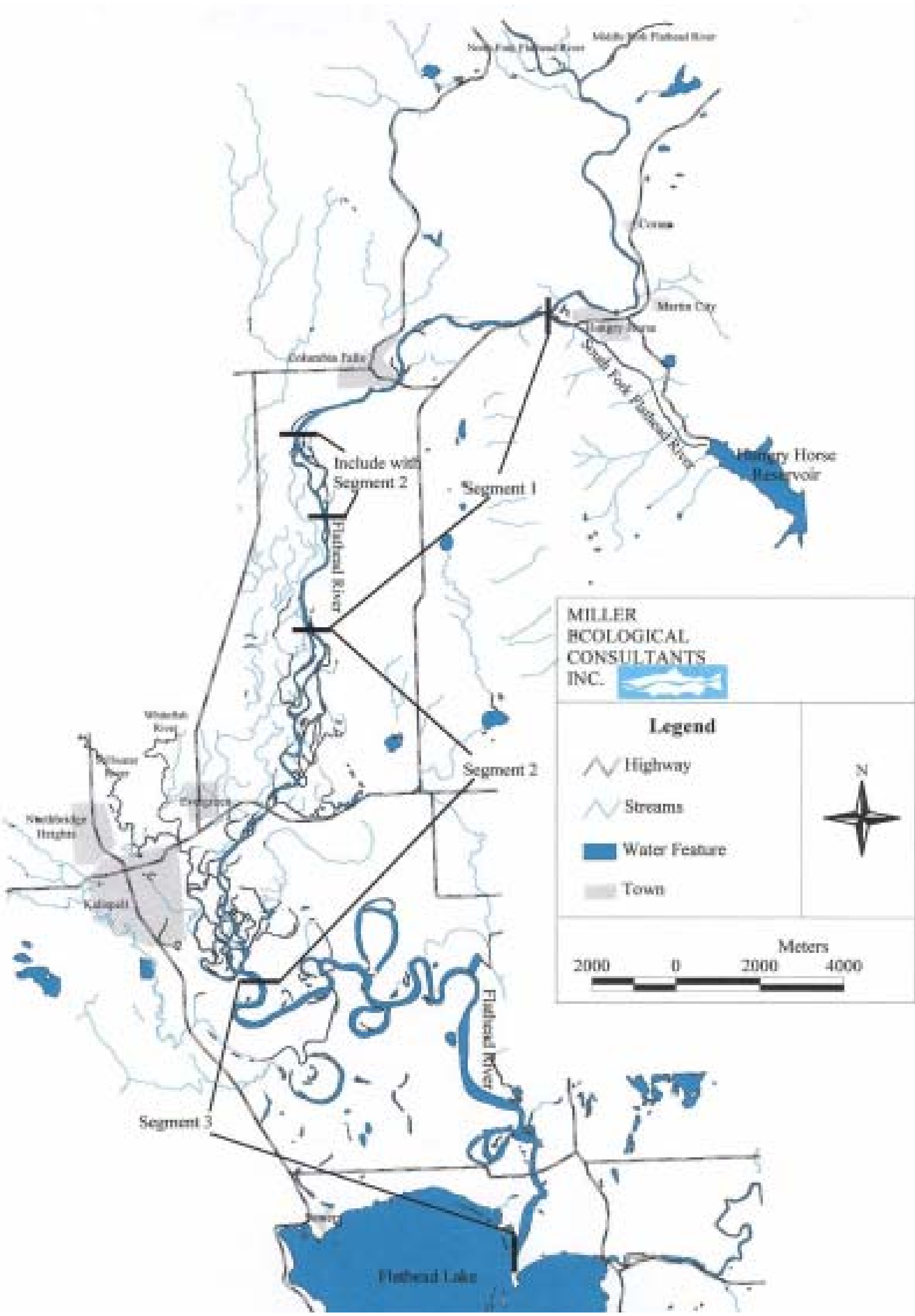


Figure 5. The Flathead River from the South Fork confluence to Flathead Lake. Segment 1 on this map includes the river near Columbia Falls, Montana, or “Reach 2” in this report. Eight representative channel cross-sections in this river reach were derived using hydroacoustic techniques (Miller and Geise 2003) and used to calibrate the river model RivBio for the Columbia Falls reach.

During each day of the RivBio simulation, the model counts the number of days each depth zone has been wet, up to a maximum number of days set by the model user (47 days was standard). Gersich and Brusven (1981) found that 47 days simulates the gradual recolonization of benthic algae and insects into newly inundated habitat. If, however, the current flow datum was less than the flow on the previous day, the status of the dewatered zone was set to –1 day. On each day, the program enumerates the number of days that a given stratum has been desiccated (up to a maximum of –5 days). All depth zones that remained wet, below the minimum flow, during a given year were considered productive (status ≥ 47 d). All depth zones that remained dry, above the maximum flow, during a particular year were scored as unproductive (status = -5 d).

Secondly, the *"condition index"* within each depth zone was scored on a relative index, scaled from 0 to 1 depending upon the zone's daily status index (0 = fully desiccated and unproductive, 1= fully recovered). The varial zone gains and loses benthic biomass throughout the year as substrate is intermittently inundated and dried. Positive status values correspond with biomass gains and negative status scores correspond with biomass losses. The "Condition matrix" inputs the daily status of each depth zone and compares it to the previous day, then adjusts the condition index based on the growth and decay curves. Daily increments or decrements in the condition index were taken directly from the growth and decay curves described in Figures 5 and 6. The rate of insect recolonization when substrate remains wet was set to 47 days. This assumption was tested using a sensitivity analysis described in the results section. Lost production was calculated as an exponential decrease over a 5-day period for each day the substrate was dry (Figure 7). The 5-day desiccation metric calculated losses in benthic biomass caused by sudden flow reductions.

Thirdly, the preliminary "*biomass index"* is calculated as the condition index in each depth zone multiplied by its wetted perimeter. The wetted perimeter relationship provides an index to the area of substrate involved. Specific biomass indices were calculated for all depth zones on each day, depending on the duration that substrate remained wet. RivBio does not have the resolution required to ascribe seasonality to the various guilds of aquatic organisms. The model did not distinguish substrate or habitat types. Insect density was assumed to be random and consistent throughout the wetted river channel after the benthos was fully recovered.

The fourth and final calculation adjusts all the raw biomass indices by the seasonality factor for each date. The model incorporated a seasonal weighting factor to describe the annual potential for biological productivity. Water temperature begins to warm in mid April and increases rapidly after the spring runoff peak in late May/early June. Water temperatures cool rapidly in October, reaching the winter low approximately in January. Benthic algae fix more carbon during the warm months as day length increases.

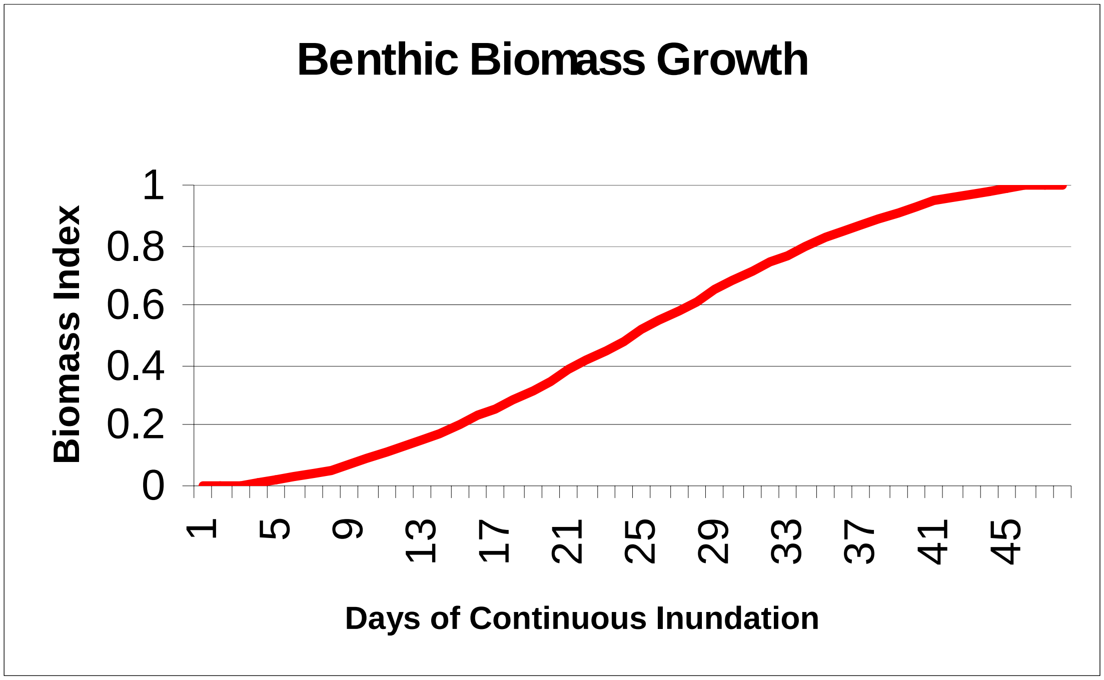


Figure 6. Sigmoid shape of biomass increase when substrate remains inundated. This index assumes a gradual increase from 0 (desiccated) to 1 (productive) over a 47-day period of continuous inundation, approximating the rate at which newly inundated substrate becomes colonized by benthic algae and aquatic insects. RivBio assumes that benthos are randomly distributed across the permanently wetted portion river bottom (score =1). Benthic biomass scores in the varial zone ranged from 0 to 1 depending on the duration substrate in each depth zone remained wet.

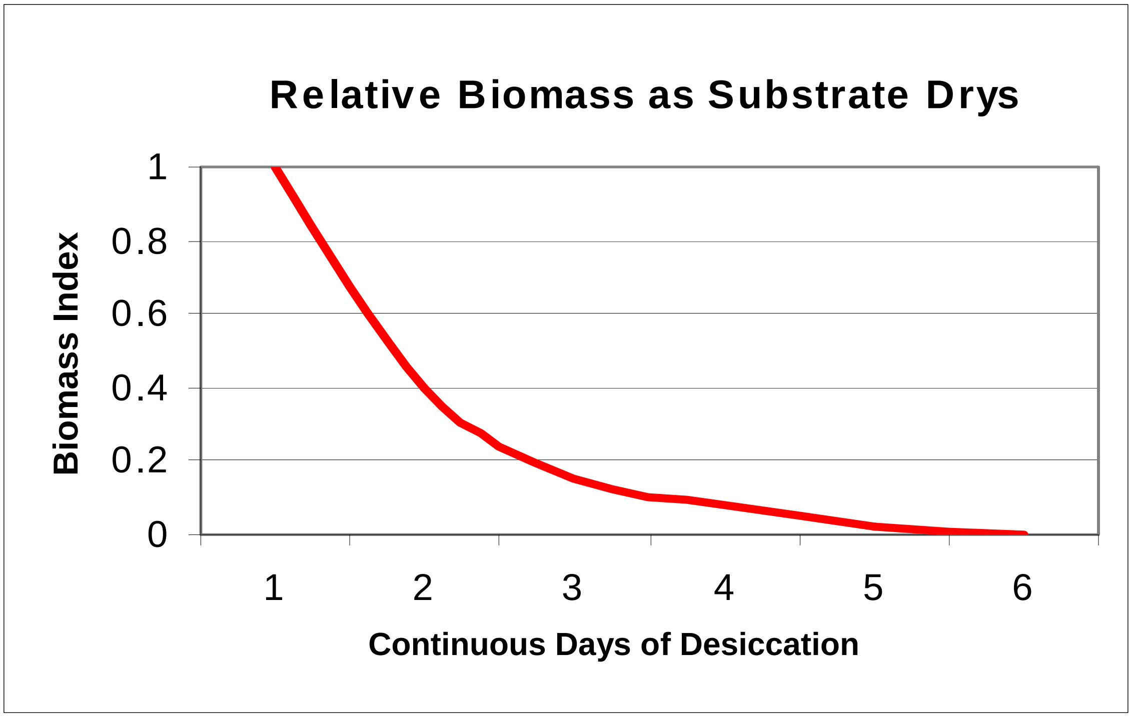


Figure 7. Exponential decay of viable biomass after productive substrate becomes dry. We assumed a complete loss of benthic productivity in each depth zone after 5 days of desiccation. All areas that remained dry for five or more days were assumed to be devoid of benthic biomass (score = 0).

Seasonality was described as a one wave-length, truncated sine wave centered on July 30 (WYD = 314; Figure 8). This un-scaled index mimicked the seasonality of longer photo-period and warmer water temperatures during summer and their influence on biological productivity. Insect emergence follows a similar annual pattern (Perry 1984; Perry *et al.* 1986; Hauer *et al.* 1994; Hauer *et al.* 1997). Although many large aquatic insects have life cycles of a year or more, multivoltic species can have more than one reproductive cycle in a growing season. For example, caddis flies emerge during the entire ice-free period providing a continuous food supply for fish, and mayflies and stoneflies have spring and fall forms and large species that emerge in early summer.

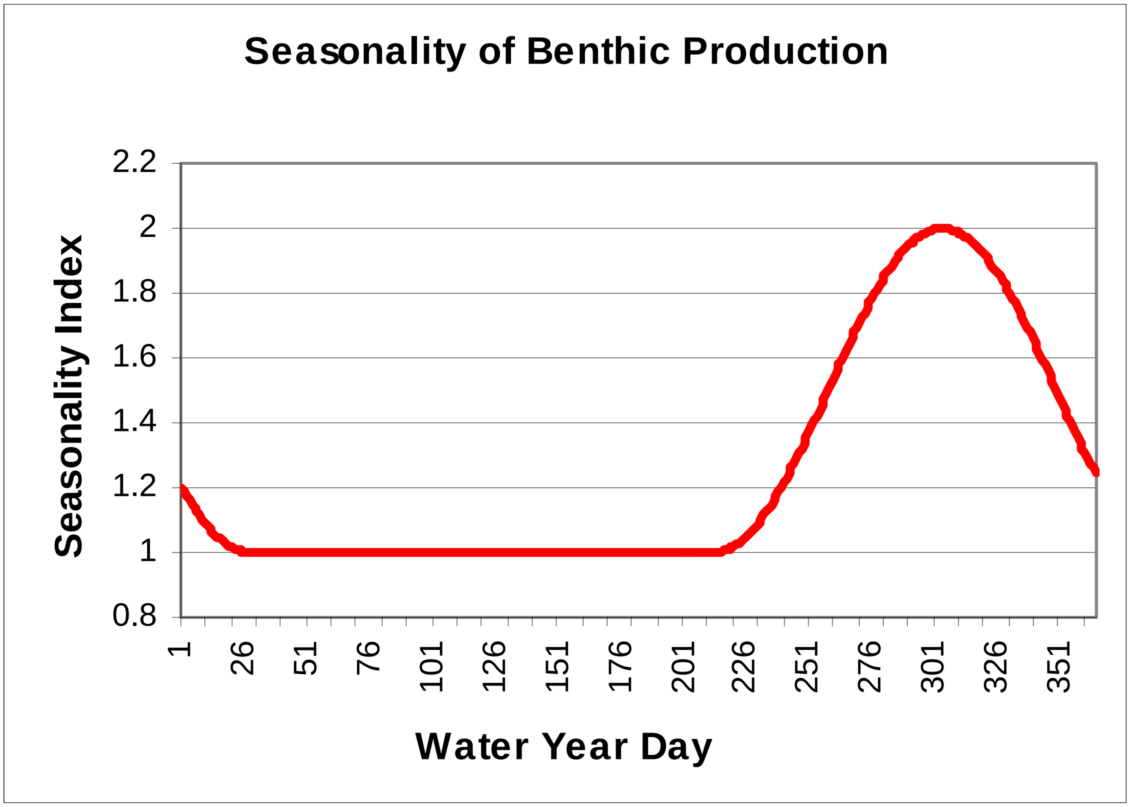


Figure 8. The seasonal index of benthic productivity was modeled as a one wave-length, truncated sine curve has the peak centered on July 30th. This un-scaled index assumed that benthic production was twice as great during summer as compared to winter to mimic the seasonal effects of photo-period and water temperature.

Ranking the relative biological potential of each alternative was performed using time series analysis on the amount of substrate that remains wet and biologically productive. Different seasons and different days have differing values depending upon how much surface had been inundated and for how long. The net of losses and gains of benthic biomass units were used to rank the alternatives. The total for each period of the year was derived by summing productivity scores for all days and depth zones, which provided the relative rank of each alternative. In this analysis, we compared relative values during the period March 1 through September 30 in the Kootenai and annual totals in the Flathead. The Corps requested that the river production calculations in the Kootenai River be limited to this period (WYD 152 to 365) because the simulated power operations during the fall and winter may vary temporally from actual operations.

We used RivBio to calculate the following physical and biological parameters:

1. Physical index: a) range of WETP range and b) range of stage variation during a given period or year;

2. Biological indices:

    a. Index of biomass gains over the year including: a) total units by depth zones, b) total units by days, and c) annual (or partial year) grand totals calculated from the amount of productive wetted perimeter; and

    b. 3. Index of the amount of potentially productive biomass achieved (or not achieved).

We report biological responses for Hungry Horse and Libby Reservoirs, the South Fork Flathead River, and Kootenai River downstream of the dams and points downstream, including the Flathead River at Columbia Falls, Flathead Lake and Bonners Ferry. Results are reported for three years in each of three categories of water availability: slightly dry, average, and slightly wet water years (Table 1). For the reservoirs, results describe trophic responses by primary producers, zooplankton, insects and fish for each year of the simulation (Figure 9).

River operations were ranked based on benthic biomass, flow seasonality and the range of fluctuation. Data sets are summarized in the report for brevity. The entire set of output files and can be viewed electronically using the accompanying compact disk (See Model Output files for each watershed).

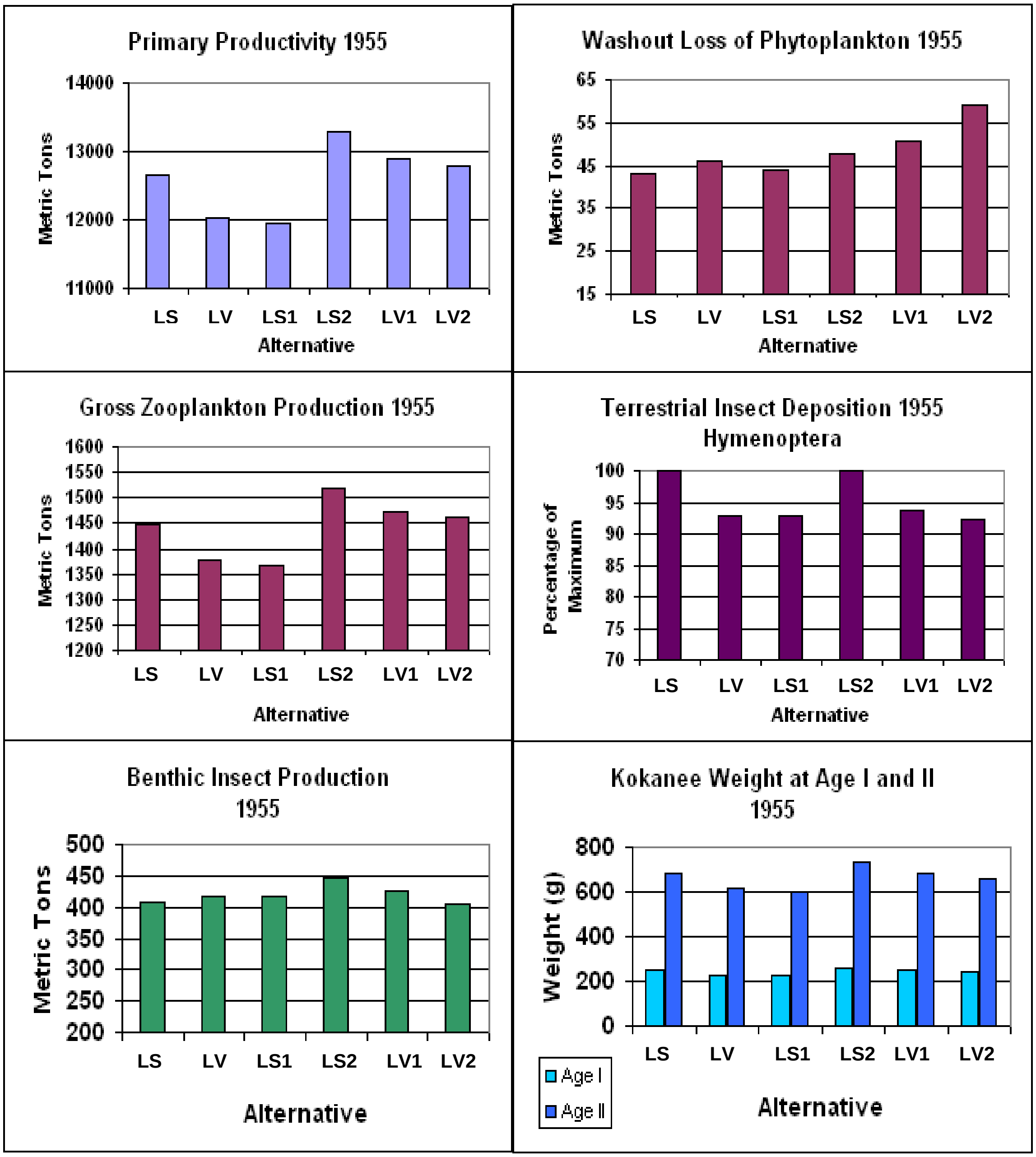


Figure 9. Example of biological results for six model simulations comparing biological responses in Libby Reservoir. Annual results for each year are named "Biol9**.xls" in folders for each simulated water year (see accompanying CD).

Modeling Assumptions

- Certain model functions were held constant during annual simulations of alternative flood control and fisheries strategies to avoid bias in model results. During all simulations, the selective withdrawal thermal control structures on Hungry Horse and Libby Dams were configured to seasonal temperature targets. Water was discharged from the appropriate layer of the reservoirs to remain within the designated minimum and maximum seasonal targets.
- 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 by MFWP.
- Meteorological parameters (i.e. inflow water temperature, air temperature, humidity wind speed, cloud cover and opacity) were modeled using modified sine waves fit to 11 years of daily records from local weather and gauging stations, correlated to measurements at each dam (Marotz *et al.* 1996). Weather effects were held constant in all model simulations.
- Water temperature in the dam discharge equals the temperature in the reservoir forebay at the depth of water withdrawal.
- All model simulations conformed to flow ramping rates and seasonal minimum and maximum flow targets specified in the NOAA-Fisheries and USFWS 2000 Biological Opinions.
- According the Corps Environmental Coordinator for this project, simulated power discharges during the winter period at Libby Dam may differ from actual operations. Therefore, we analyzed biological conditions in the Kootenai River during the period March 1 through September 30 only.
- Nutrient loading to the reservoirs has not changed significantly since the models were calibrated in 1996.
- All discharge water was assumed to pass through the turbines (no spill) and the selective withdrawal system even when default model specifications had to be superseded to accurately portray the hydrologic data provided by the Corps and Reclamation.
- Operating alternatives for Libby Dam contained fish flows as high as maximum existing turbine capacity plus 10 kcfs. Model simulations did not differentiate turbine and spillway discharge. Temperature effects of potential surface water release through the spillway could not be assessed.
- Total zooplankton production was proportional to primary productivity, minus a loss function established for plankton communities in oligotrophic, temperate waters.
- Total zooplankton production at Hungry Horse Reservoir was subdivided into estimates of production within each zooplankton genus, based on the relative biomass of zooplankton genera captured in monthly sampling series (1983-1991) (May *et al.* 1988).
- Estimated washout of zooplankton from Hungry Horse Reservoir, per discharge volume through the selective withdrawal structure (which became functional in August 1995), was assumed to be proportional to the measured density at each withdrawal depth (Cavigli *et al.* 1996).

- The vertical distribution of Chironomid larvae in the reservoir substrate was assumed to be proportional to triplicate dredge samples in each depth zone (May *et al.* 1988; Chisholm *et al.* 1989). This distribution is adjusted up or down to reflect the minimum reservoir elevation during the previous year at the beginning of each annual simulation.
- Annual water year simulations at Libby Dam are initiated at full pool elevation 2459 in benchmarks LS and LV, and 20 feet below full pool in all the alternatives (LS1, LV1, LS2, LV2).
- Annual water year simulations at Hungry Horse are initiated at the elevation specified in data provided by Reclamation.
- The seasonality and relative abundance of terrestrial insects trapped in the reservoir surfaces were assumed to be proportional to captures in duplicate surface tow nets in nearshore (<100 m) and offshore (>100 m) zones (Chisholm *et al.* 1989; May *et al.* 1988).
- Fish population sizes and relative abundance were assumed to be static for all simulations. The model design focused on the relative effects of various dam operations on fish growth in target species (westslope cutthroat trout (WCT) at Hungry Horse and kokanee (KOK) at Libby).
- Fish growth estimates assumed identical dam operations during each year of the fish's life cycle. WCT at ages IV+ and V+ and KOK at ages I+ and II+ assumed constant operation for 2 and 3 years, respectively.
- Benthic insect productivity in the river channel recovers within 47 days after dry substrate becomes inundated (Gersich and Brusven 1981). The rate of recovery in a given depth zone after inundation follows a sigmoid curve, scaled from zero to one with one being fully recovered.
- Benthic biomass was assumed to be randomly dispersed throughout the river channel; all depth zones in the wetted perimeter were considered equally productive after recovery.
- Benthic biomass in the river channel declines exponentially to zero five days after productive substrate becomes dry.
- Biological productivity in the rivers occurs on an annual cycle that approximates a one wave-length truncated sine curve centered on the end of July. To simulate a seasonal effect, benthic biomass was assumed to be twice as great during summer than during mid winter (see seasonality of measured productivity in the reservoirs).

Results

Libby Reservoir

Primary productivity

Primary production (carbon fixation) by phytoplankton was limited by changes in reservoir surface area and the volume and average temperature within each depth stratum. The model calculated the longitudinal and vertical distribution of carbon fixation and related these values to volumetric production rates ($mgC/m^3/d$) for each operating alternative. Model output included daily schedules of carbon fixed by phytoplankton (see example in Figure 10). Totals for the four alternatives and two benchmark operations were summarized by water year (Figures 11). The benchmark operations (LS and LV) begin the water year at full pool (elevation 2459) on October 1, so results were plotted separately from all other alternatives that begin the simulation 20 feet below full pool (elevation 2439).

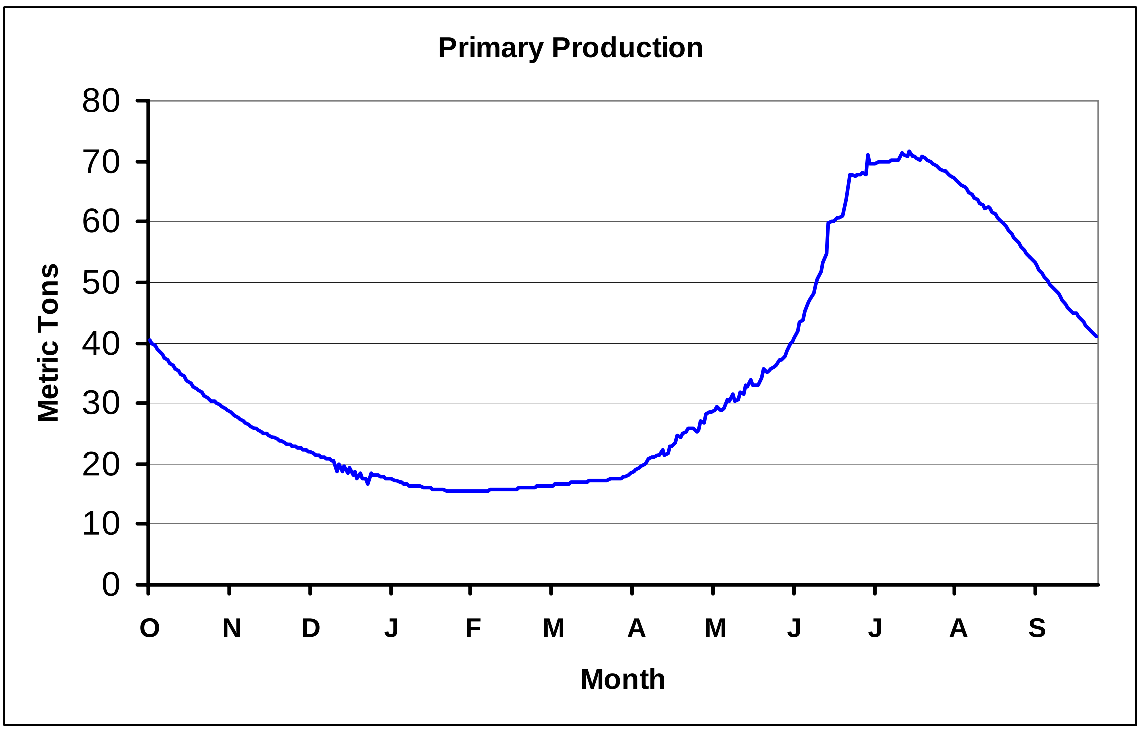


Figure 10. This annual schedule of primary production in Libby Reservoir shows model results from the 1955 benchmark LS (standard flood control without fish flows). Vertical and longitudinal distribution of primary production in the reservoir was calibrated using light and dark bottle arrays and liquid scintillation measurements of C^{14} uptake. The shape follows annual trends in water temperature and solar input.

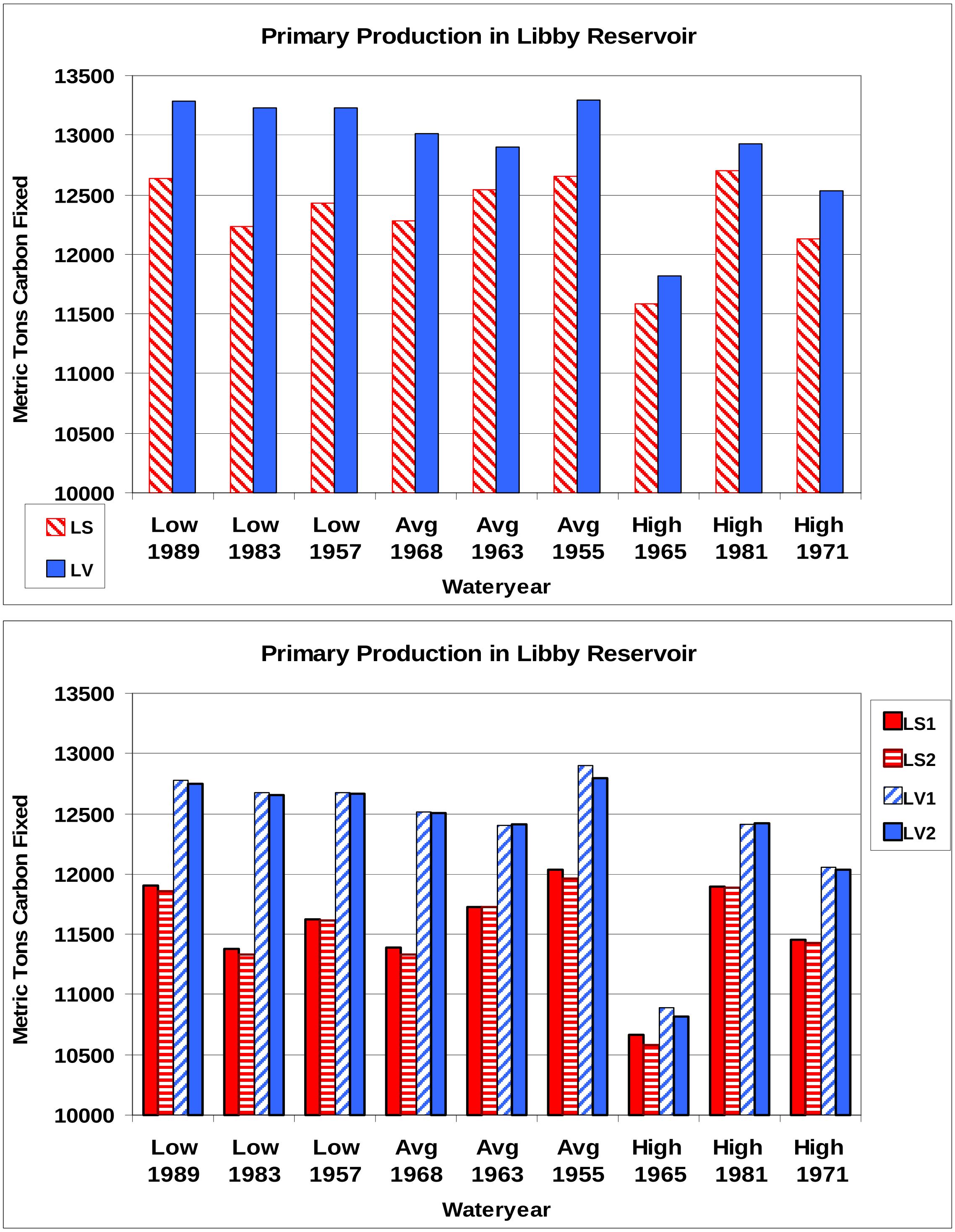


Figure 11. Primary production calculations (metric tons of carbon fixed by phytoplankton) were calculated for each of the six alternative dam operation strategies. Benchmarks LS and LV initiated at full pool, whereas the other alternatives began 20 feet below full pool, so were plotted separately. Results were arranged by water availability during each water year in order from low (X-axis left) to high water years (X-axis right).

Model calculations of primary production ranged from 10,578 to 13,289 metric tons under the six alternative dam operation strategies. Benchmarks LS and LV produced more phytoplankton because Libby Reservoir remained at or near full pool during the productive warm months. All alternatives (LS1, LS2, LV1, and LV2) provide fish flows and remained 20 feet from full pool during late-summer and fall. The VARQ FC benchmark operation without fish flows provided reservoir conditions that produced the highest values of primary production. When fish flows were added, Alternative LV1 resulted in slightly greater primary productivity than LV2 during seven of the nine water years, and LS1 produced more phytoplankton than LS2 during all nine years.

Loss of phytoplankton through the dam turbines was controlled mainly by the discharge volume and the vertical distribution of phytoplankton relative to the depth of water withdrawal. The thermal model was configured in all simulations to release reservoir water from the appropriate depth to meet the specified seasonal temperatures in the Kootenai River. This caused the depth of withdrawal, as measured from the reservoir surface, to remain relatively constant between alternatives, thus limiting the difference between the alternatives. The differing starting elevation in the simulations had little effect on results, so all alternatives were plotted on the same graph. Differences in the annual schedule of primary productivity in the reservoir and the seasonality of dam discharge volumes influenced washout losses (Figure 12). Results would differ if the selective withdrawal structure was operated differently.

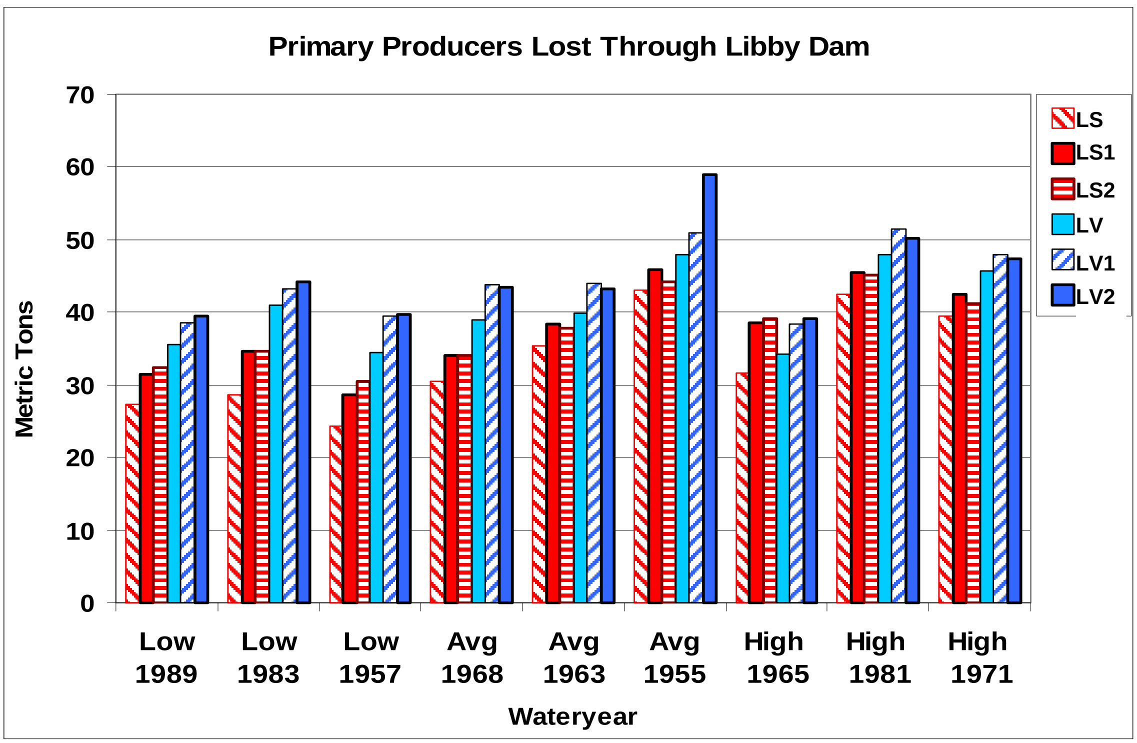


Figure 12. Estimated loss of primary producers through the dam turbines resulting from each alternative. Withdrawal depths were automated for consistency in all simulations. Therefore, loss calculations were most sensitive to production in the reservoir and the seasonality of discharge volumes.

Seasonal flows and the depth of water withdrawal influence washout of primary producers through the turbines of Libby Dam. Because selective withdrawal was modeled the same way in all simulations, the seasonal discharge volume was the strongest controlling factor in this analysis. Still, the water withdrawal depth remains an important factor determining to amount of plankton discharged through the dam. Results indicate that VARQ FC alternatives result in greater washout loss of primary producers than the Standard FC alternatives. As expected, operations that provide "fish flows" passed more phytoplankton through the dam than their respective LS or LV "flood control only" benchmarks. Alternatives LV1 and LV2 ranked highest during eight of nine water years, and LV2 had the highest losses in five of the years simulated. Losses were proportional to the level of production in the reservoir stratum at the outlet depth influenced by penstock turbulence. When more primary production occurred in the reservoir, more phytoplankton was lost through turbine penstocks. Washout losses represent a small fraction of the overall production in Libby Reservoir and provide a trophic gain to the Kootenai River.

Zooplankton Production

The annual schedule of zooplankton production was a function of phytoplankton production calibrated to reported energy transfer efficiencies as zooplankton graze on phytoplankton. Not surprisingly, a plot of the seasonality of zooplankton production is shaped very similarly to the annual schedule for primary productivity (Figure 13).

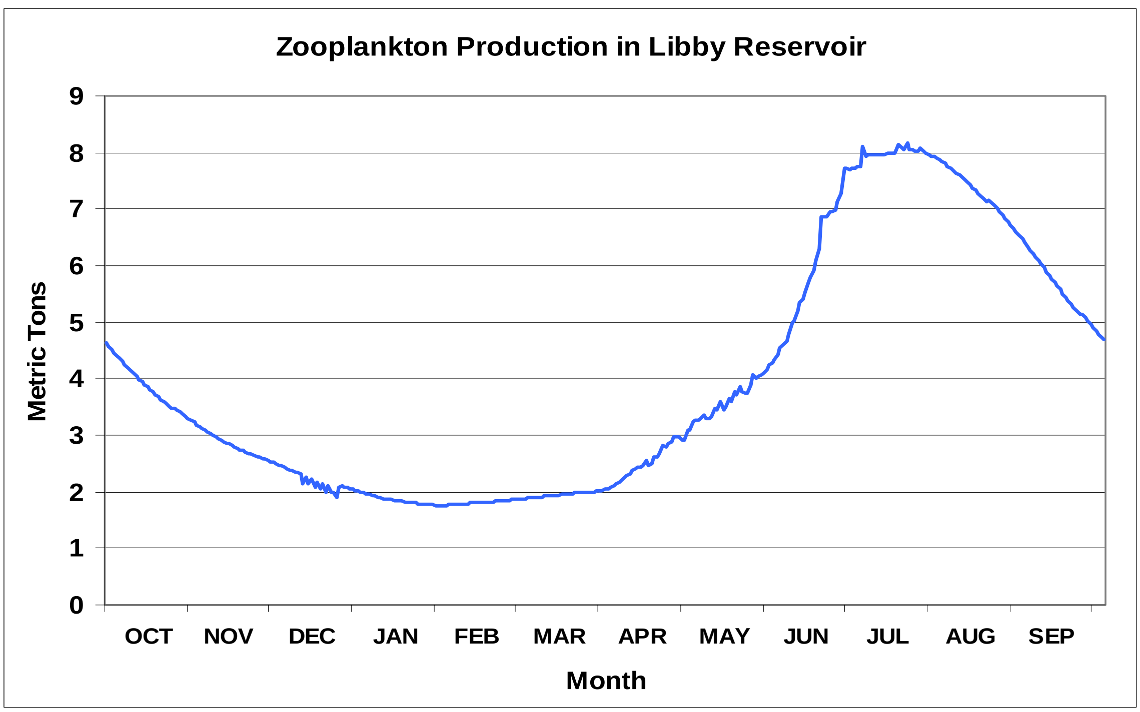
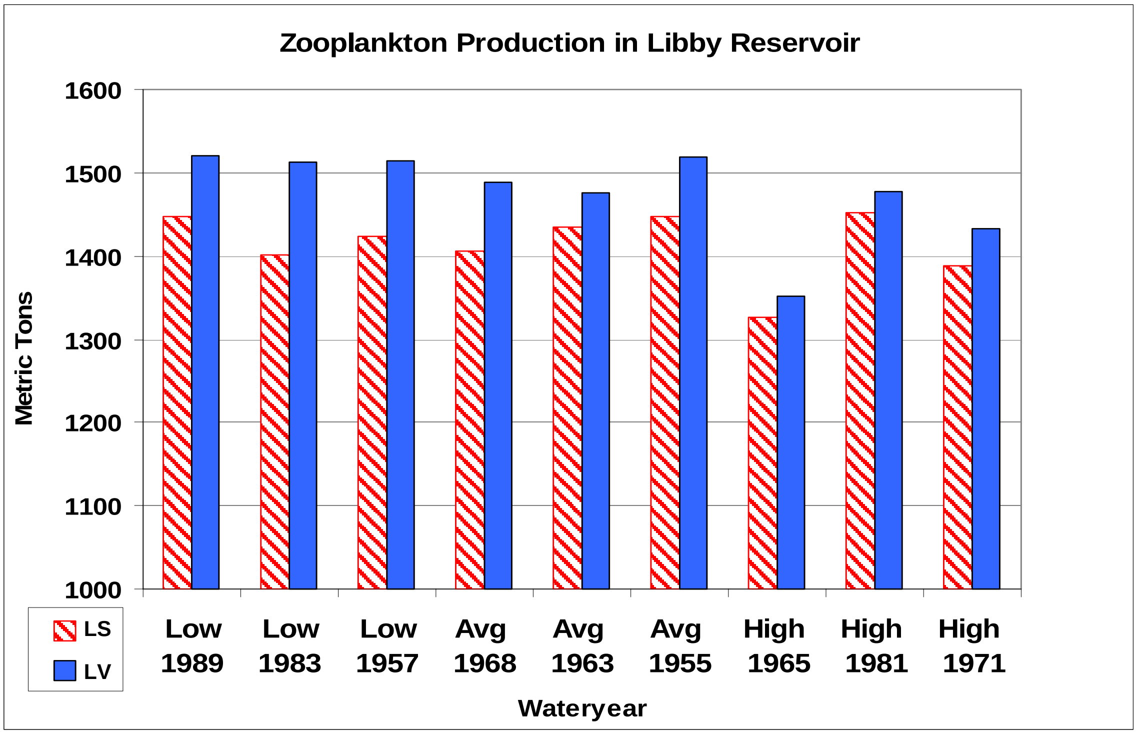


Figure 13. An example annual simulation of a zooplankton production for 1955 Benchmark LS. ASCII text files for each simulation are named Biol9**.dat, where "**" represents the last two digits of the year. This example is from an Excel file named Biol955-b.xls located in the \Libby Reservoir\1955\ folder.

Once produced, zooplankton survive in the reservoir for an indefinite period until they are eaten by predators (e.g. fish, Leptodora), die from natural causes and sink, or lost through the dam. Enough individuals survive through fall and winter that zooplankton provide the primary winter food for fish species that do not prey on fish (including westslope cutthroat trout and juvenile bull trout). Zooplankton are the primary food supply utilized by kokanee throughout their lives. Model estimates of zooplankton production under the six alternative operating strategies reflected differences in surface area and volume at depth during each simulated water year (see folders for each year containing Excel files named Biol9**.xls on the CD).

Zooplankton production estimates ranged from 1209 to 1521 metric tons across all years and alternatives. Benchmarks LS and LV began at full pool on October 1 and were not drafted during the biologically productive summer months to augment flows downstream. Operations that maximized surface area and volume during summer produced the most zooplankton. In general, the Standard FC alternative had lower reservoir elevations during spring as compared to the VARQ FC alternative, which resulted in a slower build up of zooplankton biomass in the Standard FC alternatives (Figure 14). Conversely, reduced reservoir drawdown during spring under the VARQ FC operation created a larger volume of optimal temperature water as zooplankton production increased toward the summer maxima. Alternative LV1, VARQ FC with fish flows, produced slightly more zooplankton than did LV2 during 6 of the 9 years. During the two highest water years, LV2 produced more zooplankton. Additional simulations are required to determine if a trend exists between the two VARQ FC alternatives. Logically, since LV2 increases fish flows by an additional 10 kcfs, the downstream washout of zooplankton would be greater. Further, the accelerated water exchange rate in the reservoir should delay production as the reservoir fills. Zooplankton washout under LV1 and LV2 would become more similar during high water years, as alternative operations converge (Figure 11, also see plots of all input variables in \H-Input\ for Hungry Horse and \L-Input\ for Libby). As water supply increases, the alternative operations become more similar. This is presumably because as water availability increases, Libby Dam can only regulate a progressively smaller percentage of the annual water budget.

Zooplankton washout losses could be managed to some extent using the selective withdrawal system at Libby Dam. Such control, however, may not be warranted because once zooplankton are produced they remain available to fish until they sink or wash through the dam. Although washout losses increase with higher dam discharges, the loss is a small fraction of the overall reservoir productivity. Another mitigating factor is that zooplankton swept through Libby Dam provides a trophic gain to the Kootenai River. The amount of zooplankton available as food for kokanee is therefore mainly influenced by the amount of zooplankton produced in the reservoir. Food availability is largely controlled by reservoir surface area and volume during the productive summer months.



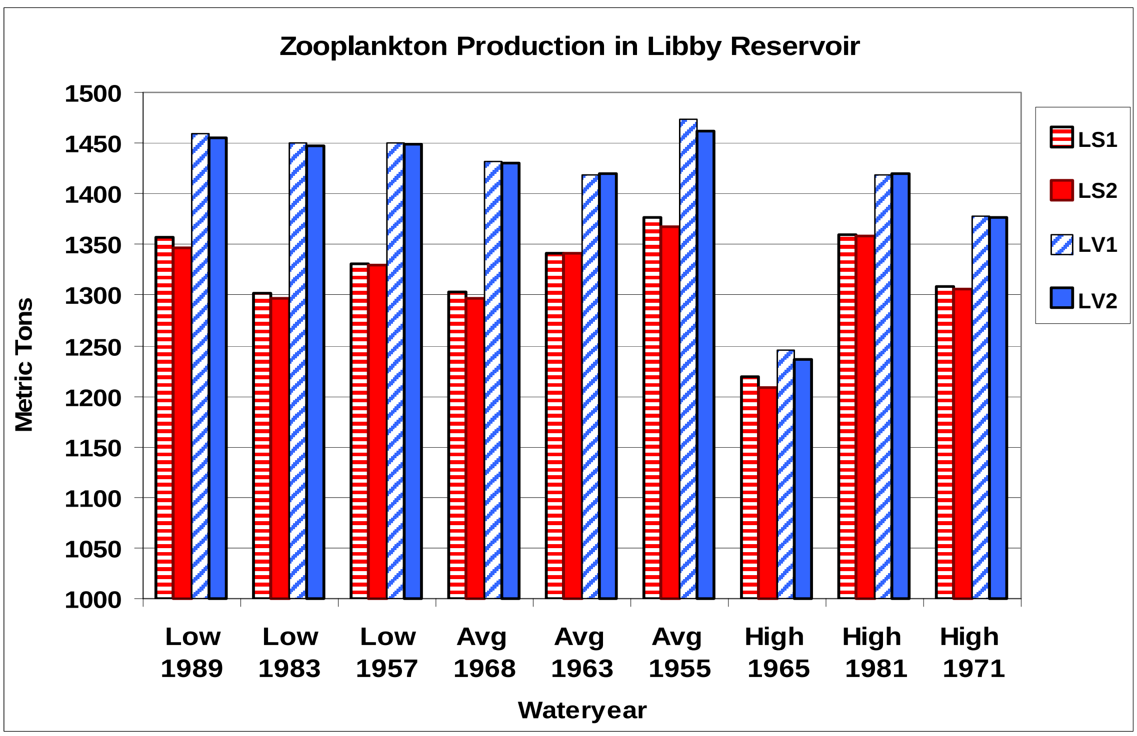


Figure 14. Zooplankton production (metric tons) in Libby Reservoir under each alternative was plotted for comparison. The "flood control only" benchmarks LS, Standard FC, and LV, VARQ FC, initiate at full pool on October 1. The "flood control with fish flows" alternatives LS1, LS2, LV1 and LV2 initiate at 20 feet below full pool, so were plotted separately. Graphs of annual reservoir surface elevation schedules can be found in "All Years Lsurf.xls".

Benthic Insect Production

Impoundment of the Kootenai River by Libby Dam and annual operations have greatly simplified the diversity of aquatic insects in Libby Reservoir by reducing insects that are adapted to flowing water (e.g. stoneflies, mayflies and caddis flies). Aquatic diptera dominate the existing reservoir insect community. Larger, long-lived species dominate the permanently wetted zone, whereas the varial zone contains mainly small, short-lived *multivoltic* species. Larvae recolonize previously dewatered substrates as the reservoir fills, and shoreline areas are dominated by multivoltic dipterans that produce cohorts throughout the warm summer months (May 1988; Chisholm *et al.* 1989).

Annual production schedules are controlled by the substrate area of each depth zone (digitized from topographic maps) and the duration each zone remains wet and productive as the reservoir refills and drafts. The model calculated daily estimates of benthic insect production during the water year (Figure 15). Annual production totals were compared between alternatives for each simulated water year and summarized for each category of water availability (Figure 16).

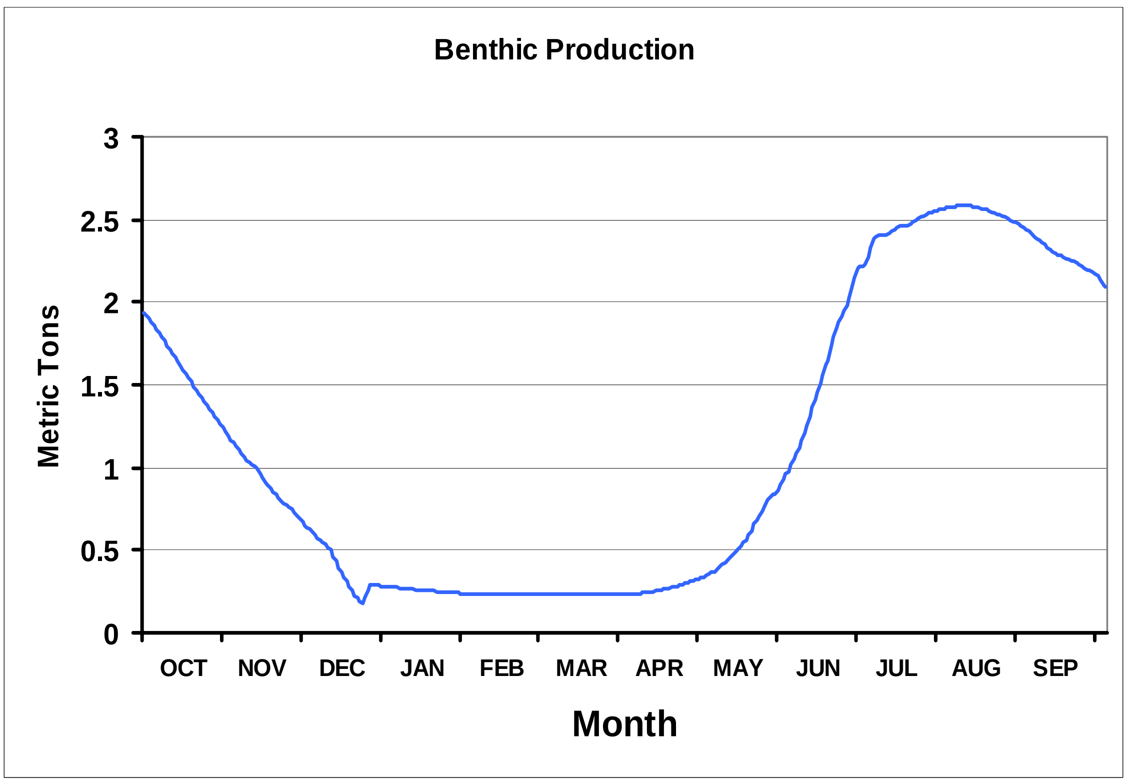
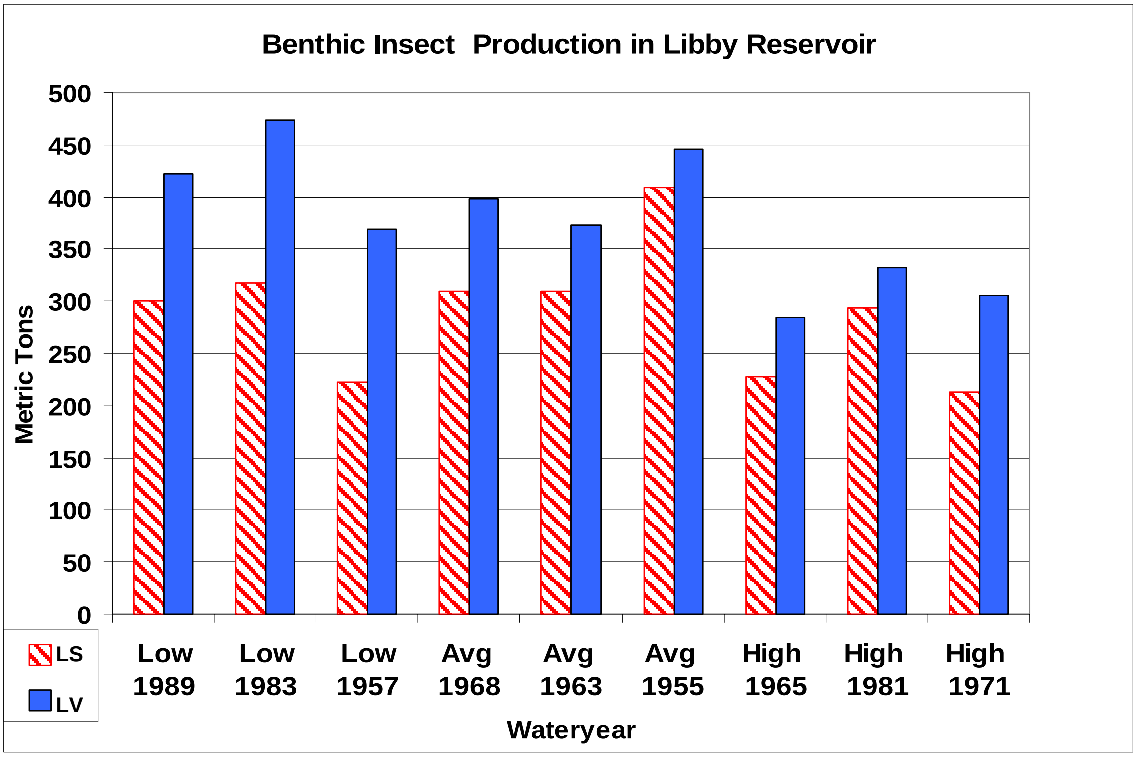


Figure 15. Daily simulations of benthic dipteran production were calibrated using dredge samples of larval distribution at depth and emergence rates from surface trapping at varying distances from shore. Results were controlled mainly by the wetted substrate area in each reservoir depth zone. The vertical distribution of larvae was adjusted to the minimum pool during the previous water year. This example is 1955, Benchmark LS. The complete data are named biol9**-*.txt in folders containing output for each year (e.g. \1955\biol955-b.txt).



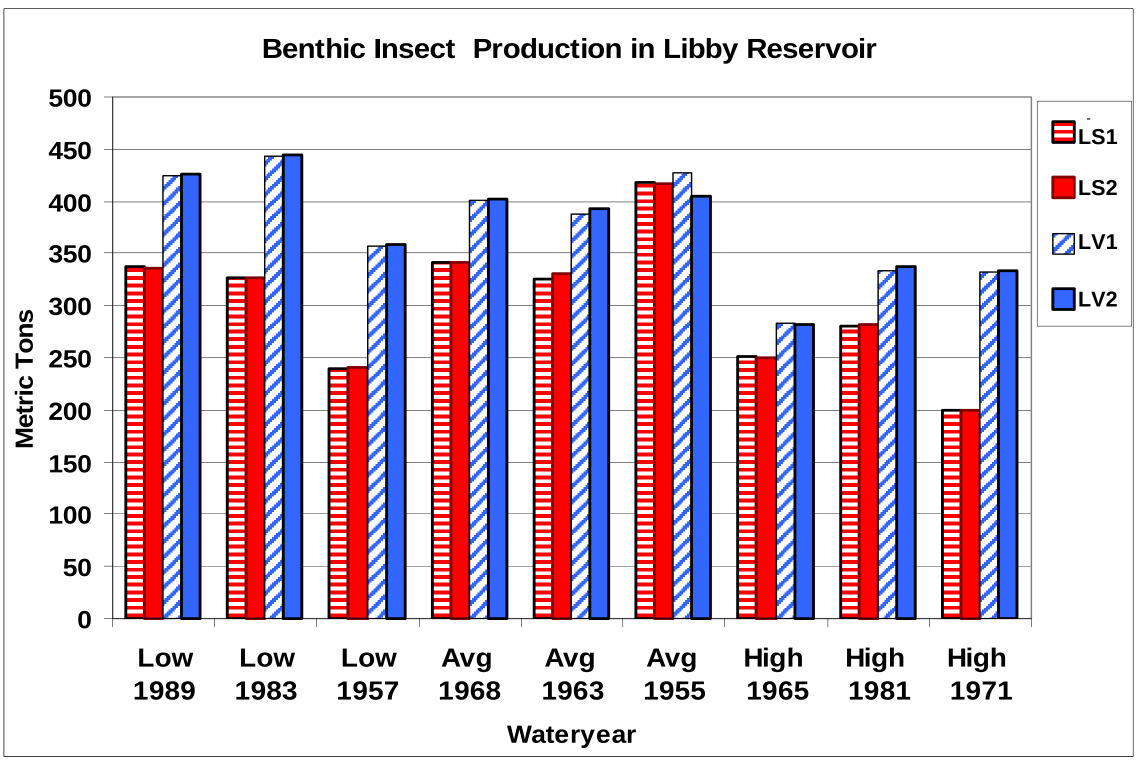


Figure 16. Estimates of benthic biomass production in Libby Reservoir were summarized for each alternative by year and category of water availability. Benchmarks LS and LV initiated at full pool on October 1, whereas all other alternatives began the water year at 20 feet below full pool.

Estimates of benthic insect production ranged from 199.7 to 473.7 metric tons across all water years and alternatives. Results indicate that benthic production is enhanced by the VARQ FC operation as compared to standard flood control. Since the vertical distribution of dipteran larvae is reset by the minimum pool during the previous water year, production values represented the build up from the existing state during each simulation. Operations that prevented substrates containing high larval densities from being desiccated and killed ranked high (LV, LV1, and LV2), whereas deep reservoir drawdowns resulted in lower production totals (LS, LS1, and LS2) (See "All Years Lsurf.xls"). "Fish flow" alternatives LV1 and LV2 ranked higher than LS1 and LS2 during all water year except 1955 when only LV1 ranked higher.

Terrestrial Insect Deposition

Of the four orders of terrestrial insects captured in near shore (< 100 m) and offshore surface tows, Hymenoptera were the most abundant by weight in surface tows and by numbers in trout stomach contents (Chisholm *et al.* 1989). During each simulation, the model calculated insect deposition as the percentage of the maximum possible deposition if the reservoir remained at full pool when each insect order is active (Figure 17). Results were also calculated for Hemiptera, Homoptera and Coleoptera (Figures 18-20).

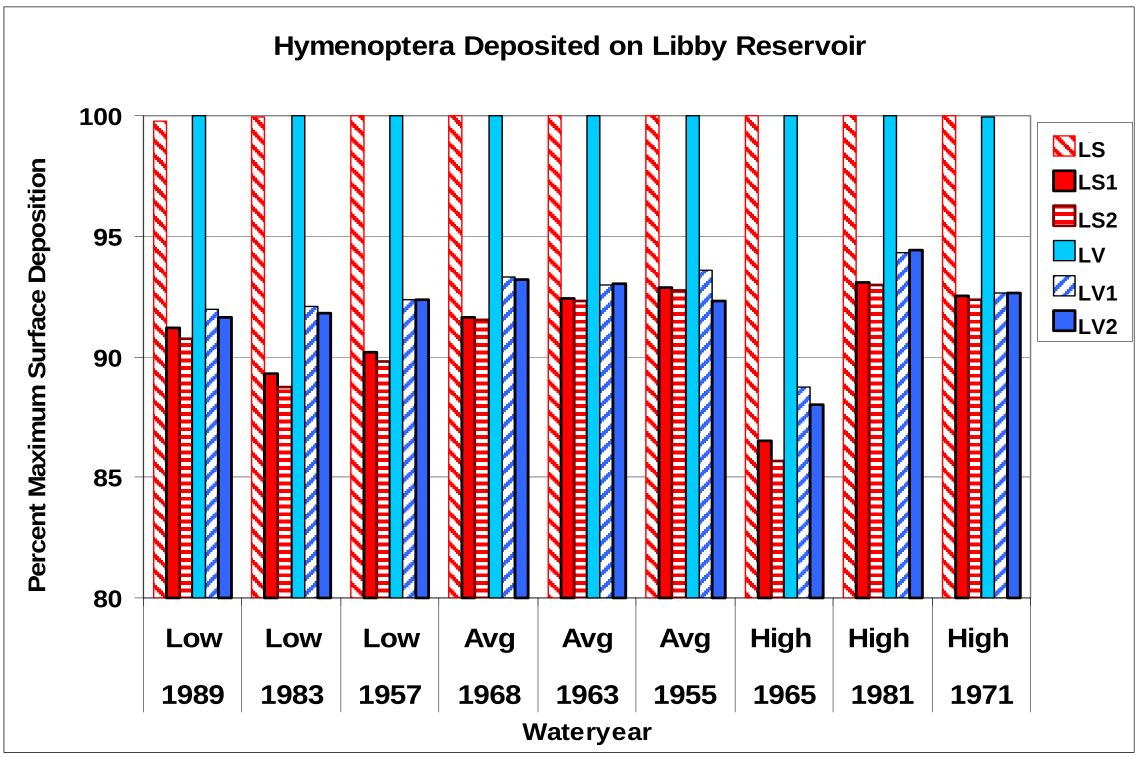


Figure 17. Deposition of Hymenoptera on the surface of Libby Reservoir. Alternatives were summarized by water year and each category of water availability. Benchmarks LS and LV remain at full pool during the entire period that Hymenoptera are active, so nearly 100 percent of the maximum were deposited on the surface. Alternatives that draft Libby Reservoir 20 feet to provide summer flow augmentation trap fewer insects, and consequently less food is available for insectivorous fish.

Hymenoptera exhibit good flight capability and are deposited in nearly equal proportions in nearshore and offshore (>100 m) areas. The amount deposited is proportional to surface area. Flood control benchmarks LS and LV remained at full pool while Hymenoptera are active, so insects are deposited and trapped by the large surface area. Alternatives that drafted the reservoir during summer to augment flows for fish in the Columbia River had a smaller surface area, thus trapped fewer Hymenoptera.

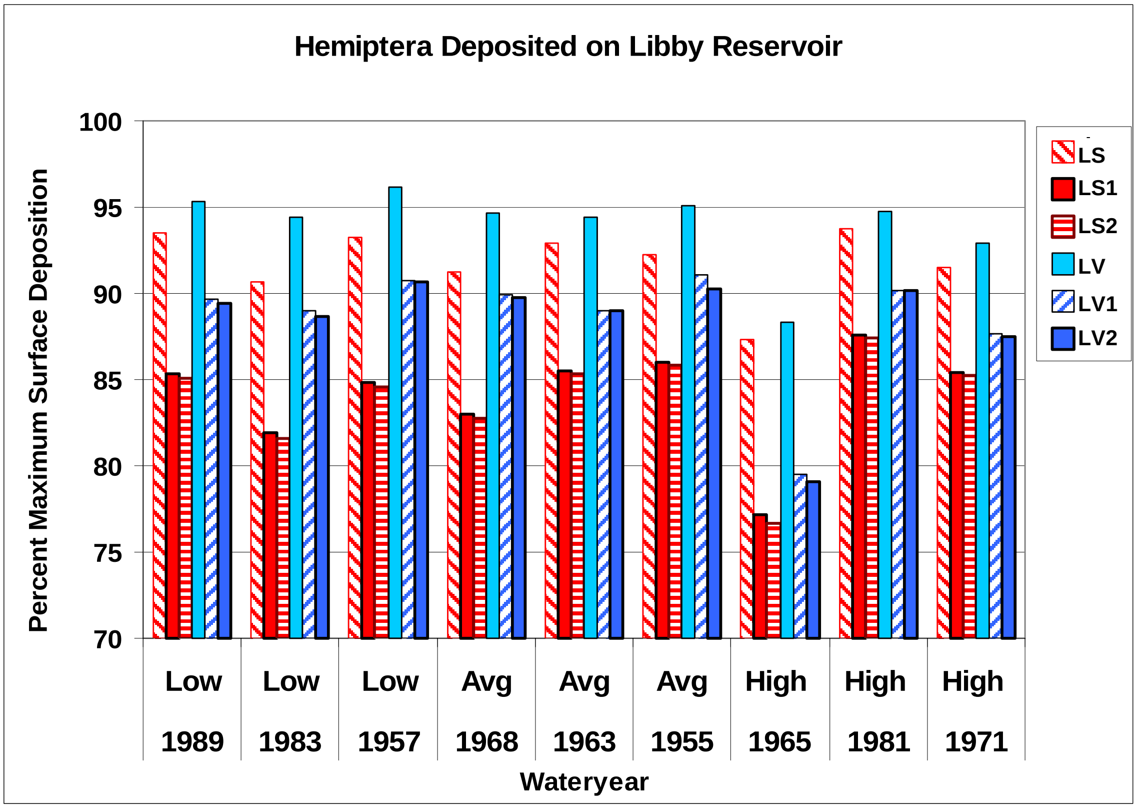


Figure 18. Hemiptera are deposited on the surface of Libby Reservoir in proportion to surface area. Benchmarks LS and LV remain near full pool during a portion of Hemipteran activity, so trap a larger percentage of available insects. Conversely, all alternatives provide water for fish flow augmentation and reservoir surface shrinks during periods of insect activity.

The VARQ FC alternatives trap more Hemiptera than their respective Standard FC counterparts. Hemipterans are deposited in significantly greater numbers within 100 m of shore. As a result, reservoir operations that caused the water to recede from shoreline vegetation during period of Hemipteran activity ranked lowest. Benchmarks LS and LV remained near full pool during the period of Hemipteran activity thus ranked highest. Of the alternatives that provided fish flows, LV1 trapped slightly more insects than LV2 during eight of the nine water years. The difference was likely caused by slightly lower reservoir elevations during late summer and fall under LV2. The Standard FC alternatives drafted Libby Reservoir deeper during spring, which delayed the refill process. Also, the reservoir remained near full pool for a shorter duration. Consequently, the reservoir surface receded from the shoreline and fewer insects were captured. Alternative LS1 trapped slightly more insects than LS2 during all water years. This is logical because LS2 released an additional 10 kcfs, reducing the reservoir surface area. Volumetrically, this effect increased as the reservoir volume decreased.

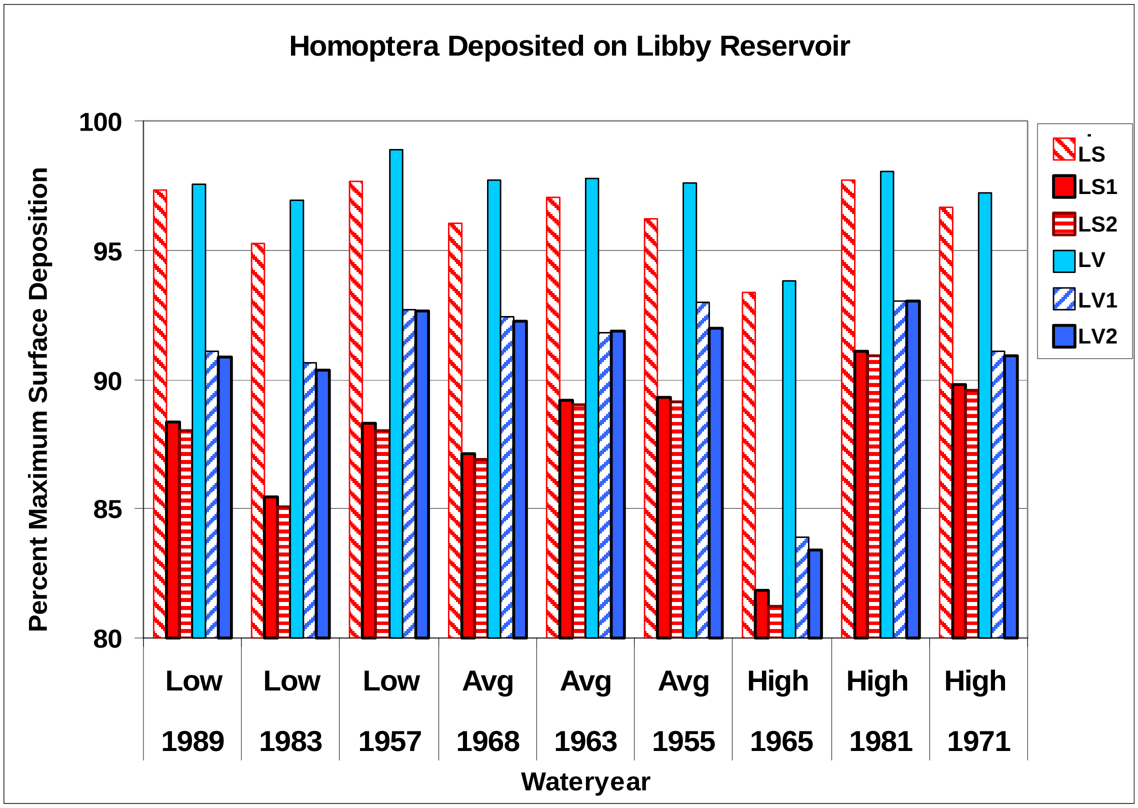


Figure 19. Homoptera deposited on the surface of Libby Reservoir summarized for each alternative and water year. Surface elevations in benchmarks LS and LV begin at full pool each year. Other alternatives begin 20 feet below full pool.

Homoptera were deposited in nearly the same amounts in nearshore and offshore areas; deposition is proportional to reservoir surface area. Benchmarks LS and LV began at full pool each water year and remained near full pool during the period of peak Homopteran activity. As a result, benchmark LV ranked the highest followed by benchmark LS, which produced a higher score than the "fish flow" alternatives that begin at 20 feet below full pool during all water years. Of the alternatives that provided flow augmentation for fish recovery, LV1 ranked the highest in seven of nine water years and LV2 ranked the highest in the remaining two years. VARQ FC alternatives remained closer to full pool and had shallower annual drafts than the Standard FC alternatives. Alternative LS1 trapped slightly more insects than LS2 during all water years.

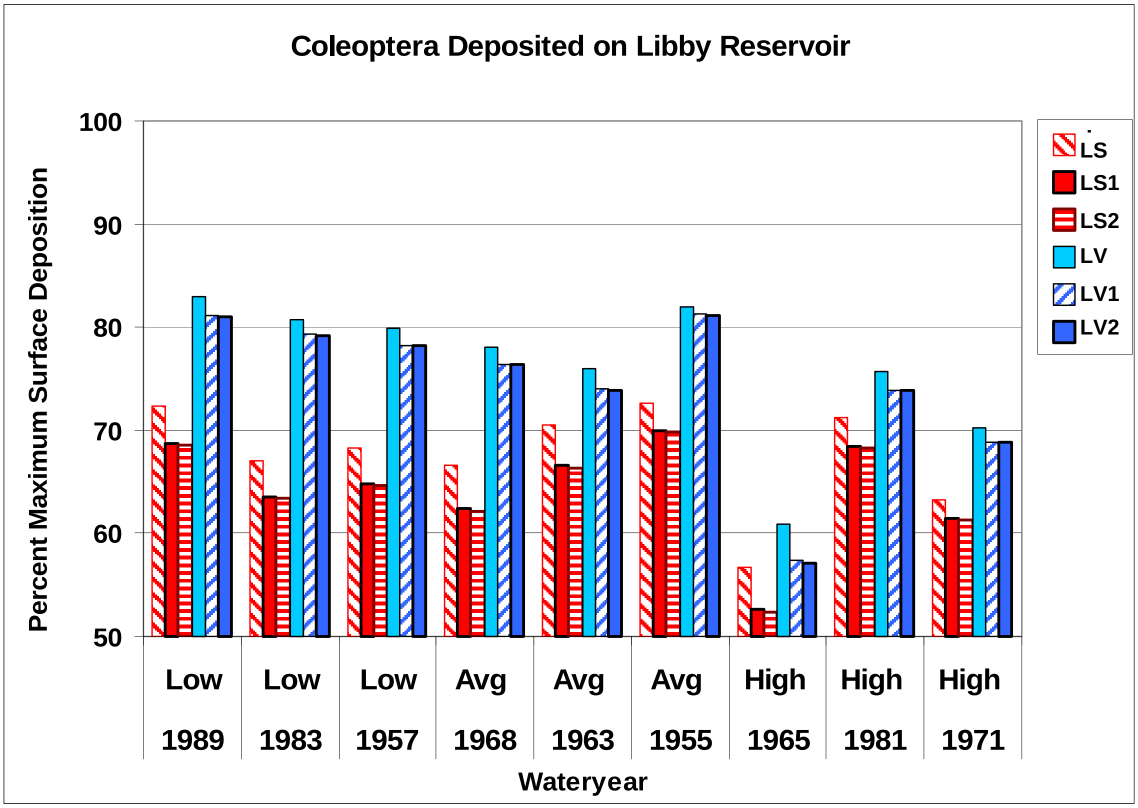


Figure 20. Coleoptera deposition on the surface of Libby Reservoir under each alternative by water year. Surface elevations in benchmarks LS and LV begin at full pool each year. Other alternatives begin 20 feet below full pool.

Coleoptera are deposited in significantly greater numbers within a 100 m of shore. As a result, dam operations that caused the water to recede from shoreline vegetation during period of Coleopteran activity ranked lowest. Benchmark LV remained closer to full pool and ranked the highest during all water years. Of the alternatives that provided fish flows, LV1 trapped slightly more insects than LV2 during six of the nine water years, and LV2 ranked higher the remaining three years. This difference was likely caused by slightly lower reservoir elevations during late summer and fall under LV2 during most average or lower water years. The Standard FC alternatives drew Libby Reservoir down to a greater depth during spring, which delayed the refill process. Also, the reservoir remained near full pool for a shorter duration. Consequently, the reservoir surface recedes from the shoreline and fewer insects are captured. Alternative LS1 trapped slightly more insects than LS2 during seven of nine water years. This is logical because LS2 released an additional 10 kcfs, reducing the reservoir surface area.

Kokanee Growth

Model calculations of kokanee growth are sensitive to food availability and the volume of water at optimal temperatures for fish growth. Kokanee diet is almost exclusively zooplankton (*Daphnia*, *Diaptomus* and *Bosmina*) and dipteran pupae are also consumed in trace quantities. Kokanee select the largest available zooplankton, then shift to smaller sizes as larger zooplankton are depleted (Chisholm *et al.* 1989). The model calculated gross zooplankton production in metric tons and assumed an average proportion based on observed relative abundances of the zooplankton genera in Libby Reservoir.

Annual simulations assumed identical reservoir conditions for kokanee growth during age I and II. Kokanee population size and age structure were assumed to be constant so that alternatives could be compared without the confounding influence of density dependant growth. Growth trajectories for age I and II kokanee were calculated during each simulation, then summarized into annual growth in length (mm) and weight (g) (Figure 21; also see files named lmfg9**.txt. Files are identified by alternative after the hyphen in the file name (for example lmfg955-b.txt is benchmark LS ["b"] during 1955). Results compare each alternative/benchmark by water year and were summarized across categories of water availability (Figures 22 and 23).

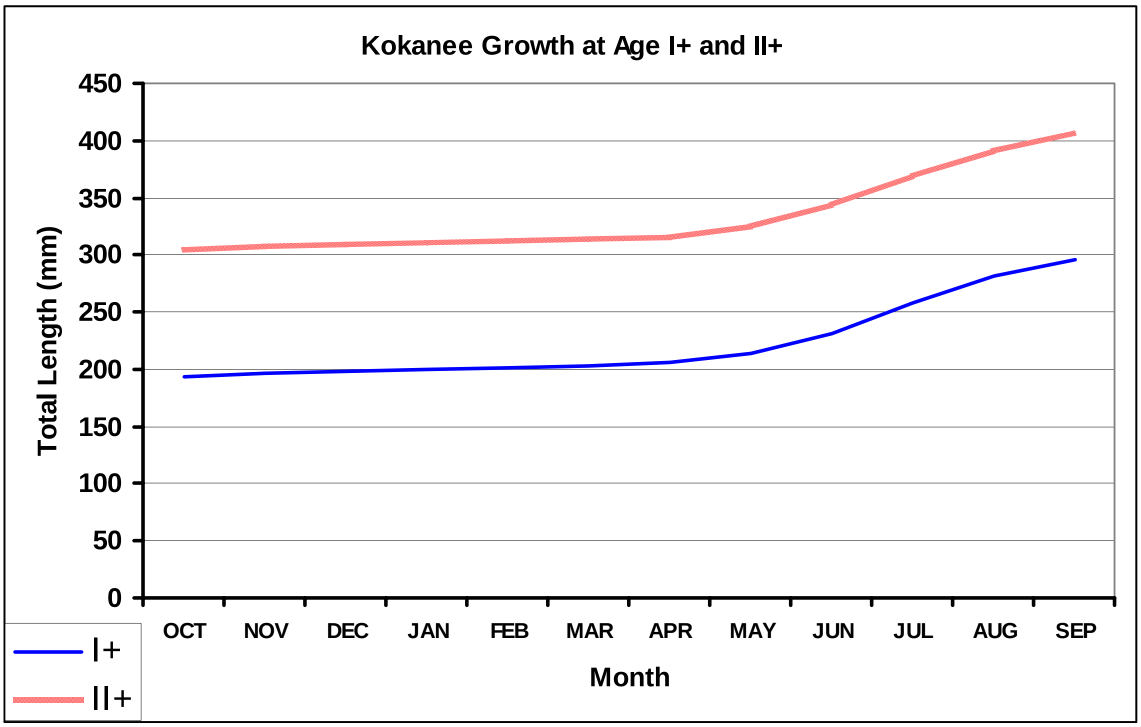
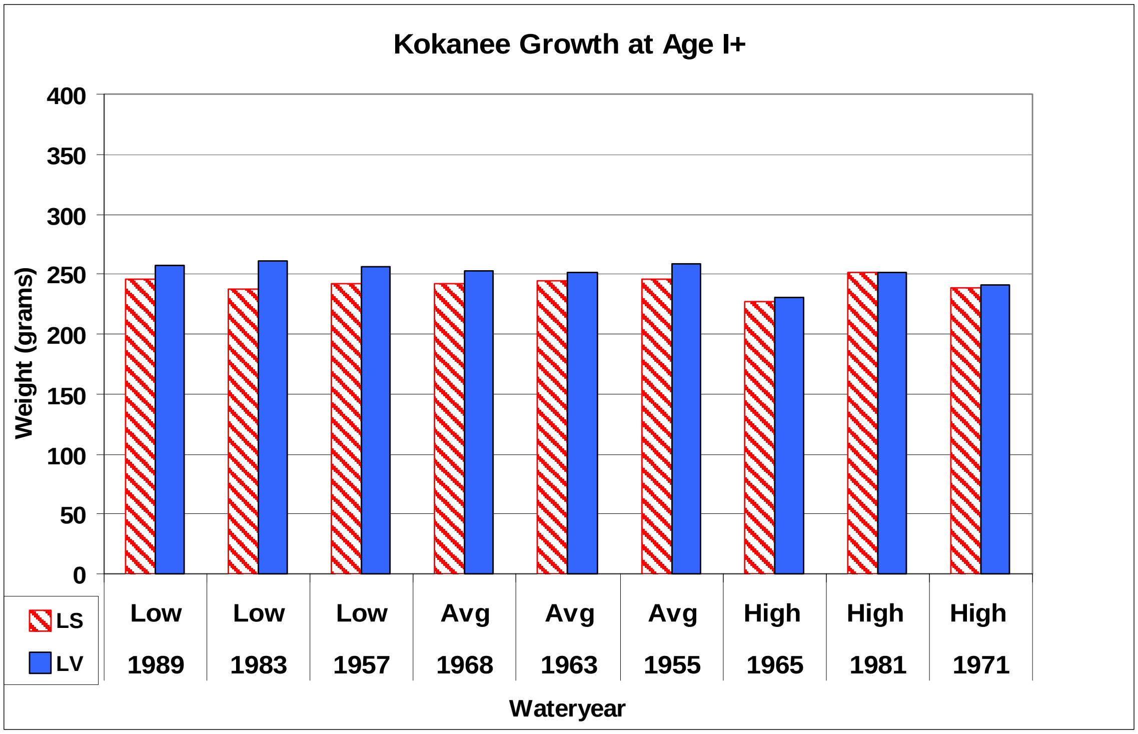


Figure 21. An example of the annual growth (total length) trajectory for age I+ and II+ kokanee. Monthly results for growth in total length (mm) and weight (g) are presented in tabular format in files named lmfg9**-*.txt for each year and alternative.



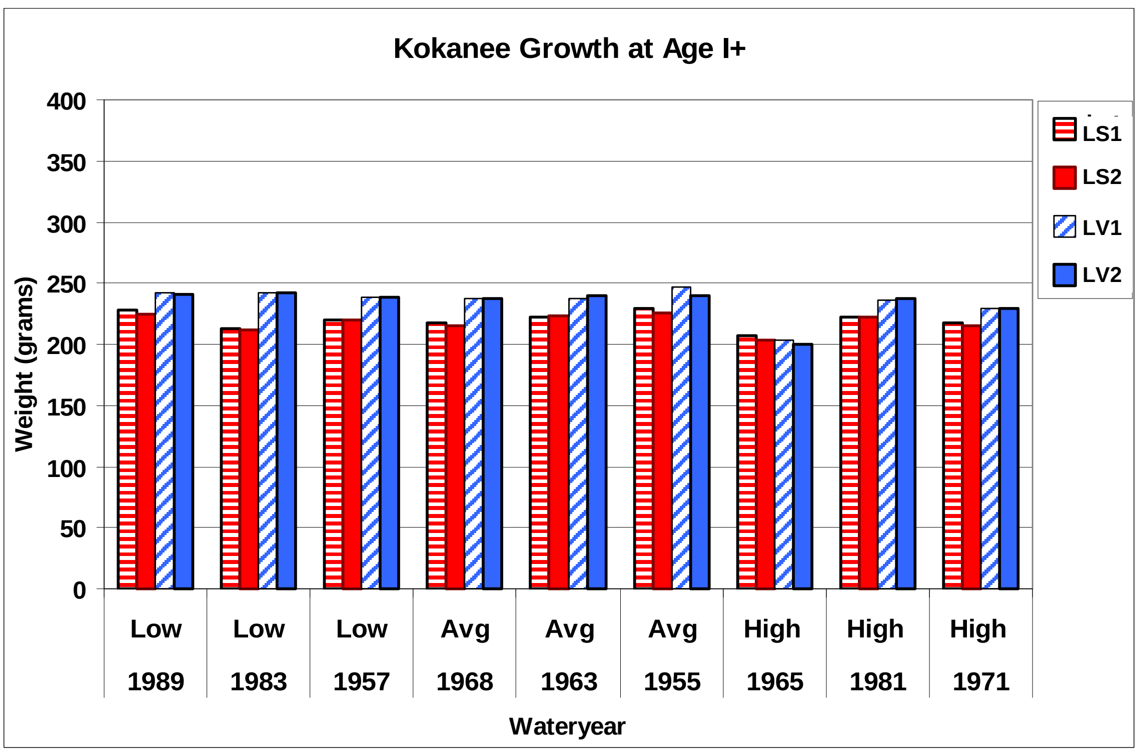
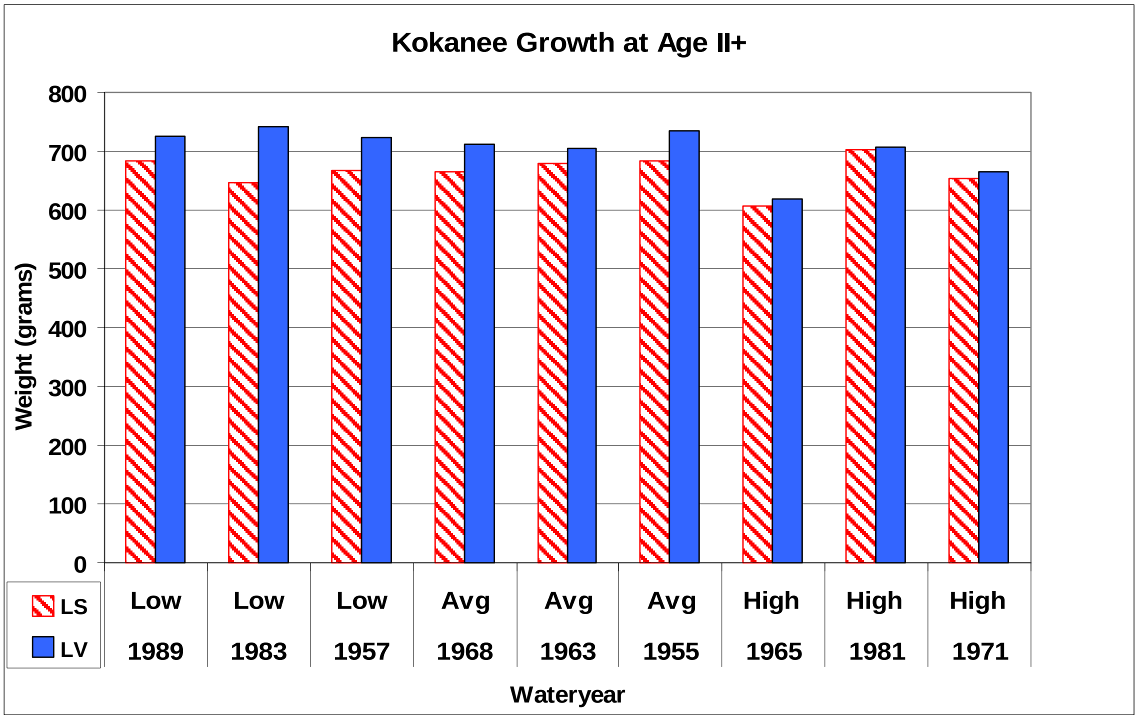


Figure 22. Comparison of kokanee growth in weight (g) at age I+ in Libby Reservoir under six alternative dam operation strategies. Bars are grouped by water year, and span categories of water availability from medium-low to medium-high. The kokanee growth model is sensitive only to gross changes in reservoir conditions. The VARQ FC alternatives ranked higher than their Standard FC counterparts during all years.



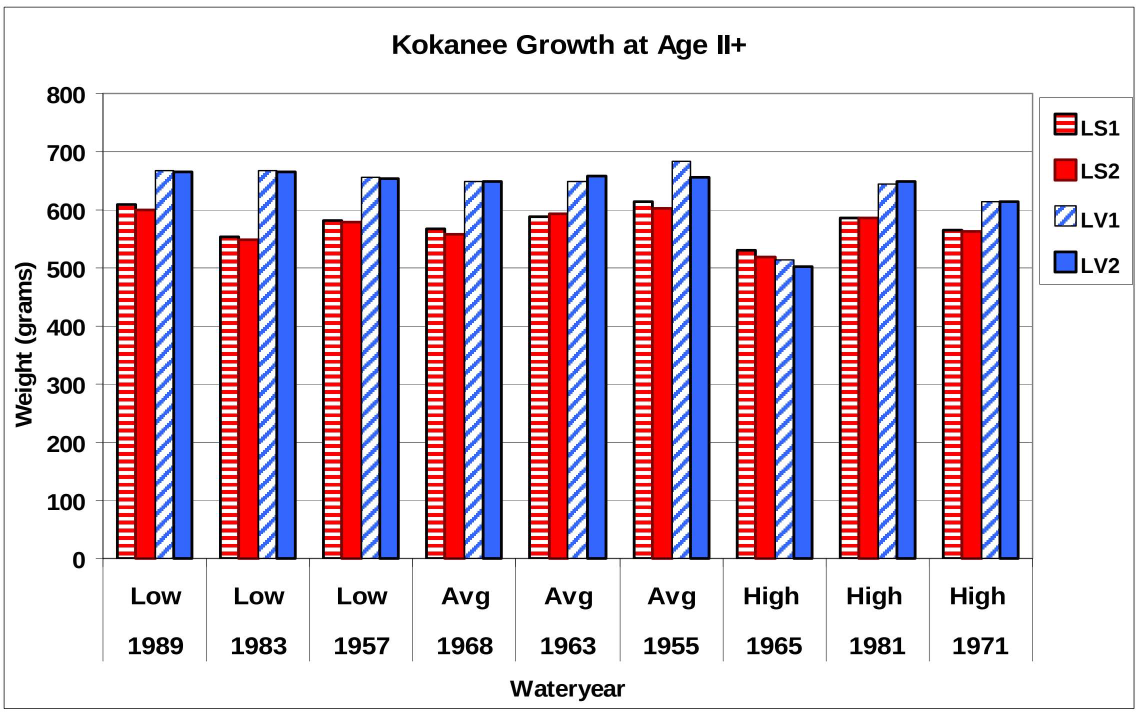


Figure 23. Comparison of age II+ kokanee growth in weight (g) at Libby Reservoir during all water years and categories of water availability. The model is sensitive only to gross changes in reservoir conditions. The VARQ FC operations ranked higher than their Standard FC counterparts during all years. Benchmarks LS and LV initiate at full pool elevation so were plotted separately.

The fish growth model assumes identical environmental conditions in the reservoir when calculating the growth of age I and II kokanee in total length (mm) and weight (g). Alternatives that provided a large surface area for zooplankton production and a large reservoir volume of optimal water temperatures for fish growth ranked highest. Benchmarks LS and LV began at full pool on October 1 each water year and maintained a relatively large surface area and volume during the productive warm months. Growth was greater under benchmark LV because reservoir drawdown was shallower than benchmark LS. The VARQ FC simulations produced greater kokanee growth than their respective Standard FC counterparts in eight of nine years.

Hungry Horse Reservoir

Primary production

Primary production (carbon fixation) by phytoplankton was controlled by reservoir surface area and volume and mean temperature within each depth stratum. The model calculated the longitudinal and vertical distribution of carbon fixation and related these values to volumetric production rates (mgC/m^3/d) for each operating alternative. Model output included daily schedules of primary production (Figure 24) and annual totals, summarized by year and overall by water year category (Figure 25).

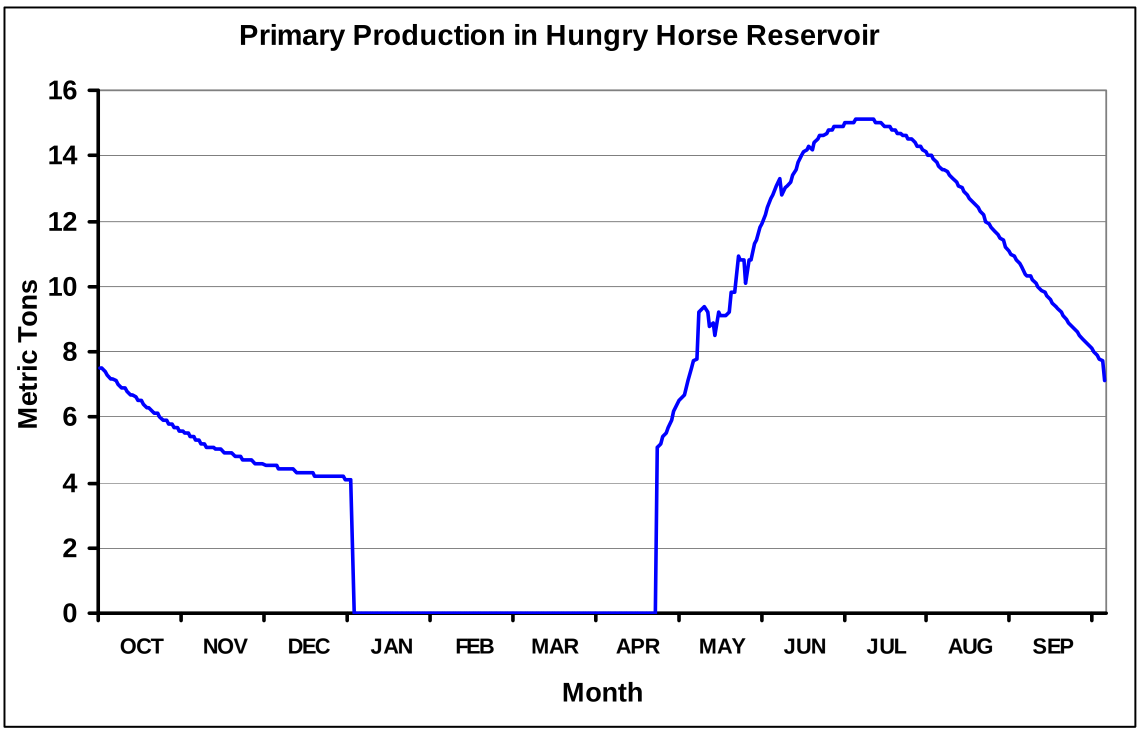


Figure 24. The annual schedule of daily primary production (metric tons of carbon fixed) in Hungry Horse Reservoir shows the biological importance of the summer growing season. Productivity drops to zero when solar input declines during periods of ice formation and snow cover. Data for each water year and operating alternative are named MPrimProd9**-*.txt. This example is MPrimProd832-v.txt representing HV (VARQ FC) in 1932.

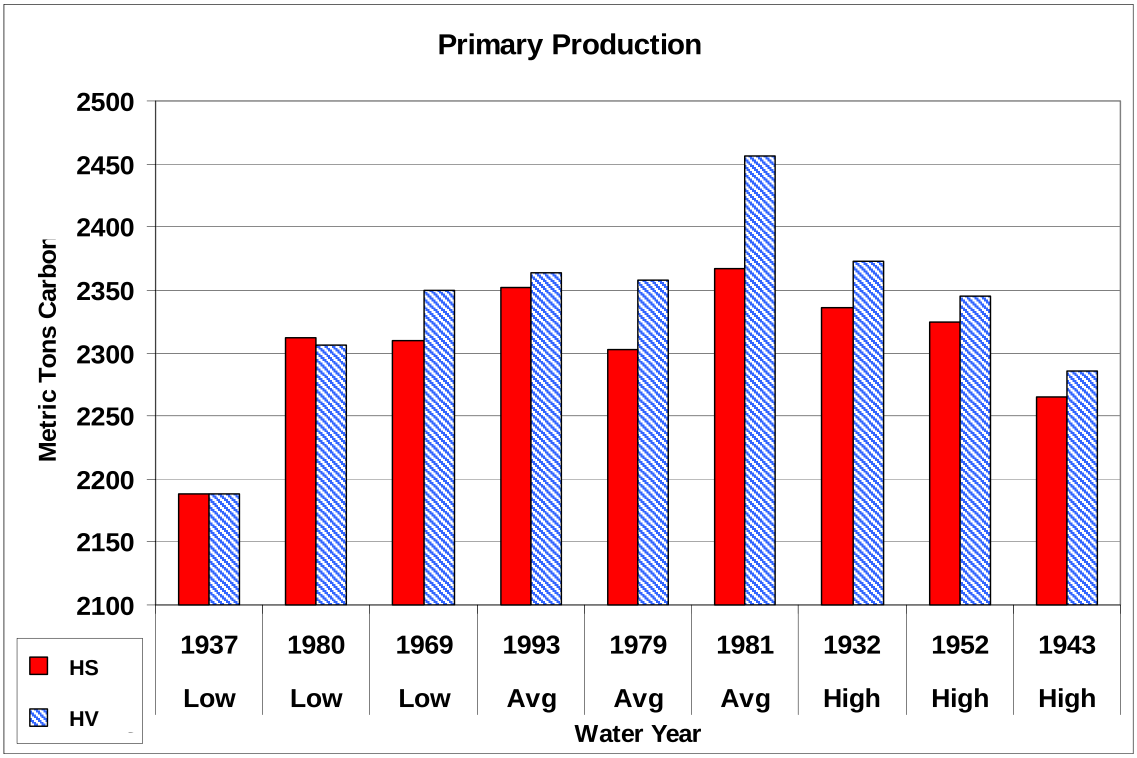


Figure 25. Total annual primary production in Hungry Horse Reservoir under the HS (Standard FC with fish flows) and HV (VARQ FC with fish flows). The X-axis is arranged by water year from medium-low (left) to medium-high (right) water years.

It is important to note that there was no difference between the alternative operating strategies for the year 1937. Primary production under HV was slightly greater than HS during all other simulated water years. Reservoir drawdown was typically greater under HS (see comparisons of surface elevations resulting from the HS and HV alternatives in \H-Input\HH Surface Elev.xls). Differences between the alternatives were offset somewhat because much of the period of low reservoir elevation correlates with the period of ice formation, when primary productivity approaches zero.

Loss of phytoplankton through the dam turbines was controlled mainly by the discharge volume and the density of phytoplankton at the depth of water withdrawal. The Hungry Horse Reservoir selective withdrawal model was configured in both alternatives to withdraw water from the appropriate depth to achieve the target temperatures in the South Fork and mainstem Flathead River. This caused the depth of withdrawal, as measured from the reservoir surface, to remain relatively constant between alternatives, thus limiting the difference between the alternatives. Differences in the annual schedule of primary productivity in Hungry Horse Reservoir resulted from changes in reservoir volume and surface area. Differences in the seasonality and volumes of dam discharge influenced washout losses (Figure 26). Results would differ if the selective withdrawal structure was operated differently.

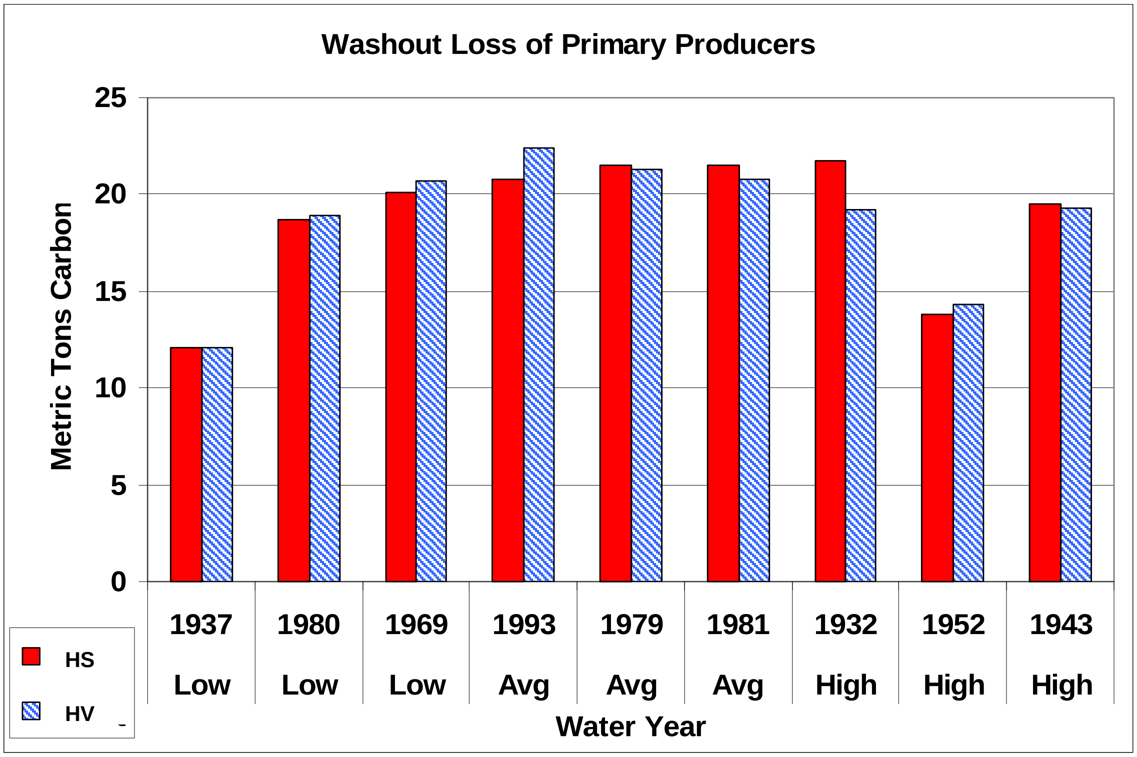


Figure 26. Washout losses through the turbines of Hungry Horse Dam are similar under the HS and HV alternatives. The X-axis is arranged by water year from medium-low water availability through medium-high water years.

Washout of primary producers through the turbines of Hungry Horse Dam was strongly influenced by seasonal discharges because selective withdrawal was standardized in all simulations. Losses were calculated in proportion to seasonal schedule of reservoir productivity and vertical distribution in the forebay. When more primary production occurred in the reservoir, more phytoplankton were lost through turbine penstocks. Model calculations of downstream losses of phytoplankton revealed little difference between HS and HV during these nine water years. However, there appears to be a trend of greater losses under HV during less than average water years and, except for 1952, greater losses during high water years under HS. More annual simulations are required to determine if this trend is supported by additional data.

The depth of water withdrawal remains an important factor that controls washout losses. Although selective withdrawal may provide a tool to control washout losses, such control may not be warranted because washout losses amounted to less than one percent of the overall production in the reservoir. Phytoplankton entrained through Hungry Horse dam provides a trophic gain to the Flathead River.

Zooplankton Production

The annual schedule of zooplankton production was calculated as a function of phytoplankton production to mimic published energy transfer efficiencies as zooplankton graze on phytoplankton (Figure 27).

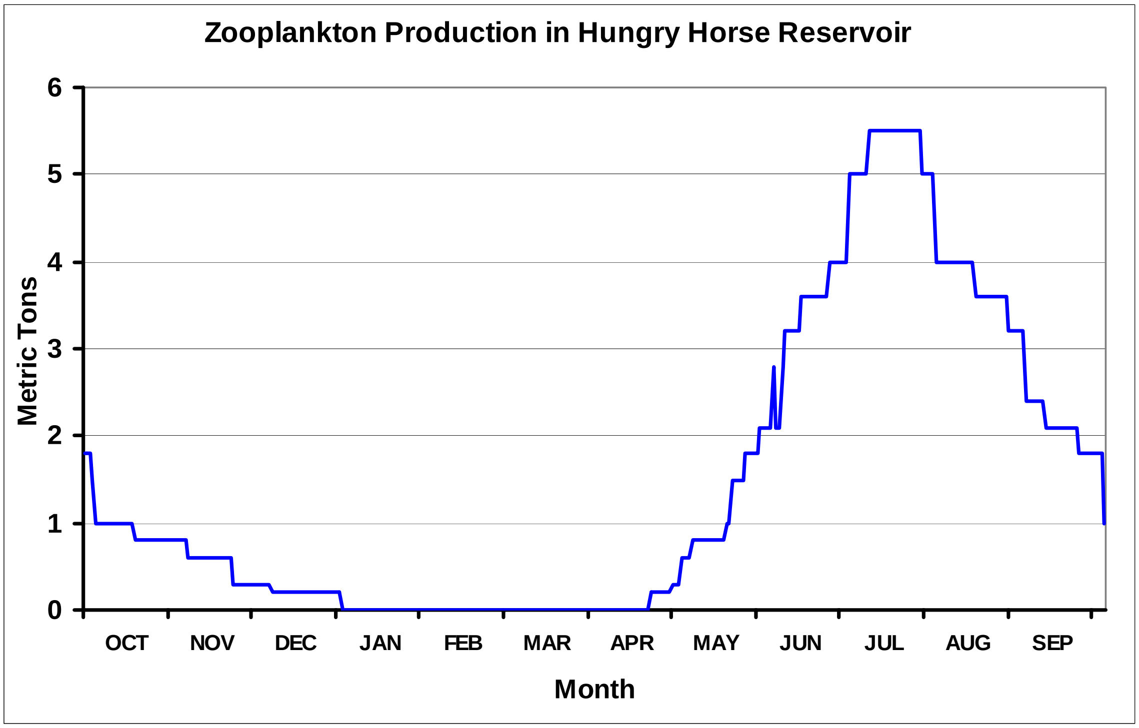


Figure 27. An example of an annual simulation of daily zooplankton production in Hungry Horse Reservoir. Data files for each simulation are named Mzooplankton9**.txt, where "**" represents the year and the final letter (b for HS, or v for HV) signifies the alternative. This is Mzooplankton932v.txt from the Hungry Horse Reservoir\1932\ folder. Data represent HV during 1932. Files contain two columns A and B. Metric tons = A*(10*B).

After hatching, zooplankton survive for an indefinite period until they are eaten by predators, die of natural causes and sink, or washed through Hungry Horse Dam. Enough individuals survive that zooplankton is the primary winter food for fish species that do not prey on fish (including westslope cutthroat trout and juvenile bull trout). Model estimates of zooplankton production under the two alternative operating strategies reflected changes in surface area and the volume at depth during each day of the simulated water year. Results were summarized for each water year and category of water availability (Figure 28).

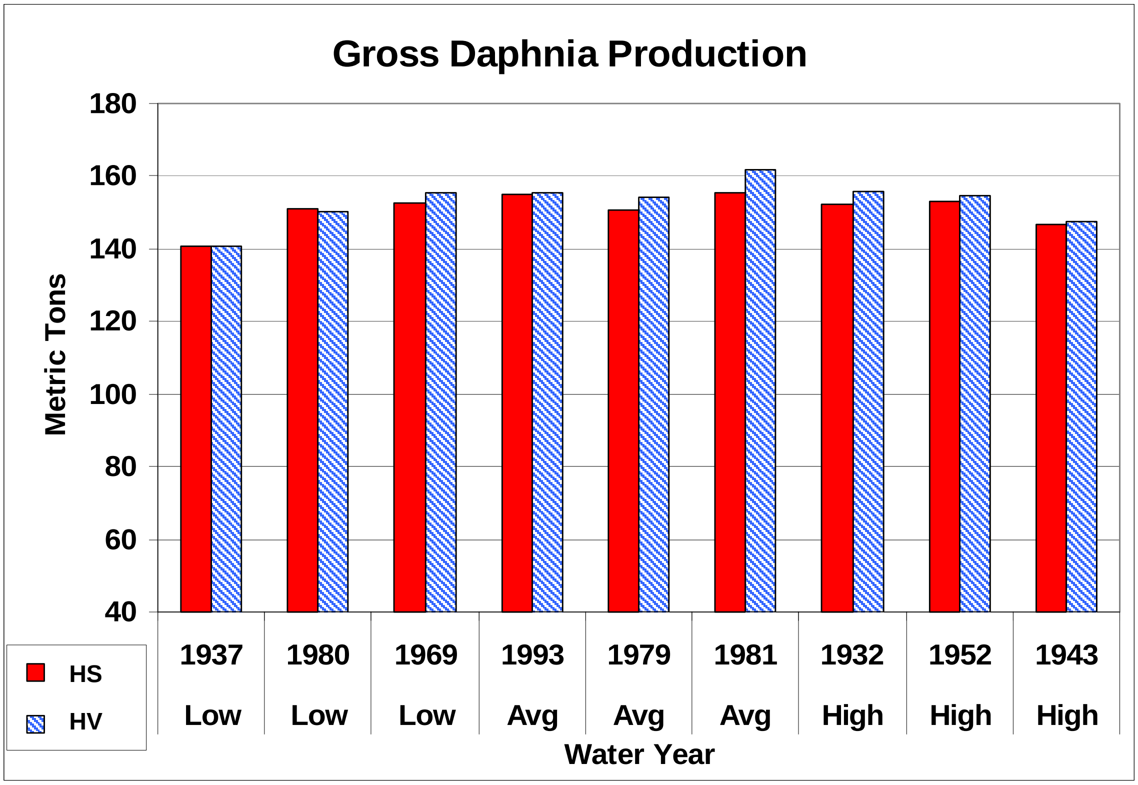


Figure 28. Calculations of Daphnia production (metric tons) in Hungry Horse Reservoir under each alternative were plotted for comparison. See complete files of reservoir surface elevations, named \H-input data\HH Surface Elev.xls.

Model results indicate that HV produced slightly more Daphnia during seven of the nine water years. Operations that maximized reservoir volume and surface area during the biologically productive summer months produced more phytoplankton, and therefore more food for zooplankton. Zooplankton production is enhanced by large volumes of optimal water temperatures during the warm months.

Zooplankton densities in Hungry Horse Reservoir were low compared to Libby Reservoir, as indicated by measuring density in numbers per m^3 in Hungry Horse, versus numbers per L in Libby Reservoir. These low densities warrant controlling the amount of zooplankton lost through the selective withdrawal device (Figure 29). Zooplankton washout losses can be managed to a limited extent using the selective withdrawal system at Hungry Horse Dam. Slide gates located 50 feet below the top of the control gate can be gradually opened during the summer to intake cool water from beneath the strata containing high zooplankton densities. In this way, warm and cool water can be mixed to achieve an intermediate tailwater temperature while minimizing zooplankton entrainment (Cavigli *et al.* 1998). Stratifying the withdrawal depth allows dam operators to reduce zooplankton entrainment, while providing optimal water temperatures downstream in the South Fork Flathead River. Such control is warranted because zooplankton production is very low in Hungry Horse Reservoir due to oligotrophic nutrient conditions. Once produced, zooplankton remain available as prey to fish until they sink or wash through the dam. Although washout losses increase with higher dam discharges and represent a substantial fraction of the overall reservoir productivity, these results do not incorporate stratified withdrawal, so actual losses may be less than predicted. Zooplankton swept through Hungry Horse Dam provides a trophic gain to the Flathead River.

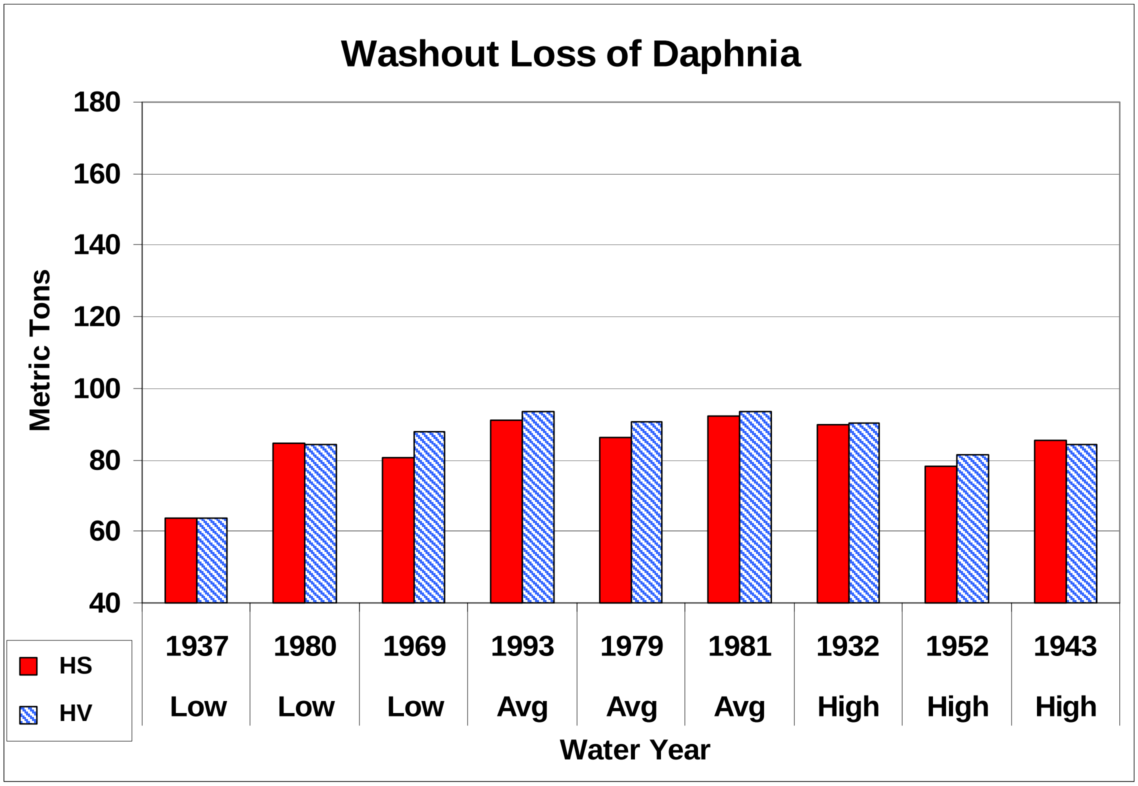


Figure 29. Washout of Daphnia through the turbines of Hungry Horse Dam was calculated for the two alternative operation strategies. Daphnia are the most important zooplankton genus in fish stomach contents. Results are proportional to total zooplankton washout.

Results indicate that zooplankton loss through Hungry Horse Dam was slightly higher under HV during six of the nine water years simulated. Since the selective withdrawal model was automated, the depth of water withdrawal differed little between the alternatives in any given year. Zooplankton washout was, therefore, most sensitive to discharge volume, especially during summer. Results are proportional to calculated production values in the reservoir pool; when more zooplankton were produced, more were washed through the dam. It is important to note that these results are sensitive to the specified withdrawal depths and that results would change if selective withdrawal was operated differently.

Benthic Insect Production

Impoundment of the South Fork Flathead River by Hungry Horse Dam and reservoir operations have greatly simplified the diversity of aquatic insects in the reservoir by reducing species adapted to flowing water (e.g. stoneflies, mayflies and caddis flies). Aquatic Diptera dominate the existing reservoir insect community. Larger, long-lived species dominate the permanently wetted zone, whereas the varial zone contains mainly small, multivoltic species. Larvae recolonize previously dewatered substrates as the reservoir fills, and shoreline areas are dominated by multivoltic dipterans that produce cohorts throughout the warm summer months (May *et al.* 1988). Annual production schedules are controlled by the substrate area of each depth zone and the duration each zone remains wet and productive. The model calculates daily estimates of benthic insect production during the water year (Figure 30).

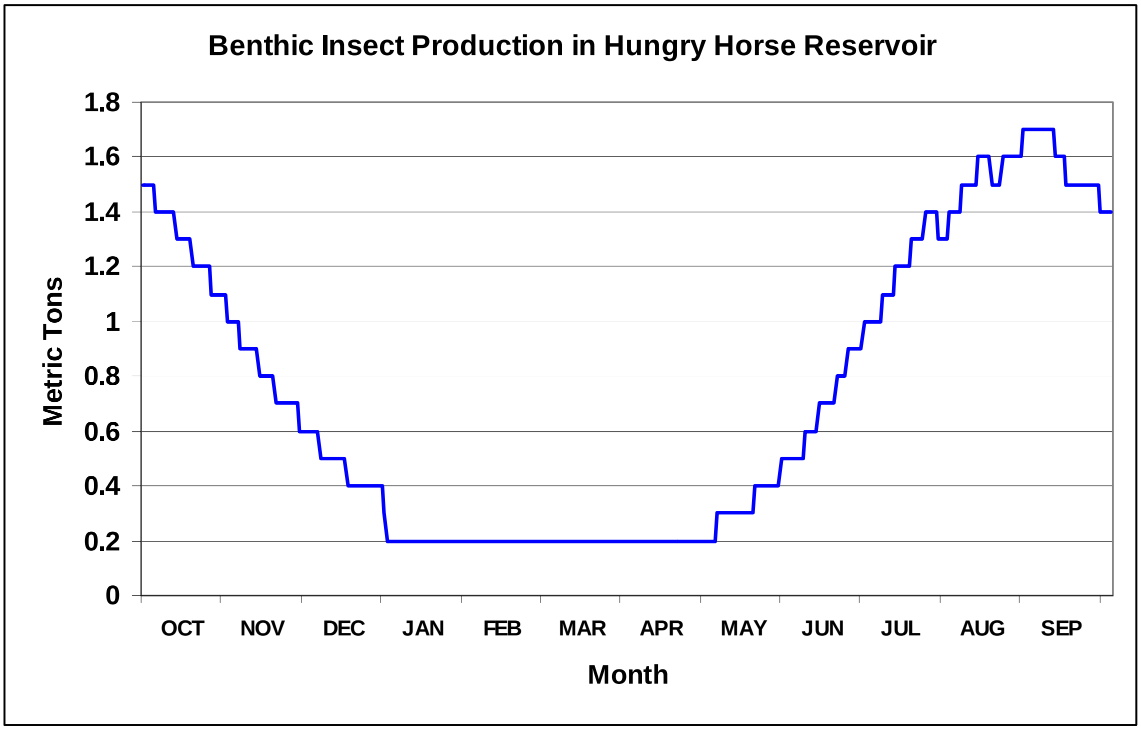


Figure 30. Daily simulations of benthic dipteran production were calibrated using dredge samples of larval distribution at depth, and emergence rates from surface trapping at varying distances from shore. Results were controlled mainly by the wetted substrate area in each reservoir depth zone. Vertical distributions of larvae were adjusted to the minimum pool during the previous water year. This example is HV in 1932. ASCII text files containing these data were named Mbenthos9**-*.txt in folders containing output for each year (e.g. \1932\ Mbenthos932-v.txt).

Benthic insects are the primary food item for westslope cutthroat trout during spring. Factors controlling benthic insect production include maximum reservoir drawdown, duration at maximum pool, and the amount of time substrate remains wet and productive. The minimum pool elevation during the previous year “resets” the vertical distribution of larval densities as reservoir drawdown desiccates substrate containing dipteran larvae. Larger, long-lived forms are dominant in the permanently wetted zones, whereas smaller, multivoltic species are more common in the zone of water fluctuation. Larvae swarm during spring as the reservoir refills. Larvae distribute randomly and their survival depends on finding suitable habitat to continue their life cycle. Larvae then pupate and ascend to the surface buoyed by air bubbles in their case. Fish prey predominantly on pupae, emerging adults and adults; however, few larvae were found in fish stomach contents in Hungry Horse Reservoir (May *et al.* 1988). Benthic insect production was, therefore, measured in units of dipteran emergence. Annual production totals were compared between the two alternatives during each simulated water year, and then summarized for each category of water availability (Figure 31).

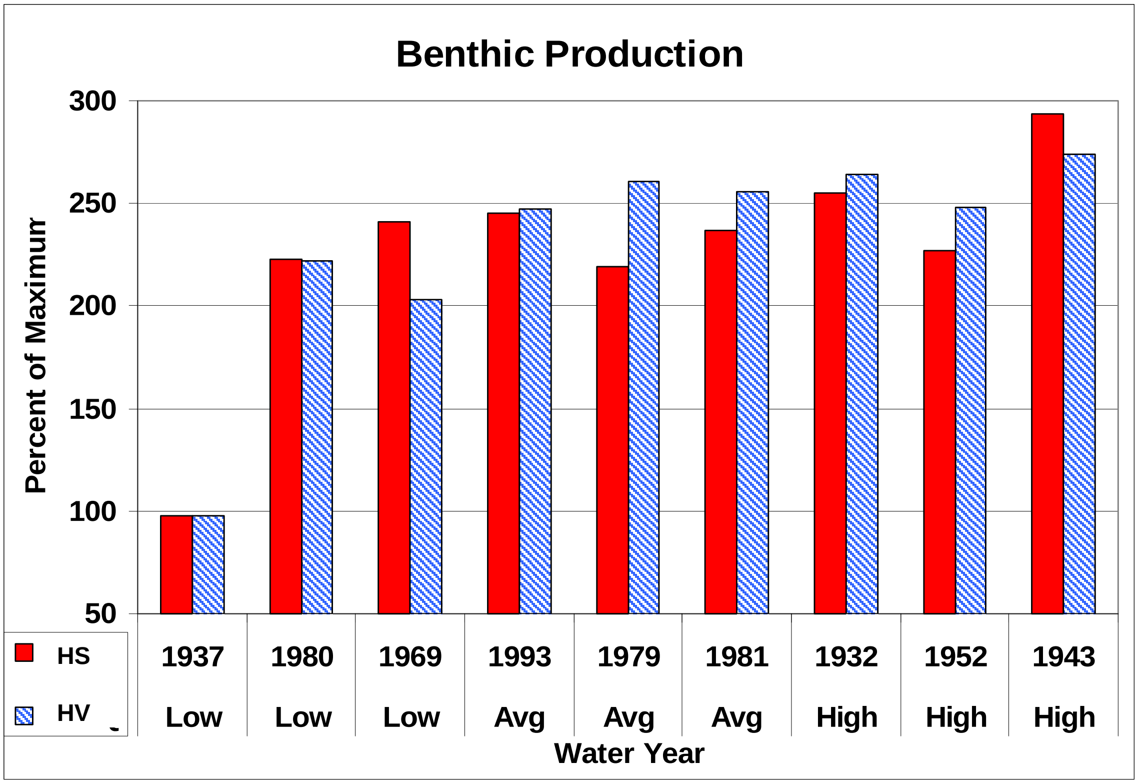


Figure 31. Estimates of benthic biomass production in Hungry Horse Reservoir was summarized for each alternative by year and category of water availability.

HV produced more benthos than HS during seven of the nine water years simulated. During 1969, HS maintained higher reservoir elevations during the fall while benthic production remained high. Although HS reached a deeper minimum pool elevation, benthic production was at the seasonal low during that period. During 1943, reservoir elevations under HS were slightly higher than HV during the reservoir refill period (see plots of Hungry Horse Reservoir elevation schedules in \H-input\ HH Surface Elev.xls).

Terrestrial Insect Deposition

Of the four orders of terrestrial insects captured in near shore (< 100 m) and offshore surface tows, Hymenoptera were the most abundant by weight in surface tows and by numbers in fish stomach contents in Hungry Horse Reservoir (May *et al.* 1988). The seasonality was significantly different among the insect orders (Marotz *et al.* 1996) and modeled accordingly (Figure 32). During each simulation, the model calculates insect deposition as a percentage of the maximum possible if the reservoir were at full pool during the period insects are active. Results were calculated for Hymenoptera, Hemiptera, Homoptera and Coleoptera (see Biological Summary.xls for Hungry Horse Reservoir). Of the four insect orders, only the deposition of Coleoptera differed between the two alternatives (Figure 33).

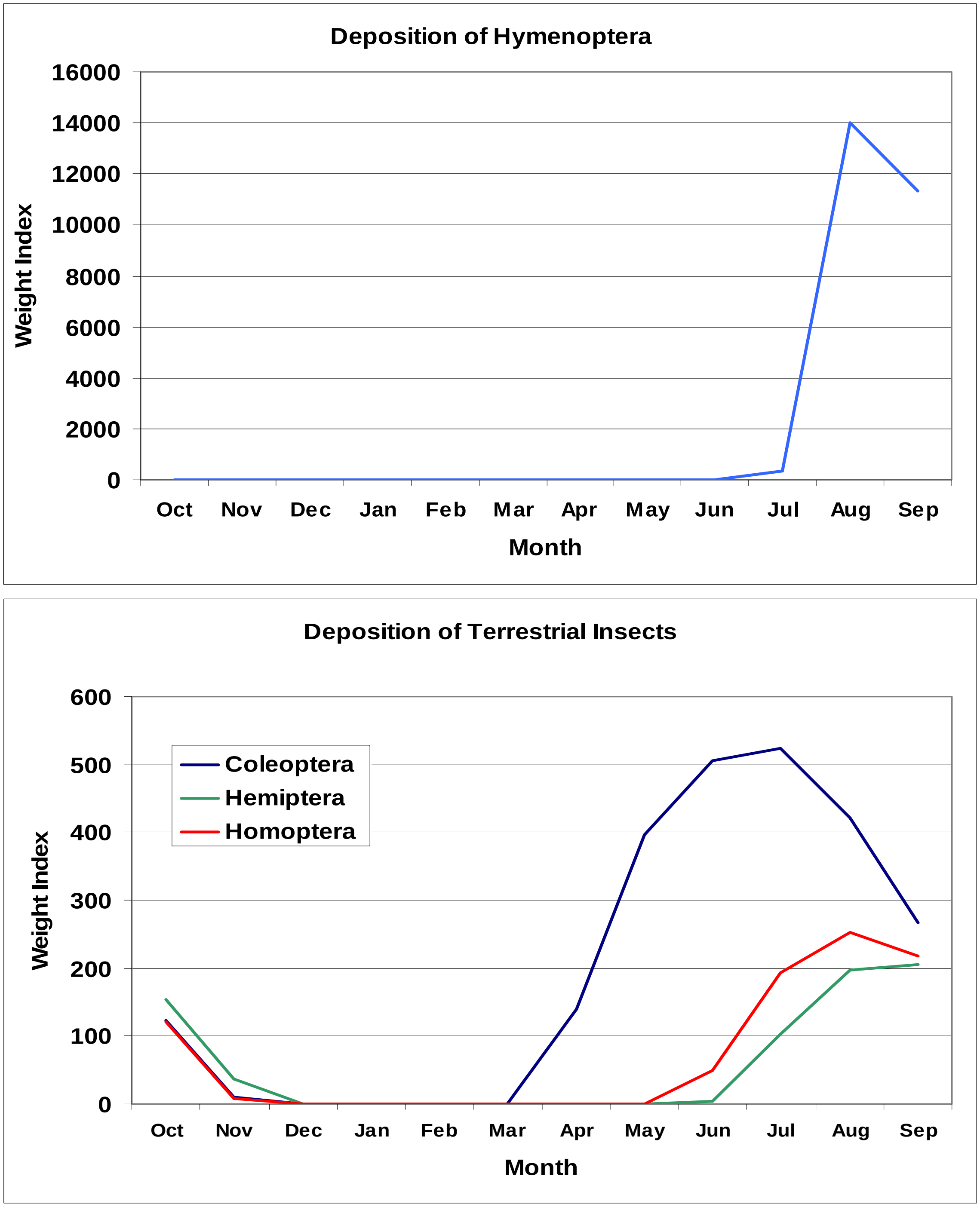


Figure 32. Seasonal periods of insect abundance differ significantly between the four main orders of insects deposited on the surface of Hungry Horse Reservoir. Hymenoptera deposition is an order of magnitude greater than the other insect orders, so was plotted separately.

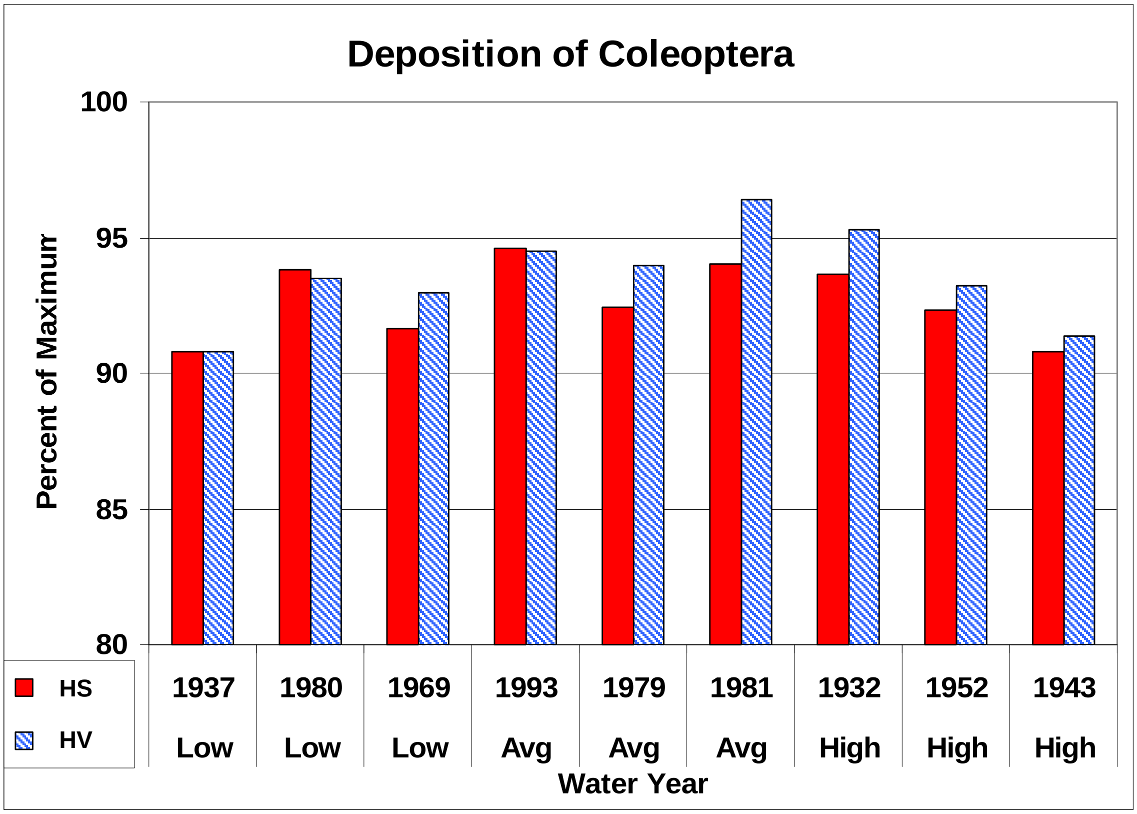


Figure 33. Deposition of Coleoptera on to the surface of Hungry Horse is charted to allow comparison of the two alternative dam operations. The x-axis arranges the water years from medium-low through medium-high categories of water availability.

As weather warms in spring and snowmelt begins to refill Hungry Horse Reservoir, westslope cutthroat trout shift their diet from benthic Diptera to terrestrial insects (May *et al.* 1988). Terrestrial insects deposited and trapped on the surface of Hungry Horse Reservoir are the primary food source for insectivorous fish between late-June and mid-November, or when freezing weather ends most terrestrial insect activity. Afterwards, zooplankton become the primary winter food of reservoir fish species that do not eat other fish.

Model results revealed no differences in the amount of Hymenoptera, Hemiptera and Homoptera deposited on the reservoir among the alternatives. However, Coleoptera deposition differed between HV and HS. Coleoptera are deposited in significantly greater numbers within 100 m of shore (May *et al.* 1988). Therefore, when surface elevation recedes from shoreline vegetation, fewer beetles are trapped on the surface and fish food availability is reduced. HV trapped as many or more beetles than HS during seven of the nine simulated water years. However, during 1980 and 1993, HS filled slightly faster and the larger surface area trapped more insects. HS resulted in greater reservoir drawdown during all years except 1937 when the alternatives did not differ. Deep drawdown slows the reservoir refill process, so the surface area remains smaller and further from shoreline vegetation and fewer beetles are trapped on the surface.

Westslope Cutthroat Trout Growth

Trout growth is controlled primarily by water temperature and food availability. Little growth occurs when water temperature is less than 6° C or greater than 18° C. For example, growth efficiency in sockeye salmon (*Oncorhynchus nerka*) peaks between 9 and 14° C, depending on food availability (Brett *et al.* 1969). Growth efficiency was optimal at lower water temperatures when food was limiting. Conversely, trout can sustain more efficient growth at higher temperatures when food is unlimited. These relationships were used to calculate growth in westslope cutthroat trout.

Westslope cutthroat trout growth was calculated using multivariate analyses of measured growth rates. Equations included water temperature and seasonal food habits. Annual growth calculations at age III, IV and V assumed that reservoir conditions remained the same during each year. Differences between the alternative operating strategies influenced the reservoir thermal structure and the production of food categories used by the growth equations. Results reflected differences in the reservoir thermal structure, and production values for zooplankton, benthic insects and Coleoptera. Growth trajectories were calculated over each water year (Figure 34, also see files for each year named Mhhtrout9***.txt, where "***" is the two digit year and the alternative code b = HS, v = HV).

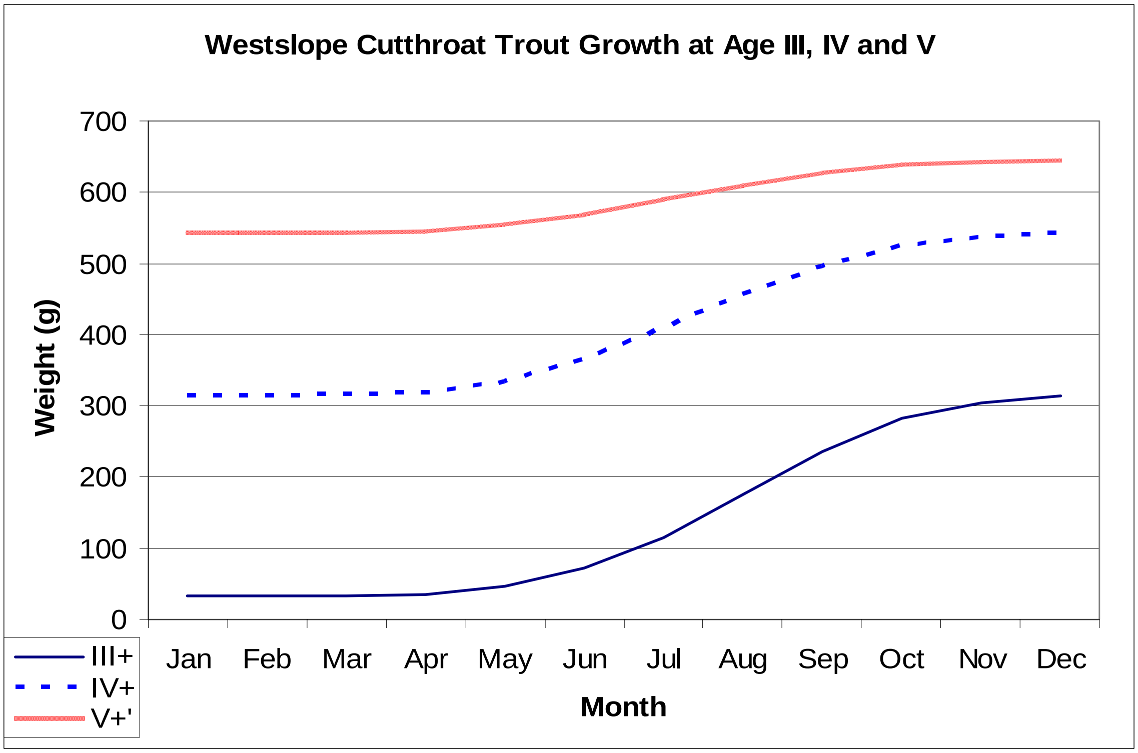


Figure 34. Annual growth trajectories for age III, IV and V westslope cutthroat trout in Hungry Horse Reservoir. This example is for the Standard alternative in 1969 (Mhhtrout969b.txt).

The total annual growth of westslope cutthroat trout was compared between the alternative operation strategies (Figure 35).

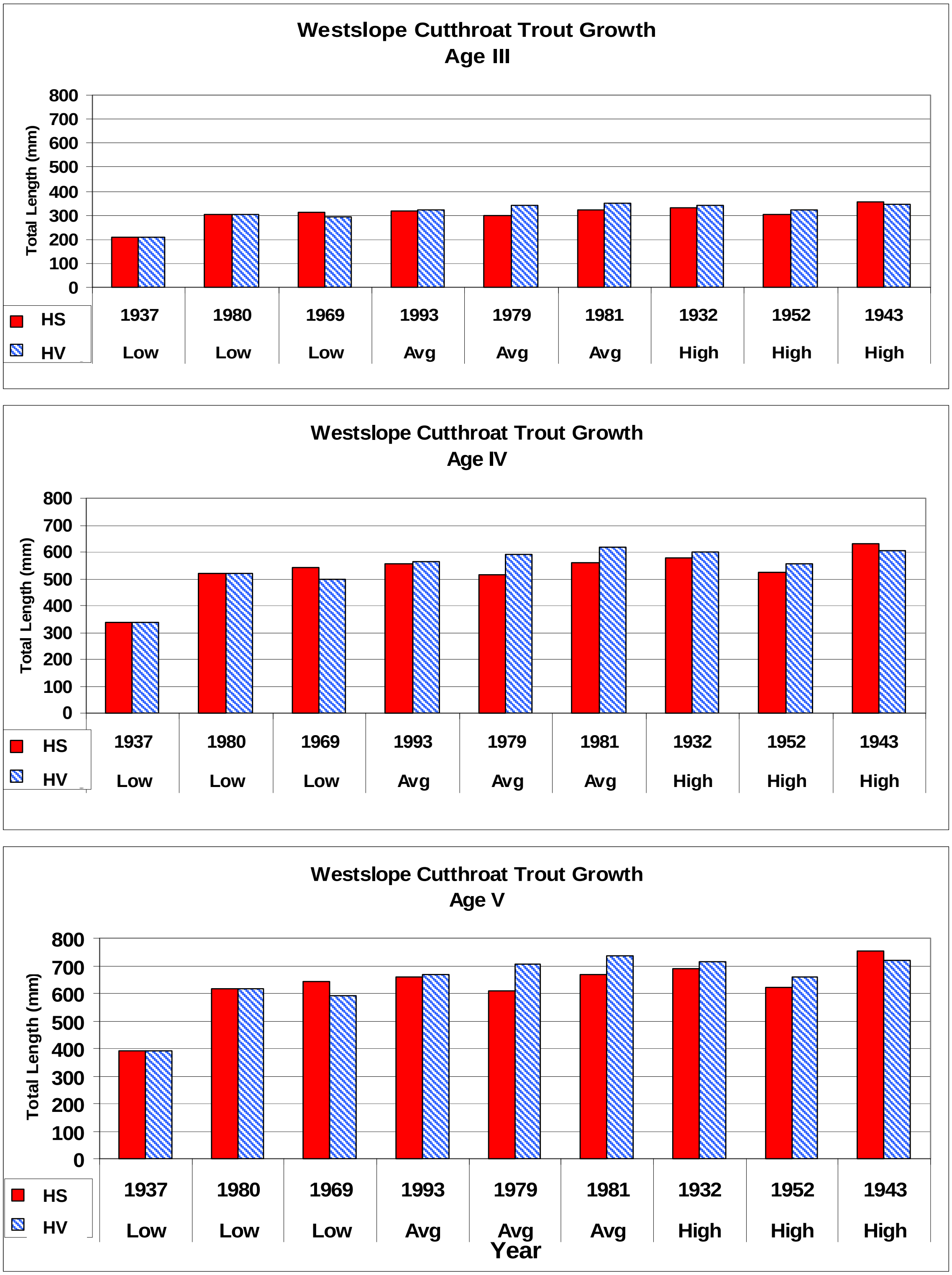


Figure 35. Westslope cutthroat trout growth (weight in grams) at age III, IV and V in Hungry Horse Reservoir. Bars in each water year compare growth under two alternative dam operation strategies.

Model results revealed slightly higher growth for all three age classes of westslope cutthroat trout under HV in five of the nine water years simulated. During the three average and the lower two high water years, HV produced greater food production in the lower trophic levels due to the large volume of reservoir at optimal water temperatures. Food availability was a primary factor that influenced trout growth. Although the availability of terrestrial insects is an important factor, model results predicted no difference in the deposition of three of the four insect orders, including Hymenoptera that is a primary food item in the diet of westslope cutthroat trout.

Westslope cutthroat trout growth was higher under HS for the two years simulated (1969 and 1943). During 1969, primary productivity and zooplankton production were slightly higher under HV, and washout losses were less compared to HS. Although HS reached a deeper minimum pool elevation, reservoir elevations remained higher during the previous fall when trout growth potential remained high (see plots of Hungry Horse Reservoir elevation in \H-Input\ All Years Hsurf.xls). During 1943, reservoir elevations under HS were slightly higher than HV during the reservoir refill period. Primary production was slightly greater under HS, whereas zooplankton production was slightly greater under HV. Washout losses of Daphnia were slightly higher under HS. The availability of terrestrial beetles was lower under HS, but due to the relatively low biomass associated with Coleoptera, growth calculations for the alternatives were not offset by this factor. Most importantly, benthic production during both years was substantially greater under HS (by 38 metric tons in 1969 and 20 metric tons in 1943) during the seasonal growth period. Benthic insects are the primary food source for westslope cutthroat trout during spring and the importance of this trophic level is weighted accordingly in the growth equation. This single factor largely resulted in better growth under HS during these two water years.

River Modeling

We conducted a sensitivity analysis to determine if the assumed rate of benthos recolonization (47 days) influenced the relative ranking of the alternative dam operation scenarios. The rate at which benthos recovers after dry substrate becomes inundated is variable depending on several factors including flow variability, water temperature, trophic state, stream morphology and insect species diversity (Armitage 1984; Cushman 1985). Gersich and Brusven (1981) found that benthic recolonization is delayed when flows vary rapidly (66 days) as compared to unregulated streams (47 days). Brusven and Trihey (1978) observed that it took a minimum of 28 days for benthic stream communities to become productive. Given this uncertainty, 144 paired simulations were performed with the benthos growth curve set at 30 days and 100 days to determine if the relative ranking of alternatives was influenced by the benthos recovery interval.

In Kootenai River simulations, the relative ranks in 96 of 108 simulations did not change when the benthic recovery interval varied from 30 to 100 days. As expected, the total sum of benthic biomass units accrued by each alternative, reduced as the duration of benthic recovery was increased. Six transpositions of rank occurred. In 1955, alternative LV2 (VARQ FC with fish flows plus 10 kcfs) was lower than predicted when the benthic recovery interval was increased from 30 to 100 days. In 1957, benchmark LV (VARQ FC without fish flows) was higher than predicted when the benthic recovery interval was increased from 30 to 100 days. In 1963, alternative LV1 (VARQ FC with fish flows) was lower than predicted when the benthic recovery interval was increased from 30 to 100 days. In 1981, benchmark LV was higher than predicted when the benthic recovery interval was increased from 30 to 100 days. In 1963, alternative LV1 (VARQ FC with fish flows) was lower than predicted when the benthic recovery interval was increased from 30 to 100 days. In 1989, alternatives LV1 and LV2 were lower than predicted when the benthic recovery interval was increased from 30 to 100 days.

Additional simulations were performed by increasing the benthic recovery interval in 10-day increments to determine when the rank transposition occurred in these alternatives. Results indicated that the ranking of alternatives remained consistent when the benthic recovery interval was set between 30 and 70 days. Ranking results remain the same between this range. Thus, our results suggest that our assumed benthic recovery interval of 47 d did not influence the relative ranking of alternatives (see RivProd (KR1-sensitivity).xls on the accompanying CD).

In Flathead River simulations, the relative rank of 34 of 36 simulations did not change when the benthic recovery interval varied from 30 to 100 days. As expected, the total sum of benthic biomass units accrued by each alternative reduced as the duration of benthic recovery increased. Only one transposition of rank occurred. In 1979, the total sum of benthic biomass units under HS was higher than under HV when the benthic recovery interval was 65 days or greater. Ranking once again remained consistent at recovery rates less than 65 days. These data suggest that the benthic recovery interval of 47 days used in this analysis did not influence the relative ranking of alternatives (see RivProd (C Falls sensitivity).xls).

Flood control operations limit high spring flows and result in physical changes to river morphology. Control of periodic flood events removes the hydraulic energy required for channel maintenance and resorting of river sediments. This generally occurred during spring runoff on average or greater water years. Under regulated conditions, frequent flow fluctuations exceed natural variability and cause extensive bank instability and erosion as water repeatedly flows into and out of the banks. Excess sediments increase substrate embeddedness and reduce interstitial habitat required by aquatic insects (Armitage 1984).

Flow regulation disrupts natural processes governing the growth of riparian vegetation. Aquatic and terrestrial vegetation that would normally provide secure habitat for fish and wildlife along the river margins, and stabilize soils, cannot fully reestablish each summer, and fine sediment materials are more easily eroded and swept back into the channel (Jamieson and Braatne 2001; Marotz *et al.* 2002).

Macroinvertebrate communities are adapted and arranged to capitalize on stream energy (velocity), such that a continuum occurs where downstream forms benefit from the inefficiency of upstream forms (Vannote *et al.* 1980; Stanford *et al.* 1988; Stanford and Ward 1989; Hauer *et al.* 1989). Flow fluctuations caused by hydropower dams impact physical habitat and biological production (Ward and Stanford 1979). Rapid flow reductions desiccate bottom substrates and may strand aquatic insects, zooplankton, fish, and fish eggs (Kroger 1973; Cushman 1985), and increase downstream drift of benthic invertebrates (Minshall and Winger 1968; White *et al.* 1981; Poff and Ward 1991). Loss of habitat due to power peaking operations results in reduced insect production and food availability for fish (Gislason 1983).

Hungry Horse and Libby Dam operations increased annual flow variability causing the zone of fluctuation, or *varial* zone, to widen (Figure 36) and become biologically unproductive (Stanford and Hauer 1978; Hauer and Stanford 1982; Fraley and Graham 1982; Shepard *et al.* 1984; Fraley and Decker-Hess 1987; Hauer *et al.* 1994; Hauer *et al.* 1997). Since 2000, ramping rate practices consistent with the 2000 U.S. Fish and Wildlife Service Biological Opinion have helped reduce rapid flow fluctuations. Many of the insect species in the Flathead and Kootenai Rivers that are sensitive to changes in flow velocity were relatively low in abundance following the installation of Hungry Horse and Libby Dams (Hauer and Stanford 1991; Hauer *et al.* 1994; Hauer and Stanford 1997). Most slow-growing univoltine insect species that are grazers or collectors/gatherers have declined and been replaced by species with short life spans (e.g., multivoltine), are sessile, or predaceous. Rapid flow reductions from Hungry Horse Dam resulted in the desiccation and/or freezing of stonefly nymphs concentrated in the lateral margins of the channel (Stanford 1975). Hauer and Stanford (1982) observed large limnephilid caddisfly larvae stranded on gravel bars and pools in summer after declining flow releases from Hungry Horse Dam, thus increasing the likelihood of desiccation and predation by birds.

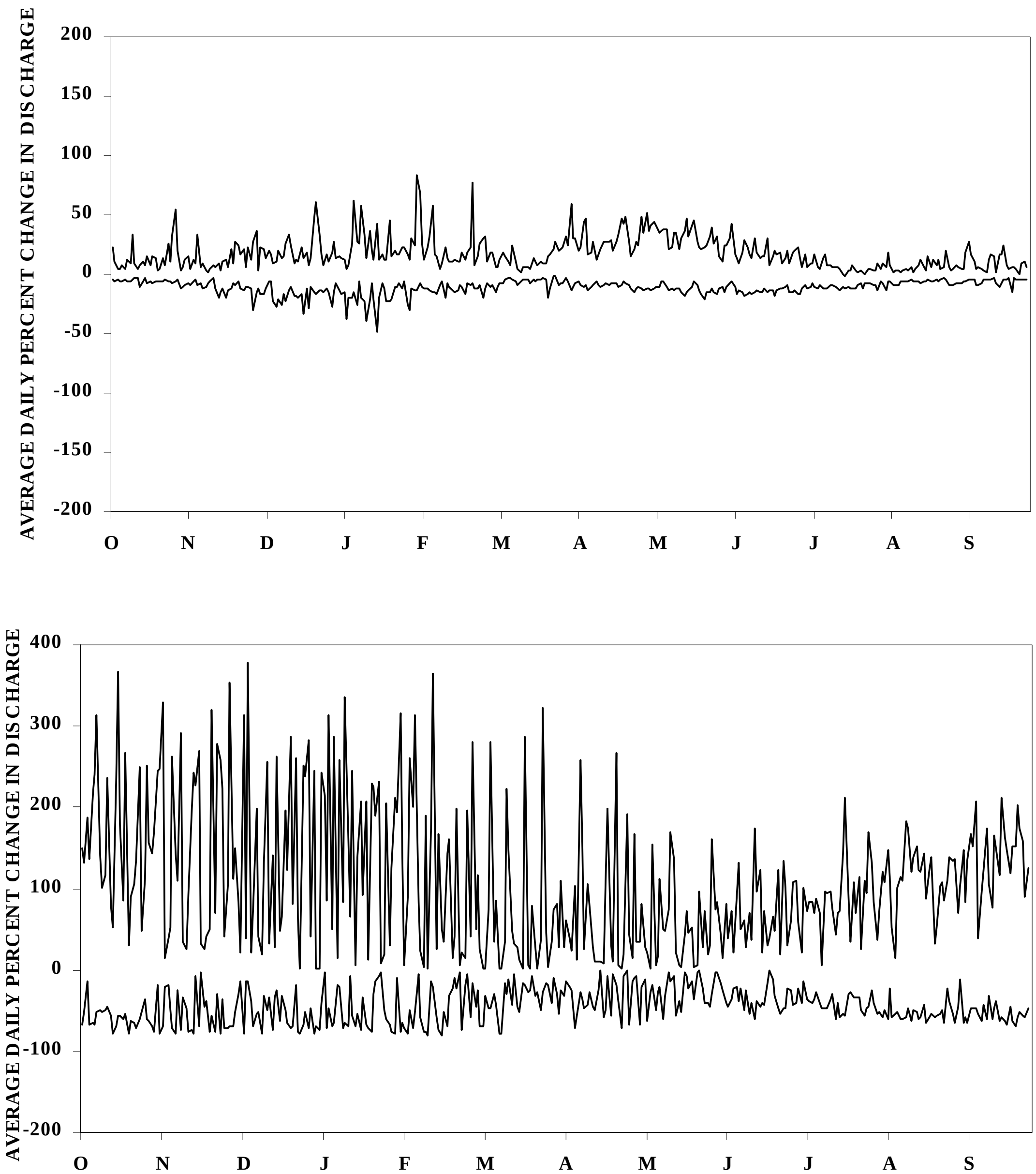


Figure 36. The analogous example of the change in daily discharge before and after regulation by hydropower operations is from the Kootenai River. Daily variance is less prior to dam installation (water year 1952 through 1971 (top)) and greater after Libby Dam began regulating flows (water years 1975 through 1995 (bottom); Hauer 1997). Intermittent fluctuations create a wide varial zone that becomes biologically unproductive.

Kootenai River

Benthic biomass calculations are presented for the Kootenai River in Reach 1 immediately downstream of Libby Dam and Reach 2 just upstream of Bonners Ferry, Idaho. Annual simulations used input files provided by the Corps for the six alternatives and nine water years. Reach 1 analyses used daily Libby Dam discharge data, and daily flow data from Bonners Ferry were used in Reach 2 calculations. The model RivBio was calibrated using survey transects specific to each river reach. For each simulation, model output included daily schedules of benthic biomass units, totals for each depth zone in the channel, and totals for the period March 1 through September 30. Comparisons of the alternatives were summarized. All output files can be examined on the accompanying CD.

Reach 1 - Downstream of Libby Dam

The effect of hydropower operations was most apparent in the Kootenai River immediately downstream of Libby Dam. Inflowing water from unregulated sources progressively moderates the influence of dam operation with distance downstream. Results reveal an increasing trend in benthic biomass with increasing water availability (Figure 37).

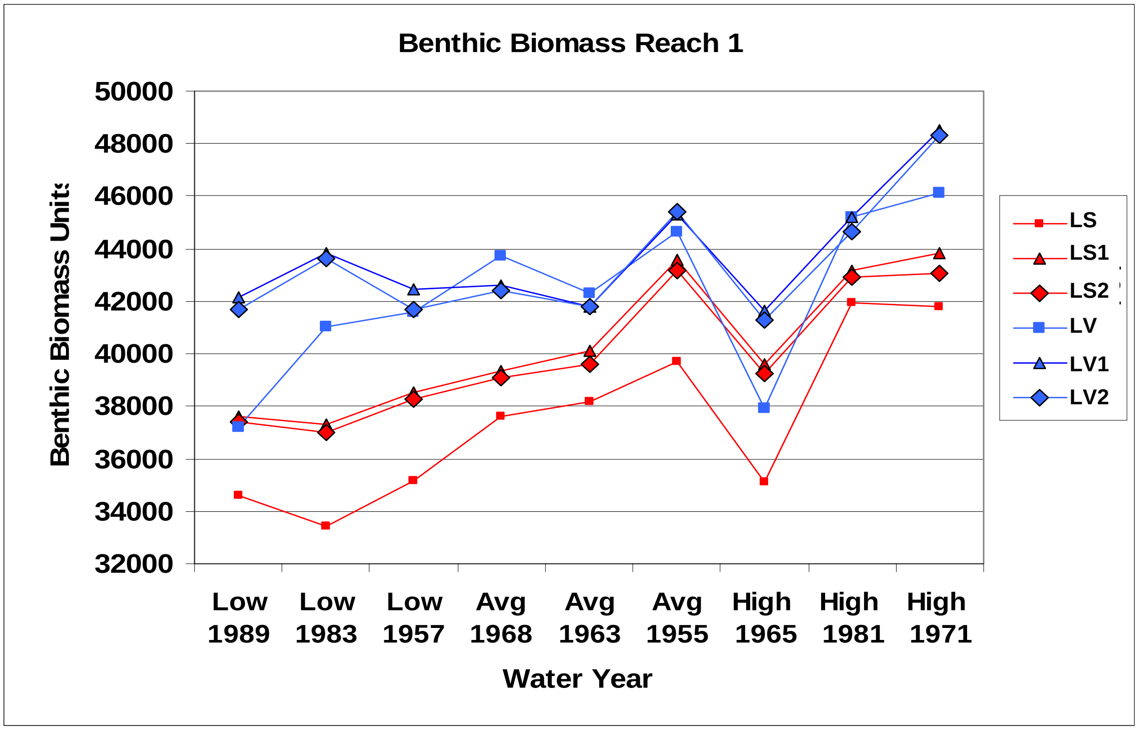


Figure 37. Model calculations of benthic biomass units accrued during the period March 1 through September 30 in the Kootenai River downstream of Libby Dam. Water years on the X-axis are arranged from driest to wettest, left to right. The four alternatives and two benchmarks are color-coded: red = Standard FC, blue = VARQ FC and identified by point symbols. Alternative LS = Standard FC only, LS1 = Standard FC with fish flows, LS2 = Standard FC with fish flows plus 10 kcfs. LV through LV2 follow the same convention for VARQ FC.

The VARQ FC alternatives and benchmark generally accrued more benthic biomass units than standard flood control alternatives and benchmark. However, in water years 1965 and 1989, benchmark LV accrued less benthic biomass than alternatives LS1 and LS2. The reason for these results is apparent in the corresponding hydrographs (Figures 38 and 39).

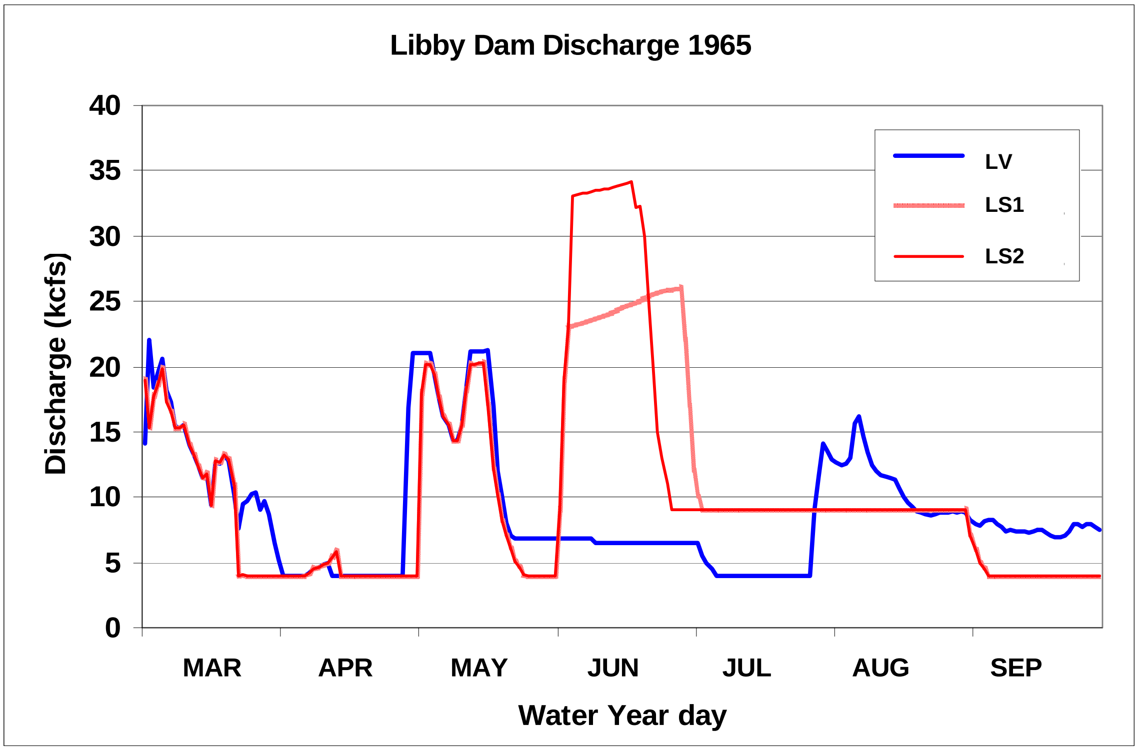


Figure 38. Comparison of Libby Dam discharge hydrographs for three alternative dam operations in 1965. Dam discharges under benchmark LV (blue line) decline toward minimum flow (4,000 cfs) during July, dewatering substrate, and then fluctuate with minimums approaching 7 kcfs. Alternatives LS1 and LS2 remain stable at 9 kcfs throughout the biologically productive summer months. Operation LV during September produces more benthic biomass than LS1 and LS2 that reduce flows to the minimum.

In 1965, the VARQ FC alternatives LV1 and LV2 produced nearly a natural hydrograph, whereas benchmarks LV and LS result in a “double peak” during spring. During the spring peak, a sudden flow reduction dewaters substrate and “resets” the benthos to the lowest flow during the preceding 30-d period. Benthic productivity was limited during brief periods of high discharge because substrate inundation was of short duration. Wetted perimeter remained wet and biologically productive during the summer months in alternatives LV1 and LV2 as flows stabilized above 11 kcfs. Summer production was also protected by alternatives LS1 and LS2 that stabilized at 9 kcfs through August. Conversely, wetted perimeter was rapidly lost in benchmark LV as flows approached minimum flow (4 kcfs) during July. This “double peak” first dewaters productive habitat, then floods substrate again during late July and August. Fluctuations during fall in benchmark LV limited benthic production to the zone that remained wet at 7 kcfs.

Benthic production during September was greater under benchmark LV as flows in LS1 and LS2 declined toward the minimum flow of 4 kcfs.

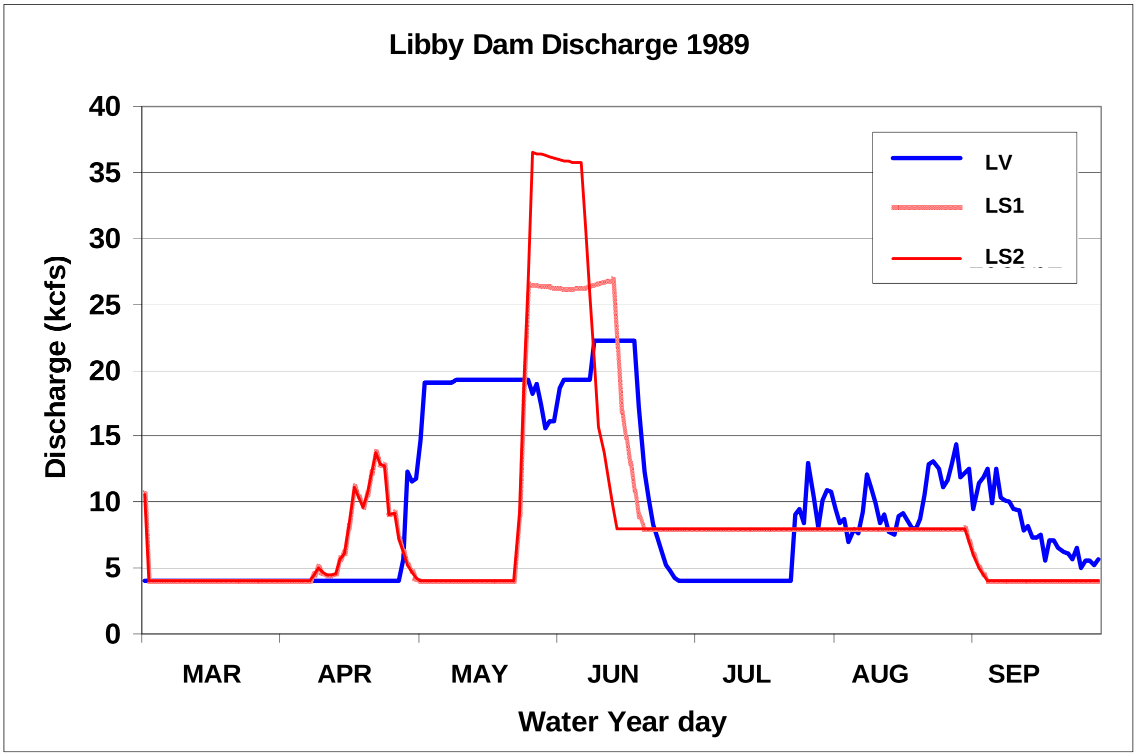


Figure 39. Discharge hydrographs for three alternative dam operations at Libby Dam in 1989. Hydrographs compare benchmark LV (VARQ FC with no fish flows) to the Standard FC alternatives LS1 (with fish flows) and LS2 (with fish flows plus 10 kcfs). Comparison of Lines superimpose until early-April. Dam discharges under LV (blue line) decline toward minimum flow (4,000 cfs) during July, dewatering substrate, and then fluctuate with minimums approaching 7 kcfs. Alternatives LS1 and LS2 remain stable at 8 kcfs throughout the biologically productive summer months. Benchmark LV during September produces more benthic biomass than LS1 and LS2 that reduce flows to the minimum.

In 1989, benthic productivity was limited in May and June during the brief high flows under alternatives LS1 and LS2. The fairly stable and prolonged spring freshet in benchmark LV facilitates the development of benthic biomass, but this potential is lost, or “reset” as substrate dries as flows reduce to minimum flow (4,000 cfs) in late-June. Benthos are maintained in riffle areas that remain wet at 8,000 cfs in alternatives LS1 and LS2 because flows are held constant at 8 kcfs during the productive summer months June through August. Conversely, benchmark LV dewaters a large percentage of riffle habitats with 4 kcfs minimum flows during July. Brief pulses above 7 kcfs in late August under benchmark LV produces a limited gain in productivity, failing to offset previous losses. Benthic production in benchmark LV exceeds the amount provided by the Standard FC operations during September as flows gradually decline from 10 to 5 kcfs.

Reach 2 – Kootenai River at Bonners Ferry

We used 26 survey transects to establish the relationship between flow and wetted perimeter (WETP) in the Kootenai River upstream of Bonners Ferry, Idaho. Stream flow data for the six alternative dam operation scenarios were examined using the river model, RivBio, to estimate benthic biomass production resulting from the various discharge schedules. The effect of Libby Dam operation is moderated in this river reach. The channel in Reach 2 has a lower gradient and is generally wider than Reach 1. Unregulated inflows from tributaries entering the Kootenai River downstream of Libby Dam dilute and mask the effects of short-duration operational changes. Results for the period March 1 through September 30 are presented in Figures 40-41.

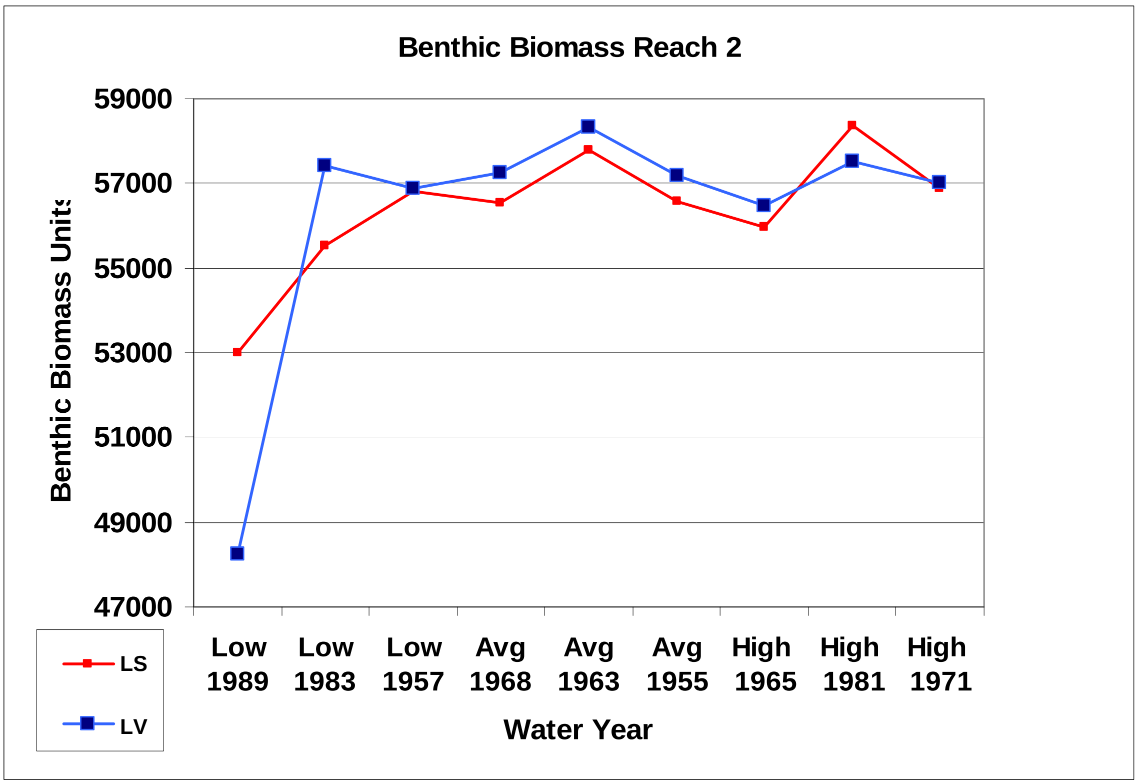


Figure 40. Benthic biomass units accrued during the period March 1 through September 30 in the Kootenai River upstream of Bonners Ferry, Idaho under the Standard FC benchmark LS and VARQ FC benchmark LV. Neither alternative provides “fish flows” for Kootenai white sturgeon, bull trout or anadromous species in the Columbia River.

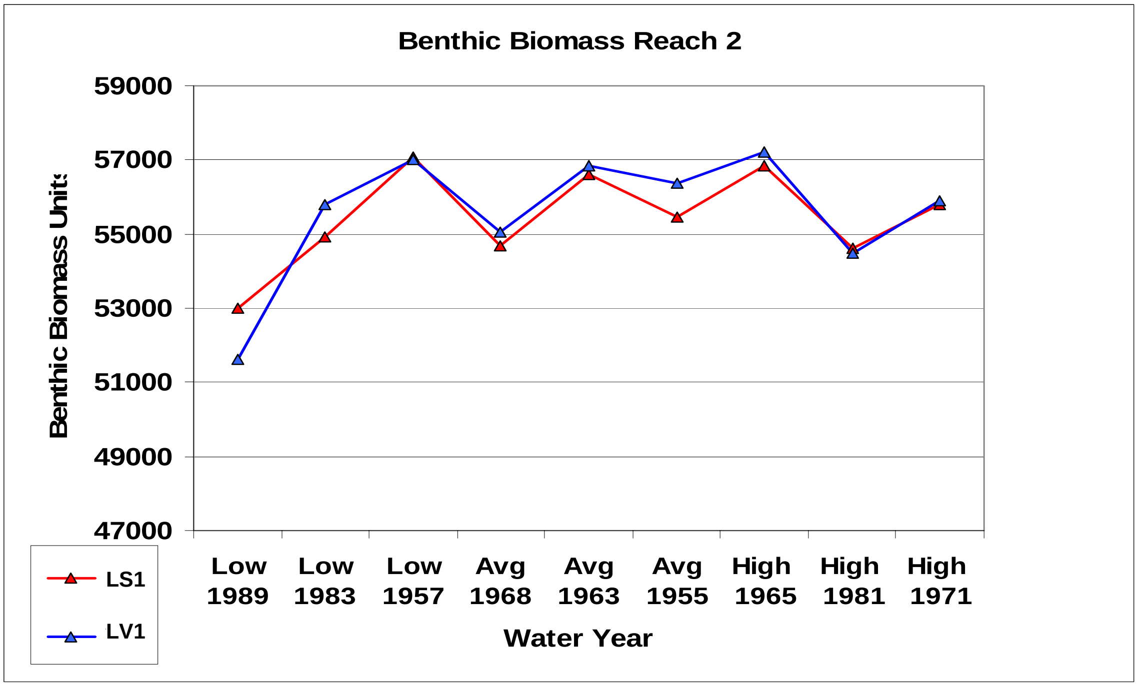


Figure 41. Benthic biomass units accrued during the period March 1 through September 30 in the Kootenai River upstream of Bonners Ferry, Idaho under alternatives LS1 and LV1. Both alternatives provide "fish flows".

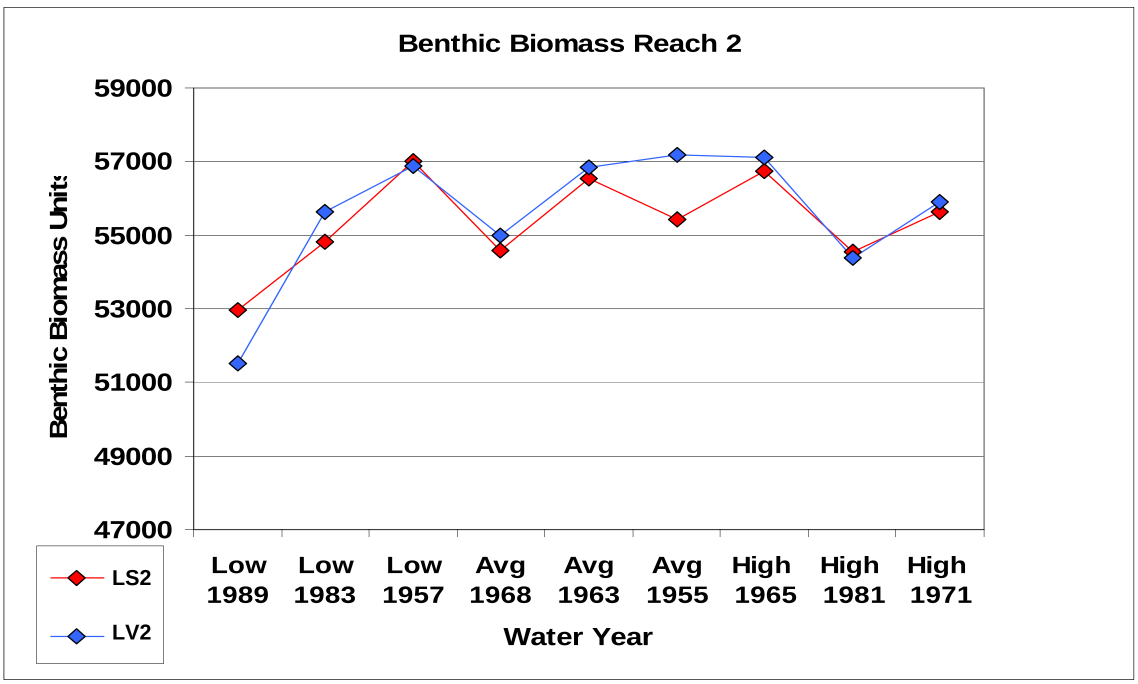


Figure 42. Benthic biomass units accrued during the period March 1 through September 30 in the Kootenai River upstream of Bonners Ferry, Idaho under the LS2 and LV2. Both alternatives provide "fish flows" for anadromous species in the Columbia River and bull trout, "plus 10 kcfs" for Kootenai white sturgeon.

The VARQ FC alternatives resulted in greater benthic biomass than the Standard FC during all years except 1989 and 1981. During 1989, flows under the VARQ FC alternatives declined toward the minimum during July and benthic organisms desiccated along the channel margins. Even after flow conditions improved, benthic biomass impacted earlier by the low flows rebounded slowly. The period totals remained lower than the Standard FC alternatives (Figure 43).

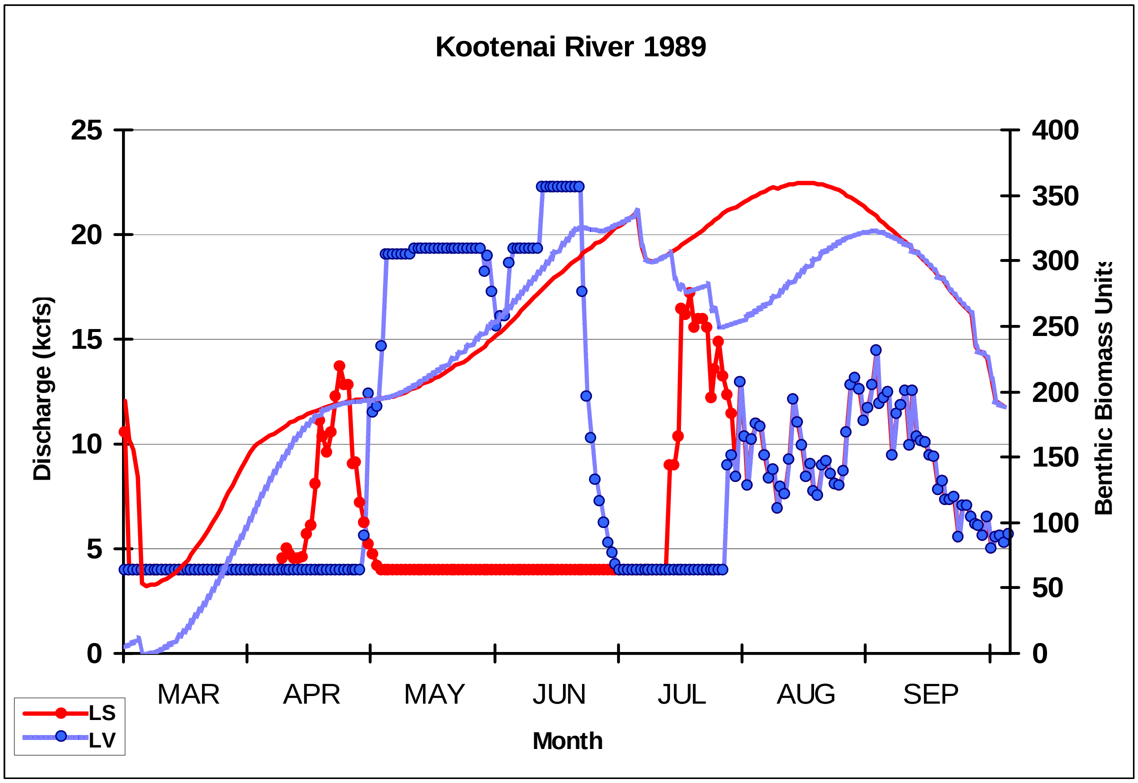
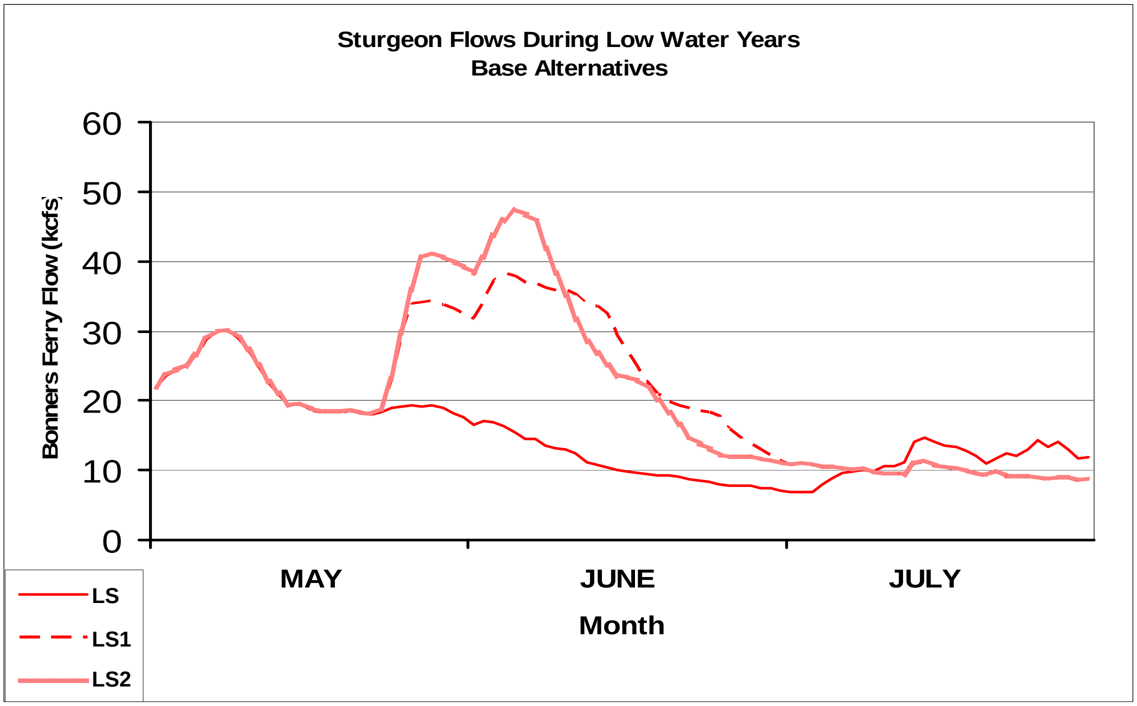


Figure 43. The daily accumulation of benthic biomass units compared to flow (kcfs) in the Kootenai River upstream of Bonners Ferry, Idaho. Lines with data points represent flow. In this example for 1989, benthic production in benchmark LV (blue) is "reset" to a lower level when Libby Dam discharges are reduced in July. The dewatered substrate later recovers, although the period total remains lower than Benchmark LS.

Flow Augmentation for Kootenai White Sturgeon

The USFWS 2000 Biological Opinion on the operation of Columbia River Dams contains reasonable and prudent alternatives for the recovery of the Kootenai white sturgeon. Flow data for the Kootenai River upstream of Bonners Ferry were summarized to determine the relative amount of flow provided by the alternatives during the sturgeon's critical spawning and early rearing phase. Differences between the alternatives that provided fish flows "LS1, LS2, LV1 and LV2" were most apparent during low water years (Figure 44, also see the complete set of plots named Bonners Flow (sturgeon flows).xls).



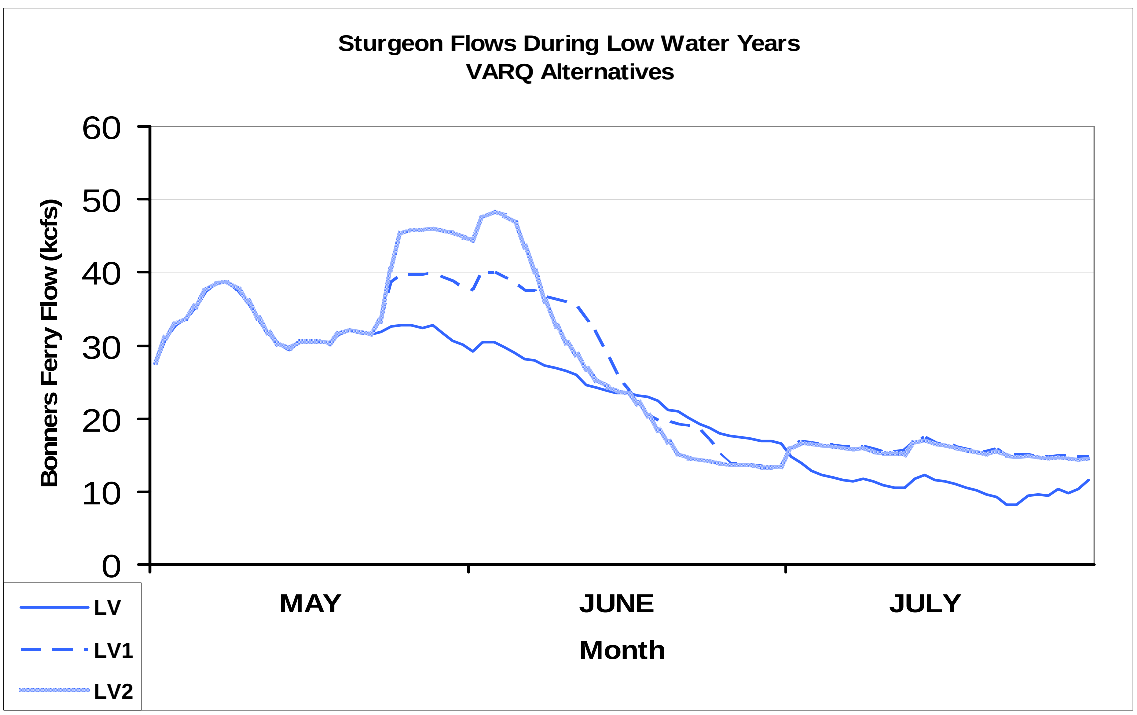


Figure 44. Average flows provided for Kootenai white sturgeon during low flow years under LS and LV benchmarks compared to "fish flow" alternatives LS1 and LV1 and the "fish flows plus 10 kcfs" alternatives LS2 and LV2.

The difference in sturgeon flows provided by the alternatives was most apparent during average and low water years. The VARQ FC alternatives LV1 and LV2 released more water during May and early June, and maintained flows at a higher stage during July.

Flathead River

Benthic biomass calculations are presented for the South Fork Flathead River immediately downstream of Hungry Horse Dam (Reach 1) and mainstem Flathead River at Columbia Falls, Montana (Reach 2). Annual simulations used input files provided by Reclamation for two alternatives and nine water years. Reach 1 analyses used daily Hungry Horse Dam discharge data. Daily flow data from Columbia Falls were used in Reach 2 calculations. The model RivBio was calibrated using survey transects specific to each river reach. For each simulation, model output included daily schedules of benthic biomass units, totals for each depth zone in the channel and totals for the year. Comparisons of the alternatives are summarized here. All output files can be examined on the accompanying CD.

Reach 1 - Downstream of Hungry Horse Dam

RivBio was calibrated using WETP survey data provided by MFWP. The reach immediately downstream of the dam has many deep runs and pools and only three riffles. This was reflected in a composite WETP versus flow relationship that was derived by averaging data from six survey transects (Figure 45).

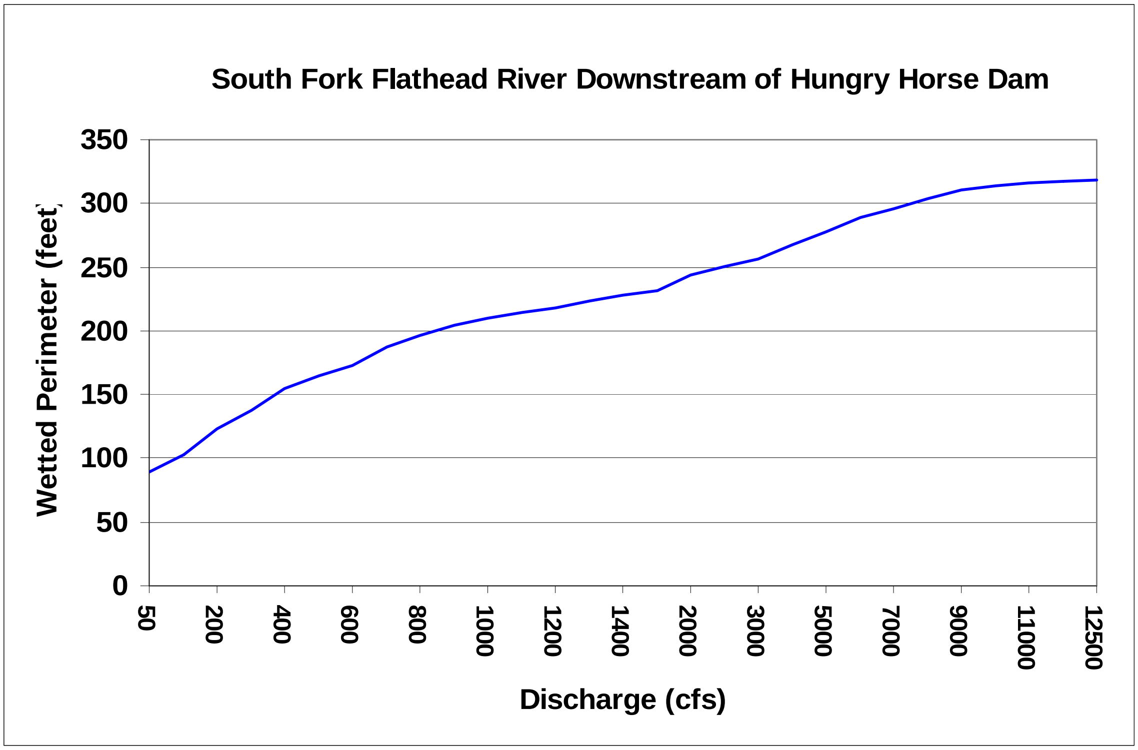


Figure 45. Wetted Perimeter and flow relationship for the South Fork Flathead River immediately downstream of Hungry Horse Dam (source: Marotz and Muhlfeld 2000).

Minimum flows in the South Fork Flathead River were established with a sliding scale to adjust to varying annual water availability. Flows of 900 cfs protect aquatic productivity in the majority of riffle areas and shallow runs. During the driest water years, the minimum flows may be reduced to 400 cfs (Marotz and Muhlfeld 2000). Discharge data provided by Reclamation adhere to these limits and so there is little difference between the HS and HV during periods at minimum flow.

The effect of hydropower operations is most apparent in the South Fork Flathead River immediately downstream of Hungry Horse Dam. Inflowing water from the unregulated North and Middle Forks of the Flathead Rivers and the Stillwater River progressively moderates the influence of dam operation with distance downstream. Results reveal an increasing trend in benthic biomass with increasing water availability (Figure 46).

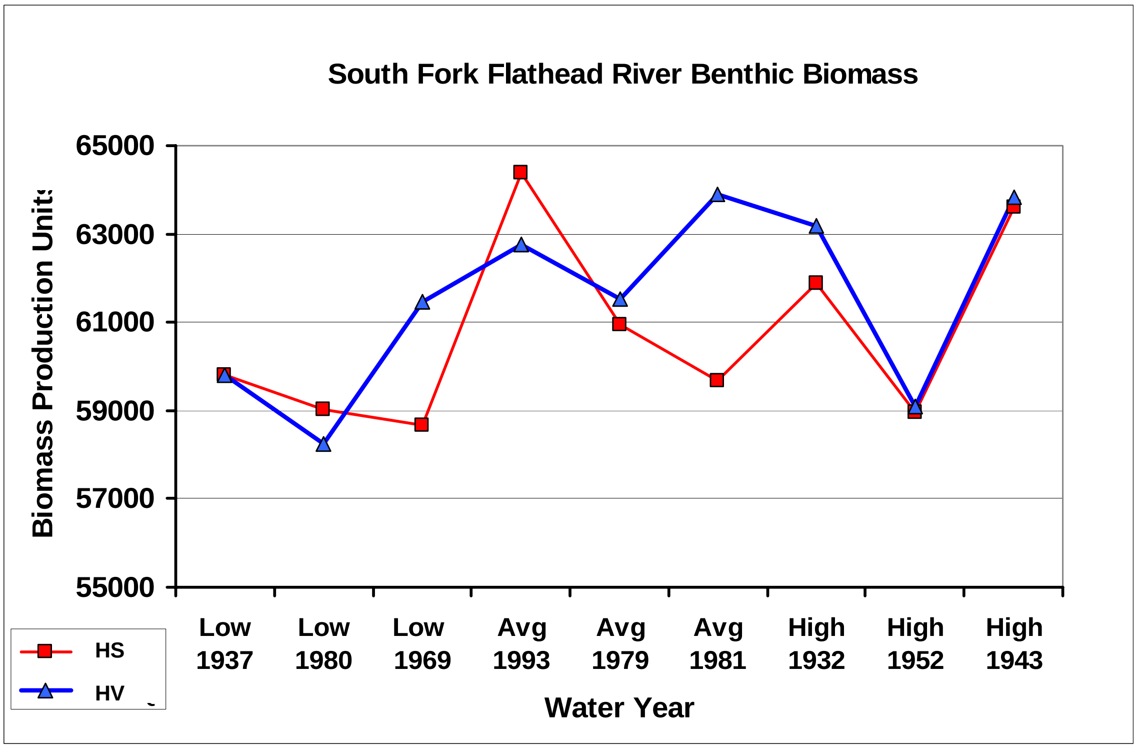
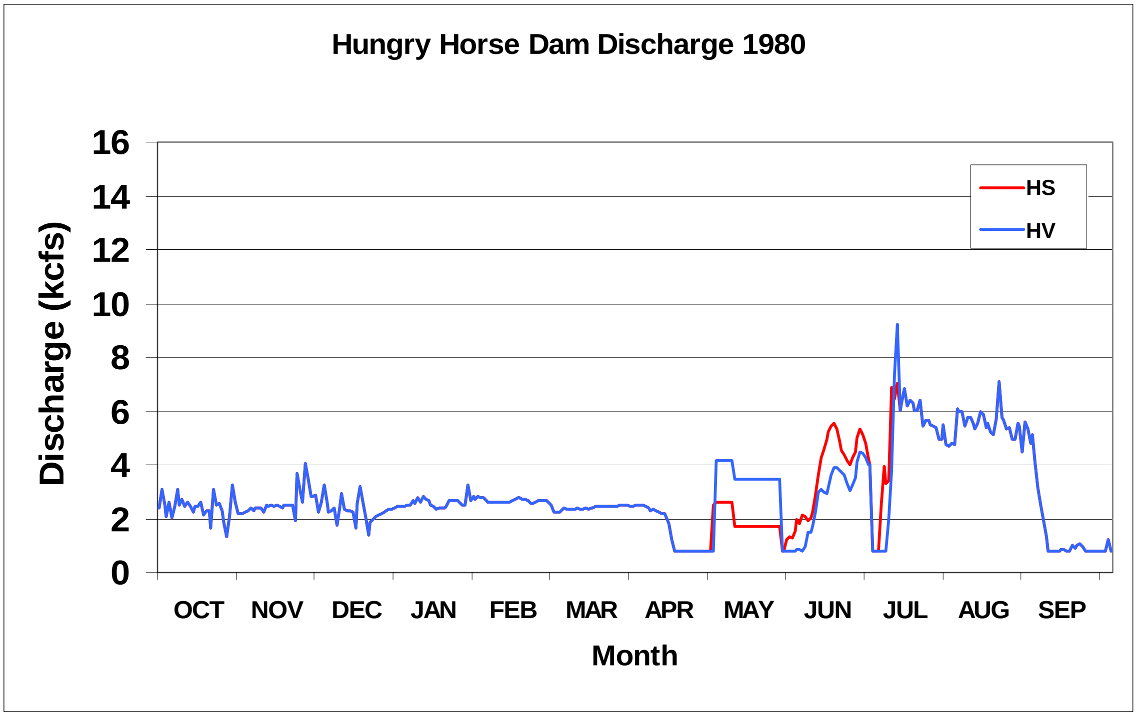


Figure 46. Benthic Biomass accumulated in the South Fork Flathead River under the HS and HV during each water year.

Benthic biomass production under HV was equal to or greater than HS during seven of the nine years. HS provided more favorable conditions for benthic production during 1980 and 1993. The reason for HS ranking higher in these two years is apparent in a comparison of the hydrographs produced by the two alternatives during these two years (Figure 43, also see plots of discharge data in the file named “HH Outflow (All Alternatives).xls”).



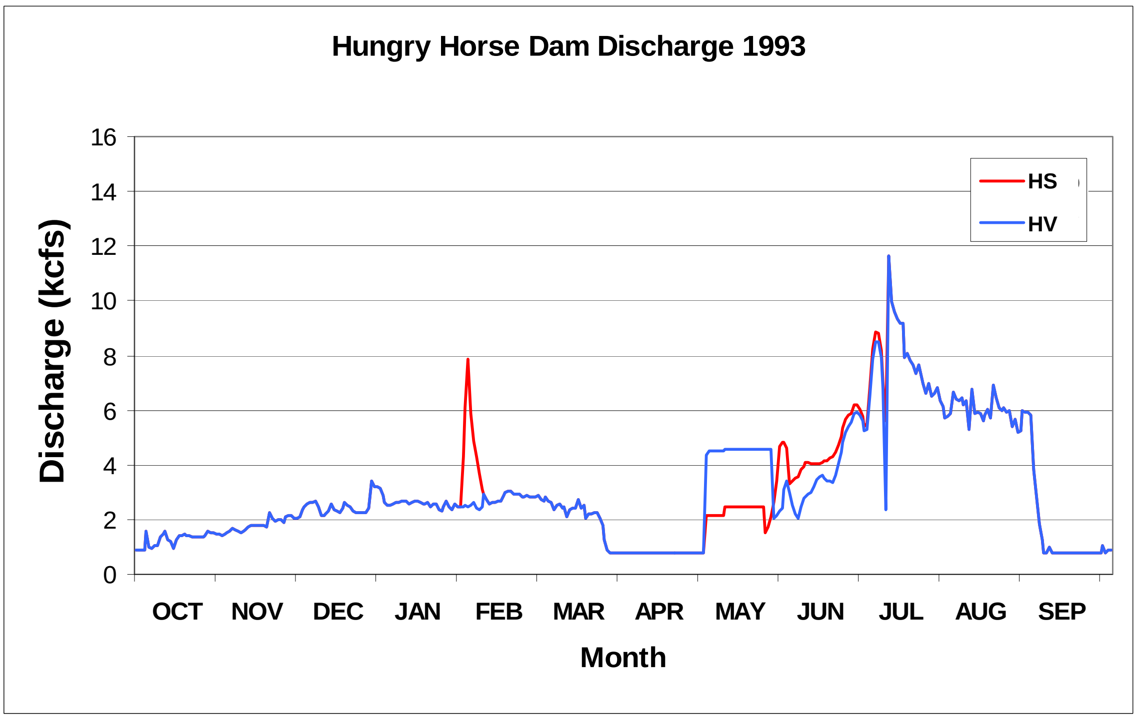


Figure 47. Hungry Horse Dam discharge (kcfs) under HS and HV operations during 1981 and 1993. Note that in both years, flows under the HS (red) were higher during June and early July. Flow increases produced by HV (blue) during May, provided little benefit to benthic production because the pulse was too brief to allow benthic recovery, then flows reduced in late-May desiccating productive substrate.

Alternatives that provided stable flows during the productive warm months produce more benthic biomass units during the water year. Sudden flow reductions “reset” the productive zone to the lowest river stage during the preceding 30-40 days.

Reach 2 – Flathead River at Columbia Falls

The wetted perimeter (WETP) methodology used 8 transects developed using hydroacoustic techniques by Miller *et al.* (2003). Transect data were averaged to establish the relationship between flow and WETP in the Flathead River at Columbia Falls, Montana. Stream flow data for the two alternative dam operation scenarios were examined using RivBio to estimate benthic biomass production resulting from the various discharge schedules. The effect of Hungry Horse Dam operation is moderated in the mainstem by unregulated flows from the North and Middle Forks of the Flathead River. Reach 2 is lower gradient and generally wider than Reach 1. Unregulated inflows from the Middle and North Forks dilute and mask the effects of short-duration operational changes. Annual results for HS and HV are presented in Figure 48.

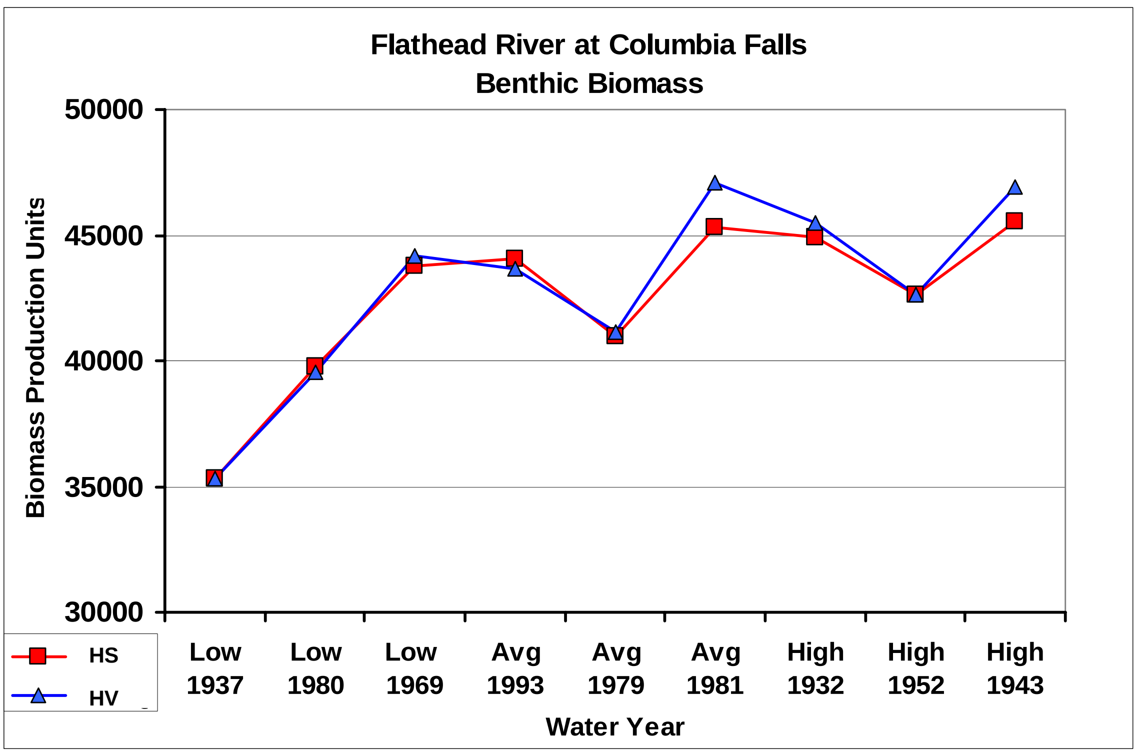


Figure 48. Benthic biomass units accrued in the Flathead River at Columbia Falls during each water year. The plot compares benthic biomass production under HS and HV. Both alternatives provide “fish flows” for bull trout in the Flathead River and anadromous species in the Columbia River.

The effects of Hungry Horse Dam operations on river biota were moderated by minimum flows established for the South Fork and the annual minimum flow limit at Columbia Falls (3,500 cfs). Since HS and HV adhere to these limits, the depth zones protected by minimum flows remained productive in both scenarios. The remaining differences were also moderated in Reach 2 by unregulated flows from the North and Middle Forks. Given this, HV produced more benthic biomass than HS in five of the nine years simulated. The two years in which HS produced more benthos, Flathead River flows were greater than HV during June and early July as explained earlier in reference to the South Fork Flathead River.

Short-term flow fluctuations for weekly load following continue to impact river biota and should be mitigated, especially during low flow periods, by reducing the rate of change or *"ramping rate"* (Marotz *et al.* 2002). Benthos are reset to the lowest flow during the preceding 30 or 40 days, so short-term flow reductions should be avoided. Bull trout and westslope cutthroat trout in the Flathead River trout are impacted indirectly by dam operation by decreased food availability and directly by habitat loss. Sporadic flow fluctuations are especially harmful to bull trout that require shallow areas along the channel margins at night (Muhlfeld *et al.* 2003). The highly variable flows apparently stress native salmonids as they move from day to night habitat locations based on depth and velocity characteristics. Miller *et al.* (2003) provides a visual characterization of habitat and Arcview project data.

Flathead Lake

During the water years selected for this analysis, conditions in Flathead Lake were minimally influenced by Hungry Horse Dam operations. Data provided by Reclamation for Flathead Lake elevations under the two alternatives were overlaid for comparison in the file: "Flathead Lake Elevations (mod comp).xls" (Figure 49) .

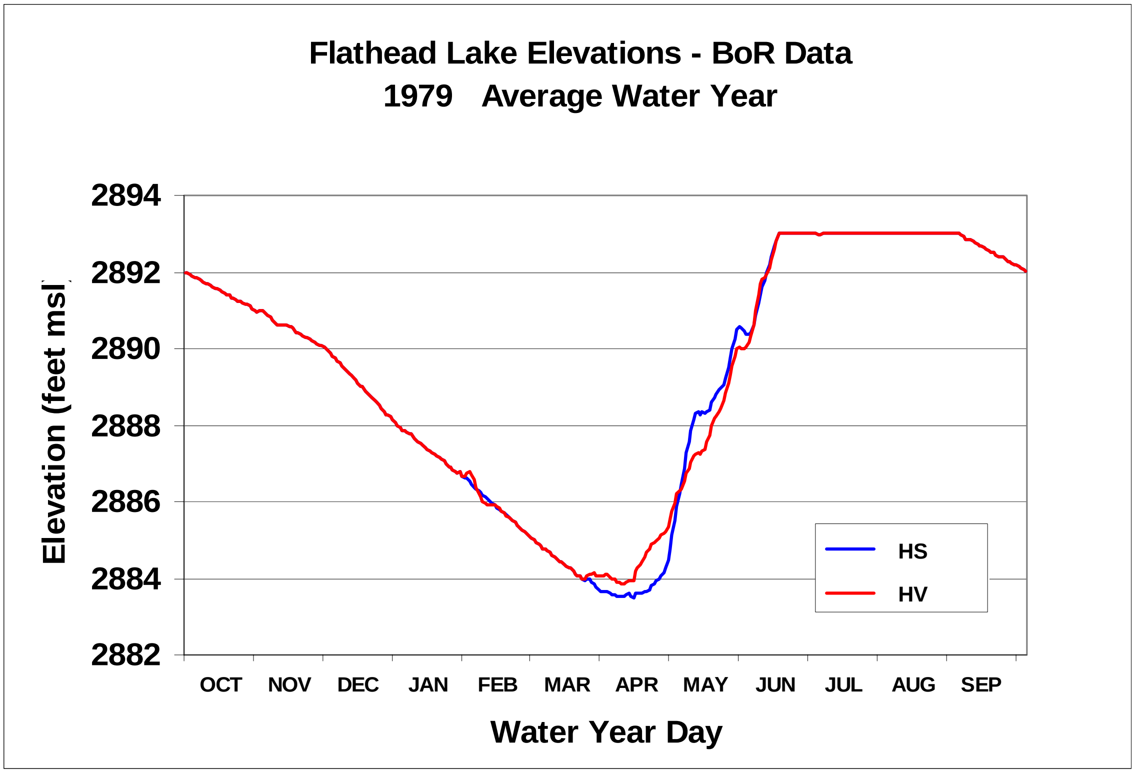


Figure 49. An example of the minimal effect of HS and HV on Flathead Lake.

Results from the Reclamation model and HRMOD were very similar. Neither model revealed a notable difference in Flathead Lake operations during water years with medium-low to medium-high water availability. Model simulations in the driest (lowest 20th percentile) and wettest (highest 20th percentile) water years may reveal greater differences between the alternatives than were found during this study. Additional simulations during the lowest and highest water years could provide greater insight into the effect of VARQ FC operations during drought and flood conditions.

Conclusions

Based on model analyses of biological responses to Standard and VARQ FC strategies, VARQ FC operations that provided fish flows generally resulted in improved biological conditions in the rivers downstream. Biological benefits in the Flathead and Kootenai rivers were moderated with distance downstream due to inflows from unregulated streams. VARQ FC alternatives also improved biological conditions in reservoirs compared to Standard FC alternatives during most years. Reservoir biota benefit when the annual reservoir drawdown is reduced and the surface remains at or near full pool during the biologically productive summer months.

Dam operations that maximize surface area and volume in the euphotic zone during the warm months produce more phytoplankton and zooplankton. Zooplankton are the primary food of non-predacious fish species during winter. At Libby Reservoir, the VARQ FC alternatives produced greater plankton production in all water years simulated. Benchmarks LS and LV that initiated at full pool produced more plankton than alternatives that began the year (October 1) 20 feet below full pool. Benchmark LV ranked highest, followed by LV1, which produced more phytoplankton than LV2 during seven of the nine years and more zooplankton during six of the nine years. At Hungry Horse Reservoir, HV resulted in greater phytoplankton and zooplankton production during seven of the nine water years. Loss of phytoplankton through the dam turbines, however, differed very little between the alternatives because the selective withdrawal was automated the same way in all alternatives. Loss of Daphnia through the turbines was higher under HV during six of the nine water years, presumably due to greater Daphnia production in the reservoir resulting from HV.

Benthic insects are the primary food for insectivorous fish species during spring. Benthic insect production is enhanced when the depth of the annual reservoir drawdown is reduced and when depth zones containing high densities of dipteran larvae remain in the euphotic zone during the productive warm months. At Libby Reservoir, benchmark LV produced more benthos than benchmark LS during all years. Of the alternatives that provided fish flows, LV1 produced more benthic insects than the Standard FC alternatives during all years. Alternative LV2 produced more benthos than the Standard FC alternatives during eight of nine water years. At Hungry Horse Reservoir, benthic production was greater under HV in five of the nine years, whereas HS produced more benthos in three of the nine water years.

Terrestrial insects become available to fish when they are deposited on the reservoir surface from the surrounding landscape and are the primary food for insectivorous fish during the summer and fall. The number of terrestrial insects captured on the reservoir surface is dependant on reservoir surface area and distance from shoreline vegetation to the water. Alternatives that remain at or near full pool during the months when terrestrial insects are active capture more insects than operations that draw the reservoirs down during summer. At Libby Reservoir, benchmarks LS and LV began at full pool and the reservoir remained full during most of the summer and fall. Benchmark LV captured more insects than any other alternative, while LS was a close second for all insect orders except Coleoptera. Of the alternatives that provided fish flows, the VARQ FC alternatives captured more terrestrial insects than the Standard FC alternatives during all water years. Alternative LV1 captured slightly more insects than LV2 with few exceptions. Similarly, LS1 nearly always captured more insects than LS2. Apparently, LS2 reduced surface area during most years and trapped fewer terrestrial insects. At Hungry Horse Reservoir, terrestrial insect deposition was nearly the same in both alternatives. Of the four insect orders, only the deposition of Coleoptera differed between the alternatives. HV captured more beetles during six of the nine water years. Deep reservoir drawdowns delay the reservoir refill process and result in a smaller surface area and greater distance from the water to shoreline vegetation. Operations that fail to refill trap fewer terrestrial insects.

VARQ FC provided environmental conditions more conducive for fish growth than Standard FC during most water years. At Libby reservoir, benchmark LV resulted in greater kokanee growth than LS during all years. Of the four alternatives that provided fish flows, the VARQ FC alternatives resulted in greater kokanee growth during eight of the nine years. Alternative LV1 produced greater kokanee growth than LV2 during five of the nine water years, while growth under LS1 was greater than LS2 during six of nine years. At Hungry Horse Reservoir, operations did not differ between the alternatives during 1937. Of the eight remaining water years, HV resulted in greater growth of westslope cutthroat trout during six of the years.

Downstream of the dams, unnatural flow fluctuations caused by dam operations disrupt natural processes and reduce biological productivity. The effect of hydropower operations is most apparent in the rivers immediately downstream of the dams. Inflowing water from unregulated sources progressively moderates the influence of dam operation with distance downstream. Short-term flow fluctuations increase the width of the zone of fluctuation, or *varial zone*, which becomes biologically unproductive.

Biological impacts associated with hydropower operations can be mitigated by restoring normative river processes (Independent Scientific Group 1999). When flows are stabilized below hydropower projects, flood plain function can be restored, reducing deleterious effects on biological production (Marotz *et al.* 2002). The Independent Scientific Advisory Board (ISAB 1997 and 1997b) recommended restoring the most natural flow regime possible under the current management constraints to protect key ecosystem processes and maintain or restore resident fish populations. Restoration of the most natural flow regime possible can partially be achieved by establishing minimum flows and seasonal flow ramping rates. Many of these beneficial measures have already been implemented at Hungry Horse and Libby Dams. Tiered flows for restoring Kootenai white sturgeon and stable summer flows for bull trout (USFWS 1999 and 2000) were included in the Libby alternatives LS1, LS2, LV1, and LV2. Similarly, both HV and HS alternatives provided “fish flows” in the Flathead River reaches. Still, short-term flow reductions continue to impact river biota below the Montana projects and annual hydrographs differ from normative conditions. The WETP technique demonstrated the importance of avoiding short-term flow reductions, especially during the productive summer months.

The VARQ FC alternatives generally accrued more benthic biomass units than alternatives that use standard flood control. In the Kootenai, alternatives LV1 and LV2 ranked similarly high during all years and benchmark LV ranked closely behind. An exception occurred during 1965 and 1989 when LV was ranked lower than LS1 and LS2. The reason LV produced less benthic biomass was evident in the hydrographs. Benchmarks LS and LV do not provide fish flows. As a result, dam discharges under LV reduced to minimum flow during the productive summer months, whereas all the alternatives that provide fish flows (LV1,LV2, LS1 and LS2) maintain higher, stable flows throughout summer. During September, however, flows under LV protected more river productivity than LS1 and LS2 by maintaining stable flows when flows under the Standard FC alternatives reduced to minimum. Although LV created better river conditions during September, benthic production was insufficient to offset the summer losses and LV ranked lower than Standard FC operations in two years. September flows remain important to river productivity. Short-term flow reductions should be avoided between summer flows and high winter flows that result when the dams begin to generate electricity to meet high winter loads. River flows should be maintained as stable as possible during the fall transition period to maintain the maximum benthic productivity during the winter high discharge period.

Differences between the alternatives were most evident in the South Fork Flathead River immediately downstream of Hungry Horse Dam. Analysis of the South Fork Flathead River revealed that alternative HV produced more benthic biomass than HS during six of nine water years. Comparison of the HV and HS in the Flathead River at Columbia Falls produced similar results, although the effect of operation was moderated by unregulated flows from the unregulated North and Middle Forks. HV produced more benthos in the mainstem Flathead River during five of the nine years. Our river modeling indicated that HV is beneficial to river productivity when flows remain stable during the productive summer and fall months.

The influence of VARQ FC on Flathead Lake was minimal over the range of flows modeled (middle 60th percentile water years). Model simulations in the driest and wettest water years may reveal greater differences between the alternatives than were found during this study. Additional simulations could provide greater insight into the effect of VARQ FC operations during drought and flood conditions.

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