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Management of Northern Pikeminnow and Implications for Juvenile Salmonid Survival in the Lower Columbia and Snake Rivers

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Abstract.—Predation by large northern pikeminnow (formerly northern squawfish) *Ptychocheilus oregonensis* is a major source of mortality for juvenile salmonids *Oncorhynchus* spp. in the lower Columbia and Snake rivers. Large-scale, agency-operated fisheries have been implemented in this area since 1990 to harvest northern pikeminnow with a goal of 10–20% exploitation. We used indirect methods to analyze the success of the fisheries, and examined benefits to salmonid populations. From 1991 to 1996, three fisheries (sport-reward, dam-angling, and gill-net) harvested approximately 1.1 million northern pikeminnow that were 250 mm in fork length or longer, with the sport-reward fishery contributing 86.5% of the total catch. Total exploitation averaged 12.0% (range, 8.1–15.5) for 1991–1996 and met program goals in all years except 1993. Gill-net and dam-angling fisheries harvested larger northern pikeminnow (which consume a greater number of juvenile salmonids) than the sport-reward fishery. Modeling results indicate that potential predation on juvenile salmonids by northern pikeminnow has decreased 25% since fishery implementation. The relative benefits of a given exploitation rate decreased with time as the number of large northern pikeminnow was reduced; however, additional reductions in potential predation are probable if exploitation is maintained at mean 1994–1996 levels. We estimate a reduction in potential predation of 3.8 million juvenile salmonids (representing 1.9% of the total population) if exploitation rates are maintained at mean 1991–1996 levels. Continued monitoring of predator populations is prudent, and we recommend that restoration and enhancement of Columbia River basin salmonids not rely solely on any one management approach.

The Columbia and Snake rivers formerly supported enormous numbers of Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss.* The number of adult salmonids returning to these rivers has declined during this century from approximately 7.5 million to 2.5 million annually, and some estimates place presettlement run sizes as high as 350 million (Chapman 1986). Overexploitation and habitat degradation were largely responsible for this decline during the late 1800s and early 1900s (Nehlsen et al. 1991; Wismar et al. 1994). Populations rebounded for a time when stricter commercial fishing regulations and habitat improvement programs were implemented; however, hydroelectric and flood control development during the 1970s led to further declines, especially for upriver stocks (Raymond 1988).

Juvenile salmonid mortality associated with hydroelectric development has been cited as the primary reason for the decline in adult returns during the last several decades (Raymond 1979, 1988). Significant losses may occur when juvenile salmonids pass through dams. Direct mortality has been estimated to be approximately 11% for smolts passing through dam turbines and 3% for smolts passing through spillways (Schoeneman et al. 1961). Direct plus indirect mortality (such as predation on smolts injured by dam passage) may approach 30% at a single dam (Long and Ossiander 1974). Passage improvements since the work of Schoeneman et al. (1961) and Long and Ossiander (1974) have reduced mortality, though recent research suggests that mortality associated with turbines, turbine bypasses, and spillways is still considerable (Rieman et al. 1991; Mathur et al. 1996). In addition, water spilled by dams may become supersaturated with atmospheric gases, causing gas bubble disease in salmonids. Mortality associated with gas supersaturation varies with dam operation and environmental variables (Ebel and Raymond 1976; Weitzkamp and Katz 1980). Intense predation by birds has been observed at some dams; Ruggerone (1986) estimated that gulls *Larus* spp. consumed 2% of all salmonids passing Wanapum Dam on the Columbia River.

Flow reductions resulting from the impoundment of the Columbia and Snake rivers also act to delay the downstream migration of juvenile salmonids, prolonging their exposure to predators (Bent-

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ley and Raymond 1976; Ebel and Raymond 1976; Raymond 1988). The native northern pikeminnow *Ptychocheilus oregonensis* is the dominant predator of juvenile salmonids in this system, and predation by this species is clearly important in relation to other sources of mortality (Poe et al. 1991; Rieman et al. 1991; Vigg et al. 1991; Ward and Zimmerman, in press; Zimmerman, in press). Northern pikeminnow were commonly known as northern squawfish until 1998 (Nelson et al. 1998). Petersen (1994) estimated the annual loss of juvenile salmonids to predation by northern pikeminnow in John Day Reservoir, Columbia River, to be 1.4 million, approximately 7.3% of all juvenile salmonids entering the reservoir. Predation is known to be higher in some areas than in John Day Reservoir and is often highest near dams (Ward et al. 1995). Consumption estimates do not appear to be confounded by dam passage mortality; Petersen et al. (1994) found that 78% of juvenile salmonids eaten by northern pikeminnow near a dam were consumed while alive. Ward et al. (1995) estimated that 48% of predation occurs in mid-reservoir areas away from dams, where juvenile salmonids are presumably alive and uninjured when consumed. Of the estimated 200 million juvenile salmonids emigrating annually through the lower Columbia and Snake rivers, approximately 16.4 million (8%) are consumed by northern pikeminnow (Beamesderfer et al. 1996).

Management fisheries for northern pikeminnow have been implemented to increase survival of juvenile salmonids in the Columbia and Snake rivers. Rieman and Beamesderfer (1990) predicted that exploiting northern pikeminnow greater than 275 mm in fork length (FL) at a sustained annual rate of 10–20% would result in a 50% annual decrease in salmonid losses to predation. The success of test fisheries by the Northern Pikeminnow Management Program (NPMP) in 1990 led to full-scale implementation of two major removal fisheries in 1991. The ‘‘sport-reward’’ fishery offers public anglers a monetary incentive to catch northern pikeminnow; from 1991 to 1994, anglers received US$3 for each fish turned into agency-operated check stations. Beginning in 1995, reward amounts were based on the number of northern pikeminnow caught by individual anglers during the fishing season. Anglers returning 1–100 fish to check stations received $3 per fish, those returning 101–400 received $4 per fish, and those returning greater than 400 received $5 per fish. The second major fishery is ‘‘dam-angling,’’ for which agency personnel were hired to angle for northern pikeminnow directly from dams or from boats operated in close proximity to the dams. In addition, a gill-net fishery has been in operation since 1994 to remove northern pikeminnow near hatchery release points, dams, tributary mouths, and other areas where high levels of predation may occur (Collis et al. 1995). Dam-angling and gill-net fisheries are driven by agency directives rather than per-fish rewards. Other fisheries (set lining by commercial fishers and agency-operated trapnetting) were employed for various amounts of time but were discontinued because of their failure to capture large numbers of northern pikeminnow or because of unacceptably high catch rates of other species (Beamesderfer et al. 1996).

The NPMP is funded by the Bonneville Power Administration (BPA). Annual funding provided by BPA to mitigate for the impacts of the Federal Columbia River Power System totals approximately $91 million for anadromous fish projects. The NPMP is the most expensive annually funded mitigation item at $3.1 million; however, this cost represents a relatively small proportion of the total (3.4%; CBFWA 1998).

Juvenile salmonids are the major dietary component of northern pikeminnow greater than 250 mm FL (Vigg et al. 1991). A 250-mm (FL) northern pikeminnow measures 279 mm (11 in) in total length (Carlander 1969), a convenient measurement for public anglers participating in the sport-reward fishery. For these reasons, all fisheries target northern pikeminnow greater than or equal to 250 mm FL.

Numerous confounding factors limit our ability to measure the success of the NPMP in terms of increased numbers of juvenile salmonids reaching the estuary or increased numbers of returning adult salmonids. Beamesderfer et al. (1996) proposed that evaluations of the NPMP be based on indirect measures, such as mark–recapture estimates of exploitation. In this paper we use indirect measures to evaluate the performance of the three major northern pikeminnow fisheries in relation to management goals, and we estimate the degree to which potential predation on juvenile salmonids has been reduced by the NPMP during the first six years of operation. To evaluate the fisheries, we (1) determined annual and total northern pikeminnow harvest, harvest effort, and catch per unit of harvest effort (CPUE) for each fishery; (2) used mark–recapture data to compare the exploitation of northern pikeminnow among years, fisheries, and areas; and (3) compared size of northern pikeminnow harvested by each fishery. We used this

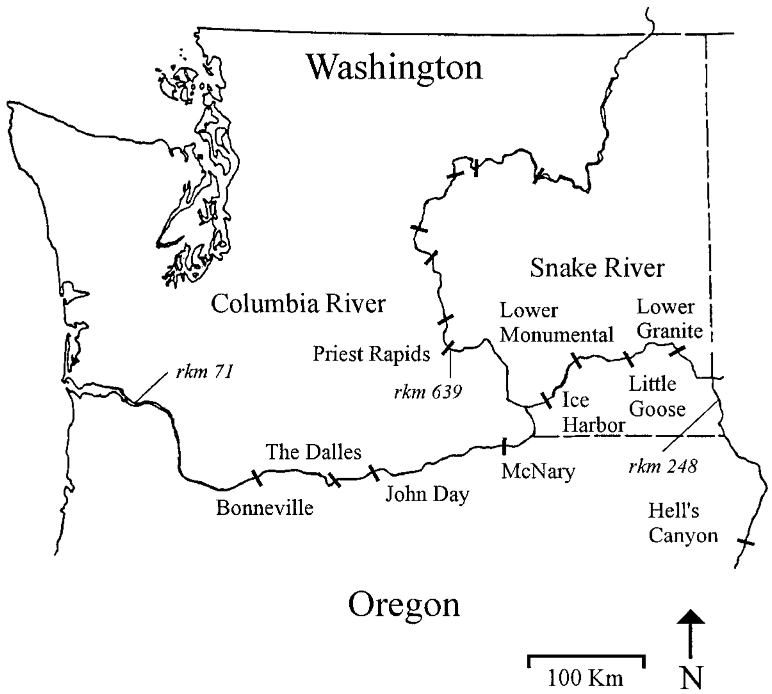

FIGURE 1.—The lower Columbia and Snake rivers. Northern pikeminnow management fisheries are implemented in the Columbia River from the mouth to Priest Rapids Dam and in the Snake River from the mouth to Hell's Canyon Dam. Dams (with corresponding reservoirs) within the area are labeled; rkm = river kilometer.

information to develop a simple model to estimate potential predation on juvenile salmonids by northern pikeminnow relative to potential predation that would occur without implementation of the NPMP.

Methods

Fishery Evaluation

The sport-reward fishery was first implemented in John Day Reservoir during 1990 to gauge the level of public participation in the program. From 1991–1996, the fishery was conducted from May to mid-September on the Columbia River from the mouth to the boat-restricted zone (BRZ) below Priest Rapids Dam and on the Snake River from the mouth to the BRZ below Hell's Canyon Dam (Figure 1). Dam-angling was implemented annually (May–September) at each of the eight dams of the lower Columbia and Snake rivers after successful experimental angling at Bonneville, The Dalles, John Day, McNary, and Ice Harbor dams in 1990. Dam-angling was conducted primarily in tailrace (the section of river directly downstream from a dam) BRZs. From 1994–1996, the gill-net fishery was implemented from April or May through June throughout the lower Columbia and Snake rivers; details of sampling methods and gear are given in Collis et al. (1995). We monitored these fisheries from 1991 to 1996 to determine annual and total harvest of northern pikeminnow, harvest effort, and CPUE.

Mark–recapture data were used to evaluate the exploitation of northern pikeminnow by each fishery from 1992 to 1996. We used electrofishing and gillnetting to collect and mark northern pikeminnow from April through June of each year. Fish were marked with serially numbered spaghetti tags and given a year-specific secondary mark consisting of a pelvic or caudal fin clip. We randomly allocated sampling effort in all river kilometers (rkm) of the Columbia River from rkm 71 to rkm 639 and in the Snake River from the mouth to rkm 248 (Figure 1). We generally sampled from 1800 hours to 0100 hours, near shorelines or structure, and in water less than 6 m deep. Sampling was discontinued in Ice Harbor Reservoir after 1992 because we were unable to capture a sufficient number of northern pikeminnow to estimate exploitation.

We based our calculation of exploitation rates for 1992–1996 on the number of tagged northern pikeminnow recovered by each fishery. Fisheries started each year before our tagging was complete; therefore, we calculated weekly estimates of exploitation by dividing the number of tagged northern pikeminnow recovered by the number of tagged fish at large and summed these estimates to yield overall estimates of exploitation. We adjusted exploitation estimates for tag loss (4.2%), determined from the recovery of secondary-marked fish with no tag. Because of uncertainties regarding tag loss over a period of two or more years, we used only northern pikeminnow tagged and recaptured within a given year to determine exploitation. We calculated annual exploitation estimates for each fishery and area (reservoir or free-flowing reach downstream from Bonneville Dam) when possible, as well as ''systemwide'' estimates for all fisheries and areas combined. Only northern pikeminnow recaptured in the same area in which they were tagged were included in estimates of area-specific exploitation.

In 1992, sampling downstream from Bonneville Dam was conducted as in other years. However, due to time constraints, we sampled only the forebay (the section of river immediately upstream from a dam), tailrace, and a randomly selected portion of the mid-reservoir area of each impoundment above Bonneville Dam, increasing the potential for bias in our estimates of exploitation. We therefore used two methods to estimate exploitation for 1992: (1) we assumed full mixing of tagged and untagged fish and random allocation of fishing effort throughout each reservoir, and (2) we assumed no mixing of fish outside the areas they were tagged, with fishery effort restricted to areas in which fish were tagged. We determined exploitation estimates for method 1 as described previously, giving a maximum estimate. For method 2, we adjusted the number of tagged northern pikeminnow in mid-reservoir areas by dividing the number of fish actually tagged by the proportion of mid-reservoir area sampled. We used the adjusted number of tags and calculated exploitation as in method 1, giving a minimum estimate. We used the mean of estimates (1) and (2) as the overall exploitation estimate.

Calculation of 95% confidence intervals for exploitation estimates was complicated because both removal efforts and tagging occurred simultaneously in the early portion of the fishing season. We therefore calculated separate confidence intervals for the periods before and after the completion of tagging. The probability that a given tagged fish would be recaptured in any week was very small; therefore, the mark–recapture data followed a Poisson distribution (Zar 1984). After tagging was complete, we estimated confidence bounds for each reservoir or area with the following formula from Elliott (1977):

$$m \pm 1.96\sqrt{m/n},$$

when $mn > 30$; m = the mean number of tagged fish recovered per week, and n = the number of sampling weeks remaining.

When tagging and fishing occurred simultaneously, the number of tagged fish at large varied substantially from week to week. We therefore calculated separate confidence intervals for each week. For single weeks, mn was always less than 30, precluding the use of Elliott's (1977) formula. We instead used values given by Ricker (1975) for a single count in the Poisson distribution. Weekly exploitation estimates were adjusted with these values (if tagging and fishing occurred simultaneously) or by using the result of Elliott's (1977) formula (after the completion of tagging), and the results were summed to give overall 95% confidence bounds. Because we calculated two exploitation estimates for 1992, we used the high confidence bound from estimate (1) and the low confidence bound from estimate (2) as the overall confidence limits.

We were unable to calculate exploitation rates for 1991 using mark-and-recapture data because no northern pikeminnow were tagged. Instead, we divided the fisheries' total catch in each reservoir or area by a population estimate of northern pikeminnow for that area. Population estimates were derived by using abundance indices for northern pikeminnow from Ward et al. (1995) and the relationship between abundance indices and population estimates from Zimmerman and Ward (in press). Because the area downstream from Bonneville Dam, The Dalles Reservoir, and McNary Reservoir were not sampled in 1991, we used abundance indices from 1990 (The Dalles and McNary reservoirs) and 1992 (downstream from Bonneville Dam) to estimate population sizes. To test the accuracy of this method, we repeated the calculations for other years by using sport-reward catch data for the area downstream of Bonneville Dam; this area exhibits the highest northern pikeminnow catch and effort.

Because the goal of the NPMP is to harvest fish greater than or equal to 250 mm FL, we further analyzed the relative efficiency of each fishery by comparing the mean size of northern pikeminnow harvested. We used data from subsamples of fish

TABLE 1.—Catch, effort, and catch per unit effort (CPUE) for northern pikeminnow (≥250 mm in fork length) harvested in the lower Columbia and Snake rivers by management fisheries 1991–1996. Catch is number of fish; units of effort are angler-days (sport-reward), angler-hours (dam-angling), and net-hours (gill-net).

	Sport-reward			Dam-angling			Gill-net		
Year	Catch	Effort	CPUE	Catch	Effort	CPUE	Catch	Effort	CPUE
1991	153,508	67,384	2.3	39,196	19,298	2.0			
1992	186,095	88,494	2.1	27,442	16,759	1.7			
1993	104,536	34,879	3.0	17,105	9,718	1.8			
1994	129,384	40,783	3.2	15,938	10,002	1.6	9,018	1,442	6.3
1995	199,788	62,725	3.2	5,397	7,289	0.7	9,484	2,431	3.9
1996	157,230	35,485	4.4	5,381	3,666	1.5	6,167	2,878	2.1
All	930,541	329,750	2.8	110,459	66,732	1.7	24,669	6,751	3.7

collected from the fisheries to compare length-frequency distributions and calculate mean fork lengths for each fishery and year. To determine the degree of association between exploitation and fork length for each fishery, we calculated catch rates of tagged fish by 50-mm length-groups and used regression analysis to describe the relationships between exploitation and fork length. We again used only fish recaptured in a given year in the analysis to reduce biases associated with tag loss among multiple years.

Reduction in Potential Predation

We developed a simple model to estimate changes in potential predation on juvenile salmonids by northern pikeminnow since implementation of the NPMP. The model was designed to estimate the effects of the NPMP if all other factors (river and ocean conditions, numbers of juvenile salmonids migrating, turbine mortality, etc.) were held constant. The model also assumed no compensation (increased growth, fecundity, consumption, etc.) by remaining northern pikeminnow and other predators in response to sustained removals of northern pikeminnow.

Model inputs included (1) an ''average'' population structure (age distribution, length at age, and natural mortality) for northern pikeminnow before implementation of the NPMP, (2) ''average'' rates of consumption of juvenile salmonids by northern pikeminnow, (3) age distribution of northern pikeminnow adjusted by observed exploitation and natural mortality, and (4) an index of age-specific potential predation on juvenile salmonids by northern pikeminnow. Few juvenile salmonids are consumed by northern pikeminnow less than 250 mm FL (Vigg et al. 1991), which are about 5 years old (Parker et al. 1995). We therefore only evaluated potential predation by northern pikeminnow age 5 or older. Model output was potential predation for each year expressed as the percent of the potential predation before implementation of the NPMP. Calculations were made for each reservoir and the Columbia River downstream from Bonneville Dam, with results summed to yield a systemwide estimate for the model output.

Because we were uncertain of some input values to the model, we calculated a range of solutions based on a minimum, maximum, and measure of central tendency for each uncertain parameter. Calculation of 95% confidence limits for exploitation provided three inputs for age-specific exploitation estimates. We also used three formulas to describe the relationship between northern pikeminnow length and consumption of juvenile salmonids. We summarized model uncertainty by reporting the median and the range (minimum and maximum) for the nine potential loss estimates. Formulas and model component details are given in the Appendix.

Results

Fishery Evaluation

During the period of full implementation of the NPMP (1991–1996 for the sport-reward and dam-angling fisheries; 1994–1996 for the gill-net fishery), the three major fisheries removed approximately 1.1 million northern pikeminnow greater than or equal to 250 mm FL from the lower Columbia and Snake rivers (Table 1). The sport-reward fishery accounted for 86.5% of the harvest, the dam-angling fishery contributed 11.2%, and the gill-net fishery 2.3%. Harvest effort for the sport-reward fishery averaged 55,354 angler-days per season, and catch per angler-day increased every year from 1992 to 1996. Dam-angling effort (angler-hours) decreased markedly from 1991 to 1996; catch per angler-hour ranged from 0.7 in 1995 to 2.0 in 1991. Effort (net-hours) in the gill-net fishery increased during each year of operation, while catch per net-hour decreased.

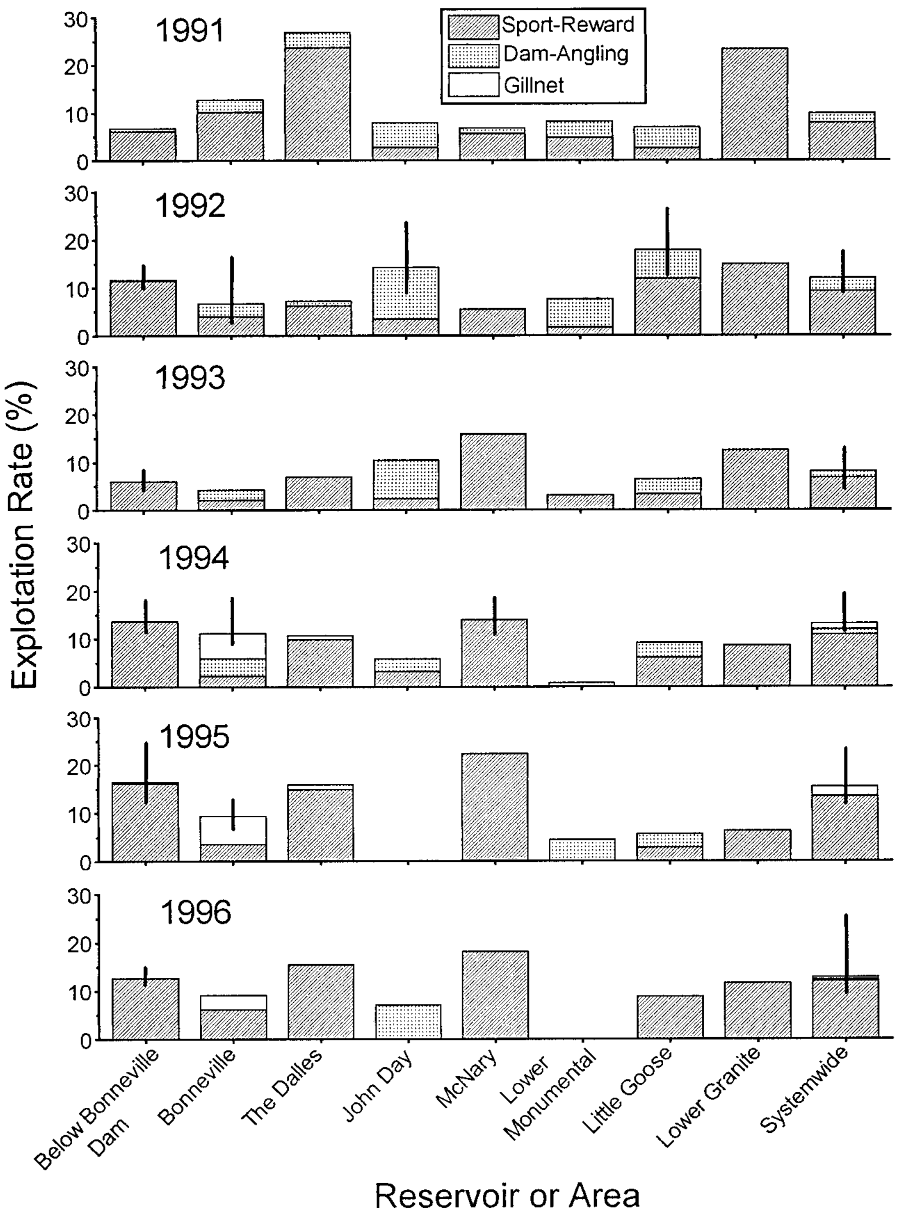

FIGURE 2.—Annual exploitation of northern pikeminnow (≥250 mm in fork length) by fishery and area, 1991–1996. Confidence intervals (95%; vertical bars) for all fisheries combined are included where a sufficient number of tagged northern pikeminnow were recaptured to estimate upper and lower bounds.

Mean systemwide exploitation (all fisheries combined) of northern pikeminnow greater than or equal to 250 mm FL from 1991 to 1996 was 12.0% and ranged from 8.1% in 1993 to 15.5% in 1995 (Figure 2). Exploitation varied among years for most areas; however, the point estimate of exploitation was generally highest in The Dalles, McNary, and Lower Granite reservoirs and downstream from Bonneville Dam. The contribution of dam-angling to total exploitation varied among years but declined considerably from 1991 to 1996. From 1994 to 1996, the gill-net fishery made an important contribution to exploitation in Bonneville Reservoir. Point estimates of systemwide

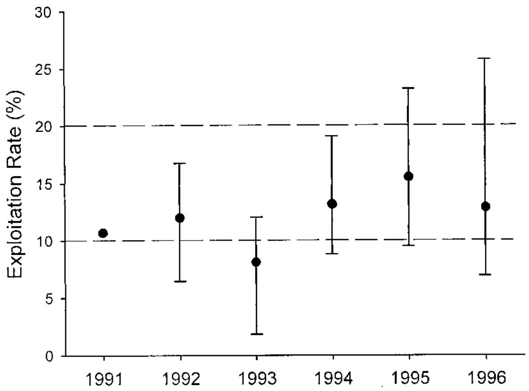

FIGURE 3.—Systemwide exploitation rate of northern pikeminnow (≥250 mm in fork length) from 1991 to 1996 relative to target exploitation rate (dashed lines; Rieman and Beamesderfer 1990). Vertical bars represent 95% confidence intervals and are included for years in which exploitation was determined by using mark–recapture data.

exploitation were greater than 10% during all years except 1993 (Figure 3). From 1992 to 1996, approximately 9.0% (range, 4.3–11.2%) of marked northern pikeminnow moved to a different reservoir or area before being recaptured.

Exploitation estimates for 1991, calculated with catch data and abundance indices, were comparable to estimates for other years calculated with mark–recapture data. Our comparison of the two methods showed that sport-reward exploitation for the area downstream of Bonneville Dam during 1992–1996 ranged from 6.0% to 16.1% (mean 12.0%; 95% confidence bounds, 7.4–16.6%) with mark–recapture data, whereas exploitation calculated with catch data and abundance indices ranged from 6.1% to 14.8% (mean 10.6%; 95% confidence bounds, 6.6–14.6%).

Small values of *m* (the mean number of tagged fish recovered per week) precluded the calculation of 95% confidence intervals for exploitation rates in some individual reservoirs, because *mn* (the product of *m* and the number of fishing weeks remaining) was less than 30. Sample sizes were sufficient to calculate confidence intervals for the area below Bonneville Dam and systemwide in all years for which exploitation rates were determined by using mark–recapture data (1992–1996). Confidence bounds for estimates of exploitation averaged 69% of the point estimate for the low confidence bound (range, 32–90%) and 155% of the point estimate for the high confidence bound (range, 118–245%).

Mean fork length of northern pikeminnow harvested by all three fisheries and all years (1990–1996) combined was 366 mm, and the sport-reward fishery harvested considerably smaller fish than the dam-angling or gill-net fisheries (Figure 4). The dam-angling fishery harvested a slightly higher proportion of northern pikeminnow greater than or equal to 250 mm FL (99.5%) than the gill-net (98.7%) or sport-reward (96.1%) fisheries.

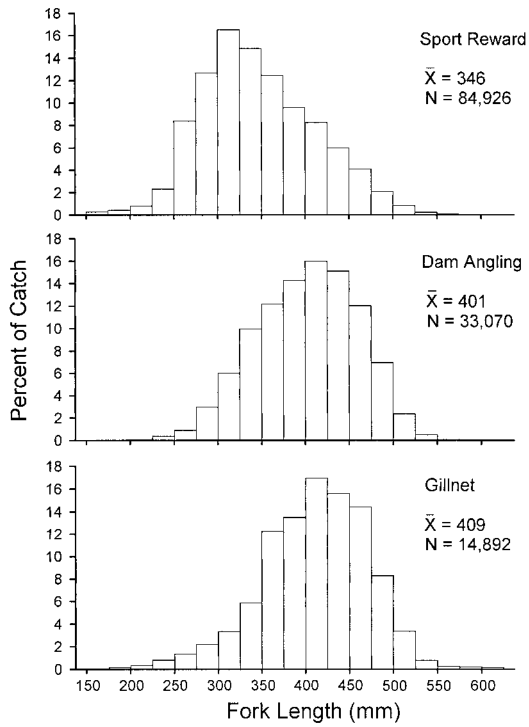

FIGURE 4.—Length-frequencies and mean fork lengths of northern pikeminnow from subsamples of fish harvested in the lower Columbia and Snake rivers by the sport-reward (1990–1996), dam-angling (1990–1996), and gill-net (1994–1996) fisheries.

Relationships between relative exploitation rate and fork length varied among fisheries; however, exploitation generally increased with fork length (Figure 5). This was especially true for the dam-angling and sport-reward fisheries, although the rate of increase for the sport-reward fishery declined somewhat as fork length increased. Gear selectivity appeared to affect the size of fish harvested by the site-specific gill-net fishery, because exploitation rose sharply but then peaked and declined for fork lengths greater than 450–500 mm.

Reduction in Potential Predation

Potential predation on juvenile salmonids by northern pikeminnow has decreased to 62–86% of

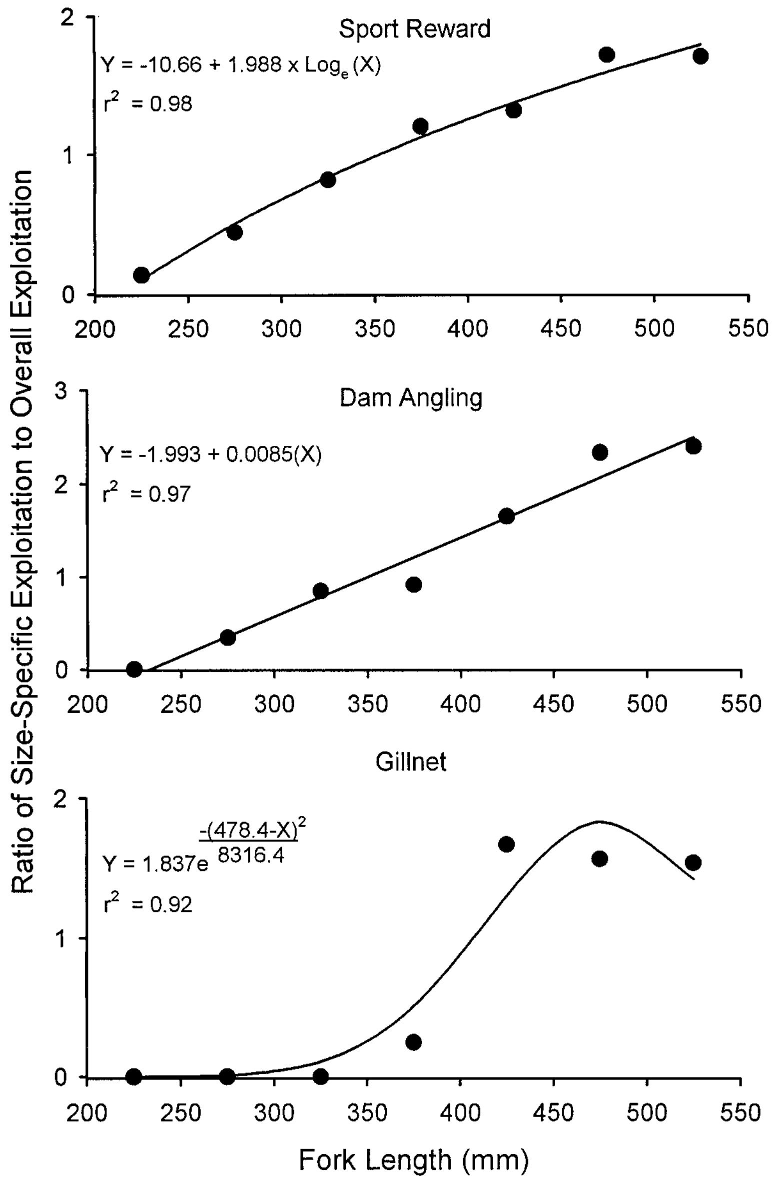

FIGURE 5.—Relationship between size-specific exploitation of northern pikeminnow (50-mm groups) and exploitation of all sizes combined for the sport-reward (1992–1996), dam-angling (1992–1996), and gill-net (1994–1996) fisheries.

pre-NPMP levels, with a median estimate of 75% (Figure 6). Relative benefits of a given exploitation decreased over time as the number of large northern pikeminnow was reduced. Therefore, continued exploitation at mean 1991–1996 levels will not result in further reductions in potential predation. Exploitation in recent years (1994–1996) has been higher than the 1991–1996 mean; therefore, further reductions in potential predation will be realized if exploitation is maintained at mean 1994–1996 levels.

Contribution by various age-classes of northern pikeminnow to overall predation by the unexploited population depended on the relationship between consumption rate and fork length (Figure 7). With exploitation, predation declined in older

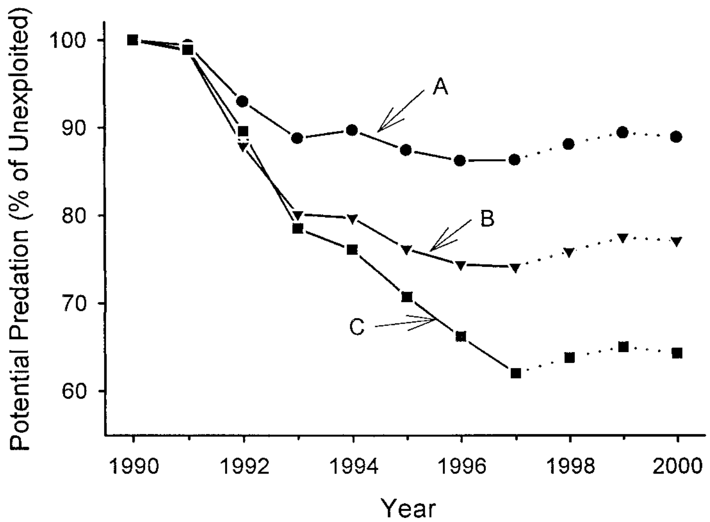

FIGURE 6.—Range of estimates of potential predation on juvenile salmonids by northern pikeminnow relative to predation by the unexploited population. Limited management of northern pikeminnow began in 1990; full implementation of management began in 1991. Scenarios represent length–predation relationship and exploitation estimates resulting in minimum estimate of eventual reduction in potential predation (A), median estimate of potential predation (B), and maximum estimate of eventual reduction in potential predation (C). Dotted lines indicate potential predation if exploitation is maintained at mean 1991–1996 levels.

fish and the relative prey consumption by age shifted toward younger fish. Predation was negligible by fish older than age 12.

Discussion

Management fisheries in the Columbia and Snake rivers are highly efficient at removing large northern pikeminnow. The sport-reward fishery is most effective in terms of total northern pikeminnow harvested, due primarily to the large amount of effort afforded by the involvement of public anglers. Although harvest effort varies annually, sport-reward CPUE has increased as veteran anglers become more efficient at catching northern pikeminnow and new anglers are recruited to the fishery. Because no reward is offered for northern pikeminnow less than 250 mm, the proportion of these fish removed by sport-reward anglers may be slightly underestimated. Anglers who caught and retained only undersized fish probably did not return to agency check stations.

Though the dam-angling fishery contributes far less to the total catch of northern pikeminnow, the fish harvested are larger and, therefore, consume a greater number of juvenile salmonids (Vigg et al. 1991) than those captured in the sport-reward fishery. In addition, this fishery targets northern pikeminnow primarily in tailrace BRZs, where high levels of predation occur (Ward et al. 1995). These areas are also inaccessible to members of the public participating in the sport-reward fishery. Low catch rates in the dam-angling fishery have resulted in a decrease in harvest effort and harvest of northern pikeminnow in recent years, which may be partially attributed to declining abundance of large northern pikeminnow throughout the Columbia and Snake rivers (Knutsen and Ward, in press). Very high river flows in 1995 and 1996 (Fish Passage Center, unpublished data) also undoubtedly affected this fishery during most of the northern pikeminnow angling season. Faler et al. (1988) found that northern pikeminnow avoid areas of high flow associated with spillgate operation in the tailrace of McNary Dam on the Columbia River.

Like the dam-angling fishery, the gill-net fishery captures northern pikeminnow considerably larger than those harvested by the sport-reward fishery, and harvest effort is concentrated in areas with potentially high predation. Collis et al. (1995) documented increases in gill-net catch and number of juvenile salmonids in the diet of northern pikeminnow after juvenile salmonid releases from hatcheries; they suggested that northern pikeminnow may aggregate to feed on salmonids during peak release times. For this reason, the contribution of the gill-net fishery to northern pikeminnow

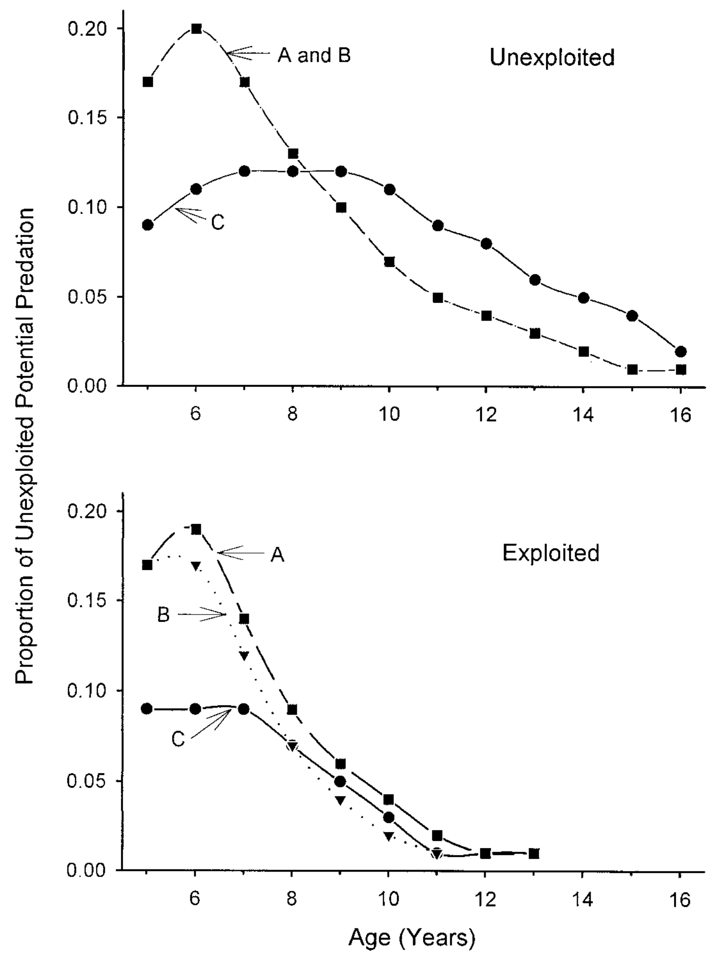

FIGURE 7.—Potential predation by age-classes of northern pikeminnow in the lower Columbia River basin with no exploitation and with observed exploitation. Scenarios represented are length–predation relationship and exploitation estimates resulting in minimum estimate of eventual reduction in potential predation (A), median estimate of potential predation (B), and maximum estimate of eventual reduction in potential predation (C).

exploitation is important, despite a relatively low number of fish harvested.

Northern pikeminnow populations may recover within a few years if management activities are halted (Rieman and Beamesderfer 1990); therefore, fisheries exploiting northern pikeminnow at a low level must be sustained. Our systemwide exploitation estimates for 1991–1992 and 1994–1996 consistently exceeded 10%, despite variations in harvest effort and CPUE. Lower rates of exploitation, as in 1993, will also have significant effects on potential predation. For example, Beamesderfer et al. (1996) predicted a 15–30% reduction in predation if exploitation is sustained at a rate of only 5%.

Some area-specific estimates of exploitation are slightly underestimated because northern pikeminnow that moved to a different area or reservoir before being recaptured were not included in our calculations. Because the proportion of fish that moved was small (9.0%), this bias is probably not important. Systemwide estimates of exploitation would not be affected unless a significant proportion of tagged fish moved out of the area open to management fisheries. We assumed an essentially closed system because (1) the Pacific Ocean and estuaries of the lower Columbia River are natural barriers to northern pikeminnow, which are not known to inhabit salt water; (2) fish passage facilities are not present at Hell's Canyon Dam; and (3) proportionally few fish are tagged near Priest Rapids Dam. Our comparison of methods used to calculate exploitation for 1991 and 1992–1996 suggests that using catch data and abundance indices (1991 estimates) rather than mark–recapture data (1992–1996 estimates) may slightly underestimate exploitation. However, mean 1992–1996 exploitation for the area below Bonneville Dam, calculated with catch data and abundance indices, was within 95% confidence bounds for estimates calculated by using mark–recapture data.

Our estimates of reductions in potential predation by northern pikeminnow are within the range predicted by Rieman and Beamesderfer (1990) and summarized by Beamesderfer et al. (1996). With information from John Day Reservoir, Rieman and Beamesderfer (1990) estimated that if northern pikeminnow recruitment was constant, sustained exploitation of 12% would reduce potential predation to about 55% of the unexploited level, compared with our median estimate of approximately 75%. The estimates differ in part because population dynamics of northern pikeminnow vary among areas of the Columbia River basin (Parker et al. 1995). Northern pikeminnow downstream from Bonneville Dam constitute 35–50% of the population in the lower Columbia River basin (Ward et al. 1995; Zimmerman and Ward, in press), so our results are highly dependent on reductions in predation by these fish. Natural mortality is higher and proportional stock density is generally lower downstream from Bonneville Dam than in Columbia River reservoirs (Parker et al. 1995; Knutsen and Ward, in press); therefore, the unexploited population contained a smaller proportion of old, highly piscivorous individuals. Consequently, exploitation downstream from Bonneville Dam had a proportionately smaller effect on predation than exploitation in reservoirs.

Although our model to estimate reductions in potential predation is similar to the model developed by Rieman and Beamesderfer (1990), important differences add significance to the similarity in results. We were able to use information on northern pikeminnow abundance, diet, and population dynamics from throughout the lower Columbia River basin (Parker et al. 1995; Knutsen and Ward, in press; Zimmerman, in press), but the only data available to Rieman and Beamesderfer (1990) was from John Day Reservoir. Biological characteristics of northern pikeminnow vary considerably throughout the Columbia River basin (Parker et al. 1995; Knutsen and Ward, in press). Because exploitation of northern pikeminnow was virtually nonexistent before implementation of the NPMP, Rieman and Beamesderfer (1990) could not predict the relationships between northern pikeminnow size and exploitation rates or how exploitation would differ among areas.

The assumption of constant recruitment by northern pikeminnow seems suitable for our analyses. Parker et al. (1995) found no correlation between northern pikeminnow density and other population characteristics. Extensive information on year-class strength of northern pikeminnow in the Columbia River (Rieman and Beamesderfer 1990), including information gathered since implementation of the NPMP (Knutsen and Ward, in press), indicates that recruitment is not related to density. Year-class strengths fluctuate randomly, or in some unknown response to environmental conditions, and average out with time. This variability adds a degree of uncertainty to our analyses, which were based on a relatively short time period (6 years). However, our potential predation model was designed to assess the relative effects of northern pikeminnow management if all other factors, including year-class strength, were held constant.

Several other assumptions of our model have been verified by recent findings. Knutsen and Ward (in press) found that relative abundance of large, highly piscivorous northern pikeminnow has declined, and that growth and reproduction of surviving northern pikeminnow have not increased. Zimmerman (in press) found no evidence of increased predation by surviving northern pikeminnow. Ward and Zimmerman (in press) found no evidence of response by smallmouth bass *Micropterus dolomieu* to sustained removals of northern pikeminnow, and Friesen and Ward (1997) found no evidence of response by walleyes *Stizostedion vitreum.*

Our modeling results can be used to estimate increases in the number of surviving juvenile salmonids that may result from sustained exploitation of northern pikeminnow. Mean annual losses of juvenile salmonids to northern pikeminnow predation in the Columbia River from the mouth to the Priest Rapids Dam tailrace and in the Snake River from the mouth to the Hells Canyon Dam tailrace are estimated to be 15.2 million individuals (Beamesderfer et al. 1996). Our estimate of percent reduction in potential predation indicates that annual losses may be reduced to 11.4 million juvenile salmonids (range, 9.4–13.1 million), a net gain of 3.8 million (range, 2.1–5.8 million) salmonids. This gain would represent 1.9% (range, 1.1–2.9%) of the approximately 200 million downstream migrants.

The relative success of the NPMP can also be measured in comparisons with other fish control programs. Brown and Moyle (1981) observed that past projects targeting northern pikeminnow were often based on anecdotal evidence or inconclusive studies. Meronek et al. (1996) judged 250 fish control programs for a variety of species on the basis of benefits to fisheries, and they found 29% to be unsuccessful and 28% to have insufficient data to determine success. They concluded that all fish control programs should include (1) critical evaluation of assumptions and of suspected causes of problems, (2) explicit rationale and objectives, and (3) pretreatment and long-term posttreatment studies. A review of northern pikeminnow studies in the Columbia River basin during the past 15 years suggests that these criteria have been met by the NPMP. Evaluation of assumptions and problems was addressed by Petersen (1994), Ward and Zimmerman (in press), Knutsen and Ward (in press), and Friesen and Ward (1997). Program rationale and objectives were established primarily by Rieman and Beamesderfer (1990); preprogram biology, population dynamics, and predation potential of northern pikeminnow were investigated by Rieman et al. (1991), Vigg et al. (1991), Poe et al. (1991), Ward et al. (1995), and Parker et al. (1995). Recent work constitutes steps towards posttreatment evaluation. Zimmerman (in press) compared diet and piscivory in predatory fish species during implementation of the NPMP; Zimmerman and Ward (in press) described predation on juvenile salmonids by northern pikeminnow from 1994 to 1996. Studies of biological responses of resident piscivores to sustained exploitation of northern pikeminnow (Friesen and Ward 1997; Knutsen and Ward, in press; Ward and Zimmerman, in press) are also important posttreatment evaluations.

Additional work could enhance future assessments of the NPMP and improve confidence in the assumptions of our potential predation model. First, northern pikeminnow catch and exploitation rates should continue to be monitored annually by indirect methods. Annual exploitation rates must be maintained to meet program goals, and this information will be needed to justify continuation or modification of the management program. The response of northern pikeminnow and other predators to exploitation should also be monitored periodically. Although recent work (Friesen and Ward 1997; Knutsen and Ward, in press; Ward and Zimmerman, in press) shows that biological compensation is unlikely, it remains possible, particularly if northern pikeminnow exploitation is continued for a long period of time (Beamesderfer et al. 1996). Hilborn and Winton (1993) suggested that 15 or more years of data may be required to effectively evaluate salmonid enhancement programs. A detailed cost analysis of removal efforts among fisheries and areas would further enhance evaluations of effectiveness. Columbia River basin fisheries managers should strive to improve the quantification of juvenile salmonid mortality, enabling more meaningful comparisons of predation with other sources of mortality. Much of the current information is outdated, particularly with regard to hydroelectric projects, or only appears in the gray literature.

We conclude, based on our use of indirect methods to evaluate the NPMP, that management fisheries are successful at removing large numbers of northern pikeminnow (≥250 mm), sustained exploitation rates of 10–15% are attainable, and this exploitation translates to an important reduction in juvenile salmonid losses to predation. However, because potential gains in terms of increased juvenile salmonid numbers are relatively modest, the benefits of the NPMP alone may not ensure the recovery of depressed salmonid stocks. In assessing the barging of juvenile salmonids around dams, Ward et al. (1997) concluded that the management of Snake River chinook salmon *O. tshawytscha* should not rely heavily on any one management activity. This conclusion also seems appropriate for northern pikeminnow management efforts. The NPMP is only one part of a multiprogram strategy for the restoration of Columbia River salmonids. The continuation of all component programs (e.g., barging, habitat enhancement, and passage improvement) should be assessed within the context of cost and relative benefits to salmonid populations.

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Appendix: Summary of Model Used to Estimate Changes in Potential Predation

Population structure before removals.—To simulate population structure of northern pikeminnow before removals, we used length distribution data collected before implementation of the NPMP (Parker et al. 1995; Knutsen and Ward, in press) for each reservoir. We pooled length-at-age data from 1990 to 1996 (Knutsen and Ward, in press) to estimate the age distribution of fish for 25-mm length intervals and to estimate mean length at each age. Because growth, annual mortality, and maximum age differ between female and male northern pikeminnow (Parker et al. 1995), we summarized data for each sex separately. We then pooled the data for females and males to estimate an average age composition before implementation of the NPMP. We used linear regression on a catch curve constructed from adjusted age frequencies (Ricker 1975) to estimate annual natural mortality rate and mean index of recruitment to age 5. Estimates of mean annual natural mortality were then used to index abundance for other ages of northern pikeminnow.

Consumption of juvenile salmonids by northern pikeminnow.—We collected consumption information from 1990 to 1996 (Zimmerman and Ward, in press), and used the consumption index (CI) developed by (Ward et al. 1995) to compute spring and summer consumption indices:

$$\mathrm{CI} = 0.0209 \cdot T^{1.60} \cdot \mathrm{MW}^{0.27} \cdot (S \cdot \mathrm{GW}^{-0.61});$$

T = water temperature (°C) at time of sampling,

MW = mean weight (g) of northern pikeminnow in sample,

S = mean number of salmonids per northern pikeminnow in sample, and

GW = mean total gut weight (g) of northern pikeminnow in sample.

Consumption indices were converted to consumption rates (C; number of juvenile salmonids per northern pikeminnow per day) as $C = -0.077 + 0.618(\mathrm{CI})$ (Zimmerman and Ward, in press).

Size (age) of northern pikeminnow is important because consumption rates increase with northern pikeminnow length (Vigg et al. 1991). Three formulas were used to estimate the potential relationship between relative consumption rate (RC) and fork length (L) of northern pikeminnow: (1) RC = $-0.858 + 0.003703L$ (Oregon Department of Fish and Wildlife, unpublished data); (2) RC = $1.631 \times 10^{-8}(L^{2.986})$ (Tabor et al. 1993; Parker et al. 1995); and (3) RC = $1.58 \times 10^{-15}(L^{6.02})$ (Rieman and Beamesderfer 1990).

Age-specific exploitation.—Overall exploitation rates (Figure 2) and relationships between exploitation, and length of northern pikeminnow (Figure 5) were used to estimate age-specific exploitation rates. Total exploitation rate for each age was calculated as the sum of the fishery-specific exploitation estimates, with a maximum exploitation of 1.0 for each age.

Changes in potential predation.—Northern pikeminnow age structure after implementation of the NPMP was adjusted for exploitation and natural mortality:

$$A_{h,j} = A_{h-1,j-1}(1 - E_{h-1,j-1})(1 - M);$$

$A_{h,j}$ = abundance index of age-h fish in year j,
$A_{h-1,j-1}$ = abundance index of fish aged $h - 1$ in year $j - 1$,
$E_{h-1,j-1}$ = exploitation rate on fish aged $h - 1$ in year $j - 1$, and
M = annual natural mortality rate.

We assumed that natural mortality occurred after fishing and that forces of natural mortality remained constant (Ricker 1975). The recruitment of fish to age 5 remained constant at the average level.

Seasonal predation by each age of northern pikeminnow was indexed as the product of (1) the abundance index, (2) the consumption rate, and (3) the number of days in the season. Predation indices were summed for all ages, reservoirs, and seasons, then expressed as a percentage of the predation index for the ‘‘average’’ northern pikeminnow population before implementation of the NPMP.