STUDY FINAL REPORT

State: Michigan

Project No.: F-35-R-22

Study No.: 650

Title: Evaluation of natural reproduction, stocking rates, and fishing regulations for steelhead *Oncorhynchus mykiss*, chinook salmon *O. tschawytscha*, and coho salmon in Lake Michigan

Period Covered: April 1, 1996 to March 31, 1997

Study Objective: To evaluate the effects of different stocking rates and fishing regulations for steelhead, chinook salmon, and coho salmon on the fisheries of Lake Michigan and selected tributaries.

Abstract: We developed an age-specific population model to predict stocking levels necessary to achieve sustainable salmonine biomass and yield in Lake Michigan. Hypothesized sustainable salmonine harvests were specified by the Great Lakes Fisheries Commission (GLFC 1994) to range from 12 to 15 million lbs, of which 20-25% is lake trout. Model simulations accurately predicted age composition and biomass of historic yields from 1985-95. Simulation results indicated stocking levels of chinook salmon, rainbow trout and brown trout must be lowered by approximately 30-70% to achieve target Fish Community Objectives for Lake Michigan salmonines, and while stocking of lake trout and coho salmon must be increased by 30-40%. Analysis of historical harvest and biomass levels suggest that mortality due to BKD increased at salmonine biomass greater than 20 million lbs, a level reached during the 1980's and predicted again for 1997. Based on the relationship between stocking levels, salmonine abundance and BKD, we estimate sustainable biomass of Lake Michigan salmonines to approximate 45 million lbs. Model predictions are most sensitive to errors in natural mortality rate, fish weight, and to pre-recruit survival.

Background: This purpose of this study was to quantify management actions necessary to achieve a predator biomass in Lake Michigan which would provide a quality fishing experience and control populations of alewife, the dominant planktivorous forage species. Sustainable levels of salmonine biomass are unknown for Lake Michigan, but management guidelines have recommended desired species composition, sustainable harvest and biomass levels based upon historic catches of lake trout during the 1930's-40's, biomass size spectra theory (Sprules et al. 1991), prey biomass (Eck and Brown 1985), and bioenergetic demand of predators (Stewart et al. 1981, Stewart and Ibarra 1990). These guidelines, or Fish Community Objectives (Eshenroder et al. 1995) specify a diverse salmonine community capable of sustaining annual harvests of 2.7 to 6.8 million kg (6-15 million lbs), of which 20-25% is lake trout. The biomass necessary to sustain this level of harvest is estimated to approximate 40 million lbs. I used an age-structured model of salmonine dynamics to predict yield as a function of stocking and size limits, and estimate the numbers stocked and size limits needed to achieve the target salmonine community specified in the Fish Community Objectives.

Procedures:

Model Description - I used an age-structured, deterministic population model ("CONNECT") that predicts fishery yield as a function of stocking. This model was developed by Richard Clark, Jr. to analyze trends in abundance of chinook salmon in Lake Michigan. Analyses of fishing regulations and stocking were conducted in conjunction with biologists representing the following management or research agencies: Richard Clark, Jr., Kelley Smith, Paul Seelbach, Michigan DNR; Dan Makauskas, Illionois DNR; James Francis, Indiana DNR; Brian Belonger, Wisconsin DNR; Charles Madenjian, USGS; Mark Holey and Shawn Sitar, USFWS; James Bence, Michigan State University; and Gregory Wright, Chippewa-Ottawa Treaty Fishery Management Authority.

"CONNECT": Connecting Stocking or Effort to Biomass and Yield:

"CONNECT" is a deterministic fish population model configured for a spreadsheet which links stocking to fishery yield. The model tracks abundance and biomass of a year class through its life using the exponential model of mortality. Recruitment (N_0), or the number of hatchery and wild smolts reaching the lake, is subjected to instantaneous rates of total mortality (Z) on an annual time step (t).

$$N_1 = N_0 * \exp^{(-Zt)}$$

Instantaneous total mortality is composed of fishing mortality (F_t) and natural mortality (M_t).

$$Z_t = F_t + M_t$$

and natural mortality is composed of sources due to predation, energy losses, etc. ($M_{tnatural}$) and a source due to Bacterial Kidney Disease (M_{BKD}).

$$M_t = M_{tnatural} + M_{tBKD}$$

The numbers of fish (N_t) leaving the lake population each year to enter tributary streams to spawn is:

$$N_t = N_{(t-1)} * \exp^{(-Zt)} * P_t$$

where P_t is the age-specific proportion (scaled 0 to 1) of the population in that age class returning to spawn. population biomass is estimated by multiplying age-specific abundance at the beginning of the year by mean weight at annulus.

The catch equation (Ricker 1975) is used to estimate age-specific harvest of fish:

$$Ct = \frac{Ft * At * Nt}{Zt}$$

where C_t = catch in numbers at age t, F_t = age-specific instantaneous fishing mortality, A_t = age-specific % mortality rate (1- % survival). Catch in numbers was multiplied by the average age-specific weight at harvest to estimate catch in biomass.

Model Inputs

General - For the analysis of stocking impacts on historical yields and fish community objectives, we ignored the considerable variability in life-history traits among strains and subpopulations of Great Lakes salmonines (Biette et al. 1981). We assumed all wild smolts left tributaries at the same age, and all strains grew and died at equal rates.

Age and Growth - Age frequency distributions, and mean weights at annulus and at harvest were estimated from numerous sources. Age distributions and mean weights of fish were available from creel survey data (coho, chinook, lake trout, brown, steelhead) or from weir harvest records (eg. coho: Pecor 1992; steelhead: Hay 1992). Age and growth studies also provided information on age-frequency distribution and length-weight relationships for chinook salmon (Hesse 1994; Wesley 1996), steelhead (Rand et al. 1993; Seelbach 1993) and lake trout (Rybicki and Keller 1978; Rybicki 1991) sampled from lake and stream populations.

Coho Growth - Coho weight at age was calculated as the weighted average of weights of fish harvested as the bulk of the population migrates and grows around the lake (Appendix Table 1A). The coho migration begins in southern lake Michigan, migrates west and northwest to Illinois and Wisconsin waters, and finally returns to Michigan waters in fall to stage and spawn.

Chinook Growth - Mean length and weight at annulus, and at harvest were estimated from Wesley's (1996) study of age and growth of chinook in Lake Michigan. Growth was assumed to decrease from 1979 to 1988 as the population biomass increased above 20 million lbs in the lake. Mean weight at harvest then increased back to pre-1979 levels after 1988 as population biomass decreased (Appendix Table 1A).

Lake Trout Growth - Age and growth data on lake trout were obtained from creel-survey data reported in Rybicki and Keller (1978), Clark and Huang (1985), and Rybicki (1991). Growth was assumed constant among years (Appendix Table 1A).

Steelhead Growth - Lengths at annulus of steelhead were obtained from back-calculated growth curves, and weights at annulus and harvest were calculated from length-weight relationships (Seelbach 1986; Appendix Table 1A).

Brown Trout Growth - Data on length at age and age composition of brown trout in the sport harvest were available from Wisconsin DNR and Michigan DNR creel surveys. Growth rates were assumed constant over time (Appendix Table 1A).

Recruitment - Recruitment was quantified as the number of individuals (or yearling-equivalents) entering the lake fishery, and equaled the sum of hatchery and naturally-reproduced production. Records of hatchery plants by all agencies were summarized by Holey (1996). Natural reproduction of chinook and coho salmon was estimated from regression analysis (MDNR unpublished data), stream surveys (Carl 1982), weir harvest records (Pecor 1992, Hay 1992), and by the ratio of wild to hatchery adults sampled in the lake (Patriarch 1980, Hesse 1994) or in tributary streams (MDNR unpublished data), assuming equal survival between hatchery and wild fish during the yearling-to-adult period. Numbers of steelhead yearling-equivalents were estimated by Rand et al. (1993) for 1975 to 1990, and then updated. Brown trout and lake trout were assumed to have no natural reproduction. To estimate numbers of hatchery yearling-equivalents for all species, actual numbers of fall fingerlings or yearlings stocked (Holey 1996) were adjusted for survival from stream to the lake, or for immediate post-stocking survival. These adjustments and survival rates varied by species and size of fish and are discussed in detail below. Yearling brown trout and lake trout were assumed to have 100% survival during stocking.

Chinook Recruitment - Chinook recruitment in yearling equivalents increased to approximately 3 million in 1985, dropped to 2.8 million in 1987 and 1988, increased to 3.7 million in 1990 and 1991, and has remained at 3 million since (Appendix Table 2A). Recruitment of chinook was composed primarily of hatchery smolts, with some naturally-reproduced smolts from Lake Michigan tributaries. The contribution of natural smolts to the lake fishery currently represents 30% of the hatchery contribution (Hesse 1994), or 2.2 million smolts. Total recruitment in smolt equivalents was calculated by adjusting hatchery plants for post-stocking survival (X 0.9), adding in naturally-reproduced smolts, and applying first-year survival (smolt-to-age 1 survival = 0.40).

Coho Recruitment - Coho recruitment depends mainly on hatchery stocking. Coho were first introduced into Lake Michigan tributaries in 1966. In the case of coho, yearling equivalents are the same as smolts. The numbers stocked increased from 330,000 smolts in 1966 to 2 million hatchery smolts by 1979, and in recent years have fluctuated around 1 million smolts/yr (Appendix Table 3A). Estimates of hatchery recruitment, expressed in hatchery smolt equivalents, were obtained by multiplying yearling and fingerling hatchery smolt numbers by 0.5. This number represents an unknown but significant overwinter survival by fall fingerlings planted in Wisconsin, and instream survival by hatchery plants until they reach the lake proper. Although states differ in time of release for coho, they all release hatchery plants at a size of approximately 125 mm TL, or 5 inches.

Estimates of natural recruitment were low relative to hatchery production. We assumed natural smolt production was 10% of hatchery production from 1975-85 (Patriarche 1980), and declined to 5% starting in 1990. Charles Pecor (MDNR fisheries, personal communication) has indicated that coho do not seem to persist in Michigan rivers where they are not stocked, supporting recent observations that natural recruitment of coho is low (Patriarch 1980; Carl 1982; Pecor 1992; MDNR unpublished data).

Steelhead Recruitment - In the case of steelhead, yearling equivalents are the same as smolts. Total recruitment of steelhead increased from approximately 100,000 smolts in 1965 to 1 million in 1976, fluctuated between 500 and 1.5 million smolts from 1977 to 1991 and has remained above 1 million smolts since 1991 (Appendix Table 4A). Recruitment of steelhead to the Lake Michigan fishery was composed predominantly of hatchery smolts, particularly from 1983 to present. Rand et al. (1993) estimated numbers of wild steelhead smolt-equivalents using Seelbach's (1993) relationship between winter temperature and production of Little Manistee River smolts, and then adjusting by the percentage (roughly 20%) of the wild lake population composed of Little Manistee River steelhead. To calculate hatchery smolt-equivalents, Rand et al. (1993) adjusted the actual numbers of hatchery smolts or fingerlings to account for size at planting and stream type: bigger smolts were estimated to have higher survival from plant site to lake; and stable, cold-water streams supported higher survival than did warmer streams. Numbers of smolt-equivalents entering the fishery since 1990 were estimated by adding the average wild recruitment from 1975-90 to reported numbers stocked by Holey (1996), which were adjusted by the ratio (0.5) of smolts predicted by Rand et al. (1993) to those predicted by Holey (1996).

Brown Trout Recruitment - Recruitment in yearling equivalents steadily increased from 26,000 in 1966 to reach 1.05 million smolts by 1982, and has remained near 1.0 million since (Appendix Table 5A). Hatchery plants of brown trout have included both fall fingerlings and yearlings. We assumed 100% survival of the 6-in. average yearling smolts from their stocking sites to the lake, and no production of wild smolts to the lake fishery. The numbers of fall fingerlings were reduced by 75% before being added to yearling smolt production to account for overwinter mortality.

Lake Trout Recruitment - Recruitment of lake trout is entirely dependent on hatchery plants as there is no natural reproduction (Appendix Table 6A). Stocking levels have fluctuated between 1.2-3.0 million plants. Lake trout are planted as yearlings at a size of 150 mm.) with an assumed stocking survival of 100%.

Mortality - Total instantaneous mortality rates were estimated from age- or length-frequency data collected by resource agency creel surveys and reported by Rybicki (1973, 1991) and Stewart et al. (1981). Fishery-independent gill-net sampling of aged adults provided more recent estimates of total mortality. Instantaneous mortality rates due to natural causes (M_t) were estimated for lake trout by Clark and Huang (1985) and Rybicki (1991), or were assumed based on data from similar-sized west-coast salmonid populations. For chinook salmon, natural mortality due to Bacterial Kidney Disease (M_{BKD}) was estimated by the difference between total mortality of chinook before 1986 (pre-BKD) and total mortality rate immediately following 1986 (post-BKD). Fishing mortality then was estimated as the difference between total mortality and assumed, age-specific instantaneous mortality rates due to natural causes. Fishing mortality rates were adjusted to match predicted harvest and age composition data with historical trends in lake harvest and age composition. Vulnerability of fish to the fishery was simulated by adjusting age-specific fishing mortality rates.

Coho Mortality - Instantaneous total mortality rates of coho in Lake Michigan averaged Z = 0.56 for the first year in the lake, decreased from Z = 0.6 to 0.44 in lake-year 2, and were increased to Z = 2.6-2.8 in their 3rd summer to eliminate any individuals from the model population. These estimates were chosen to match the percent returns by year classes to the weir of hatchery smolts planted in the Platte River (Pecor 1992), to represent the decrease in mortality with size, and to achieve a total annual survival rate of around 14%. Percent returns are minimum estimates of survival, and do not include individuals which survived but did not return to the Platte River. The total mortality rates were increased in recent years to match the observed decrease in hatchery returns to the weir starting in the mid-1980’s.

Instantaneous annual rates of natural mortality were assumed to be age-specific and constant at M = 0.5 for age 1.0, M = 0.1 for age 1.1, and M = 2.5 for age 1.2 (Appendix Table 7A). Instantaneous annual rates of fishing mortality were varied to match the observed harvest of coho from the lake. These rates were held constant from 1965-84 for age 1.0 (F=0.06), age 1.1 (F=0.5), and age 1.2 (F=0.3). The age-specific rates were decreased from 1985 to present, and averaged F=0.013 for age=1.0 fish and F=0.48 for age=1.1 fish (Appendix Table 8A). The proportion of fish in the population which returned to tributary streams to spawn or be caught was assumed a constant 5% for age 1.0 fish, and 100% for age 1.1 fish (Appendix Table 7A). These proportions were chosen to reflect the proportion of jacks in the weir harvest observed at the Platte River weir, which ranged from 1.6 to 15.5 % and averaged 5% (Pecor 199).

We assumed no other source of natural mortality, including BKD, influenced lake populations of coho.

Chinook Mortality - Trends in mortality of chinook were positively associated with changes in population abundance (Clark 1996). Natural mortality in the lake from sources other than BKD was assumed to be age-specific and constant. Lake fishing mortality was positively related to abundance and was lowered by nearly 40% to account for the decline in effort and catch after 1986 (Appendix Table 8A). Mortality due to BKD was assumed 0 before 1986, then increased to Z=0.626-1.042 from age 1-4 from 1988 to 1994 (Appendix Table 7A). Incidence of BKD-related mortality has declined in recent years as abundance of adults has declined.

Lake Trout Mortality - Instantaneous total mortality of lake trout ranged from 0.63-0.66 from 1965-83, and from 1992 to present. Mortality of lake trout increased to Z=1.44 from 1984-87, then decreased to Z=0.96 from 1988-91. The increase in mortality was attributed entirely to increased fishing pressure as natural mortality rate remained at a constant 0.36 for recruited fish (Appendix Tables 7A, 8A). Lake trout were considered fully vulnerable by age 5 (Rybicki 1991).

Steelhead Mortality - Total instantaneous mortality rates of steelhead were estimated for lake fish from smolt-to-returning adult survival rates estimated by Seelbach (1993) for Little Manistee River steelhead. Mortality was increased at ages 6-8 to balance the relative proportions and abundances of individuals appearing in the lake and weir harvests. Natural mortality of steelhead comprised the greatest proportion of total mortality. Mortality during the stream phase was slightly higher than mortality due to fishing in the lake (Appendix 7A, 8A).

Brown Trout Mortality - To our knowledge, mortality of brown trout in Lake Michigan has not been estimated to date. We assumed natural mortality rate was equal to mortality of steelhead trout, and varied fishing mortality rate to match predicted and observed catches (Appendix Tables 7A, 8A). Instantaneous fishing mortality rate exceeded mortality from natural causes at ages 2-5 as fish became vulnerable to the fishery, but losses associated with spawning exceeded both sources after age 1.

Harvest, Effort, Catch Rates - Creel surveys conducted by resource agencies in lakes and streams provided estimates of harvest, effort, and catch rates (eg. Rakoczy and Svoboda 1995)

Model Calibration and Simulations **-** We calibrated the 'CONNECT' model by matching predicted and observed harvests for the Lake Michigan sport fishery from 1985 to 1995. We also attempted to match predicted vs observed age composition of fish sampled from the lake fishery and from tributary weir surveys. For all species except brown trout, fishing mortality rate and BKD mortality rate were adjusted to match predicted and observed catches while maintaining the general temporal pattern of angler effort. Mean weight at harvest also was used to calibrate coho catches. For brown trout, model predictions of harvest at age were compared to observed harvests at age for the 1985-95 period using a maximum likelihood algorithm.

After calibrating model parameters, we adjusted stocking levels to match community composition, harvest and biomass levels targeted by Fish Community Objectives (Eshenroder et al. 1995), and estimated the forage prey biomass consumed by these model populations. We ran model scenarios to estimate the numbers of fish stocked by species to achieve Fish Community Objectives of 12-15 million lbs harvest, with 20-25% composed of lake trout. A critical assumption was the nature of the relationship between BKD-mortality and stock biomass of chinook salmon. This relationship is unknown, but we assumed it to be linear and positive, because of the positive linear relationship observed between chinook stocking numbers and incidence of BKD in sampled fish (Clark 1996). We varied BKD mortality levels from M=0.0 to

0.94 for recruited fish to simulate BKD effects on stocking densities and biomass of chinook salmon and resultant effects on prey fish consumption.

We estimated the impact of stocking scenarios on the available forage biomass by extending Stewart and Ibarra's (1990) and Rand et al.'s (1993) analysis of lakewide predator consumption. They estimated the forage necessary to support growth of each species salmonines during its life in the lake, and expressed it relative to millions of fish stocked. In this way, stocking can be linked to forage biomass in a deterministic manner.

Sensitivity Analysis - We analyzed the relative sensitivity of model-predicted yield to variation in parameter estimates for chinook salmon. Parameters included pre-recruit survival, recruitment, lake natural mortality other than BKD, BKD-related mortality at high (M>0.50) and low (M<0.18) levels, the proportion of chinook leaving the lake to spawn, and fishing mortality rate. We varied each of the above parameters by 25%, and calculated the percent deviation in yield of chinook from a baseline simulation with low BKD-mortality (M=0.1-0.18) and 1996 levels of fishing mortality (F=0.03-0.35) and stocking (6.2 million smolts).

Recapitulation:

Job 1: <u>Use mathematical modeling to project results of alternative management strategies.</u>

Findings:

<u>Harvest and Biomass</u>

Coho Salmon - Coho harvest trends predicted by the model closely matched observed trends in harvest (Figure 1). Observed total harvest in weight from Lake Michigan ranged from 27,300 lbs in 1966, peaked at 2.5 million lbs in 1980, then decreased steadily to 323,000 lbs in 1991 before increasing back to 668,000 lbs in 1996. The predicted percent composition of jacks in the lake harvest matched the observed composition in the MDNR creel survey and weir data, which ranged from 1.6 to 15.4 % and averaged 5 %.

Chinook - Predicted trends in age composition and harvest matched observed patterns well for both the lake and stream fisheries (Figures 1, 2). Harvest of chinook increased to 9.4 million lbs from 1965 to 1986, decreased sharply to 380,000-460,000 lbs from 1990 to 1993, then has increased back to 950,000 lbs in 1996, with a projected harvest in 1997 of 1.5 million lbs (Figure 1). Changes in harvest were caused primarily by variation in natural mortality due to BKD, as effort declined by only 50-60% over this period (Rakoczy and Svoboda 1995) and recruitment was relatively stable or increased (Figure 3).

Estimated population biomass of chinook salmon peaked at 36 million lbs in 1987, declined sharply to 15 million lbs in 1995, and then increased to 26 million lbs in 1996. The projected biomass in 1997 will again equal the peak biomass in the 1980's (Figure 4).

Lake Trout - Model predictions of lake trout harvest fitted the general trend in observed harvest, but matched harvest poorly during 1987-88 and 1993-94 (Figure 1). Lake trout harvest in weight increased sharply to peak at 5.8 million lbs in 1983 because of the increased fishing pressure, then decreased to 2.5 million lbs by 1985, and has since varied between 1.1-2.1 million lbs.

Trends in population biomass of lake trout population levels reflected trends in fishery harvest. Current biomass levels are 11 million lbs.

Steelhead - Age composition and trends in observed harvest of steelhead were well described by the model (Figures 1, 2). Steelhead biomass harvested from Lake Michigan increased from 600,000-700,000 lbs before 1985 to 1.1 million lbs by 1992. The increase in harvest was most likely due to increased effort for steelhead, which coincided with the discovery of the offshore scumline fishery as abundance and harvest of chinook declined during the late-1980's and early 1990's. Total population biomass increased from 6 million lbs in 1976 to approximately 11 million lbs by 1988, with most of the increase attributable to stocking.

Brown Trout - Model predictions generally fit the observed age composition and trend in brown trout harvest, but consistently underestimated harvest from 1985-95 (Figure 5). Harvest of brown trout ranged from 500,000 to 750,000 lbs in 1985-87, decreased to 250-300,000 lbs in the late 1980's and early 1990's, then increased to 550,000 lbs before dropping back to 400,000 lbs in 1995. Total population size of brown trout in Lake Michigan increased steadily to 3 million lbs by 1979, and at present is approximately 4 million lbs.

Fish Community Objectives

Model predictions indicate current levels of stocking and mortality (M_{BKD}=0.15-0.37) will not produce salmonine harvests approaching the 6-15 million lbs targeted in the Fish Community Objectives (Eshenroder et al. 1995). The 1996 harvest of chinook salmon was 35% lower than FCO levels, and harvests of coho salmon and lake trout also were 33 and 28% lower, respectively. Harvest of brown trout and rainbow trout are currently above their target FCO harvest levels. To achieve FCO harvest levels, stocking of chinook will have to increased by 2-fold to 12 million hatchery plants to recover the targeted harvest. This level of stocking would produce a standing stock of 62 million lbs of chinook, and a total salmonine biomass of 85 million lbs.

Under more optimistic scenarios of low (M_{BKD}<0.18) or no BKD-related mortality, stocking of chinook salmon, steelhead and brown trout would have to be reduced 30-70% from current levels to achieve target biomass and harvest levels (Table 1). These stocking numbers would generate a predator biomass in Lake Michigan of 44.9-47.4 million lbs, which approximates the salmonine biomass targeted in the Fish Community Objectives. Biomass of chinook under this scenario would comprise 49-51% of the total salmonine biomass. Stocking of lake trout would have to be increased by 40% over present levels to make up the 20% of the total predator harvest specified under the Fish Community Objectives. The estimated predatory demand on the forage base from this level of predation would be 61.4 million lbs., of which 57% would be alewife (Table 2).

If BKD-related mortality remains high (M_{BKD}>0.50), the model predicts it will be impossible to achieve the Fish Community Objectives under a feasible stocking effort. Numbers of stocked chinook needed annually to achieve FCO's would approach 24 million, more than 4 times the number currently stocked (Table 1). The resulting biomass of salmonids would consume an estimated 152.3 million lbs of forage fish, of which 64% would be alewife.

Sensitivity Analysis

Our results indicate that model predictions of yield are most sensitive to error in BKD mortality, pre-recruit survival, and mean weight of adults (Figure 6). The most sensitive parameter to error was BKD mortality under high levels (M_{BKD}=0.56-0.90). Error in BKD mortality at low levels (<M=0.18) had relatively little effect. A 25 % error in estimates of pre-recruit survival or mean weight of chinook would change model predictions of yield by nearly 20%. An error in fishing mortality, natural mortality rate, and recruitment estimates produced less dramatic effects, while error in the proportion of adults leaving the lake to spawn had no effect on yield.

Discussion

Our modeling efforts indicate that Fish Community Objectives may be achieved by reducing the numbers of fish stocked and the available population biomass. Although modeling simulations indicated that increased stocking numbers are needed for medium and high levels of BKD, the stocking numbers suggested by the analysis are impractical given the hatchery systems produce one-half that amount under full capacity. The potential for growth-related stress to increase disease transmission would only increase as the resulting population levels would exceed those present during the mid-1980's. A more cautious and feasible approach would be to cut stocking, reduce the numbers of predators in the lake, and increase the probability of survival as salmonine density decreases, which would eventually produce better growth and survival once forage levels have rebounded.

Historical analysis indicated the increase in BKD-related mortality during the 1980's coincided with an increase in predator biomass levels to greater than 40 million lbs. Many hypotheses have been advanced to explain the decline, including growth-related stress due to overstocking and consumption of prey (Stewart et al. 1981, Stewart and Ibarra 1990) and poor rearing practices in hatcheries. The subsequent decline in mortality of chinook by the mid 1990's could be explained either by better hatchery management or by reduced predation pressure on the forage base. In any case, the reduced predation pressure by salmonines has allowed alewife populations to rebound. In 1994 and 1995, as in the 1970's (Rybicki 1973), salmonines were less abundant and their diets were less diverse and contained more year classes of alewives compared to the mid-1980's, when salmonine abundance was high and gut analysis indicated only the young age classes were present (Robert Elliot, USFWS personal communication; Jude et al. 1987; Stewart and Ibarra 1990).

Near-term model predictions suggest the incidence of BKD mortality may soon flare up in the chinook population. Chinook biomass levels in 1997 and 1998 are likely to reach 30 million lbs, which would increase the salmonine biomass in Lake Michigan to above 60 million lbs, the level at which chinook populations dropped precipitously in the 1980's (Figure 4). Preliminary indications from MDNR survey sampling are that incidence of BKD is once again increasing dramatically, as the majority of chinook sampled in May and June 1997 show signs of infection.

Our modeling approach provided a simplistic, yet rapid approach to analyze management options for Lake Michigan fisheries, but should be considered a first step in the analysis of a complex problem. More refined and accurate analyses will come from more accurate estimates of mortality, prey abundance and dynamics (Brandt et al. 1991), direct bioenergetic modeling (Jones et al. 1993; Rand et al. 1993), and analysis of spatial heterogeneity of predator-prey relationships (Goyke and Brandt 1993; Mason et al. 1995). Because carrying capacity of Lake Michigan for predators is ultimately determined by production of forage fishes, it will be essential to accurately quantify forage fish production over time to monitor the response to salmonine predation and changes in primary and secondary production. Sensitivity analysis indicated model predictions of yield were robust to changes in recruitment and fishing mortality, but were highly sensitive to variation in pre-recruit survival, and estimates of BKD mortality. Variability in recruitment and natural mortality (at high levels) are common sources of error for dynamic pool approaches to stock assessment, particularly when fishing mortality rate is relatively minor, as is the case with all Lake Michigan salmonines except lake trout.

We assumed observed changes in harvest were caused by changes in effort and abundance, and not by changes in vulnerability of fish to anglers over time and space. Catch of salmonines may be highly dependent on the location of thermal ecotones (thermal bar, thermocline, upwellings) and wind-generated surface slicks which may aggregate prey as well as provide optimal thermal refuge. Harvest of salmonines depends not only on their relative abundance, but on the ability of anglers to locate them. Angler efficiency for some species likely has increased since the mid-1980's with the advent of thermal surface maps, now available over the Internet through NOAA's Coastwatch program. Increased vulnerability to anglers would raise our estimates of fishing mortality rate, and lower the relative weight of BKD to mortality, although it would not qualitatively affect our predictions since total mortality has decreased since the 1980's.

Other sources of variability which should be considered in future analyses include differences in growth and behavior among stocked strains. These differences become significant for steelhead and brown trout, whose strains differ in survival from smolt to returning adult, and in age at maturity. Although stocking must be reduced to achieve Fish Community Objectives, it should not be eliminated; lake trout, brown trout, and coho are entirely dependent upon stocking to maintain population levels.

We estimated salmonine consumption of alewives to range from 16-24 million lbs during 1986 and in 1997. These estimates are likely overinflated because survival of salmonines from smolt to adult was curtailed by BKD, and spatial and temporal discontinuities in distributions were not considered in the analysis (Brandt et al. 1991; Mason et al. 1995). Factors which would counterbalance errors in salmonine consumption rates include consumption by other predators, chiefly burbot, which were not included in our model. The ability of alewife to sustain predation pressure not only depends upon spatial distributions of predator and prey, but environmental factors affecting recruitment and overwinter survival of adults (Eck and Brown 1985).

The life cycle of chinook, the most abundant and effective predator in Lake Michigan, is relatively short and dynamic. Observed harvest and biomass data demonstrated how rapidly chinook abundance may fluctuate; chinook population biomass decreased from 36 million lbs in 1986 to 13 million lbs in 1990 due to an increase in BKD mortality and slight reduction in stocking, then has rebounded back to near 20 million lbs in 1997 because of relaxed fishing mortality and lowered BKD mortality and increased forage biomass. This rapid response to environmental changes warrants caution when recommending management policy. Sustainability of the fishery depends on having enough prey to sustain salmonines at both high and low predator levels. Perhaps alternate controls on salmonine biomass, such as increased fishing or decreased stocking, could be exerted at high levels which would lower the potential for boom and bust cycles to occur. In Lake Michigan, however, the potential to control salmonine survival through fishing is low given most mortality is from natural causes.

Job 2: Write Final Report.

Findings: This report was written and submitted on schedule.

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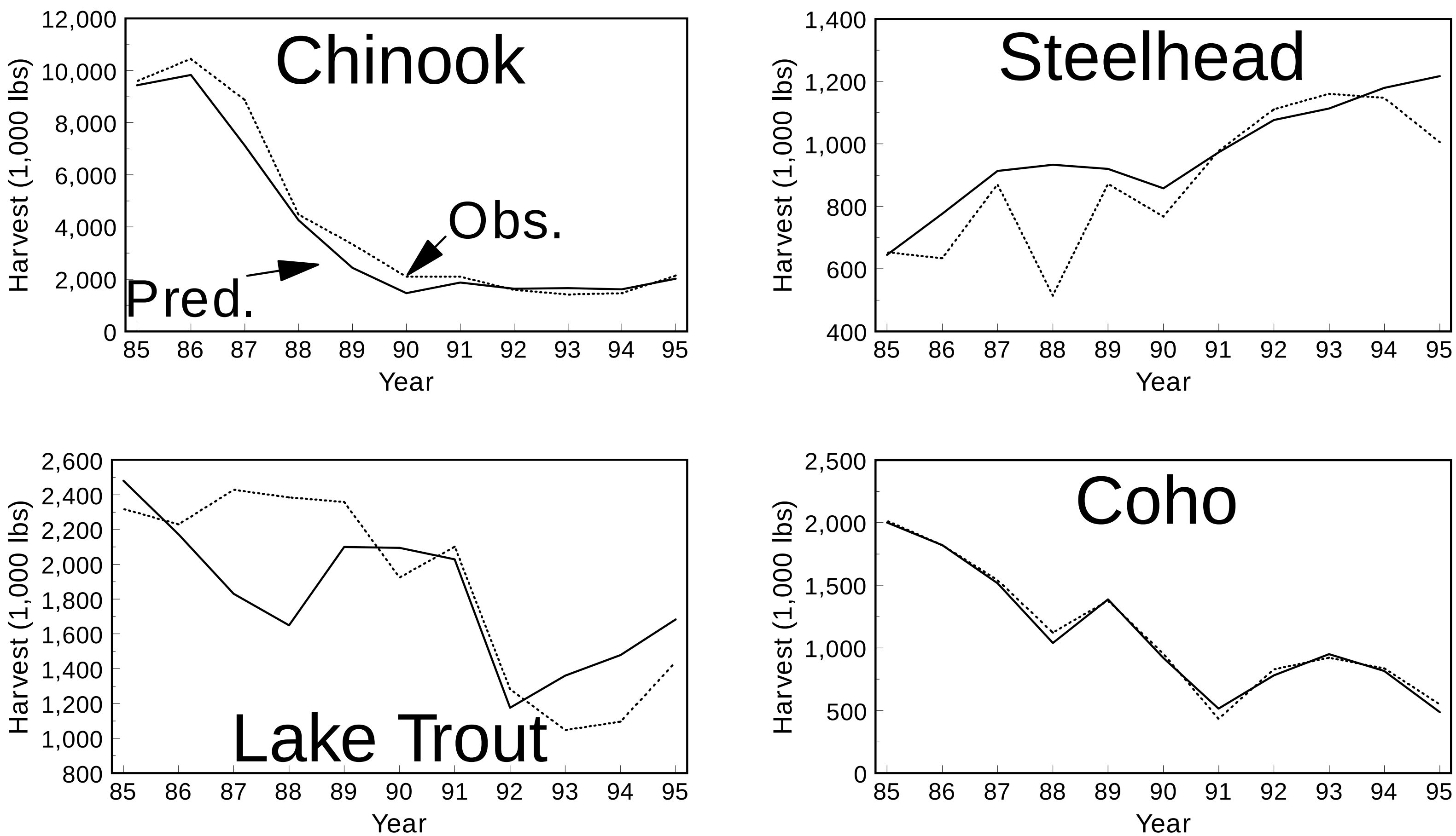

Figure 1.–Model-predicted (dashed line) and observed (solid line) harvests (1,000 lbs.) of chinook, lake trout, steelhead, and coho salmon in Lake Michigan, 1985-95. Note change in scale of Y-axis among figure panels.

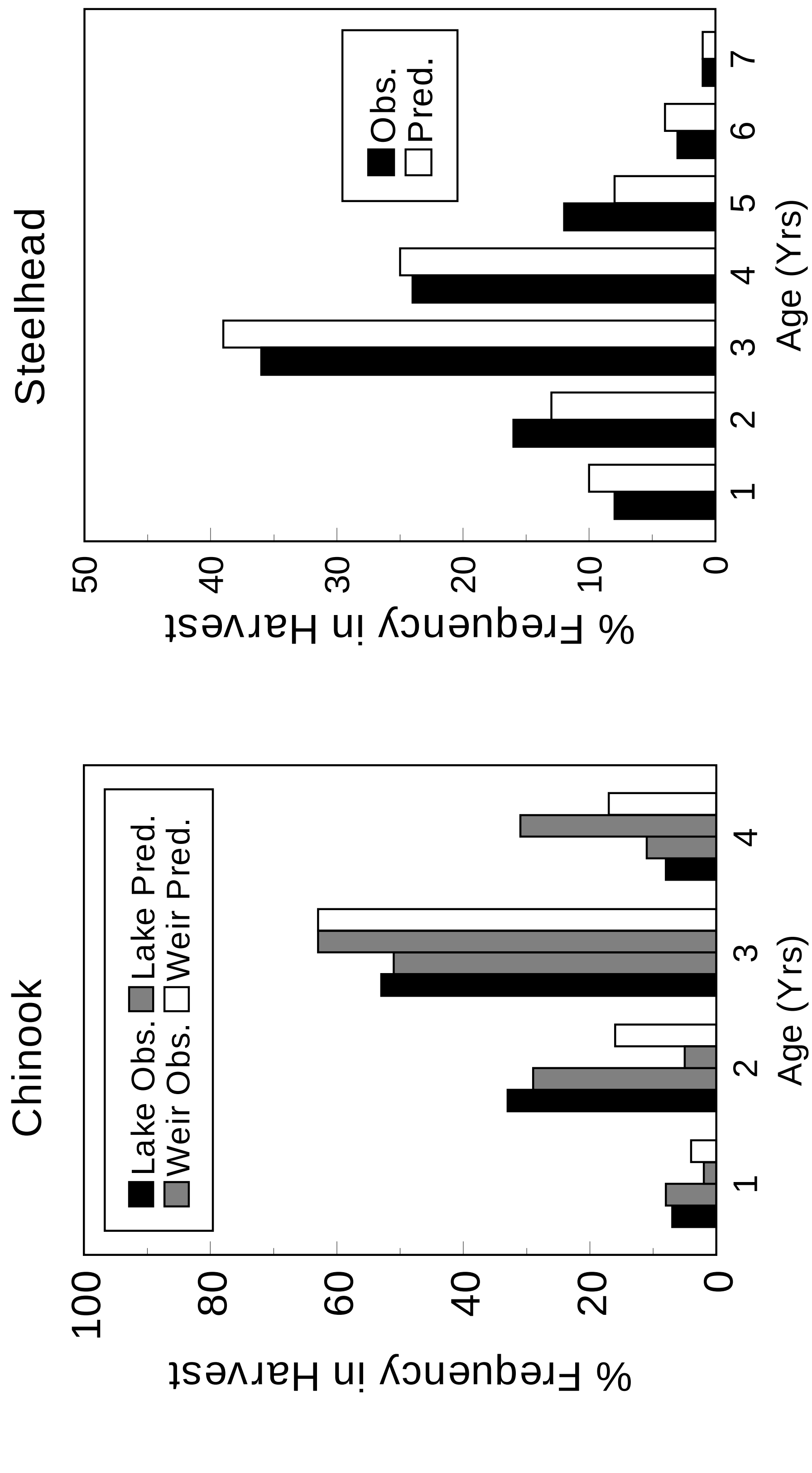

Figure 2.–(Left) Model-predicted and observed age-frequency composition of recreational harvest for chinook salmon in Lake Michigan and streams during 1986. (Right) Model-predicted and observed age-frequency composition of recreational harvest for steelhead in Lake Michigan during 1986.

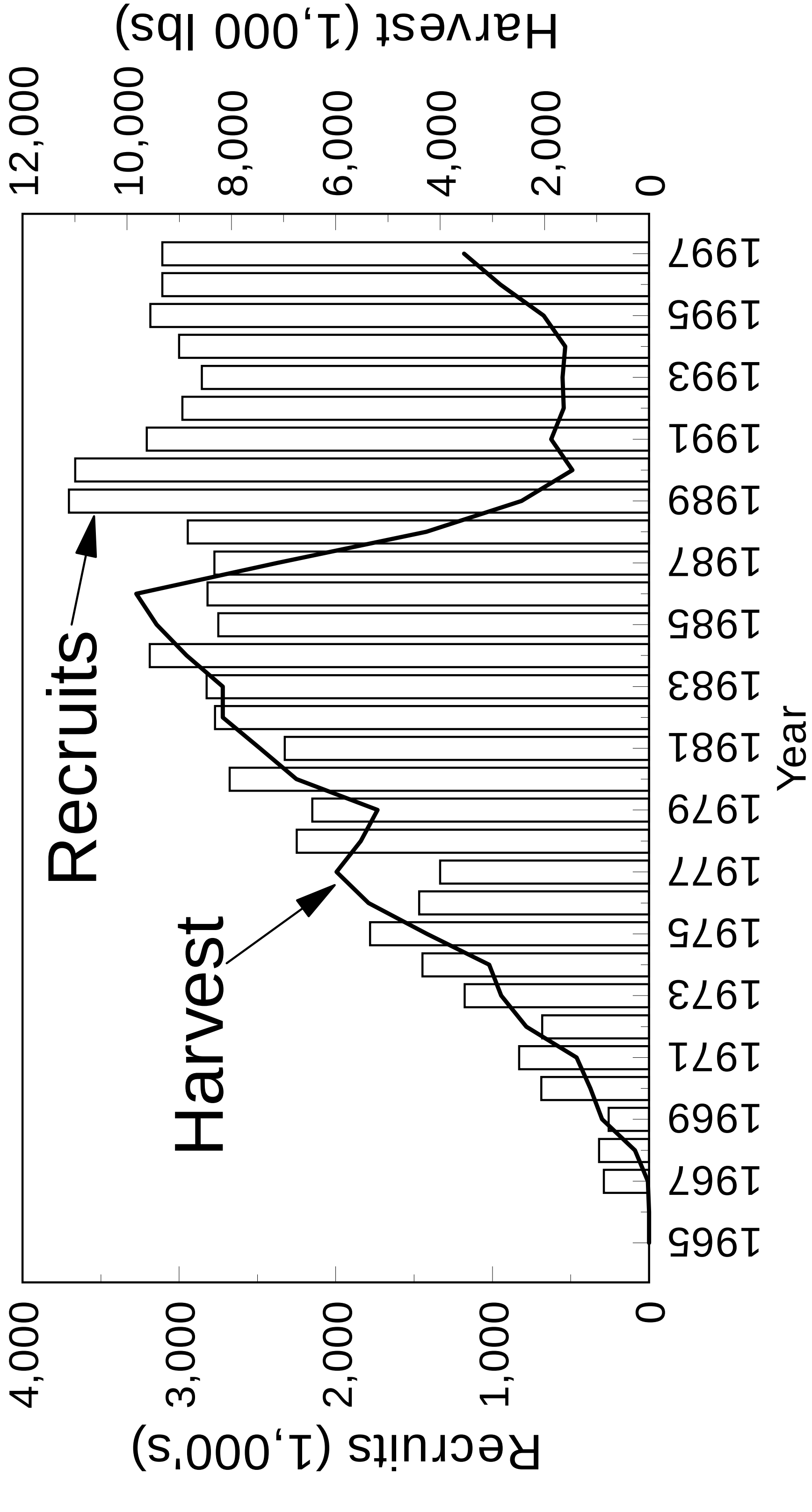

Figure 3.–Estimated recruitment (1,000's smolt-equivalents) and recreational harvest (1,000 lbs.) of chinook salmon in Lake Michigan, 1965-97.

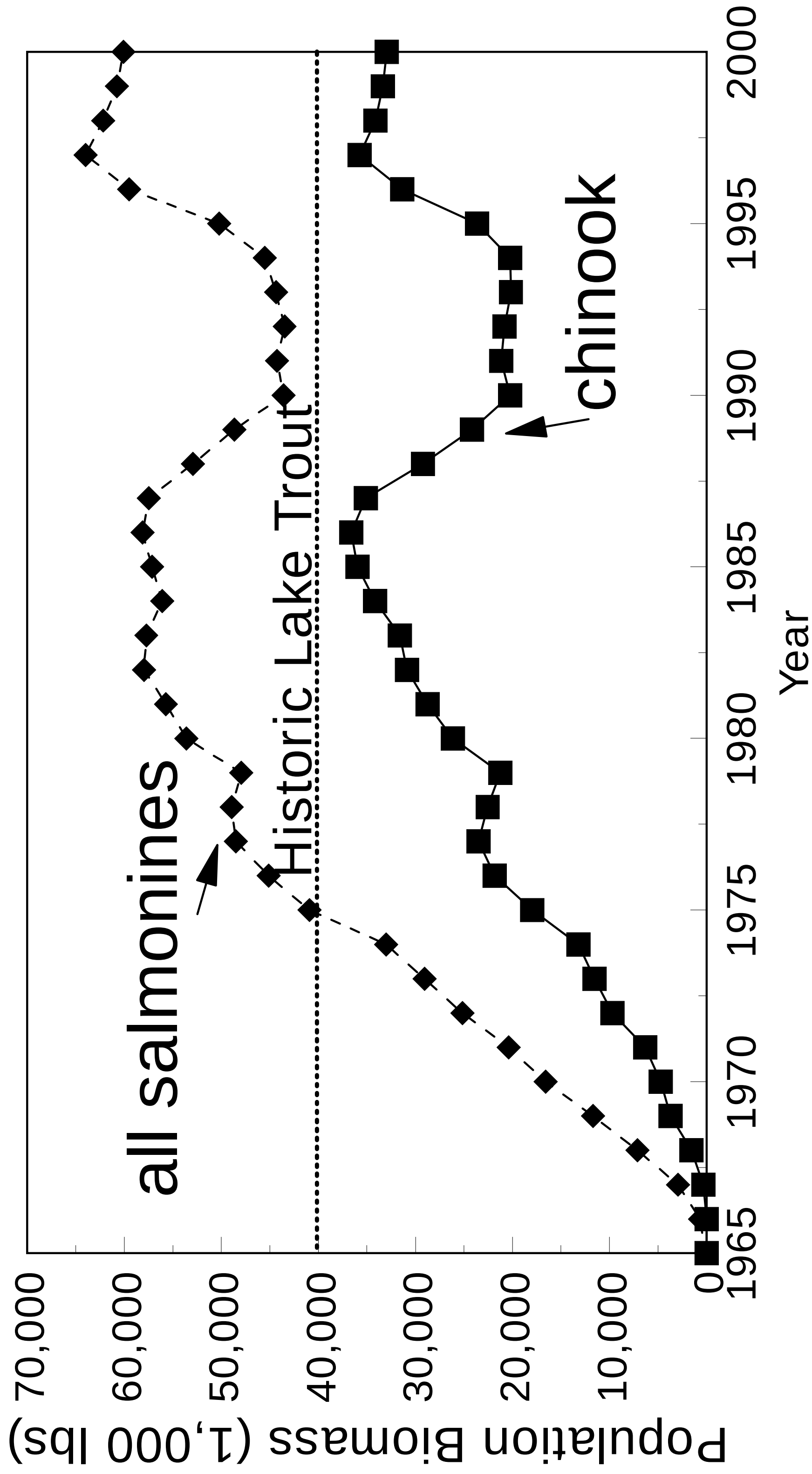

Figure 4.–Model-predicted biomass (1,000 lbs.) of all salmonines and chinook separately from 1965-2000 in Lake Michigan. Dashed line represents historical estimated biomass of lake trout in Lake Michigan during the 1930's and 1940's.

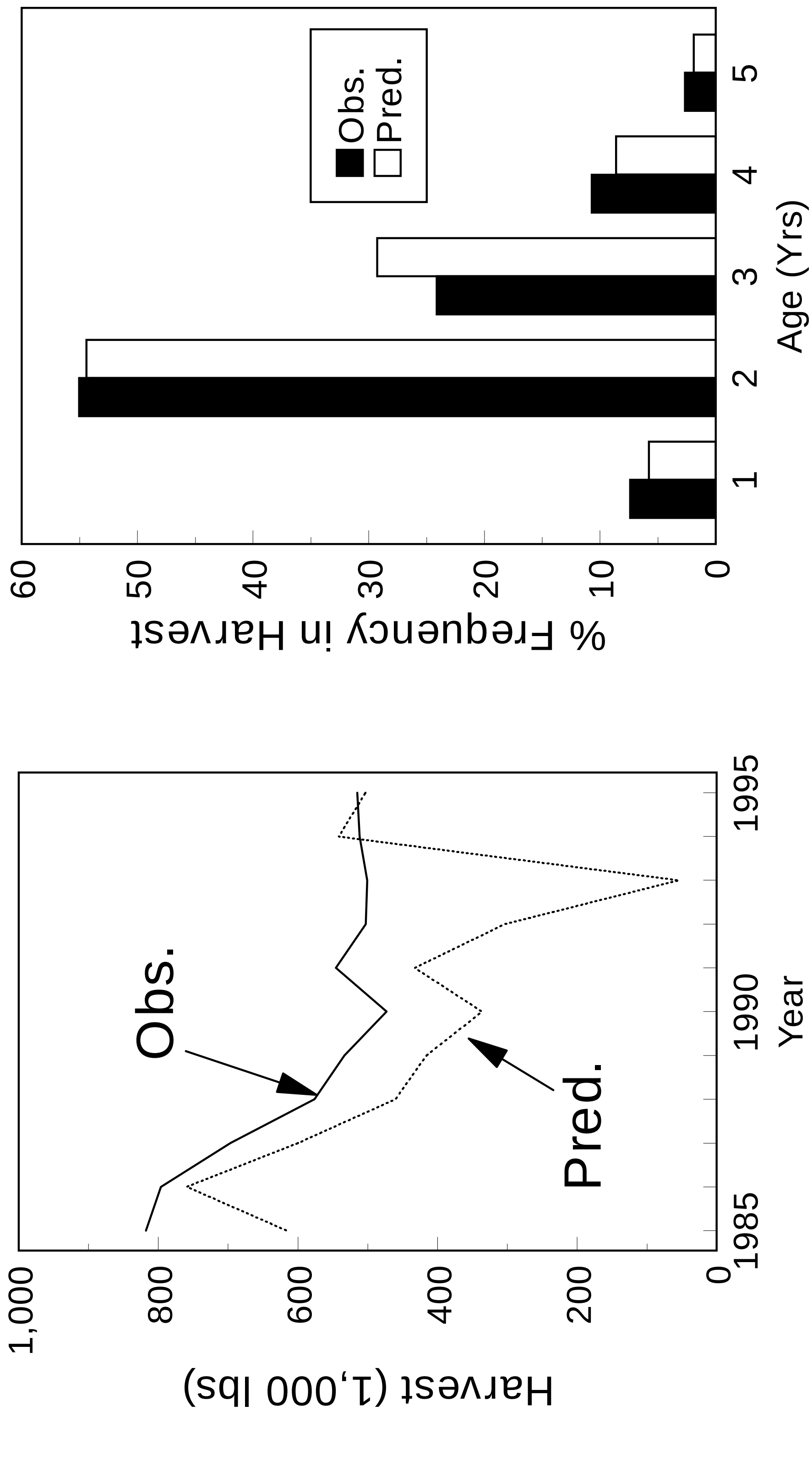

Figure 5.–(Left panel) Model-predicted (dashed line) and observed (solid line) harvest of brown trout in Lake Michigan, 1985-95. (Right panel) Model-predicted and observed age-frequency composition of recreational harvest for brown trout in Lake Michigan during 1986.

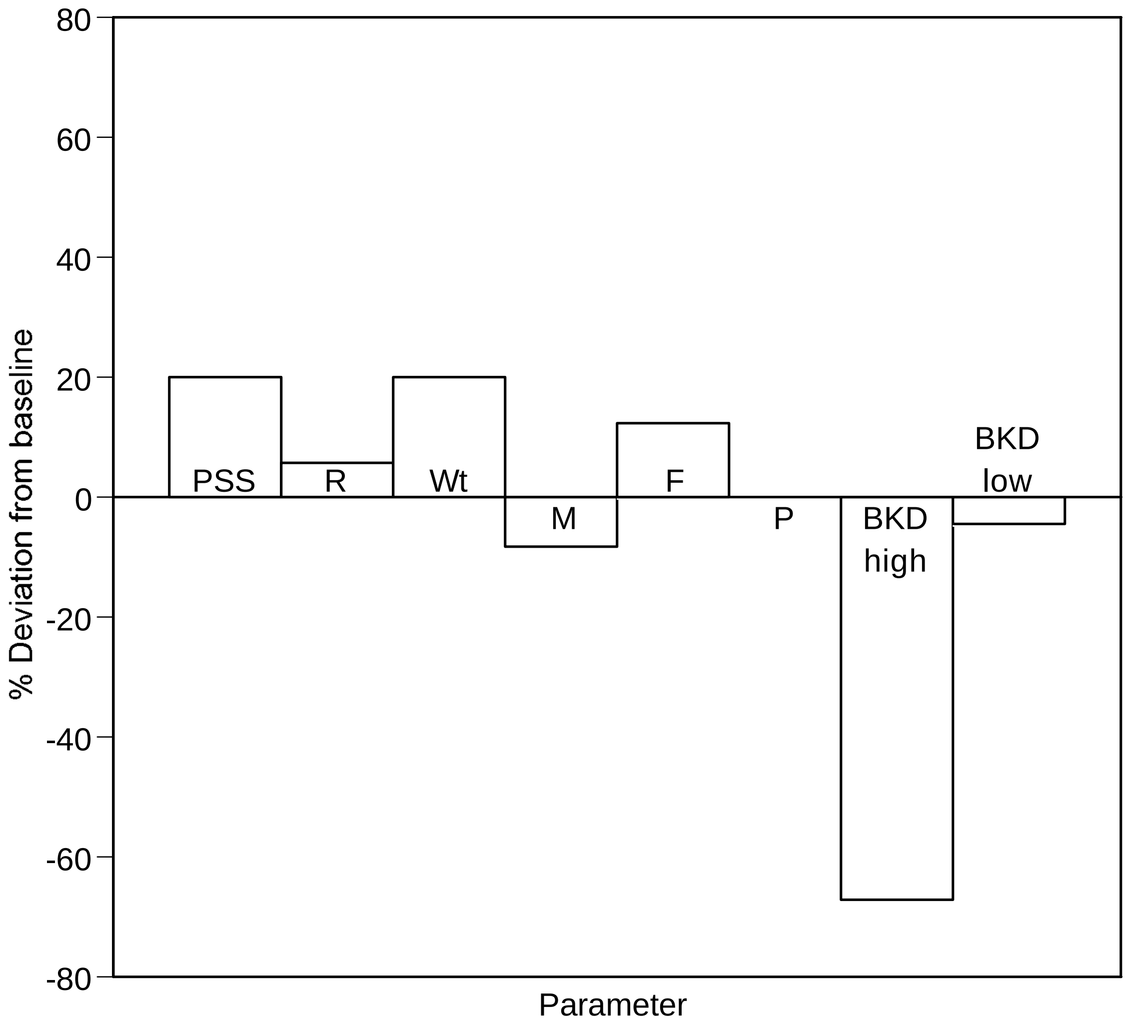

Figure 6.–Sensitivity of model predictions in yield of chinook salmon to a 25% change in model parameters. The parameters include “PSS”=pre-smolt survival rate, “R”=recruitment (smolt-equivalents), “Wt”=mean weight at harvest, “M”=instantaneous natural mortality rate in lake, “F”=instantaneous fishing mortality rate in lake, “P”=proportion of adult chinook population leaving lake to return to streams, “BKD-high”=predicted chinook yield assuming BKD mortality is greater than M=0.5, “BKD-low”=predicted chinook yield assuming BKD mortality is less than M=0.18. Y-axis values represent the % deviation from the baseline prediction of chinook yield assuming fishing mortality F=0.03-0.35, BKD mortality rate $M_{BK}D$=0.10-0.18, and stocking rate of 6.2 million smolts.

Table 1.–Model predictions of fishery yield (‘Yield’, million lbs.) and standing stock (‘SS’, million lbs) of salmonines in Lake Michigan under varying scenarios of mortality and stocking (million smolt-equivalents). Scenarios include historical conditions observed during 1996 (“Current”), 1986, and conditions required to achieve Fish Community Objectives of yield and population standing stock (see text). Species are chinook salmon (CHK), steelhead (STT), lake trout (LT), coho salmon (CS), and brown trout (BT). ‘Low BKD’ assumes BKD-related mortality estimated for chinook salmon during 1996. ‘High BKD’ assumes BKD-mortality estimated for chinook salmon during 1989.

	CHK			STT			LT			CS			BT		
Scenario	Stock	Yield	SS	Stock	Yield	SS	Stock	Yield	SS	Stock	Yield	SS	Stock	Yield	SS
Current	6.16	4.48	36.31	0.94	1.64	10.52	2.44	1.75	10.67	1.12	1.11	1.49	1.12	1.04	4.29
1986	5.60	11.41	36.60	1.13	0.76	9.62	2.92	2.17	6.36	1.15	2.15	1.79	0.72	0.80	3.76
FCO’s															
No BKD	1.85	6.84	22.67	0.28	0.67	4.29	3.37	2.42	14.73	1.57	1.55	2.05	0.48	0.45	1.84
Low BKD	3.14	6.84	25.17	0.28	0.67	4.29	3.37	2.42	14.73	1.57	1.55	2.05	0.48	0.45	1.84
High BKD	23.91	6.82	45.02	0.28	0.67	4.29	3.37	2.42	14.73	1.57	1.55	2.05	0.48	0.45	1.84

Table 2.–Model predictions of forage consumption (million lbs.) by salmonines in Lake Michigan under varying scenarios of mortality and stocking. Scenarios include historical conditions observed during 1996 ("Current"), 1986, and conditions required to achieve Fish Community Objectives of yield and population standing stock (see text). Salmonine predator species are chinook salmon (CHK), steelhead (STT), lake trout (LT), coho salmon (CS), and brown trout (BT). Forage prey species include alewife 'AW'; other fish species including bloater, rainbow smelt, sculpins, etc. 'OF'other fish'; and invertebrate zooplankton, amphipods, mysids, etc. 'IV'. 'Low BKD' assumes BKD-related mortality estimated for chinook salmon during 1996. 'High BKD' assumes BKD-mortality estimated for chinook salmon during 1989. Forage consumption was calculated using relationships between numbers stocked and prey consumption following Stewart and Ibarra (1991) and Rand et al. (1993).

	CHK			STT			LT			CS			BT		
Scenario	AW	OT	IV	AW	OT	IV	AW	OT	IV	AW	OT	IV	AW	OT	IV
Current	26.0	13.0	1.4	3.4	2.5	2.2	6.5	5.4	1.3	3.9	4.2	0.9	3.4	2.5	2.2
1986	24.2	12.1	1.3	2.9	2.1	1.9	6.4	5.3	1.3	4.7	5.0	1.0	2.8	2.0	1.8
FCO's															
No BKD	12.9	6.5	0.7	1.4	1.0	0.9	8.9	7.4	1.9	5.4	5.7	1.2	1.5	1.1	1.0
Low BKD	16.9	8.4	0.9	1.4	1.0	0.9	8.9	7.4	1.9	5.4	5.7	1.2	1.5	1.1	1.0
High BKD	79.5	39.7	4.2	1.4	1.0	0.9	8.9	7.4	1.9	5.4	5.7	1.2	1.5	1.1	1.0

Appendix Table 1A.–Estimated mean weights at harvest of chinook salmon, lake trout, coho salmon, rainbow trout, and brown trout in Lake Michigan, 1965-1997.

	Chinook		Lake	Coho		Rainbow	Brown
Age	1965-78	1978-88	Trout	<1988	>1988	Trout	Trout
1	3.3	3.3	0.2	1.8	1.8	1.9	0.8
2	8.8	8.0	0.9	5.4	3.3	4.2	4.5
3	15.0	13.1	2.0			7.2	7.6
4	18.5	16.9	3.4			9.8	10.4
5	20.9	20.4	5.0			11.8	10.4
6			6.8			13.1	
7			8.5			13.2	
8			10.2			13.3	
9			11.7			13.5	
10			13.1				
11			14.4				
12			15.5				
13			16.5				
14			17.4				
15			18.1				
16			18.7				
17			19.3				
18			19.7				
19			20.1				
20			20.4				
21			20.7				
22			20.9				
23			21.1				
24			21.3				
25			21.4				

Appendix Table 2A.–Estimated recruitment (yearling equivalents) of chinook salmon in Lake Michigan, 1965-97. Yearling equivalents were estimated as: yearling-equivalents (1,000’s) = [0.9*(hatchery plants(1,000’s)) + wild smolt production (1,000’s)]*0.4.

Year	Hatchery	Wild	Yearling Equivalents
1965	0	0	0
1966	0	0	0
1967	802	0	289
1968	887	0	319
1969	718	0	258
1970	1904	10	689
1971	2247	50	829
1972	1819	70	683
1973	3046	200	1177
1974	3578	400	1448
1975	4280	600	1781
1976	3302	700	1469
1977	2819	800	1335
1978	5365	800	2251
1979	5085	800	2151
1980	6106	1200	2678
1981	4798	1500	2327
1982	6035	1500	2773
1983	6180	1500	2825
1984	7170	1520	3189
1985	5955	1520	2752
1986	5607	2000	2819
1987	5485	2000	2775
1988	5739	2200	2946
1989	7846	2200	3705
1990	7125	2748	3664
1991	6237	2406	3208
1992	5795	2235	2980
1993	5491	2200	2857
1994	5894	2200	3002
1995	6400	2200	3184
1996	6193	2200	3109
1997	6193	2200	3109

Appendix Table 3A.–Estimated recruitment (yearling-equivalents) of coho salmon in Lake Michigan, 1965-1997. Yearling-equivalents were estimated as: yearling-equivalents (1,000's) = [0.5*1,000 hatchery plants) + wild smolt production (1,000's)].

Year	Hatchery	Wild	Yearling Equivalents
1965	0.0	0.0	0.0
1966	330.0	0.0	330.0
1967	866.0	0.0	866.0
1968	592.0	10.0	602.0
1969	1619.0	50.0	1669.0
1970	1768.0	50.0	1818.0
1971	1371.5	100.0	1471.5
1972	1312.0	100.0	1412.0
1973	1132.5	100.0	1232.5
1974	1772.0	177.2	1949.2
1975	1184.0	118.4	1302.4
1976	1468.5	146.9	1615.4
1977	1507.0	150.7	1657.7
1978	1315.0	131.5	1446.5
1979	2000.0	200.0	2200.0
1980	1471.5	147.2	1618.7
1981	1231.5	123.2	1354.7
1982	1090.0	109.0	1199.0
1983	1182.0	88.7	1270.7
1984	1514.0	113.6	1627.6
1985	1329.5	99.7	1429.2
1986	1145.5	85.9	1231.4
1987	1152.0	86.4	1238.4
1988	1605.0	120.4	1725.4
1989	1167.0	87.5	1254.5
1990	1190.0	59.5	1249.5
1991	1235.5	61.8	1297.3
1992	1372.0	68.6	1440.6
1993	854.5	42.7	897.2
1994	735.5	36.8	772.3
1995	1199.0	60.0	1259.0
1996	1200.0	60.0	1260.0
1997	1200.0	60.0	1260.0

Appendix Table 4A.–Estimated recruitment (yearling-equivalents) of rainbow trout (steelhead) in Lake Michigan, 1965-1997. Yearling-equivalents were estimated by Rand et al. 1993 before 1990. After 1990, yearling-equivalents were estimated as: yearling-equivalents (1,000's) = [0.5*1,000 hatchery plants) + wild smolt production (1,000's)].

Year	Hatchery	Wild	Yearling Equivalents
1965	0.0	100.0	100.0
1966	97.5	100.0	197.5
1967	22.0	100.0	122.0
1968	196.8	100.0	296.8
1969	205.0	100.0	305.0
1970	147.5	100.0	247.5
1971	342.0	100.0	442.0
1972	442.6	100.0	542.6
1973	784.6	100.0	884.6
1974	491.7	100.0	591.7
1975	449.0	320.0	769.0
1976	734.0	283.0	1017.0
1977	593.0	98.0	691.0
1978	463.0	98.0	561.0
1979	922.0	98.0	1020.0
1980	859.0	98.0	957.0
1981	587.0	209.0	796.0
1982	434.0	93.0	527.0
1983	614.0	267.0	881.0
1984	1054.0	434.0	1488.0
1985	798.0	178.0	976.0
1986	1132.0	65.0	1197.0
1987	1034.0	172.0	1206.0
1988	644.0	80.0	724.0
1989	788.0	137.0	925.0
1990	826.0	111.0	937.0
1991	920.5	171.3	1091.8
1992	911.5	171.3	1082.8
1993	903.0	171.3	1074.3
1994	1050.0	171.3	1221.3
1995	930.5	171.3	1101.8
1996	1000.0	171.3	1171.3
1997	1000.0	171.3	1171.3

Appendix Table 5A.–Estimated recruitment (yearling-equivalents) of brown trout in Lake Michigan, 1965-1997. Yearling-equivalents were estimated as: yearling-equivalents (1,000's) = [0.25* fall fingerlings) + yearlings].

Year	Hatchery	Wild	Yearling Equivalents
1965			0
1966	16300	21700	26
1967	12540	35935	39
1968	172400	79190	122
1969	57200	84377	99
1970	94540	129820	153
1971	531804	177311	310
1972	722740	203469	384
1973	1313842	598953	927
1974	469300	363358	481
1975	82647	425345	446
1976	227172	653188	710
1977	362200	793525	884
1978	854247	655202	869
1979	663947	548202	714
1980	753074	554564	743
1981	562546	591242	732
1982	1516793	642821	1022
1983	1527052	670682	1052
1984	1149178	653768	941
1985	1127110	670437	952
1986	719318	714735	895
1987	811485	531684	735
1988	783652	761627	958
1989	753140	751175	939
1990	736747	841024	1025
1991	639296	743983	904
1992	765382	849225	1041
1993	869905	888817	1106
1994	953528	927527	1166
1995	1014458	861602	1115
1996	1014458	861602	1115
1997	1014458	861602	1115

Appendix Table 6A.–Estimated recruitment (yearling-equivalents) of lake trout in Lake Michigan, 1965-1997. Yearling-equivalents were estimated as yearling hatchery plants (1,000's).

Year	Yearlings
1965	1273.9
1966	1665.7
1967	1763.5
1968	2109.3
1969	1999.8
1970	1960.0
1971	2135.5
1972	2605.4
1973	2375.3
1974	2260.1
1975	2528.9
1976	2548.0
1977	2390.0
1978	2501.0
1979	2427.0
1980	2604.0
1981	2295.0
1982	2264.0
1983	2241.0
1984	1245.0
1985	3024.0
1986	2917.0
1987	1984.0
1988	2180.0
1989	3332.0
1990	1317.0
1991	2779.0
1992	3027.0
1993	2699.0
1994	3062.0
1995	2264.0
1996	2200.0
1997	2200.0

Appendix Table 7A.–Estimated instantaneous natural mortality rates (M_t), mortality due to Bacterial Kidney Disease (M_{BKD}), and percentages (P) of stream-run adults of chinook salmon, lake trout, coho salmon, rainbow trout, and brown trout in Lake Michigan, 1965-1997.

	Chinook			Lake Trout		Coho		Rainbow Trout		Brown Trout	
Age	M_t	M_{BKD}	P	M_t	P	M_t	P	M_t	P	M_t	P
1	0.30	0.07-0.56	0.02	0.35	0	0.50	0.07	0.50	0.02	0.30	0
2	0.10	0.12-0.90	0.10	0.23	0	0.10	1.00	0.10	0.07	0.10	0
3	0.10	0.12-0.94	0.60	0.23	0	2.50		0.10	0.21	0.10	0
4	0.20	0.18-0.85	0.80	0.23	0			0.10	0.31	0.10	0
5	2.50	0.18-0.90	0.80	0.36	0			0.50	0.31	0.10	0
6				0.36	0			1.00	0.31		
7				0.36	0			1.80	0.31		
8				0.36	0			1.80	0.31		
9				0.36	0						
≥10				0.36	0						

Appendix Table 8A.–Estimated ranges of instantaneous fishing mortality rates of chinook salmon, lake trout, coho salmon, rainbow trout, and brown trout from 1965-1997 in Lake Michigan.

Age	Chinook	Lake Trout	Coho	Rainbow	Brown
1	0.012-0.030	0	0.030-0.060	0.110-0.018	0.005-0.010
2	0.060-0.150	0.020	0.200-0.500	0.025-0.030	0.064-0.125
3	0.140-0.350	0.050	0.050-0.300	0.060-0.090	0.090-0.175
4	0.140-0.350	0.180-0.450		0.100-0.150	0.089-0.173
5	0.140-0.350	0.300-0.810		0.100-0.150	0.089-0.173
6		0.300-0.810		0.100-0.150	
7		0.300-1.080		0.100-0.150	
8		0.300-1.080		0.100-0.150	
9		0.300-1.080			
≥10		0.300-1.080			

Prepared by: Edward Rutherford
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