Analysis of Potential Impacts to Resident Fish from Columbia River System Operation Alternatives

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ABSTRACT / The US Army Corps of Engineers, the US Bureau of Reclamation, and the Bonneville Power Administration initiated the Columbia River System Operation Review (SOR) in 1990. The SOR will assist agencies in comparing the benefits and risks to Columbia River uses and natural resources from alternative strategies for using Columbia River water. Focusing on 14 federal dams within the basin, the agencies are attempting to improve on the efficient and coordinated use of the Columbia River system. An initial screening of all potential strategies of reservoir operation was necessary to reduce the number of possibilities to a limited set for detailed analysis. To that end, the Resident Fish Work Group of the SOR developed spreadsheet models capable of assessing the impacts of different management strategies on resident fish at six storage reservoirs. The models include biological, physical, and hydrological relationships important to resident fish specific to each reservoir. Alternatives that kept the reservoirs near full pool and held stable during the growing season resulted in positive benefits to resident fish at all locations modeled. Conversely, alternatives designed to improve anadromous fish survival with increased instream flow generally had a negative impact on the resident fish in the reservoirs modeled. The models developed for resident fish in the screening analysis phase of the SOR were useful in assessing the relative impact to resident fish from a large number of alternatives. The screening analysis demonstrated that future analytical efforts must consider trade-offs among river uses/resource groups, among reservoirs throughout the basin, and among resident fish species within a reservoir.

The Columbia River is the fourth largest river by drainage area in North America (Shiklomanov 1993). Development of the Columbia River Basin has provided economic benefits to nearly every Pacific Northwest resident, but varied interests are increasingly competing for limited water. The federal and nonfederal dams that have been constructed in the basin (Figure 1) provide hydroelectric generation, flood control, irrigation, and inland navigation. However, conversion of the river into a series of reservoirs has severely impacted the river's natural resources. For example, the Kootenai River white sturgeon (*Acipenser transmontanus*) and two species of Pacific salmon (sockeye salmon, *Oncorhynchus nerka*, and chinook salmon, *O. tshawytscha*) have been listed as endangered under the Endangered Species Act (ESA), and additional petitions to the ESA for both anadromous and resident fish are being reviewed. Water quality has deteriorated in some areas, and wildlife habitat has become fragmented and reduced.

Resident fish (fish that spend their entire life cycle in freshwater) are present in nearly every waterbody in the Columbia River Basin. They are an important and integral part of the Columbia River ecosystem. The recreational opportunities provdied by resident fish are often more popular than those provided by anadromous fish because of more angling opportunities. Resident fish also are an important part of Native American subsistence and culture. In addition, many resident fish species provide food for other fish and wildlife.

As the Columbia River Basin has been developed for economic benefits, populations of native fish species (Table 1) have been reduced in number. Native species such as the Kootenai River white sturgeon have been listed under the ESA. Bull trout (*Salvelinus confluentus*) are presently being reviewed for listing under the ESA. Westslope cutthroat trout (*O. clarki lewisi*), redband trout (*O. mykiss*), shorthead and torrent sculpin (*Cottus confusus* and *C. rhotheus*), Snake River white sturgeon,

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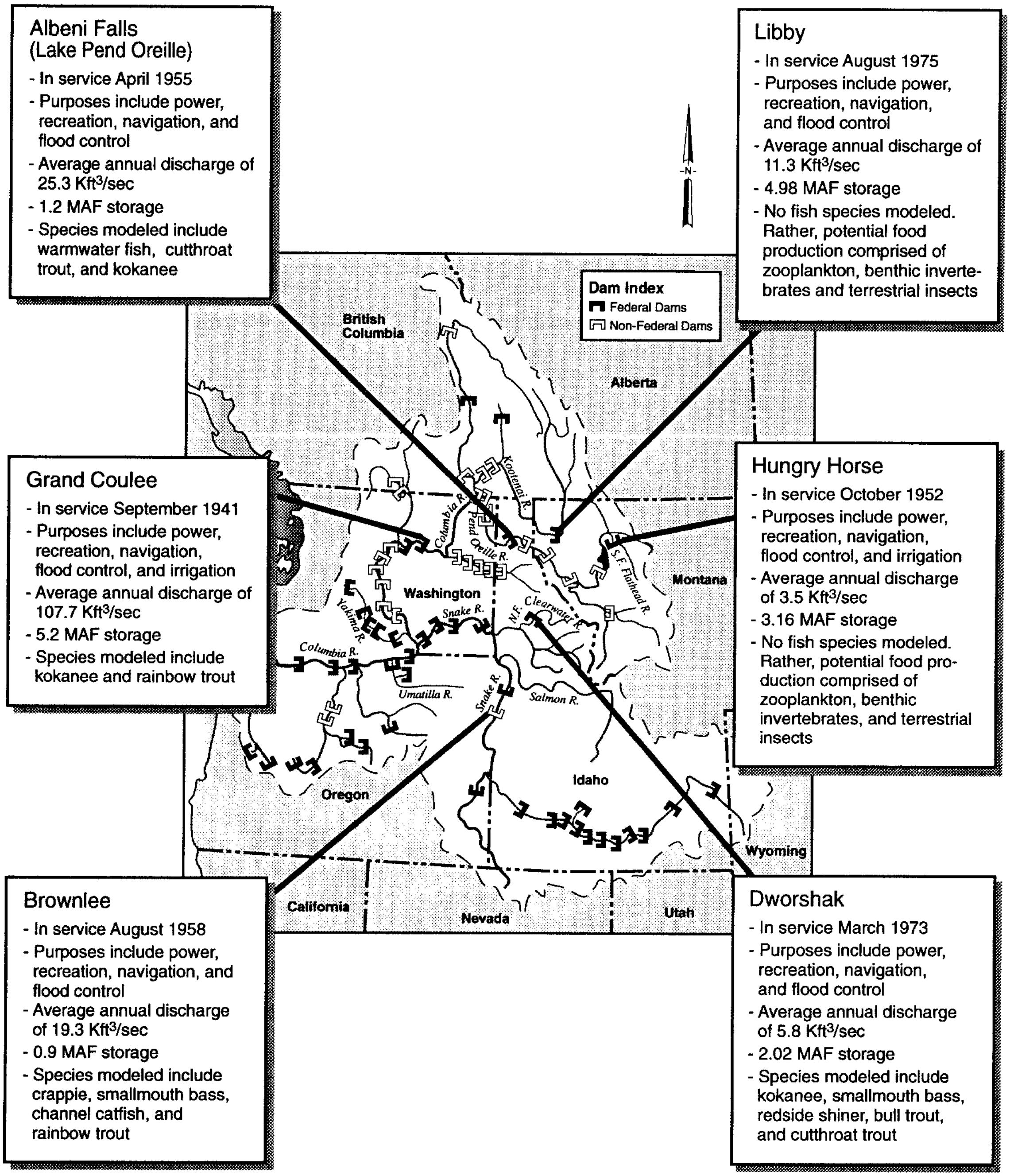

Albeni Falls
(Lake Pend Oreille)
- In service April 1955
- Purposes include power, recreation, navigation, and flood control
- Average annual discharge of 25.3 Kft³/sec
- 1.2 MAF storage
- Species modeled include warmwater fish, cutthroat trout, and kokanee

Libby
- In service August 1975
- Purposes include power, recreation, navigation, and flood control
- Average annual discharge of 11.3 Kft³/sec
- 4.98 MAF storage
- No fish species modeled. Rather, potential food production comprised of zooplankton, benthic invertebrates and terrestrial insects

Grand Coulee
- In service September 1941
- Purposes include power, recreation, navigation, flood control, and irrigation
- Average annual discharge of 107.7 Kft³/sec
- 5.2 MAF storage
- Species modeled include kokanee and rainbow trout

Hungry Horse
- In service October 1952
- Purposes include power, recreation, navigation, flood control, and irrigation
- Average annual discharge of 3.5 Kft³/sec
- 3.16 MAF storage
- No fish species modeled. Rather, potential food production comprised of zooplankton, benthic invertebrates, and terrestrial insects

Brownlee
- In service August 1958
- Purposes include power, recreation, navigation, and flood control
- Average annual discharge of 19.3 Kft³/sec
- 0.9 MAF storage
- Species modeled include crappie, smallmouth bass, channel catfish, and rainbow trout

Dworshak
- In service March 1973
- Purposes include power, recreation, navigation, and flood control
- Average annual discharge of 5.8 Kft³/sec
- 2.02 MAF storage
- Species modeled include kokanee, smallmouth bass, redside shiner, bull trout, and cutthroat trout

Figure 1. The Columbia River Basin showing key federal and nonfederal dams (modified from Bonneville Power Administration and others 1991). Information on date of service, purpose, average annual discharge (thousand cubic feet per second; Kft³/sec), reservoir storage capacity (million acre feet; MAF), and fish species modeled is included for those projects where resident fish models were constructed.

sandroller (*Percopsis transmontana*), and burbot (*Lota lota*) are either threatened, endangered, or species of special concern in Washington, Oregon, Montana, and/or Idaho.

Nonnative resident species have been introduced throughout the Columbia River Basin, usually to improve angler opportunities. For example, kokanee salmon (*O. nerka*), smallmouth and largemouth bass (*Micropterus dolomieui* and *M. salmoides*), lake trout (*S. namaycush*), and channel catfish (*Ictalurus punctatus*)

Table 1. Key resident fish species of the Columbia River Basin (Bonneville Power Administration and others 1994)

Common name	Scientific name
Western brook lamprey	*Lampetra richardsoni*[a]
Pacific lamprey	*Entosphenus tridentatus*[a]
White sturgeon	*Acipenser transmontanus*[a]
Lake whitefish	*Coregonus clupeaformis*
Pygmy whitefish	*Prosopium coulteri*[a]
Mountain whitefish	*Prosopium williamsoni*[a]
Cutthroat trout	*Oncorhynchus clarki*[a]
Rainbow trout (includes redband trout)	*Oncorhynchus mykiss*[a]
Kokanee (sockeye salmon)	*Oncorhynchus nerka*[a]
Atlantic salmon	*Salmo salar*
Brown trout	*Salmo trutta*
Bull trout	*Salvelinus confluentus*[a]
Brook trout	*Salvelinus fontinalis*
Lake trout	*Salvelinus namaycush*
Northern pike	*Esox lucius*
Chiselmouth	*Acrocheilus alutaceus*[a]
Goldfish	*Carassius auratus*
Common carp	*Cyprinus carpio*
Lake chub	*Couesius plumbeus*[a]
Tui chub	*Gila bicolor*
Peamouth	*Mylocheilus caurinus*[a]
Northern squawfish	*Ptychocheilus oregonensis*[a]
Longnose dace	*Rhinichthys cataractae*[a]
Leopard dace	*Rhinichthys falcatus*[a]
Speckled dace	*Rhinichthys osculus*[a]
Redside shiner	*Richardsonius balteatus*[a]
Tench	*Tinca tinca*
Longnose sucker	*Catostomus catostomus*[a]
Bridgelip sucker	*Catostomus columbianus*[a]
Largescale sucker	*Catostomus macrocheilus*[a]
Mountain sucker	*Catostomus platyrhynchus*[a]
Black bullhead	*Ameiurus melas*
Yellow bullhead	*Ameiurus natalis*
Brown bullhead	*Ameiurus nebulosus*
Channel catfish	*Ictalurus punctatus*
Tadpole madtom	*Noturus gyrinus*
Flathead catfish	*Pylodictis olivaris*
Mosquitofish	*Gambusia affinis*
Burbot	*Lota lota*[a]
Three-spine stickleback	*Gasterosteus aculeatus*[a]
Sandroller	*Percopsis transmontana*[a]
Pumpkinseed	*Lepomis gibbosus*
Warmouth	*Lepomis gulosus*
Bluegill	*Lepomis macrochirus*
Smallmouth bass	*Micropterus dolomieui*
Largemouth bass	*Micropterus salmoides*
White crappie	*Pomoxis annularis*
Black crappie	*Pomoxis nigromaculatus*
Yellow perch	*Perca flavescens*
Walleye	*Stizostedion vitreum*
Coastrange sculpin	*Cottus aleuticus*[a]
Prickly sculpin	*Cottus asper*[a]
Mottled sculpin	*Cottus bairdi*[a]
Piute sculpin	*Cottus beldingi*[a]
Slimy sculpin	*Cottus cognatus*[a]
Shorthead sculpin	*Cottus confusus*[a]
Reticulate sculpin	*Cottus perplexus*[a]
Torrent sculpin	*Cottus rhotheus*[a]

[a] Species native to the Columbia Basin.

provide recreational opportunities at many lakes and reservoirs in the basin.

The Bonneville Power Administration (BPA), the US Army Corps of Engineers (ACOE), and the US Bureau of Reclamation initiated the Columbia River System Operation Review (SOR) in 1990. The purpose of the SOR is to assist federal agencies in assessing the trade-offs of future operations among 10 river uses and/or natural resource groups: anadromous fish, irrigation, flood control, recreation, water quality, wildlife, navigation, power, cultural resources, and resident fish. The end product of the SOR will be a record of decision by the three agencies that identifies a preferred Columbia River operating strategy. The SOR is the first effort to evaluate trade-offs among all river users in the Columbia River Basin.

The SOR is being conducted in three analytical phases. The pilot analysis was performed to test the decision analysis methodology. The second phase, screening analysis, examined potential operating strategies using a simplified analytical approach. Initial screening of all potential strategies of reservoir operation at a cursory level was necessary to reduce the number of possibilities for detailed analyses. The final phase, the on-going full-scale analysis, is examining in detail a reduced number of alternatives from the screening analysis. Here we report on the screening analysis of impacts to resident fish.

The screening analysis included a large number of interest groups as well as a large number of ways to operate the Columbia River. Thus, a tool that assessed the impacts to resident fish species was needed. This is not unlike many resource evaluations where comparisons among impacts and river uses must be made. This paper describes the methods the Resident Fish Work Group (RFWG) of the SOR used to estimate the relative impacts to resident fish in the Columbia River Basin from 90 proposed operating strategies.

Methods

Scenarios

A technical work group representing each of the 10 river uses and/or natural resources developed one or more alternatives that were expected to benefit its interests. Alternatives the work groups proposed were translated into reservoir operating rules for each of 14 federal hydroelectric projects. The BPA and ACOE simulated operations for each of the alternatives using their hydroregulation models Hydrosim and HYSSR, respectively. The hydroregulation models estimated monthly (August and April were each further divided into two periods) pool elevations and flows that would have existed if the operating rules had been used during selected periods within the past 75 years. Five different water years (high flow, 1955–1956; medium–high flow, 1956–1957; medium flow, 1937–1938; medium–low flow, 1939–1940; and low flow, 1930–1931) were used to represent the natural variability of the unregulated inflows.

The 90 alternatives proposed for hydroregulation analyses were grouped into five general categories: base case (N = 3), flow augmentation (N = 46), drawdown (N = 16), stable pool (N = 21), and power (N = 4). The base-case alternatives represented different interpretations of system operating conditions in 1990–1991, prior to listing Snake River chinook and sockeye salmon as endangered under the ESA. The BPA and ACOE simulated the first two base-case operations using Hydrosim and HYSSR, and all subsequent alternatives were compared to their respective base-case alternative. If an alternative was simulated using Hydrosim, it was compared to the BPA base-case alternative. Likewise, if an alternative was simulated using the HYSSR model, it was compared to the ACOE base-case alternative. The results were not much different between the two base-case alternatives. In addition to these two base-case alternatives, an additional base-case alternative was simulated using the HYSSR model (observed base case). This alternative simulated base-case operating conditions by using the actual reservoir elevations and outflows for five water years selected from the past 15 years of operation. This alternative was used by the work groups as a comparison to the other two base-case alternatives.

Flow augmentation alternatives modify water storage and flow requirements, primarily for the benefit of anadromous fish. Drawdown alternative involve lowering the reservoirs in the lower Snake River to increase water velocities, again primarily for the benefit of anadromous fish. Stable pool alternatives result in stable storage reservoir elevations, primarily for the benefit of resident fish, irrigation, wildlife, transportation, and recreation. Power alternatives emphasize power system planning and operation.

Rather than show the results for all 90 alternatives, four representative alternatives plus the three base-case alternatives were selected from each of the five general categories for analysis in this paper (Table 2). Detailed results for all alternatives can be found in Bonneville Power Administration and others (1992).

Table 2. Representative alternatives from each of four general categories

Alternative category	Alternative description	Reference number from SOR
Base case	BPA base case	1
	ACOE base case	2
	Observed base case	42
Increased flow	Existing conditions	88
	Year-round flow increases	27
	Modified year-round flow increase	29
	Spring flow increase	6
Drawdown	Natural river	18
	Fixed drawdown	49
	Drawdown to reach target velocities	51
	Wildlife drawdown	66
Stable pool	Full, stable pool	56
	Maximum water retention time in Lake Roosevelt	57
	Water conservation	65
	Compromise full-pool	73
Power	No restrictions	77
	Optimize economic value	78
	Seasonal exchange of power	80
	Canadian flow	81

Alternatives that represented existing conditions, year-round flow increases, modified year-round flow increases, and spring flow increases were selected to represent the increased flow alternatives. The existing conditions alternative reflects the way the system was operated in 1992 after two species of Snake River salmon were listed under the ESA by the National Marine Fisheries Service. Under this alternative, Dworshak and Brownlee reservoirs are drafted on a forecast-based variable scale to provide water for anadromous fish passage and spawning. The year-round flow increase alternative attempts to achieve flow targets set on the Columbia and Snake rivers for every month of the year to improve anadromous fish survival. Federal storage projects such as Dworshak and Grand Coulee would be drafted as much as needed to meet these flow targets. The modified year-round flow alternative is similar to the year-round alternative except that there are restrictions on drafting Dworshak and Grand Coulee reservoirs. The spring flow increase alternative attempts to provide increased flows for anadromous fish while operating the system so that the federal power system is assured of 90% of its 1990–1991 firm energy load carrying capacity capability.

Alternatives that represented natural river conditions, fixed drawdown, drawdown to meet target velocities, and drawdown to benefit wildlife were selected to represent the drawdown alternatives. The natural river alternative operates the system as close to a natural river as possible with all reservoirs held to their minimum elevations. Runoff is returned to a natural hydrograph with all inflow passed at the spillway crest. The fixed drawdown alternative involves drawing down all four lower Snake River reservoirs to near spillway crest from

16 April through 15 August. No generation at the projects is allowed under this alternative. The drawdown to meet the target velocities alternative is very similar to some of the increased flow alternatives, but drafts the Snake River projects in an attempt to achieve an increase in flow velocity. Increased flow velocities are hypothesized to increase juvenile migration speed (Northwest Power Planning Council 1994). The drawdown alternative that benefits wildlife attempts to lower the storage and run-of-river reservoirs to expose maximum riparian, wetland, and nesting island acreage year-round. This alternative is designed to promote increased production of wildlife by providing long-term reservoir stability.

Alternatives that represented full pool, maximum water retention time, compromised full pool, and water conservation were selected to represent the stable pool alternatives. The full-pool alternative provides full, stable pool elevations at storage and run-of-river reservoirs year-round with no provisions for power peaking. The alternative was designed to resemble natural lake and river systems. To this end, all inflow at each project is passed naturally. The maximum-water-retention-time alternative attempts to retain resident fish within Grand Coulee Reservoir while providing flows for anadromous fish passage downstream. The alternative attempts to maximize resident fish production by retaining zooplankton in the reservoir. The compromise alternative was an attempt to provide good environmental conditions for resident fish at the storage projects while providing increased flow for power production, anadromous fish, recreation, flood protection, and irrigation. The water conservation alternative attempts to model a reduction in the consumptive use of water in the upper Snake River basin through improved irrigation practices. New upstream storage, use of uncontracted storage space, buy-backs of exiting water rights, and low flow year lease options are all assumed to be possible under this alternative.

Representative power alternatives included an alternative that removed all nonpower restrictions, an alternative that optimized the economic value of the system based on anticipating streamflows, one that exchanged power seasonally with California, and one that assumes Canadian flows are sufficient to generate 500 MW that can be transferred to California.

Model Development

The work groups were charged with developing models capable of estimating the impacts to their river use and/or resource for each of the 90 alternatives. The RFWG developed reservoir-specific spreadsheet models at six storage reservoirs (Figure 1). Minimal data on resident fisheries and other food-web components were available in the projects selected for modeling. The exception was Hungry Horse Reservoir where at least 10 years of research on resident fish have been conducted as part of the BPA's Fish and Wildlife Program (May and McMullin 1984, May and Zubik 1985, May and Fraley 1986, May and Weaver 1987, May and others 1988). Research on resident fish at other projects, however, has received relatively little attention compared to anadromous fish. This lack of adequate data hindered the modeling process and introduced considerable uncertainty in many of the relationships modeled.

Several of the models incorporated modified versions of a generic food production model for Hungry Horse and Libby reservoirs (Fraley and others 1989) in which food production was a function of reservoir volume, reservoir elevation, and area wetted bottom. These parameters were assumed to affect phytoplankton, zooplankton, and benthic insect production as well as terrestrial insect deposition.

Spreadsheet models were constructed using empirical data from each of the six reservoirs. Using Dworshak Reservoir as an example, the screening process is shown in Figure 2. Inputs to the spreadsheets models were monthly reservoir elevations and discharges obtained from the hydroregulation modeling results for each of the 90 alternatives.

The relationships between reservoir operation and resident fish were modeled using species-specific indices of habitat suitability that were based on data specific to each project. For example, at Dworshak Reservoir approximately 25% (range 5%–30%) of the tributaries to Dworshak Reservoir in which kokanee spawn may be inaccessible if the reservoir is lowered to 1450 ft above mean sea level (Maiolie and other 1993, M. Maiolie personal communication) (Figure 3A). Kokanee entrainment increases (i.e., reduced habitat suitability index) as average annual discharge increases from 2000 to 6000 ft^3/sec (Figure 3B). As the reservoir elevation is reduced, kokanee become concentrated and more susceptible to anglers (Figure 3C).

Smallmouth bass spawning and incubation success was modeled in Dworshak Reservoir by assessing the change in reservoir elevation between the period 15 May to 15 August (Maiolie and others 1993, D. Statler personal communication) (Figure 3D). Smallmouth bass rearing habitat is estimated to decrease as much as 40% (range 20%–50%) as the reservoir elevation is reduced from full pool (Figure 3E). Redside shiner (*Richardsonius balteatus*) spawning success was modeled because of their importance as a forage fish to cutthroat and bull trout in Dworshak Reservoir (Maiolie and others 1993, D. Statler personal communication). Redside shiner spawning success was modeled based on reservoir fluctuations between 1 May and 15 July (Figure 3F).

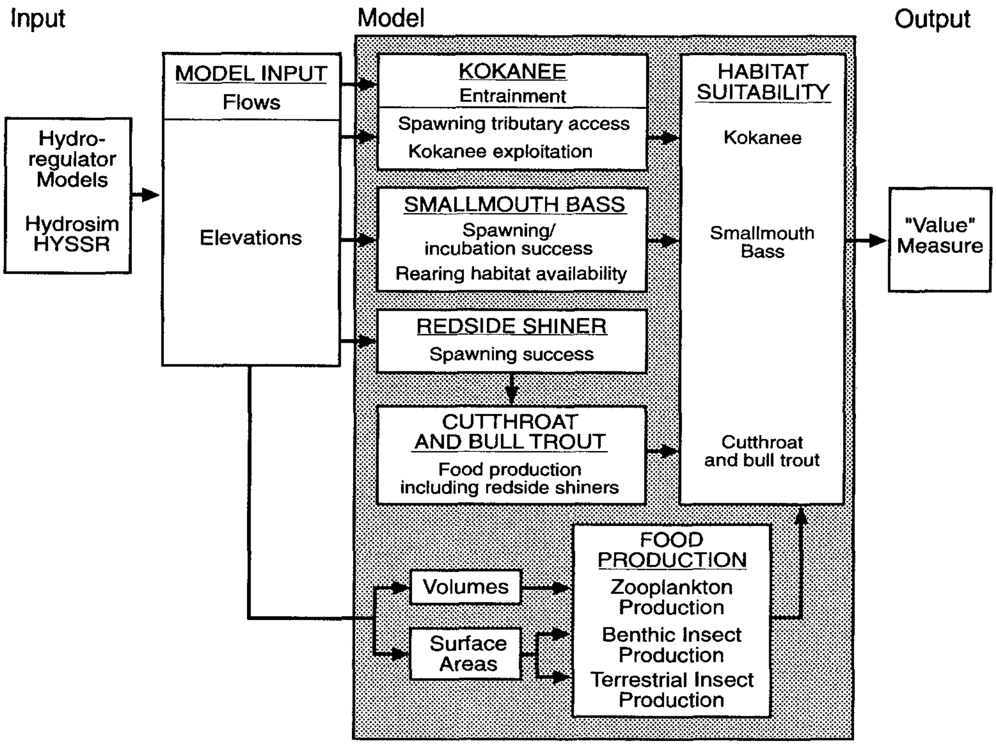

Figure 2. Alternative screening process at Dworshak Reservoir. Flows and elevations generated over 20 time steps are input to the model and used to calculate habitat suitability indices. In this example, outflows at Dworshak Dam are used to estimate the habitat suitability index associated with kokanee entrainment. Pool elevations are used to estimate; (1) habitat suitability indices for kokanee, smallmouth bass, and redside shiner (see Figure 3) and (2) to determine volumes and surface areas for use in the food production component of the model. Habitat suitability indices for each species are weighted and combined in a linear manner to produce a single "value" measure.

Additional relationships between habitat suitability and reservoir operation were used at other projects (Table 3); additional detail can be found in Bonneville Power Administration and others (1992, 1994).

The habitat suitability indices for species considered at each project were combined into an overall index termed a "value measure." The value measures are project specific and represent a linear combination of one or more weighted habitat suitability indices. The weighting of individual habitat suitability indices was done at each project by local and regional experts. Value measures from each alternative were scaled to the best possible value from each project in order to compare to the appropriate base case alternative, and ranged from 0 to 100%. Value measures are not meant to be a specific or comprehensive measure of fish health, but rather a relative indicator of general impacts. Again, using Dworshak Reservoir as an example, the estimated habitat suitability indices for kokanee, smallmouth bass, and cutthroat and bull trout are combined to form a value measure that represents all resident fish in Dworshak Reservoir (Figure 2).

Sensitivity Analysis

Many relationships used in the models were subject to significant uncertainty. Sensitivity analyses were performed on the models to quantify the impact of the uncertainty in a specific relationship and/or hydrology on the combined value measure. Members of the RFWG defined best-case (high), worst-case (low), and average-case relationships between habitat suitability and reservoir operation wherever uncertainties were identified (see Figure 3 for an example from Dworshak Reservoir). The value measures for individual projects were computed with all the uncertain relationship was individually set to its high or low state with all other uncertain relationships set to their average states. The computed value measure of this perturbed state was then compared to the base values. The relationships that showed the greatest impact on the combined value measure were included in the subsequent probabilistic assessment.

The probabilistic assessment consisted of a series of repeated analyses of each alternative using each of the spreadsheet models. This assessment computed a com-

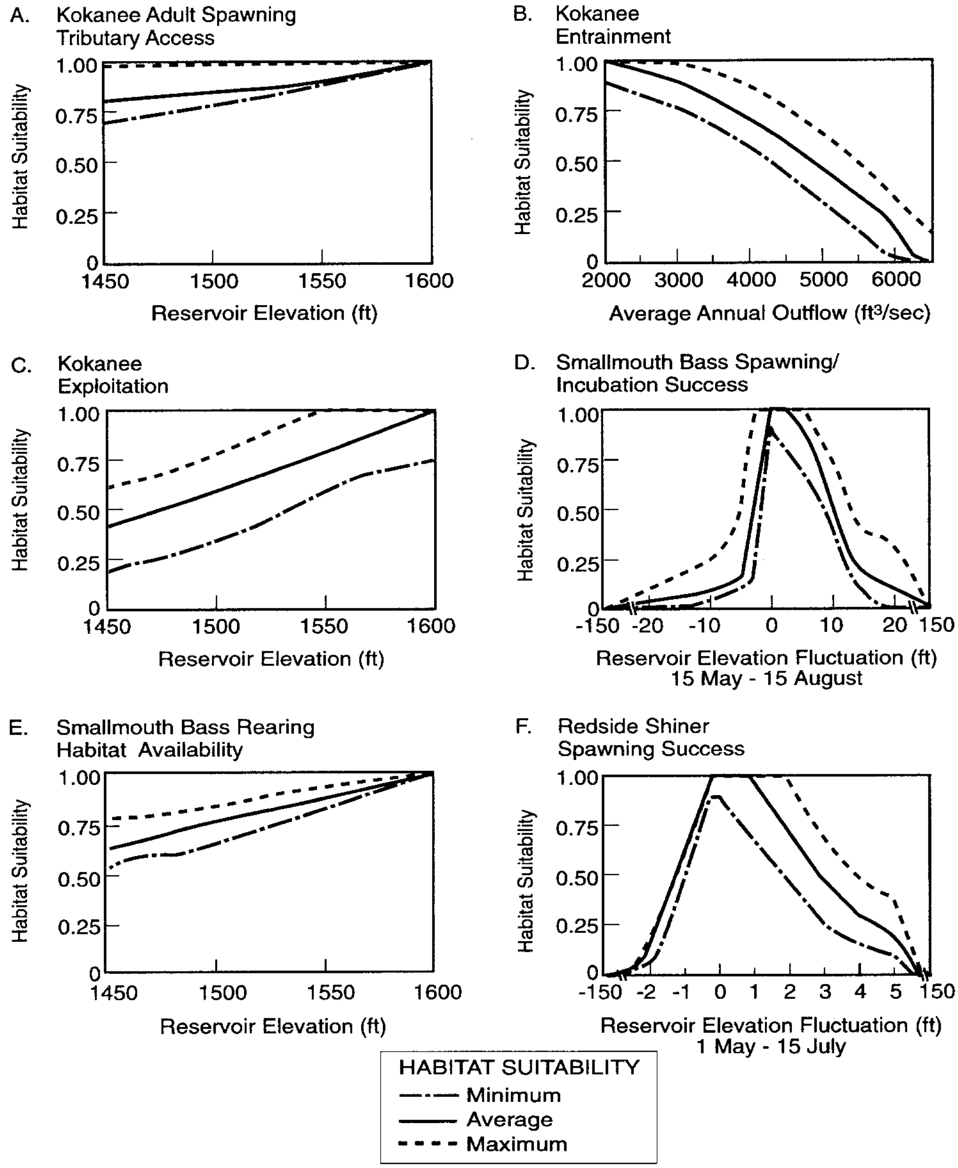

Figure 3. An example of habitat suitability as a function of reservoir operations. These relationships are incorporated into the Dworshak model and are used to estimate impacts to key species from alternatives. In this example, habitat suitability indices were created using empirical data specific to Dworshak Reservoir. Members of the Resident Fish Work Group defined best-case (maximum), worst-case (minimum), and average-case relationships whenever uncertainties were identified.

bined value measure for all possible combinations of the significant uncertain relationships that were determined from the sensitivity analyses and computed the associated probability of each of those combinations of relationships occurring. All relationships were treated as statistically independent. The cumulative distribution of the combined value measure was calculated. The expected value, the value exceeded in 10% of the cases, and the value exceeded in 90% of the cases are reported here.

Results

Base-Case Alternatives

The predicted value measures for the three base-case alternatives were consistently low at most projects (Figure 4). Under the base-case alternatives, Hungry Horse and Libby reservoirs failed to refill in low-water years because of deep reservoir drawdown. Deep drawdowns in successive years would reduce benthic insect

Table 3. Relationships between project operation and habitat suitability for projects modeled[a]

		Model relationships	
Project	Species modeled	Project operation	Habitat suitability index
Hungry Horse, Libby	None, food production	Pool elevation	Zooplankton production
		Pool elevation	Terrestrial insect deposition
		Area wetted bottom	Benthic insect production
		Reservoir volume	Phytoplankton production
Grand Coulee	KOK, RBT	Water retention time (storage ÷ outflow)	Growth and entrainment
Brownlee	SMB, CRP	Change in pool elevation (avg Apr–Jun)	Spawning/incubation success
	CHC	Change in pool elevation (avg Aug–Sep)	Spawning/incubation success
	SMB, CRP, CHC, RBT	Pool elevation and outflow	Food production (see above)
Pend Oreille	KOK	Pool elevation (avg Nov–Jan)	Spawning habitat availability
		Change in pool elevation (avg Nov–May)	Incubation success
	CRP, PER, SMB, LMB	Pool elevation (avg May–Oct)	Fingerling to adult survival
		Pool elevation (min Feb–Apr)	Overwintering survival
		Pool elevation (avg May–Jul)	Spawning habitat availability
		Pool elevation and volume	Food production (see above)
	CUT	Pool elevation (avg May–Jun)	Spawning habitat availability
	BUL	Pool elevation (avg Aug–Oct)	Spawning habitat availability
		Pool elevation and outflow	Kokanee abundance

[a] See Figures 2 and 3 for a description of relationships at Dworshak Reservoir. Species key: KOK, kokanee; RBT, rainbow trout; LMB, largemouth bass; SMB, smallmouth bass; CRP, black crappie; CHC, channel catfish; PER, yellow perch; CUT, westslope cutthroat trout; and BUL, bull trout.

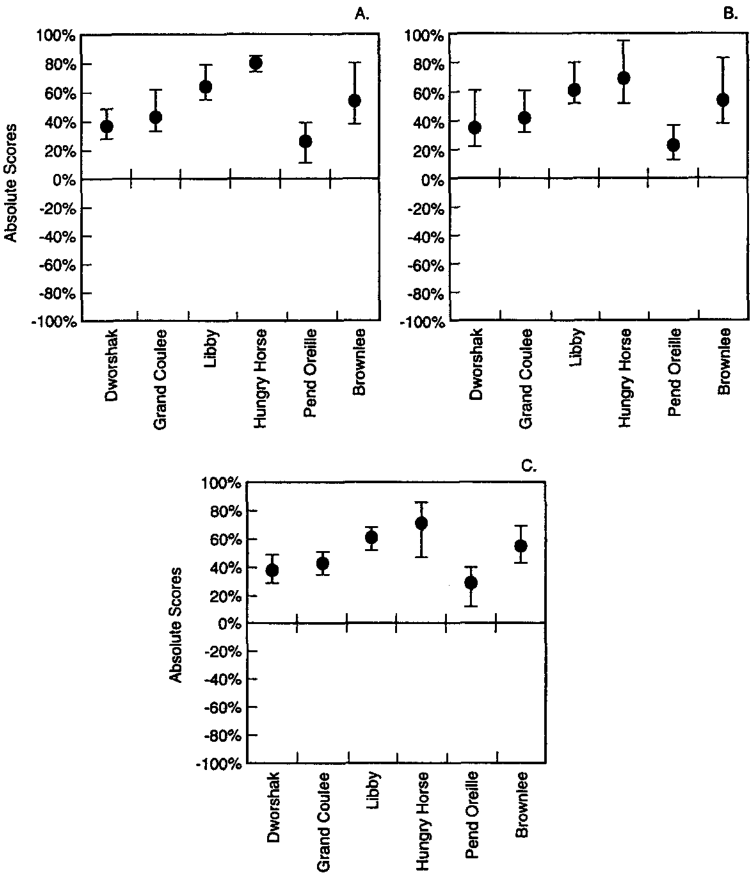

Figure 4. Absolute values of base-case alternatives for each reservoir modeled using the resident fish models: **(A)** BPA base-case alternative, **(B)** ACOE base-case alternative, and **(C)** observed base-case alternative. The circles represent the expected value (i.e., value expected 50% of the time). The range bars represent the values that could be expected 10% (lower bar) and 90% (upper bar) of the time. Depending on the hydroregulation model used, all subsequent alternatives were compared to either the BPA base-case alternative **(A)** or the ACOE base-case alternative **(B)**.

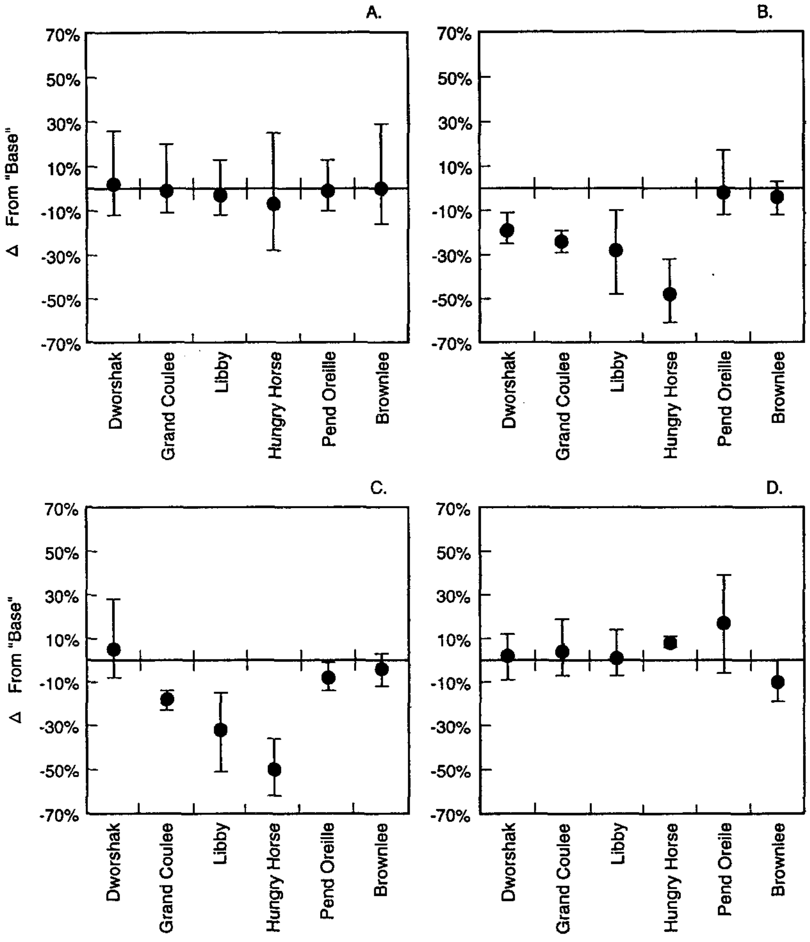

Figure 5. The change from base-case alternatives for the increased flow alternatives: (**A**) existing conditions, (**B**) year-round flow increase, (**C**) modified year-round flow increase, and (**D**) spring flow increase. The circles represent the expected value (i.e., value expected 50% of the time). The range bars represent the values that could be expected 10% (lower bar) and 90% (upper bar) of the time. The resident fish models expressed the value measure as a percentage of the best possible value in each reservoir. As a consequence, the percentate change from the base case for each alternative is absolute rather than relative.

production and spring food supply. The base-case alternatives resulted in short retention times and low fish production at Grand Coulee. This is possibly because vital nutrients and food are washed through the system rather than used in the food web (Beckman and others 1985).

Kokanee, bull trout, and kamloops (rainbow trout) populations at Lake Pend Oreille have been on the decline since 1964 (Paragamian and Bowles 1995). The base-case alternatives apparently do not result in significant changes in system operation to reverse these declines, as the value measures are consistently less than 30%. Smallmouth bass and kokanee habitat at Dworshak is not improved over existing conditions in any of the base-case alternatives. The value measures for all species at Brownlee Reservoir decline under each of the base-case alternatives.

Increased-Flow Alternatives

The flow-increase alternatives generally negatively affected resident fish in each reservoir (Figure 5). Each alternative resulted in weak kokanee age classes in some years at Lake Pend Oreille; a result of lake-level drawdowns during the October and November kokanee spawning period. Deep drawdown and refill occur frequently at Hungry Horse and Libby reservoirs under each alternative, resulting in severely reduced benthic food production and low value measures for resident fish. Lowered water retention time from deep drawdowns results in low value measures for kokanee and rainbow trout at Grand Coulee Reservoir, especially during low water years.

Drawdown Alternatives

Drawdown alternative generally negatively impacted resident fish at each of the reservoirs that were modeled (Figure 6). The natural river alternative resulted in significant impacts to resident fish at all projects except Lake Pend Oreille (Figure 6A). To compensate for foregone losses in flow in the Snake River, significant drawdowns would be needed in Libby and Hungry Horse reservoirs. Because Lake Pend Oreille cannot provide significant flows for downstream use, the impacts of this option on resident fish are moderated.

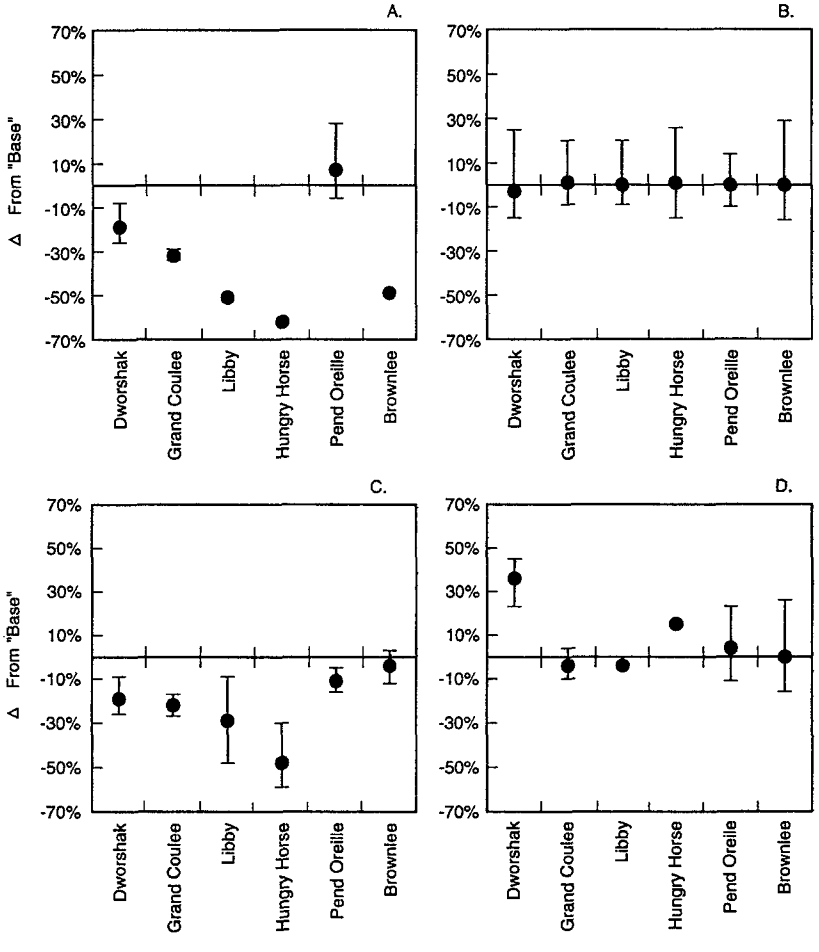

Figure 6. The change from base-case alternatives for the drawdown alternatives: (**A**) natural river, (**B**) fixed drawdown, (**C**) target velocities, and (**D**) wildlife drawdown. The circles represent the expected value (i.e., value expected 50% of the time). The range bars represent the values that could be expected 10% (lower bar) and 90% (upper bar) of the time. The resident fish models expressed the value measure as a percentage of the best possible value in each reservoir. As a consequence, the percentage change from the base case for each alternative is absolute rather than relative.

The fixed drawdown alternative results in little change form the base-case alternative at any of the projects (Figure 6B). This alternative results in weak kokanee age classes at Lake Pend Oreille during some years. Smallmouth bass would be impacted at Dworshak Reservoir because of dewatered spawning areas. No spawning would be expected for white sturgeon downstream of Libby Dam. Low water retention time would result in high entrainment of kokanee from Grand Coulee Reservoir, especially during low-water years.

The drawdown-to-meet-flow-targets alternative also negatively impacts resident fish in each of the storage reservoirs (Figure 6C). The impact would be comparable to the impacts under the increased-flow alternative.

The wildlife enhancement drawdown alternative actually benefits resident fish at Dworshak and Hungry Horse reservoirs, but shows little change from the base case at all other projects modeled (Figure 6D). Consistent drawdowns and assured refill would be beneficial for resident fish in Hungry Horse Reservoir. This alternative could be one of the better alternatives for Lake Pend Oreille. Reduced lake levels that are stable during the spawning period of kokanee should help keep spawning gravel cleaned and free of silt. Stable pool levels in Libby Reservoir would be good for fish, but reduced volume reduce production of fish significantly.

Stable-Pool Alternatives

Stable-pool alternatives were very good for resident fish at each of the projects (Figure 7). The full-pool alternative resulted in one of the best alternatives modeled for resident fish (Figure 7A). The relative improvement from the base case for all projects except Grand Coulee Reservoir was substantial. Holding the pool near full and passing all inflow maximizes biological production within the reservoirs. Rooted aquatic vegetation can become established when the reservoir is held constant. This provides increased cover for fish and a nutrient source for aquatic invertebrates. However, at Grand Coulee Reservoir the stable-pool alternatives decrease water retention, thereby decreasing resident fish habitability.

The maximum water retention time alternative did not provide the benefits to resident fish that were ex-

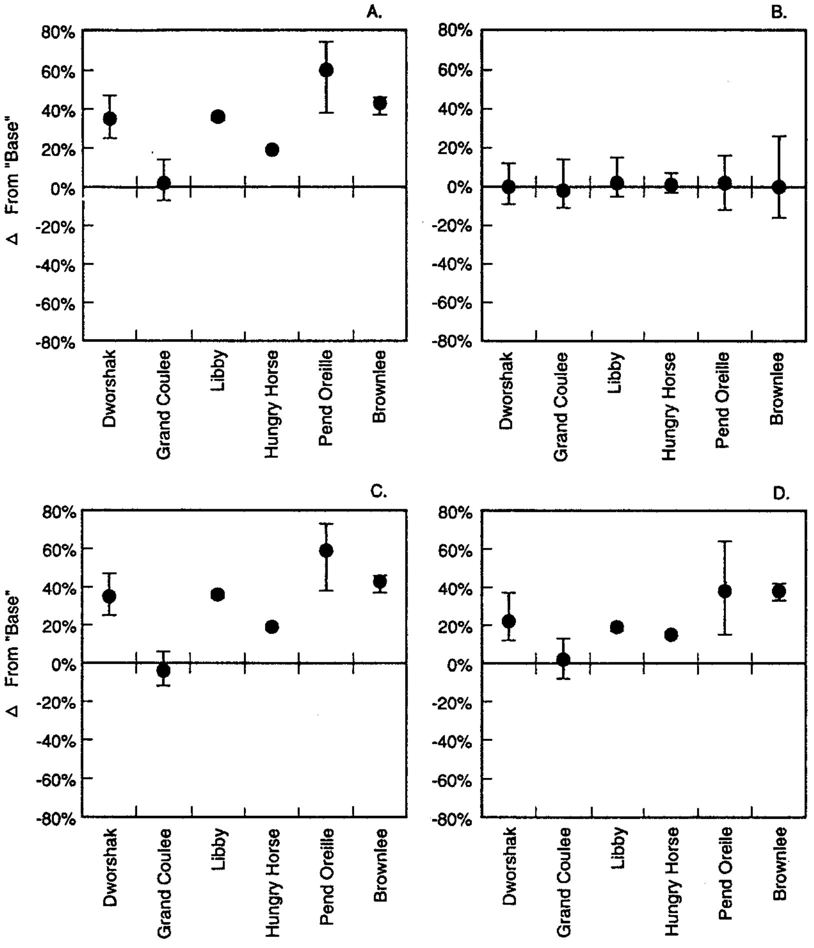

Figure 7. The change from base-case alternative for the stable pool alternatives: (**A**) full, stable pool, (**B**) maximum water retention time, (**C**) water conservation, and (**D**) compromise. The circles represent the expected value (i.e., value expected 50% of the time). The range bars represent the values that could be expected 10% (lower bar) and 90% (upper bar) of the time. The resident fish models expressed the value measure as a percentage of the best possible value in each reservoir. As a consequence, the percentage change from the base case for each alternative is absolute rather than relative.

pected (Figure 7B). Value measures for most projects either declined or remained unchanged from the base case. However, the compromise alternative generally provided positive benefits to resident fish in most storage projects (Figure 7C). The exception was at Grand Coulee, where the value measure remained unchanged from the base case. The water conservation alternative also provided benefits to resident fish (Figure 7D), but again, Grand Coulee Reservoir did not show improvements for resident fish from the base-case alternatives.

Power Alternatives

All power alternatives indicate little or no improvement over the base-case alternatives for resident fish (Figure 8). In some cases up to a 20% decrease from the base case would be likely. These alternatives would result in weak kokanee year classes in some years at Lake Pend Oreille, probably because of drawdown of the lake level during the spawning period. High flows and low water retention time cause the value measures at Grand Coulee to generally fall below the base case values. Drafting of Hungry Horse Reservoir early in the fall removes flexibility in system operation. This results in deep drawdowns and higher likelihood of failure to refill in most years. Conditions for resident fish in Libby and Brownlee reservoirs also are predicted to deteriorate.

Discussion

Hydrologic uncertainly, the variation between water years, had the greatest impact on model results. Model results were not as sensitive to relationships that were more deterministic in nature (i.e., elevation to volume or elevation to surface area). Although this indicates that these relationships are better understood, it should not be interpreted that they are any less important. Sensitivity analysis reflects model uncertainties, not necessarily biological significance.

The biological, geographical, and jurisdictional issues that are involved in modeling resident fish population are complex and diverse. Different resident fish species have different biological needs. The conversion of riverine systems to constantly changing reservoir environments that contain introduced populations of resi-

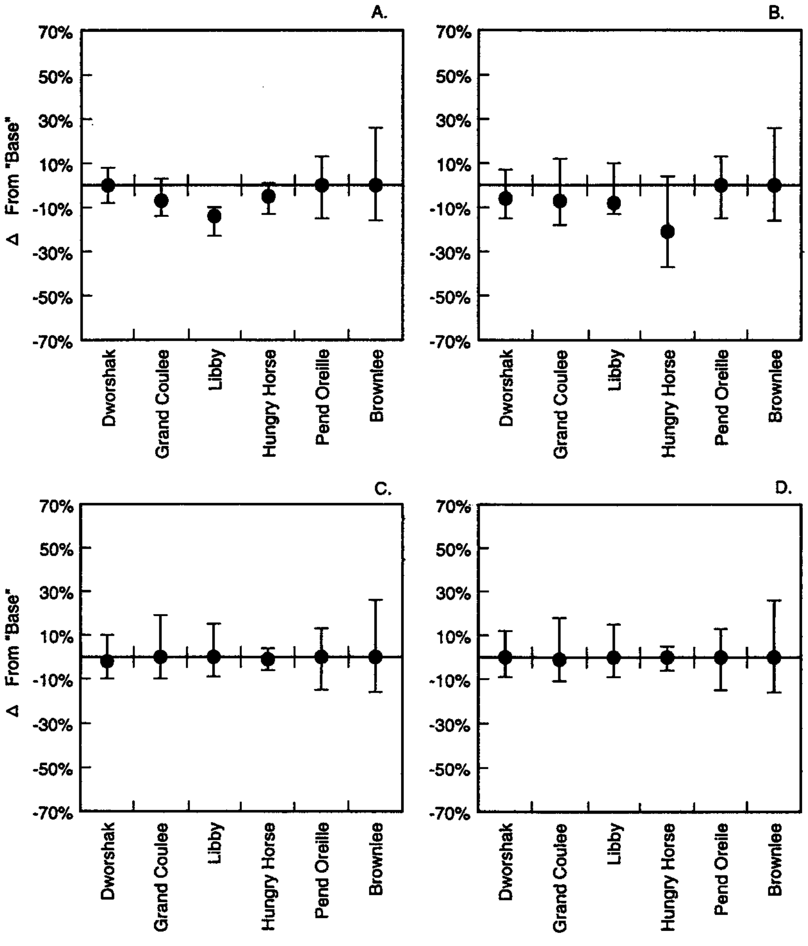

Figure 8. The change from base-case alternatives for the power alternatives: **(A)** no restrictions; **(B)** optimize economics, **(C)** seasonal exchange, and **(D)** Canadian flow. The circles represent the expected value (i.e., value expected 50% of the time). The range bars represent the values that could be expected 10% (lower bar) and 90% (upper bar) of the time. The resident fish models expressed the value measure as a percentage of the best possible value in each reservoir. As a consequence, the percentage change from the base case for each alternative is absolute rather than relative.

dent fish has resulted in resident fish management conflicts within and between reservoirs. Because of these conflicts, it is difficult to consolidate value measures across reservoirs. This results in some alternatives that are good at one location and poor at another location. For example, operating the system to benefit riverine fish such as Kootenai River white sturgeon may be detrimental to the kokanee fishery at Lake Roosevelt. A very controversial resource management dilemma is created when other water-dependent uses, such as anadromous fish, power production, and irrigation, are also considered. Multiobjective trade-offs are necessary.

The modeling used in this portion of the SOR demonstrated that single-purpose alternatives developed in the screening phase did provide benefits to their respective river use and/or resource group. Benefits for one interest group did not necessarily lead to positive benefits for other interest groups. Figure 9 shows the relative rankings for each river use and/or resource group from the alternatives we considered in detail. Stable pool alternatives that should be very good for resident fish usually resulted in negative impacts to anadromous fish. Stable pool alternatives also should benefit recreation and irrigation because they benefit from full pools during the spring, summer, and early fall. On the other hand, alternatives that generally benefited anadromous fish usually would not be good for resident fish. Anadromous fish alternatives would result in deep drawdowns of reservoirs to provide additional water for fish flows. This would disrupt resident fish spawning and rearing habitats through a reduction in area or change in temperature regimes.

Reservoir drawdown appears to impact nonnative resident fish species more than native species. This may be because nonnative species are more dependent on the reservoir during critical life cycle periods (i.e., spawning, early life history rearing). However, there is a lack of information on the relationships between native resident fish species and reservoir operation, suggesting this comparison should be viewed cautiously.

The SOR is attempting to evaluate the specific impacts to river uses and natural resources that will result from changes in present system operation. It is apparent from our modeling that existing operations (represented by the base-case alternatives) are not beneficial

	Power	Recreation	Wildlife	Irrigation	Anadromous Fish		Resident Fish	Flood Control
					Spring	Fall		
Base Case								
BPA	●	◑	⊙	◙	⊙	⊙	◑	◑
ACOE	●	◑	⊙	◙	⊙	⊙	◑	◑
Observed	●	⊙	⊙	◙	⊙	◙	◑	●
Increase Flow								
Existing Conditions	◑	◑	⊙	◙	○	⊙	◑	◑
Year-round	⊙	○	○	◙	◑	◑	⊙	◑
Modified Year-round	⊙	○	⊙	◑	⊙	◑	⊙	◑
Spring Flow	◙	◙	⊙	◑	◑	⊙	◙	◑
Drawdown								
Natural River	○	○	◙	○	●	◑	○	○
Fixed	◑	◑	○	⊙	?	?	◑	◑
Target Velocities	○	○	○	⊙	?	?	◑	⊙
Wildlife	○	⊙	◙	◑	○	⊙	◙	⊙
Stable Pool								
Full, Stable	⊙	◙	◙	◑	⊙	⊙	●	⊙
Max,, Water Retention	◑	◙	⊙	◑	○	⊙	◑	⊙
Water Conservation	◑	◙	⊙	◑	○	○	◙	⊙
Compromise	○	◙	◑	◑	◙	◑	●	○
Power								
No Restrictions	●	⊙	⊙	◑	○	⊙	◑	◙
Optimize Economics	●	⊙	⊙	◑	⊙	○	◑	◑
Seasonal Exchange	●	◑	⊙	◑	⊙	⊙	◑	◑
Canadian Flow	●	◑	⊙	◑	⊙	⊙	◑	◑

● = Better
◙
◑
⊙
○ = Worse

Figure 9. Relative comparison between selected alternatives for selected resource groups.

to fish and wildlife resources, but are beneficial to power and irrigation interests. This points to an increased urgency to develop alternative ways to operate the Columbia River hydropower system.

The models developed for resident fish in the screening analysis phase of the SOR were useful in assessing the relative impact to resident fish from a large number of alternatives. Based on the results from screening, strategies that combine the favorable elements of alternatives were formed and are being analyzed in detail during the full-scale phase. The screening analysis also demonstrated that future analytical efforts must consider trade-offs among and within user groups/natural resources, among reservoirs throughout the basin, and among resident fish species within a reservoir. Only by analyzing trade-offs can effective operating strategies for the Columbia River basin be developed.

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