QUOTA MANAGEMENT OF LAKE ERIE FISHERIES

A Report of the Lake Erie Fish Community Workshop
Held in Bowling Green, Ohio, from 21-25 June 1982

by

Joseph P. Koonce (Editor)
Douglas B. Jester, Jr.
Bryan A. Henderson
Richard W. Hatch
Michael L. Jones

SPECIAL PUBLICATION 83-1

Great Lakes Fishery Commission

1451 Green Road
Ann Arbor, Michigan 48105

January 1983

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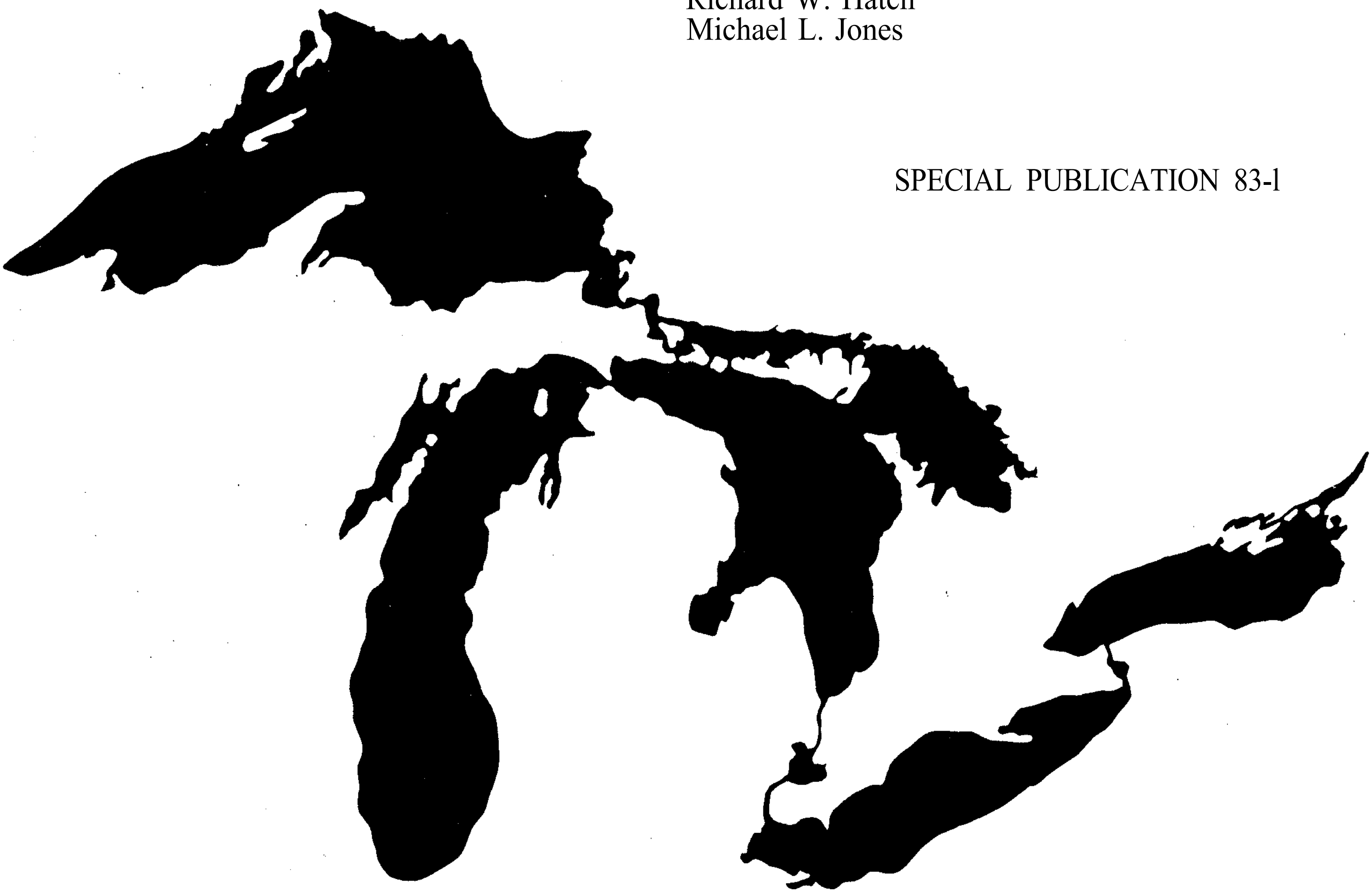

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INTRODUCTION

At the request of the Lake Erie Committee, the Great Lakes Fisheries Commission provided partial support for a Lake Erie fish community workshop. An Adaptive Management workshop was held on the campus of Bowling Green State University in Bowling Green, Ohio from 21 June to 25 June 1982. Participants listed in Appendix A, represented various provincial, state, and federal fisheries agencies as well as several ares universities. This workshop represented the second in a series of Adaptive Management workshops sponsored by the Great Lakes Fisheries Commission. As part of its, responsibility to facilitate communication among Great Lakes fisheries biologists, the GLFC invested in a training workshop at the University of British Columbia for Great Lakes Fishery Scientists and in computer hardware to be used in the workshops.

Adaptive Management is a communication and problem solving process developed by Drs. Holling and Walters and their associates at the University of British Columbia. The workshop, which is reported herein, is only one part of the Adaptive Management process. The first phase is a scoping meeting in which a client group and the workshop staff define a problem to be addressed in a workshop and develop a list of invited participants. In this case, the client group was the the Lake Erie Committee, and a scoping meeting was held in Sandusky, Ohio on 25 May 1982. An intensive workshop follows and involves policy makers, managers and technical specialists to address a problem of concern to the client group. A specific objective of the workshop is to develop a simulation model appropriate to the problem. The construction of this model provides an opportunity to air conflicting ideas, to identify important research needs, and to explore various policy options. Finally, the workshop staff consolidates the workshop activities and model to prepare a report to the client group, and the workshop staff and client group meet again to review progress and possible future work. This document, therefore, is a record of the Lake Erie Fish Community Workshop held from 21 to 25 June 1982 as well as a report to the Lake Erie Committee.

PROBLEM DEFINITION

As expressed in its Task Group structure; the Standing Technical Committee of the Lake Erie Committee has three main areas of concern: Walleye rehabilitation and management in Western Lake Erie, Yellow Perch Management, and Lake Trout rehabilitation in Eastern Lake Erie. Many issues underlie these main concerns, but those involving the determination of an endpoint for Walleye rehabilitation and the problems and uncertainties of quota management seemed most urgent. Given these issues, the Lake Erie' Committee chose the following problem statement as the focus of an Adaptive Management workshop: What are the consequences for the fish community and fisheries of various quota management policies for Walleye, Yellow Perch, and White Bass in Lake Erie?

PROBLEM BOUNDING

The problem statement selected by the Lake Erie Committee was the starting point for the workshop. Many interpretations of the problem statement were possible, and the purpose of the problem bounding exercise was to achieve consensus on an approach to solving the problem. The first step in the problem bounding process was to decide upon major areas of emphasis. Three areas of emphasis emerged as most important to the workshop participants: quota derivation procedures, stock and quota interactions, and details of individual stock dynamics. To understand the scope of these areas, the participants next developed lists of possible actions that could be taken to manage the fishery resources of Lake Erie. A summary of these actions is given in Table 1. Clearly, fishery regulation is the central action important to the participants, and this action emphasis can accomodate many different kinds of quota derivation procedures or policy goals.

As will be illustrated more below, actions form one of the bounds on the kind of simulation model that will be produced by the workshop. The model must at a minimum be able to accomodate the actions most important to the participants. Similarly, the kind of output or indicators of the model are equally important. The indicators selected by the participants are listed in Table 2. Again measures of the performance of the fishery regulations are quite important, but more general environmental/contaminant measures were also suggested. Given the time constraints of the workshop, however, the participants agreed to limit the model to those indicators, necessary to judge the consequences of fishery management to the fishery and the fish community. Additional bounds on the model were obtained from a discussion of the appropriate spatial and temporal resolution of the model. The participants felt that a 20 year time horizon was sufficient to detect major trends and that annual or at most biannual summaries of the indicators would be sufficient. Discussion of the spatial scale was less conclusive and raised some important issues for future attention. The selection of individual basins as minimum geographical resolution did not seem too controversial, but its sufficiency to represent major interbasin migration was questioned. Important forage species such as smelt, for example, have substantial migrations between basins, and it was suggested that seasonal differences in Walleye diet could be attributed these migrations. Because of the computational difficulties that could arise from a multiple basin model with several species, the participants agreed to limit this initial inquiry to a single basin geographical resolution, but also agreed that the model should allow for possible migration and should be applicable to any of the three basins in Lake Erie. The initial model formulation, however, would be for the Western Basin.

From the problem statement of the client group and the lists of actions and indicators, participants agreed to the following division of the model into submodels:

Walleye and White Bass
Yellow Perch
Forage species
Fisheries and Quota.

Table 1. Summary of Actions considered by workshop participants.

Category	Actions
Fishery Regulation	*Set Gear and Creel Regulations *Limit Access *Set Quotas *Adjust Quota Allocation among User Groups
Fish Community Changes	*Selective Removal of Less Desired Species *Introduction of Exotic Species
Environmental Regulation	*Habitat Protection and Restoration *Reduction in Contaminant Loading *Reduction of Power Plant Impingement

Table 2. Summary of indicators that would be useful in the evaluation of fishery management practices.

Category	Indicators
Fishery Statistics	*Harvest *Effort by Gear *Catch per Unit Effort *Mean Age of Catch *Economic Value *Fishing Mortality Rates
Population Statistics	*Estimates of Standing Crop *Estimates of Reproduction *Size at Age
Community Statistics	*Forage Abundance -*Forage Diversity
Environmental	*Impingement Mortality *Contaminant Levels in Fish

Given these submodels, the final problem bounding exercise was to establish linkages among the models. According to these linkages, each submodel would receive specific information from other submodels and would be expected to provide specific information in return. The information linkages are summarized in Fig. 1. The level of resolution of each of the submodels was ultimately the responsibility of the group of participants who chose to work on it, but the bounds discussed above set a minimum level of resolution. Details in submodel derivation, therefore, had to be justified as necessary to the overall level of resolution of the model.

DOCUMENTATION OF MODEL

Model Structure

For convenience, a common computational sequence was adopted for all submodels. The order of submodel execution and responsibility for action and indicator accomodation is summarized in Fig. 2. The rules by which Walleye, White Bass, Yellow Perch, and the various forage species change in time were all executed as the first operation in the submodel. In the final version of the model, annual time steps were used.

Documentation of Submodels

Walleye/White Bass Submodel

Participants: Baker, Hewett, Margraf, Nepszy, Pikitch, and Spangler.

Staff: Hatch.

Walleye Component. The Walleye submodel is an age-structured model with growth dynamics. Five age groups (0 to 4+) were considered adequate. For all age groups, only three mortality sources were considered: natural mortality, which was a function of consumption rate; mortality due to power plants; and fishing mortality. Natural mortality was computed from the per cent maximum ration calculated in the feeding and forage submodel:

$$AP = AD(i) + 0.01*(1-AM(i)),$$

where AD(i) is the baseline natural mortality (2.0 per yr for age 0 and 0.218 per year for all older animals) and AM(i) is the fraction of maximum ration. Harvest for each age group is as follows:

$$AH = (1 - \exp(-AZ))*UA(i)/AZ,$$

where AZ is the total instantaneous mortality of the age group and UA(i) is fishing mortality. Growth is calculated from consumption rates, which are also determined in the feeding and forage submodel:

$$AS(i) = AS(i) + AE(i)*AC(i),$$

where AC(i) is the consumption by age group i and AE(i) is conversion efficiency (assumed values were 0.307, 0.2, 0.18, 0.15, and 0.11 for ages 0 to

Fig. 1. Information exchange among submodels.

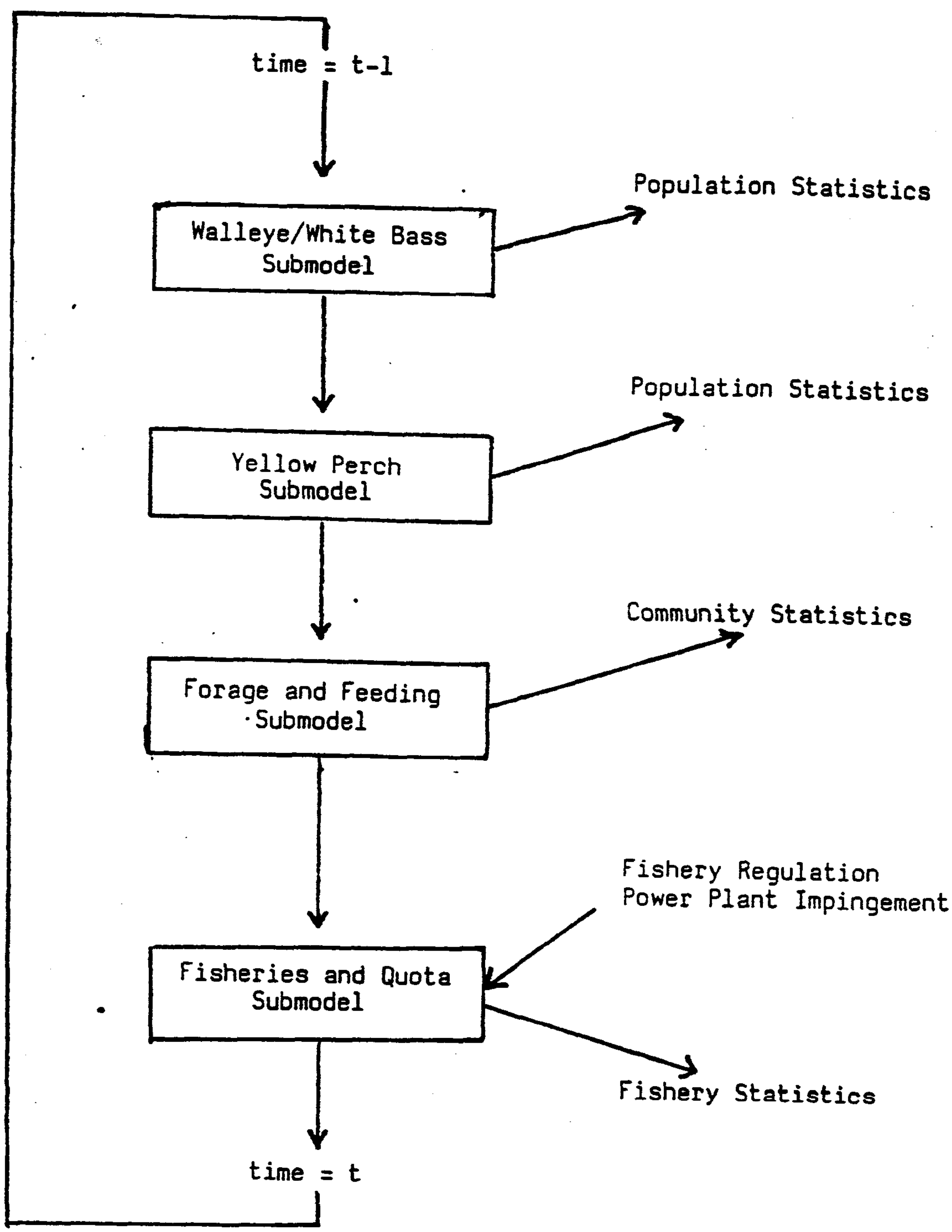
TO / FROM

density in # years/hectare

$m^3 m^2$ = hectare
absolute for output

FROM \ TO	QUOTA & FISHERIES	PICKEREL & W.B.	PERCH	FORAGE
QUOTA & FISHERIES	Species composition of harvest Economic--landed value	Fishing mortality by age	Fishing mortality by age	(Impingement - instant. rate)
PICKEREL & W.B.	Number age Size at age % maximum ration harvest (numbers / weight	Number size in age Harvest Growth Rate Mortality rate	Predation rate by size WB # years/ha YOY	Predation rate by size (Inst./year) by season
PERCH	Number age Size at age % maximum ration harvest (numbers / weight	# yrs/ha by size class abundance size 3 classes by two seasons	# size age in harvest Growth rate Mortality rates	Predation rate by size (inst./year) On plankton as well (inst. rate/years)
FORAGE	-	# yrs/ha by size	# yrs/ha YOY (fixed size) or < 80 mm plankton # kg/ha	

Fig. 2. Computational sequence of model and submodel responsibilities for : Actions **and** Indicators.



4+ respectively).

Reproduction and survival of YOY is assumed to be a Ricker type function:

AR = 45.3*AG*exp(-0.105*AG + 0.6*ZR),

where AG is the adult density, ZR is a standard normal random variable. The coefficients were obtained from regression analysis of historical data. Adult density is the sum of density of age 4+ and a fraction, AF, of the density of age 3 fish:

AF = (-1 + 0.004*AS(3)),

where AS(3) is the size of 3-yr olds. AF is constrained to be between 0 and 1.

White Bass Component. The White Bass submodel is very similar to the Walleye submodel. Natural mortality is a function of the fraction of maximum ration:

BP = BD(i) + 0.1*(1 - BM(i)),

where BD(i) is the baseline natural mortality and BM(i) is the fraction of maximum ration for each age group. YOY White Bass are subject to predation in the Forage and Feeding submodel, and the mortality for YOY is returned from that subroutine. Both harvest and growth are calculated as in the Walleye submodel, but efficiencies, BE(i) are different (0.307, 0.249, 0.27, 0.22, and 0.13 for age groups 0 to 4+ respectively).

Reproduction is also assumed to be a Ricker type function. Parameters for the Ricker coefficients were obtained by regression of Ohio DNR index data for YOY and adult White Bass. These values were converted to absolute densities by using correction coefficients derived for Walleye by the Scientific Protocol Committee. Adults were assumed to be age 2 and older animals.

Yellow Perch Submodel

Participants: Belonger, Cornelius, Hayward* Kenyon, Knight, Lahr, and Petzold.

Staff: Henderson.

The Yellow Perch submodel is based on an age-structured population model. To accomodate the wide range of maturity schedules observed in Lake Erie, six age groups (ages 0 to 5+) were required. Growth is calculated from the consumption rates supplied by the Forage and Feeding submodel:

ES(i) = ES(i) + EG*EC(i),

Fig. 3. Flow chart for the Walleye/White Bass submodel.

↓

WALLEYE COMPONENT

↓

Compute Total Mortality and Harvest

↓

Update Density and Size

↓

Compute % Age 3 Mature

↓

Compute Adult Stock

↓

Compute Reproduction

↓

Compute Lengths

↓

Save Z Values

↓

WHITE BASS COMPONENT

↓

Compute Total Mortality and Harvest

↓

Update Density and Size

↓

Compute Reproduction

↓

Compute Lengths

↓

Save Z

Table 3. Documentation of variables and parameters used in the Walleye/White Bass submodel.

VARIABLE	DESCRIPTION	VALUE	UNITS
AA	Mortality Fraction	*	U
AC(i)	Consumption by Walleye by age	£	g/g/yr
AD(i)	Baseline Natural mortality	!	1/yr
AE(i)	Walleye Conversion Efficiency	!	U
AF	Fraction 3-yr Old Walleye Mature	*	U
AG	Walleye Spawning Adults	*	no./ha
AH	Walleye Harvest	*	no./ha
AI	Fecundity factor	0.004	1/g
AJ	Size of Walleye YOY	30	g
AL(i)	Length of Walleye by Age	*	mm
AM(i)	Fraction of Maximum Ration	£	u
AN(i)	Density by age,	*	no./ha
AP	Instantaneous Non-pred. Mortality	+	1/yr
AQ	Ration Dependent Mort. Coef.	0.01	1/yr
AR	YOY Reproduction	*	no./ha
AS(i)	Size at Age	+	g
AU	Reproduction Coefficient	45.3	U
AV	reprocution Coefficient	0.105	ha/no.
AX	Coef. in Length-Weight Function	1.6E-6	u
AY	Coef. in Length-Weight Function	.302	U
AZ	Total Instantaneous Mortality	*	1/yr
A3	Std. Dev. of variation in Reproduction	0.6	U
BA	White Bass Mortality Fraction	+	U
BB(i)	White Bass Pred. Mort. by age	£	1/yr
BC(i)	White Bass Consumption by age	£	g/g/yr
BD(i)	White Bass Baseline Nat. Mort.	0.34	1/yr
BE(i)	White Bass Conv. Efficiency	!	U
BG	White Bass Spawners	*	no./ha
BH	White Bass Harvest	*	no./ha
BJ	Size of YOY White Bass	1.5	g
BM(i)	White Bass Frac. Max. ration	£	U
BN(i)	White Bass Density by Age	+	no./ha
BP	White Bass Ins. Non-pred. Mort.	*	1/yr
BQ	White Bass Mort. Coef.	0.1	1/yr
BX	Coef. in Length-Weight Func.	1.79E-5	U
BY	Coef. in Length-Weight Func.	0.34	U
BZ	White Bass Total Ins. Mort.	*	1/yr
B1	White Bass Rep. Coef.	225	
B2	White Bass Rep. Coef.	.091	ha/no.
B3	White Bass Rep. Variabiltiy Coef.	1.0	

*= values updated in model; £= values from other submodel; != values in text

where EC(i) is the consumption (g/ind/yr) from the Forage and Feeding submodel and EG is conversion efficiency. Conversion efficiency is assumed to vary . with body size:

EG = 0.2 - 0.0008*ES(i).

EG is constrained to have a value greater than or equal to zero. Emigration is also assumed to be a function of feeding rate:

GJ = 1.55*exp(-10*EM(i)) + 0.05.

Harvest is calculated as the proportion of total annual mortality due to fishing, and lengths are calculated as a power function of body weight.

Reproduction of Yellow Perch is a function of body size dependent fecundity and maturity:

EF = FA*(20.2*ES(i) - 427);

where FA is the fraction of individuals mature at size ES(i). Maturity fraction is assumed to be 1 for animals over 101g, and increases with body weight for smaller sizes:

FA = 0.0152*ES(i) - 0.5398.

Only 7% of eggs are assumed to hatch on average, but environmental variability with a log-normal standard deviation of 0.2 is a stochastic influence. Finally, a sex ratio of 0.5 is assumed for calculation of egg production.

Forage and Feeding Submodel

Participants: Davies, Forney, Kitchell, Paine, Stein, and Wissing.

Staff: Jester.

The forage submodel has two components. First, the submodel computes the dynamics of the forage units, and second it computes the feeding mortality and consumption rates for all the other species represented in the model. These components will be documented in their calculation order.

<u>Forage Dynamics Componen</u>t. The original intent of the submodel group was to develop a dynamic model for six forage groups. Five of these groups were to represent the main forage fish species (Emerald Shiner, Spottail Shiner, Rainbow Smelt, Gizzard Shad, and Alewife) by 25 mm size groups. The sixth group was zooplankton. Due to time constraints, the dynamics of these groups was not completed, and they assume constant values during the simulation. Abundance of these six groups was estimated from icthyoplankton sampling data. Estimated abundance by group (number/ha) was 5E5, 1E5, 1E5, 5000, 5000, and 10E6. Body sizes (g) were also estimated as 0.1, 0.25, 1.1, 7.5, 14.0, and 0.05. The only dynamics in the “forage base,” therefore, is that contributed by YOY of Yellow Perch and White Bass and Yellow Perch yearlings.

Fig. 4. Yellow Perch submodel flow chart.

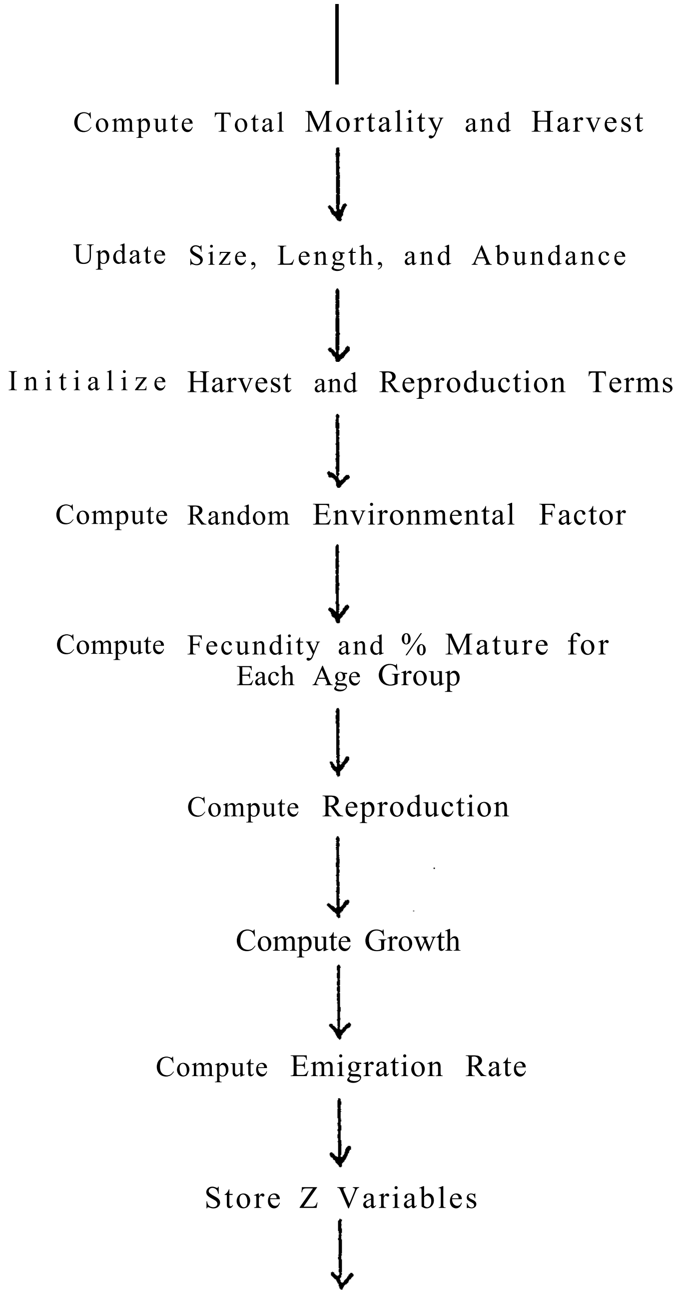


Table 4. Documentation of variables and parameters in the Yellow Perch submodel.

VARIABLE	DESCRIPTION	VALUE	UNITS
EA(i)	Natural Mortality	!	1/yr
EB(i)	Predatory Mortality	£	1/yr
EC(i)	Consumption Rate	£	g/g/yr
EF	Fecundity Coefficient	*	U
EG	Conversion Efficiency	+	U
	Harvest	*	number
EL(i)	Length at Age	+	mm
EN(i)	Abundance at Age	*	no./ha
EP	Fecundity Slope Coefficient	0.152	1/g
EQ	Fecundity coefficient	0.5398	u
ES(i)	Body Size at Age	*	g
ET	Fecundity Coefficient	427	U
EV	Mean Egg to YOY Survival	0.0665	u
EW	YOY Reproduction	*	no./ha
FA	Adult Abundance	*	no./ha
	Total Abundance	*	no./ha
FE	Conversion Efficiency Coef.	0.0008	1/g
FF	Conversion Efficiency Coef.	0.2	u
FH	Conversion Efficiency Coef.	120	g
FP	Weight at Age 0	1.0	g
FQ	Length at Age 0		mm
FR	Fecundity Coefficient	20.2	no./ha/g
FX	Minimum Fecundity Size	36	g
FY	Maximum Maturity Size	101	g
FZ	Random Variable for Reproduction	*	U
GJ	Migration Mortality	*	1/p
GK	Max. Migration Mart.	1.55	1/p
GM	Min. Migration Mort.	0.05	1/p
GN	Length-Weight Coef.	3E-5	U
GP	Length-Weight Coef.	0.308	U
GQ	S.D. of Reproduction Var.	0.2	U
GT	Total Instananeous Mort.	*	1/yr
GV	Mortality Fraction	*	U
GW	Harvest Fraction of Mortality	*	U

£= values from other submodel, != values in text, and u= unitless

Feeding and Mortality Component. Feeding and mortality calculations in this submodel are based on a multiple species disc equation:

$$A(i, j) = RS(i,j)*TS/(1 + \sum_j RS(i,j)*RH(i,j)*QN(j))$$

where RS(i,j) is the effective search rate of predator i for prey j per-day, TS is the number of days in the growing season per year, RH(i,j) is the handling time in days of prey j by predator i, and QN(j) is the density of prey j. In this formulation A(i,j) is the number of attacks on prey j per predator i per yr. The effective search rate is on an areal basis:

$$RS(i, j) = QW(i,j)*SS*PL(i)*RC*RC,$$

where QW(i,j) is the probability of capture of prey j by predator i given an encounter, SS is an areal swimming velocity in units of 1/(mm body length*day), PL(i) is the body length of predator i, and RC is the visual radius of predator i for prey j. QW(i,j) is a function of the ratio of prey to predator length:

$$QW(i, j) = QL(j)*(PA(i) + PD(i)*PL(i) - QL(j)/PL(i)),$$

where QL(j) is the length of the prey, PL(i) is the length of the predator, and PA(i) and PD(i) are constants. Values of the constants did not change with age, and the PA(i) and PD(i) values for Walleye, White Bass, and Yellow Perch were 0.5 and -0.0004; 0.5 and -0.0007; and 0.5 and -0.001 respectively. A limit of QW(i,j)>=O is placed on the function. Swimming speed, SS above, is a weighted function of mean basin depth and average swimming speed over the growth period:

$$ss = 3.1416*1E-4*V/ZB,$$

where ZB is the mean depth of the basin and V is the swimming speed in units of m/(mm body length)/day. Visual radius of prey j by predator i is only a function of the length of the prey:

$$RC = RV*QL(j),$$

where RV is a constant (0.0075 M/mm). RC has a maximum value of 1.5 m. Finally, handling time is a function of maximum consumption rate of predator i and the ratio of prey to predator size:

$$RH(i, j) = QS(j)*SA*PS(i)*SB,$$

where QS(j) is the size of prey, PS(i) is the size of predator, and maximum consumption rate is assumed to be a power function of predator size with SA and SB taken to be constants of 4.0 and -0.73 respectively. Consumption of prey by each predator is calculated next:

$$PC(i) = \sum_j (QA(j)/QZ(j)*RS(i,j))/(1 + \$H(i,j)*RS(i,j)*QN(j)).$$

Instantaneous mortality due to predation for each prey species is

$$QZ(j) = \sum_i (PN(i)*A(i,j)),$$

Fig. 5. Flow Chart for Forage Submodel.

↓

Set UP PL, PN, and PS Vectors for Predators

↓

Set Up QL, QN, and PS Vectors for Prey

↓

Calculate Capture Probabilities

↓

Calculate Attack and Mortality Rates

↓

Calculate Consumption Rate

↓

Assign Values To Submodel Variables

↓

Table 5. Variables used in the Forage and Feeding Submodel.

VARIABLE	DESCRIPTION	VALUE	UNITS
PA(i)	Baseline Preference Index	*	l/day
PB(i)	Summation Term	*	v
PC(i)	Consumption per Predator	*	g/ind/yr
PD(i)	Coefficient for Preference	see text	b1/day/mm
PL(i)	Length of Predator	*	mm
PM(i)	Fraction of Maximum Ration	+	U
PN(i)	Abundance of Predator	*	number/ha
PS(i)	Weight of Ind. Predator	+	g
P1	Dummy Variable	1E-6	U
QA(j)	Total Weighted Feeding on Prey	*	g/yr
QL(j)	Length of Prey	*	mm
QM(j	Baseline Mortality of Prey	0*1/yr	
QN(j)	Abundance of Prey	*	number/ha
QS(j)	Size. of Ind. Prey	+	g
QT	Dummy Variable	*	v
QW(i j)	Prob. of Attack of Pred. i on Prey j	*	U
QZ(j)	Instantaneous Mortality of Prey	*	1/r
RC	Dummy, Variable	*	
RH	Handling Time	*	day
RL	Maximum Visual Distance	1.5	m
RS(i,j)	Effective Search Rate	*	ha/day/pred
RV	Coefficient for Maximum Search Distance	0.0075	m/mm
SA	Coefficient for Handling Time	4.0	day
SB	Coefficient for Handling Time	-0.73	U
SN(j)	Abundance of Prey	*	number/ha
S P	Dummy Variable	1	a
SR	Dummy Variable	1	a
ss	Swimming Speed	9.0432E-4	m/mm/day

*= variable changes in value, u= unitless

where PN(i) is the predator density and A(i,j) is the attack rate defined above. Total consumption of prey j follows directly from instantaneous mortality:

$$QA(j) = (1 - EXP(-QZ(j))*QN(j)*QS(j).$$

Total consumption by predator species i is then computed from its contribution to the mortality of each of the prey species as defined above.

Fisheries and Quota Submodel

Participants: Carline, Eshenroder, Isbell, Loblaw, and Paxton.

Staff: Koonce.

Based on age structure and abundance of Walleye, Yellow Perch, and. White Bass, the Fisheries and Quota submodel calculates fishing mortality on these three species. The fishery is assumed to consist of two main components: a sports fishery with variable effort year to year and a well regulated commercial fishery . By assuming that commercial fisheries can be held to their alloted quota, all gear types can be merged into a single, hypothetical ‘gear. Catchability in this hypothetical commercial gear is then based on a composite estimate of vulnerability of each species and age group to commercial fishing. Policy options may be explored for multiple species management through key variables in this submodel. The primary action is setting the target fishing mortality level, and a secondary action is the fraction of the quota to be . allocated to commercial fisheries.

Possible fishery regulatory decisions may also be explored by varying catchability coefficients for the sports and/or commercial fisheries. For each species, quota estimates are based on the policy fishing mortality level and the size of the fishable stock. To simplify computations, the fishable stock is computed as follows:

$$FS = \sum_i (qc(i)*A + (1-A)*qs(i))*n(i)$$

where qc(i) is the relative catchability in the commercial fishery of age group i, qs(i) is the relative catchability in the sports fishery of age group i, A is the allocation fraction to the commercial fishery, and n(i) is the absolute abundance of age group i.

Relative catchabilities in these computations are the ratio of the catchability of the age group to the maximum catchability of the species. Quotas are then calculated assuming that fishing mortality is the only source of mortality:

$$Q = FS *(1 - exp(-F))$$

where F is the policy fishing mortality level. Commercial fishing effort in relative units of 1/yr is next calculated as:

$$E = -LOG(1 - Q*A/FS)$$

Fig. 6. Flow chart for the Quota and Fisheries submodel.

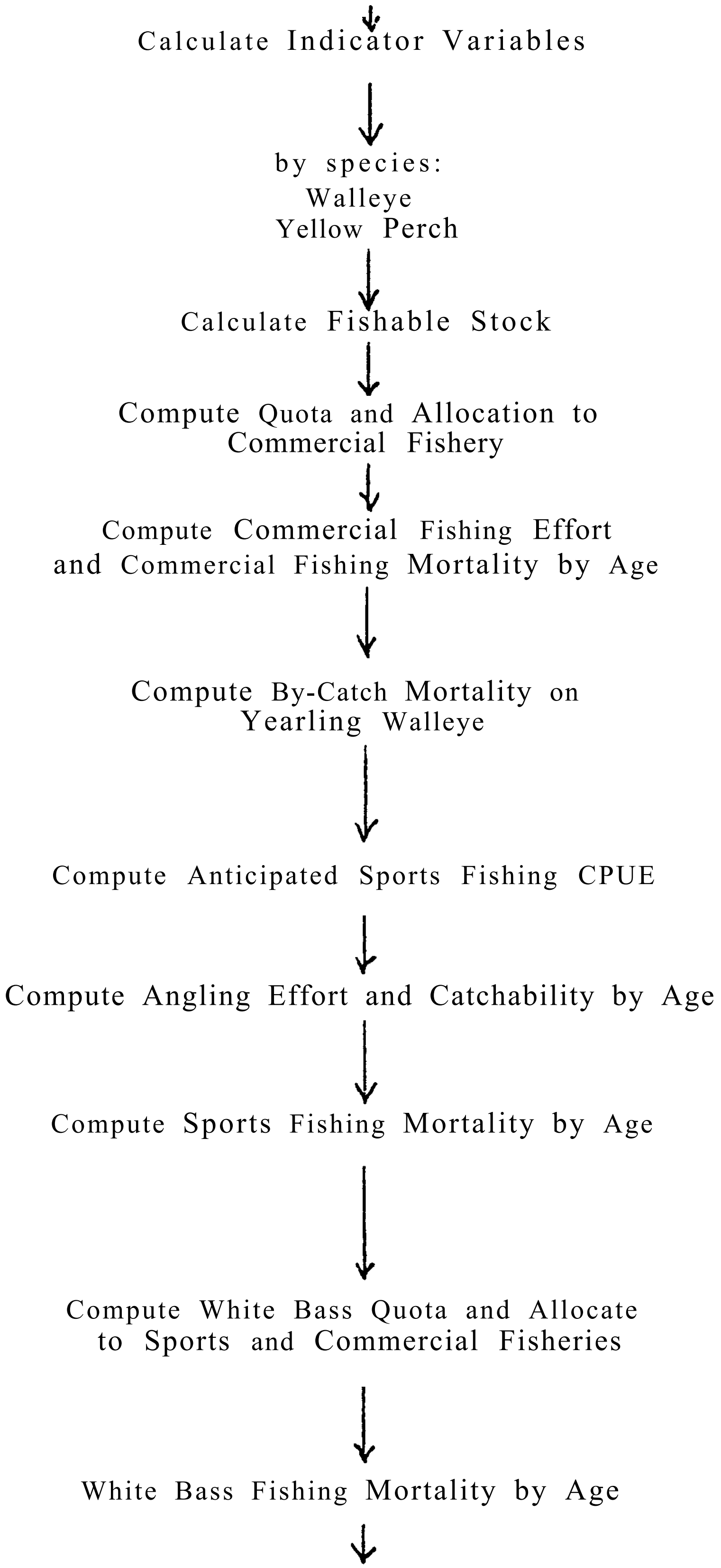


Table 6. Documentation of Variables Used in the Quota and Fisheries Submodel

VARIABLE	DESCRIPTION	VALUE	UNITS
UA(i)	Fishing Mortality by Age for Walleye	*	1/yr
UB(i)	Fishing Mortality by Age for White Bass	*	1/yr
UC(i)	Walleye Sports Catchability by Age	£	l/ang-hr
UD	Walleye Fishable Stock	*	number
UE(i)	Fishing Mortality by Age for YP	*	1/yr
UF	Walleye Commercial Fishing Effort	*	1/yr
UG(i)	Walleye Commercial Catchability by Age	£	U
UI	Anticipated CPUE for Walleye	*	no. fang-hr
UJ	Coefficient for Maximum CPUE	0.8	no./ang-hr
UK	Fishable Stock at Half Maximum CPUE	12.5E7	number
UN	By-catch Coefficient for Walleye Mortality	0.025	U
UP(i)	Power Plant Mortality	0	1/yr
UQ	Annual -Walleye Quota	*	number
UR	Fraction of Quota to Commercial Fishery	0.3	U
uz	Policy Fishing Mortality for Walleye	0.24	1/yr
uo	Dummy Variable	+	
U2	Sports Fishing Effort for Walleye	*	ang-hr
U3	Effort Coefficient for Walleye	14E6	ang-hr
U4	Effort Coefficient for Walleye	0.4	no./yr
U9	Satiation Coef. for Walleye Catchability	.1	U
VC(i)	YP Sports Fishing Catchability	£	1/ang-hr
VD	YP Fishable Stock	*	number
VF	Commercial Fishing Effort on YP	*	1/yr
VG(i)	YP Rel. Catchability in Commercial Fishery	£	U
VI	YP Anticipated CPUE	*	no./ang-hr
VJ	Maximum CPUE for YP	7.0	no./ang-hr
VK	YP Fishable Stock at Half Maximum CPUE	7.5E6	number
VN	By-catch Coeffiecient for YP Mortality	0.05	U
VQ	Annual YP Quota	*	number
VR	Fracton of YP Quota to Commercial Fishery	0.3	U
VZ	Policy Fishing Mortality for YP	1.0	1/yr
V2	Sports Fishing Effort for YP	+	ang-hr
V3	Coef. of Max. Effort for YP Sports Fishery	4E6	ang-hr
V4	CPUE at Half Maximum Effort for YP	1	/no./ang-hr
V5	Fraction of Sports Effort Variabililty	*	U
V6	Std. Dev. of Sports Fishing Variabililty	0.15	U
V9	Coef. far YP Satiation Effects on Catchabiltiy	0.1	u
XC(i)	White Bass Rel. Catchability in Sports Fish.	£	U
XD	White Bass Fishable Stock	*	number
XF	White Bass Commercial Effort	*	1/yr
XG(i)	White Bass Rel. Catchability in Comm. Fish.	£	U
XQ	White Bass Quota	*	number
XR	Fraction of White Bass Quota to Comm. Fish.	0.98	U
xz	Policy Fishing Mortality for White Bass	0.2	1/yr

*= values change, £= from other submodel, u= unitless

Commercial fishing mortality by age is then calculated as the product of commercial fishing effort and the relative catchability of the age group. The only by-catch considered in the submodel is for yearling Walleye. Given current characteristics of the commercial fishery, the submodel group estimated that by-catch mortality on yearling Walleye would be 5% of the adult Yellow Perch mortality plus 2.5% of the adult Walleye mortality.

In the submodel, sports fishing is assumed to be much more dynamic than commercial fishing. The dynamics of the sports fishery are based on variable effort and variable catchability. The submodel group assumed two sources of effort variability. The first was based on the historically observed association between angling effort and catch rates in the Ohio sports fishery in the Western Basin of Lake Erie. It was noted, however, that catch rates were related to fishable stock size by some type of asymptotic function. Based on Ohio data, the following functional relationships defined an anticipated catch rate:

for Walleye,

$$CPUE = 0.8 + FS/(12.5E6 + FS),$$

and for Yellow Perch,

$$CPUE = 7.0 * FS/(75E6 + FS)$$

With these anticipated catch rates, effort for the year could be calculated along with the second source of effort variability, which was a stochastic variable with a 15% standard deviation about the calculated effort:

for Walleye,

$$E = ZR*0.15*(14E6*CPUE\text{-}2/(CPUE2 + 0.16))$$

and for Yellow, Perch,

$$E = ZR*0.15*(4E6*CPUE^{\wedge}2/(CPUE^{\wedge}2 + 1)),$$

where ZR is a standard normal random variable. Catchability also could be variable from year to year as a function of the feeding satiation of each age group:

$$qs(i) = qs(i)*(1 - b*PM(i)),$$

where b is a value ranging from 0 to 1 and PM(i) is the feeding satiation calculated in the forage submodel. Sports fishing mortality by age was then calculated as the product of the catchability (in units of angler-hrs) and the effort for the year.

Because White Bass sports fishing is heavily dominated by river fishing, the subgroup adopted a different procedure to calculate fishing mortality by age. The quota is calculated in the same manner as for Walleye and Yellow Perch, however, both sports and commercial fisheries are assumed to be highly regulated and the quota is simply allocated between the two fisheries. Each fishery, however, has its own catchability characteristics.

SCENARIO. ANALYSIS

The model documented above, like any model, is only an approximation of reality. The purpose of scenario analysis is thus not to validate the model, but to determine if it may be used to explore trends and examine interrelationships among fishery policies and the various populations in the fish coinmunity of Lake Erie. In this context, the scenario analyses become tests of the model, and to the extent that the model behaves reasonably, we can place more confidence in it as a tool to explore various policies. In the end, however, all policies and the rationale for their selection will be tested as they are applied to Lake Erie. The simulations we perform here, therefore, also develop expectations that can be tested in real situations. Four. different scenarios were recommended by the participants:

> Baseline Scenario (BLS). This scenario represents our best guess about the current state of the fish community in the Western Basin of Lake Erie and current fishing practices. To simplify analysis, however, this scenario is deterministic and all stochastic variables are removed;
>
> No Fishing Scenario (NFS). Starting with the parameter set for BLS, all fishing mortality is eliminated;
>
> Hard Fishing Scenario (HFS). Starting with the parameter set for BLS, fishing mortality on fully recruited age groups is raised to 3.0 per year; and
>
> Forage Collapse Scenario (FCS). Starting with the parameter set for BLS, the forage base is assumed to decline 10% per year from year 2 of the simulation.

The Baseline Scenario does not include many of the random factors developed in the submodels. This change makes comparison of alternative scenarios and some policy analysis simpler, but it may also result in a loss of realism. To check this potential problem, a fully stochastic versions of BLS was also created (SBLS). Comparisons of stochastic and deterministic version of BLS are made in Figs. 7 to 10. Walleye adult abundance, Yellow Perch abundance, and Walleye sports fishing effort all appear similar. White Bass patterns, as exemplified by the adult abundance dynamics (Fig. 8), differs in amplitude but-not in fundamental pattern. Because the kind of model developed in the workshop is fairly simplistic, less attention should be given to exact values of variables, rather trends or patterns in the dynamics of the variables may be qualitatively more reliable. In the remainder of the report, therefore, only deterministic versions of the scenarios will be explored.

The general trends in Figs. 7 to 10 suggest that the current walleye rehabilitation policy has not resulted in an unstable community structure. This generalization also holds for patterns in harvest from all three species (Fig. 11). The initial parts of these simulations (i.e. the first 2 to 3 years undoubtedly have some transient dynamic behavior that can be attributed to the selection of initial values of variables. Nevertheless, Walleye abundance seems to oscillate about current values in both -deterministic and stochastic versions (Fig. 7). This behavior of the model, however, is strongly influenced by two assumptions. First, the Walleye submodel assumes that a

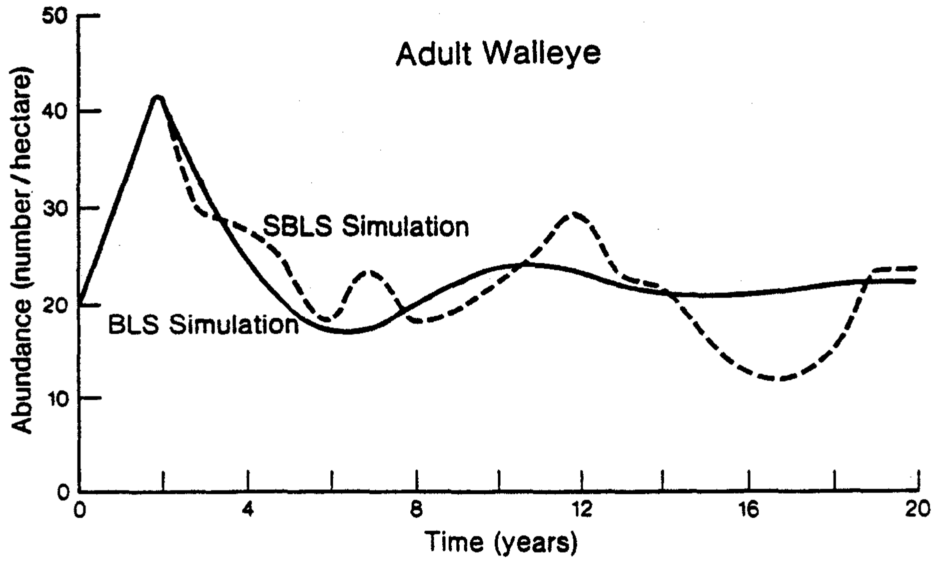


Fig 7. Dynamics of adult Walleye in the BLS (solid line) and SBLS (dashed line) simulations.

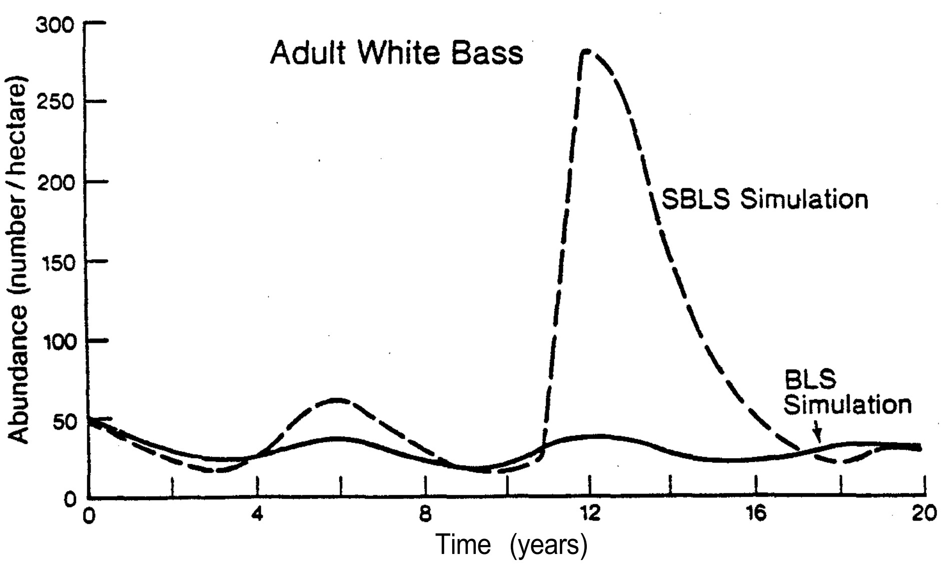


Fig. 8. Dynamics of adult White Bass in the BLS (solid line) and SBLS (dashed line) simulations.

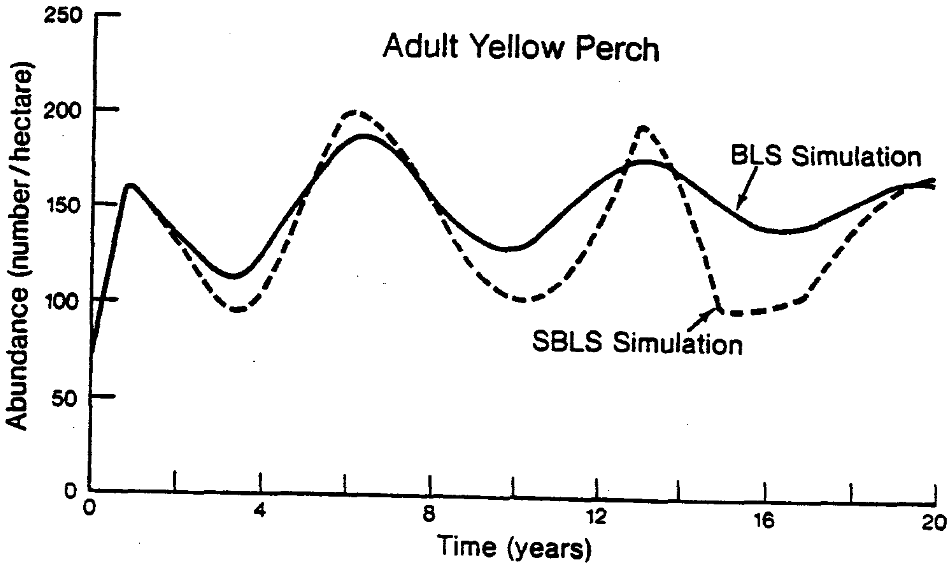


Fig. 9. Dynamics of adult Yellow Perch in the BLS (solid line) and SBLS (dashed line) simulations.

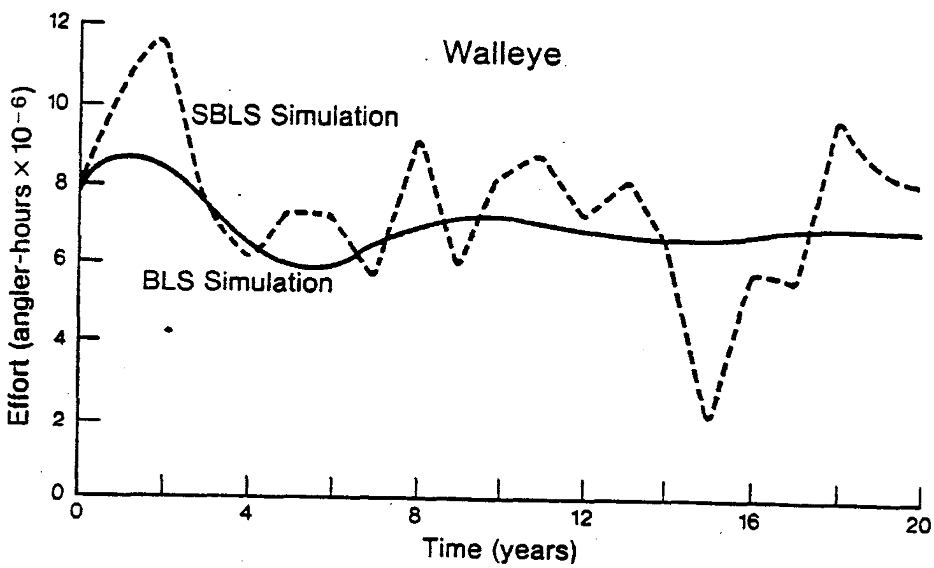


Fig. 10. Dynamics of Walleye sports fishing effort in the BLS (solid line) and SBLS (dashed line) simulations.

stock-recruitment relationship is intrinsically a property of the Walleye population. Secondly, forage species other than YOY of Walleye, White Bass, and Yellow Perch have constant abundance. The importance of this last assumption is illustrated in the Forage Collapse Scenario.

The Forage Collapse Scenario assumed that from year 2 onward the forage base (excluding YOY of the three. quota species) declined 10% per year. It is suprising that even the first 10% reduction in year 3 led to pronounced decline of adult Yellow Perch and White Bass (Fig. 12). This result seems caused by large increases in the mortality of YOY and decreases in growth rate. Walleye also show a dramatic decrease in size of fish in the oldest age group, but population dynamics do not seem to be affected by the forage collapse. The insensitivity of the Walleye population dynamics to forage abundance is clearly the result of assumptions built into the model rather than an expected trend. YOY Walleye were not considered as potential prey, and fecundity was not related to body size of the oldest age group. Because this last assumption. was also made in the White Bass submodel, the most significant omission appears to be exclusion of predation of YOY Walleye. Under more normal circumstances, however, Walleye young-of-the-year do not seem to be a significant component of the diet of any predator in Western Lake Erie. Nevertheless, this omission and the exclusive reliance on a stock-recruitment relationship to calculate YOY survival for Walleye should be more carefully examined in future work.

The extreme fishing scenarios (NFS and HFS) are relatively straight forward tests of the model. Both Yellow Perch and Walleye behave as expected (Figs. 13 and 15). highest abundances are attained with no fishing pressure and lowest under high fishing pressure. Again, these results suggest that Walleye rehabilitation is complete and that no adverse effects of high Walleye abundance can be detected. This assessment, however, needs to be carefully weighed against the weaknesses revealed in the Walleye submodel by the Forage Collapse Scenario. In contrast, White Bass reach the highest abundance under high fishing pressure and are nearly exterpated under-no fishing pressure. These results seem to be caused by predation on YOY White Bass by both Yellow Perch and White Bass adults. Although not shown, the extreme fluctuations of White Bass adults in the No Fishing Scenario (Fig. 14) are associated with single strong year classes moving through the population. In general, these results, while in part counter intuitive, are nevertheless reasonable, and with the reservations outlined above, the model certainly seems to be a useful tool with which to explore some policy options. As an aside, however, the parameter requirements to set up the Hard Fishing Scenario were unexpected. To achieve these high fishing mortality levels, nearly all of the quota had to be allocated to the commercial fishery. According to the behavior characteristics of the sports fishery postulated by the fishery submodel, the maximum fishing mortality possible out of the sports fishery was 0.3 and 0.17 per year for Walleye and Yellow Perch respectively.

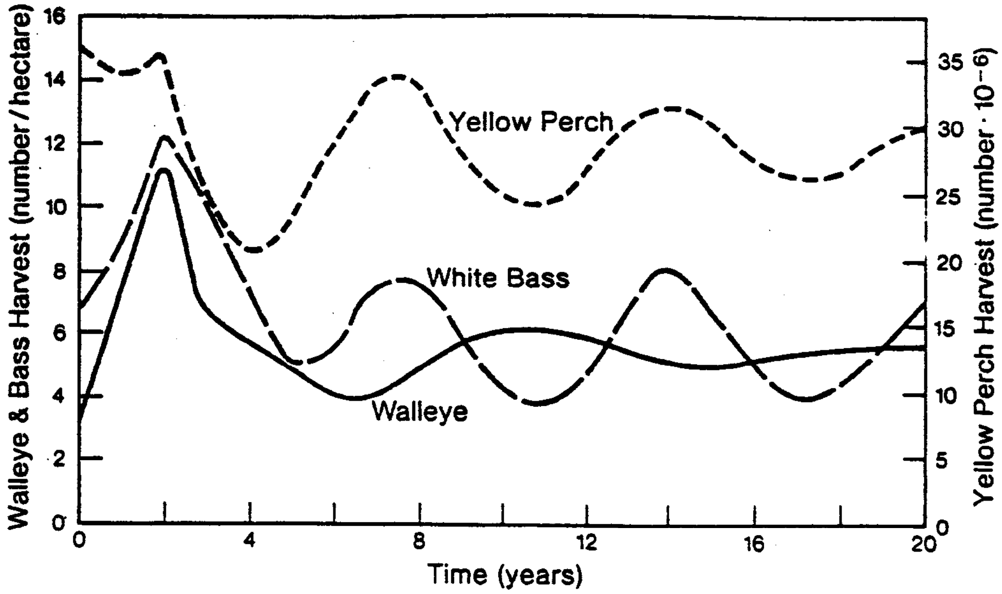


Fig. 11. Patterns in harvest predicted by BLS simulations for Walleye, Yellow Perch, and White Bass.

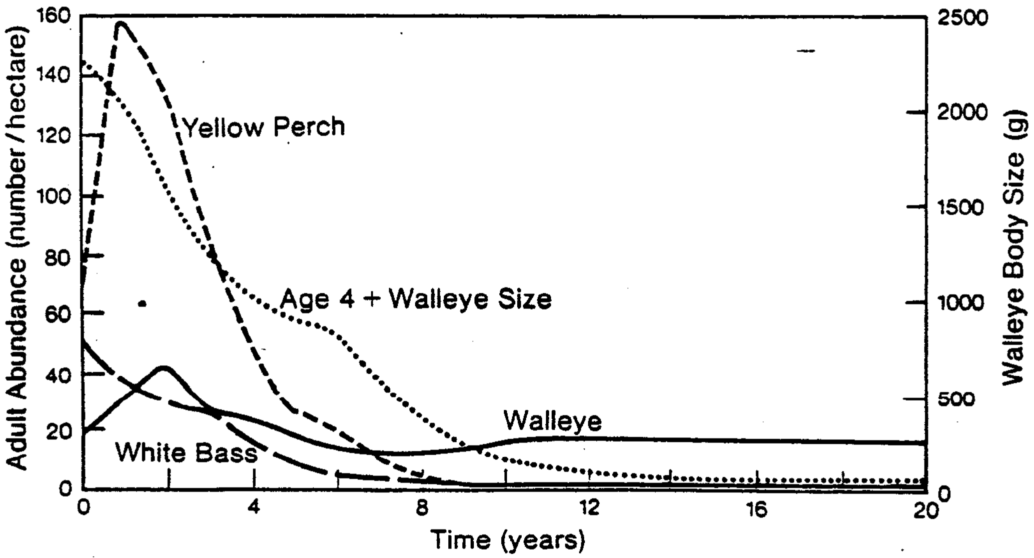


Fig. 12. Dynamics of Walleye, Yellow Perch, White Bass, and body size of age 4+ Walleye.

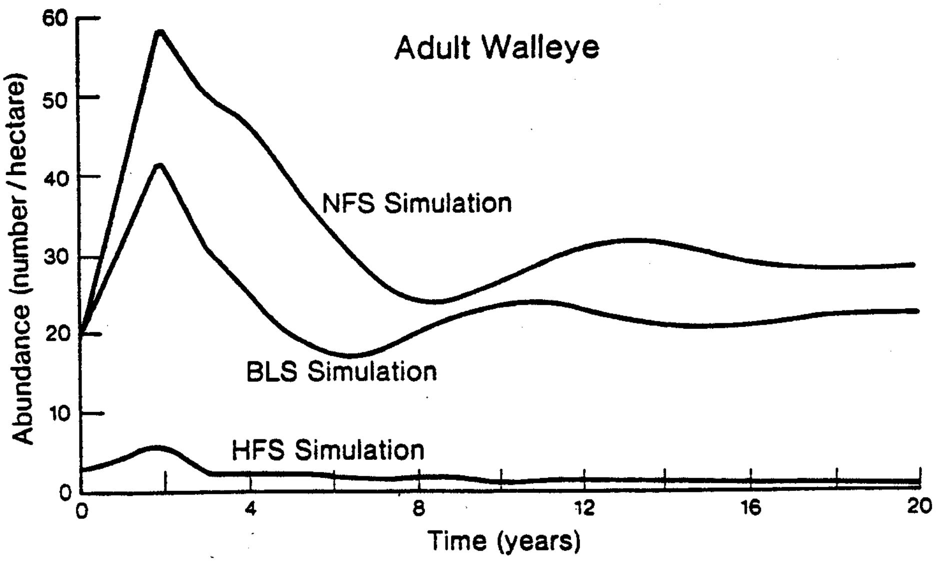


Fig. 13. Comparison of dynamics of adult Walleye in the BLS, NFS, and HFS simulations.

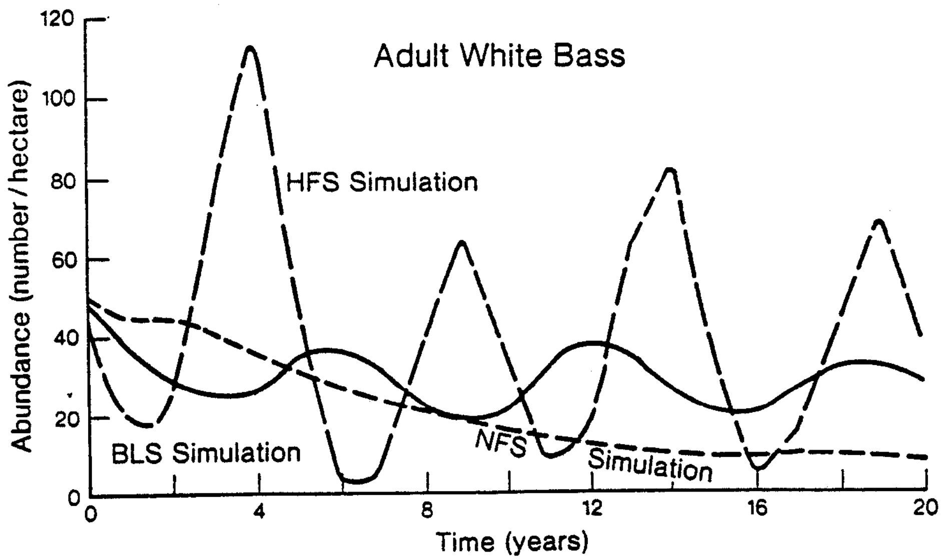


Fig. 14. Comparison of dynamics of adult White Bass in the BLS, NFS, and HFS simulations.

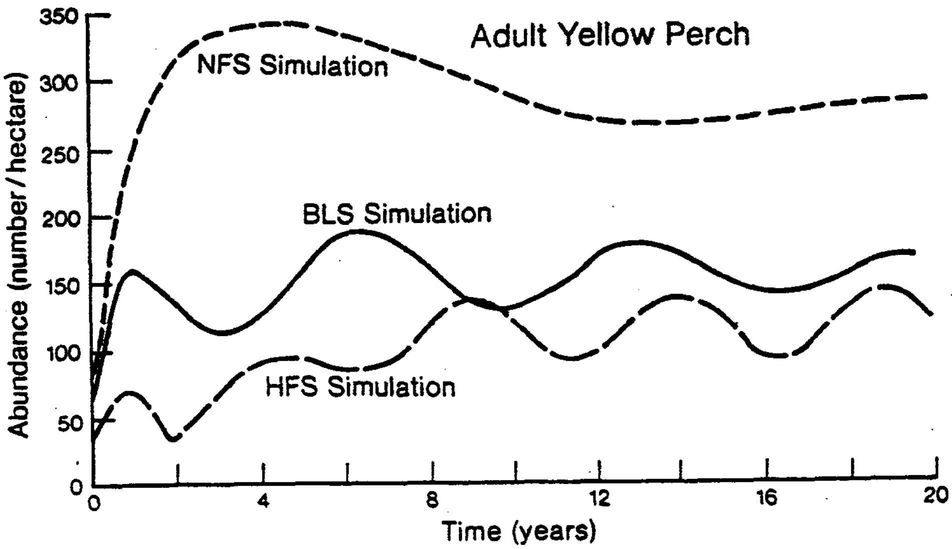


Fig. 15. Comparison of dynamics of adult Yellow Perch in the BLS, NFS, and HFS simulations.

POLICY ANALYSIS

Various sets of policy options were considered by the workshop participants. A partial listing policy options using a quota system include:

*Maximize yield for all three species;
*Maintain current Walleye sports catch rates;
*Maximize Walleye sports effort;
*Maximize total sports fishing effort;
"Stabilize the fish community; and
*Stabilize harvests.

Implementation of any of these policy options in the model requires specification of target fishing mortality for each age group for each species to be managed under quota. The model itself could be used to examine the trade-off between policies that seek to maximize some aspect of the fishery and those that seek to stabilize aspects of the fishery or fish community. This sort of gaming, in fact, is an important application of this type of simulation model. The emphasis that developed in the workshop, however, was not a detailed exploration of policy options, but rather a development of a tool for policy analysis by the Lake Erie Committee. Nevertheless, this potential use of the model can be illustrated in a series of simulations directed toward an assumption that quota policies for each of the three species may be derived independently.

To test the assumption that management policies may be derived independently for Walleye, Yellow Perch, and White Bass requires a set of simulations in which fishing mortality is varied systematically. Starting with the BLS parameter set, a total of eighteen 20-yr simulations were run according to the following design:

1. Nine simulations representing a contengency arrangements of three fishing mortality levels for Walleye (0.2, 1.0, and 1.5 per yr) and the same three levels of fishing mortality for Yellow Perch. White Bass fishing mortality remained a constant 0.4 per yr in all simulations.

2. Nine simulations representing a contengency arrangements of three fishing mortality levels for White Bass (0.2, 1.0, and 1.5 per yr) and the same three levels of fishing mortality for Yellow Perch. Walleye fishing mortality remained a constant 0.3 per yr in all simualtions.

Means and standard deviations of harvest (number/ha) for various combinations of Walleye and Yellow Perch fishing mortality policies are summarized in Table 7. The same summary is in Table 8 for combinations of White Bass and Yellow Perch fishing mortality levels.

Two important features emerge from these simulations. First, the simulations nicely illustrate the way the model can be used to examine trade-offs between variability in harvest and the mean annual harvest that. could be expected from a given policy. A complete analysis along these lines, however, might require a wider range of fishing mortalities as well as smaller intervals between mortality levels. Second, the combination of simulations

Table 7. Annual mean and standard deviation of Walleye and Yellow Perch harvest (number/ha) for various combinations of Walleye and Yellow Perch mortality levels. Statistics are for 20-yr simulations and White Bass fishing mortality is assumed to be 0.4 per year.

Walleye Policy Fishing Mortality		Yellow Perch Policy Fishing Mortality 0.2		1.0		1.5	
		W	YP	W	YP	W	YP
0.2	Mean	7.85	56.6	7.88	88.8	7.91	91.0
	SD	(2.39)	(8.23)	(2.40)	(17.9)	(2.40)	(20.3)
1.0	Mean	14.8	55.8	14.8	87.0	14.8	89.1
	SD	(2.84)	(8.77)	(2.84)	(16.9)	(2.84)	(19.6)
1.5	Mean	15.3	56.3	15.4	88.4	15.4	90.7
	SD	73.33)	(8.68)	(3.32)	(16.5)	(3.32)	(19.3)

Table 8. Annual mean and standard deviation of Yellow Perch and White Bass harvest (number/ha) for various combinations of Yellow Perch and White 'Bass mortality levels. Statistics are for 20-yr simulations and Walleye fishing mortality is assumed to be 0.3 per year.

White Bass Policy Fishing Mortality		Yellow Perch Policy Fishing Mortality 0.2		1.0		1.5	
		WB	YP	WB	YP	WB	YP
0.2	Mean	3.06	50.0	4.54	74.2	4.84	73.0
	SD	(1.13)	(13.0)	(0.93)	(22.3)	(1.04)	(27.0)
1.0	Mean	6.17	58.2	11.3	93.4	13.1	95.8
	SD	(3.30)	(7.59)	(6.62)	(20.0)	(9.02)	(23.0)
1.5	Mean	6.64	58.5	12.2	94.4	14.3	97.2
	SD	(3.82)	(7.42)	(7.99)	(20.2)	(11:2)	(23.5)

directly addresses the assumption of fishery independence. -Both the pattern in annual mean and variability of harvest for Walleye shows very little response to changing Yellow Perch fishing mortality levels (Table 7). The reverse situation does not hold, however. Yellow perch harvest means and standard deviations do vary with Walleye fishing mortality levels. Nevertheless, the changes are small enough that independent management might seem a reasonable prospect.

In contrast, White Bass and Yellow Perch fishing policies are very interactive (Table 8). Both species yield much higher harvest if the other species is harvested at a high rate. In this case, prudent management would seem to weigh against independent policy derivation. These results also cast doubt on the seeming independence of Walleye and Yellow Perch in Table 7. As was illustrated in the extreme fishing scenarios, the interacting policies for White Bass and Yellow Perch are due to YOY predation interactions. The primary weakness in the model is that Walleye are excluded from these interactions, and it would seem premature to conclude that Walleye/Yellow Perch interactions are qualitatively different from white Bass/Yellow Perch interactions. These findings are also remarkable because of the minimal by-catch characteristics assumed in the Fisheries and Quota submodel. In situations in which significant by-catch occurs, interactions of fishery policies may be even more evident.

CONCLUSIONS AND RECOMMENDATIONS

Firm conclusions are difficult to draw from the results of the workshop model. Two weakness, in particular, need to be overcome to increase confidence in the findings. These two weakness are the exclusive reliance on a stock-recruitment relationship to predict YOY survival for Walleye and the lack of a dynamic model of the forage community. At the workshop, there was considerable disagreement about the appropriate level of resolution for the forage submodel. Unfortunately, severe information gaps on forage standing crop and its dynamics limit purely empirical approaches to the problem. Nevertheless, the demonstrated importance of YOY interactions to White Bass and Yellow Perch simulations as well as the sensitivity of the model to small changes in overall forage levels Suggest that concern with some details-of the forage community is not misplaced.

Despite the weaknesses of the workshop model, some qualitative indications point to key findings. For example, one of the questions originally raised by the client group was whether quota systems would work in multiple fisheries settings. Predictability of sports fishing effort, in particular, seems to be a problem. However, the lack of ability to anticipate sports effort is only a problem for low fishing mortality policies, and thus this difficulty may not be very serious in situations of high population density such as currently occur in Western Lake Erie. In addition, single species management, especially in a quota system, may not function well and could lead to poor performance of the fisheries.

Based on these conclusions and other concerns raised during the workshop, the following recommendations are offered to the Standing Technical Committee:

1. There are indications that Walleye rehabilitation has now produced a population density near its upper limit. While there are no indications of adverse effects of current or higher levels of Walleye abundance on' Yellow Perch, the key importance of the forage assumptions seems to require a careful review of various approaches to address the consequences of incomplete information in this area;

2. Multiple species management seems to be preferable to continued emphasis on single species management. The existing Walleye and Yellow Perch Task Groups should be encouraged to explore consequences of policy interactions through the fish community as well as fishery by-catch problems; and

3. The effects of interbasin migrations on fish communities in the individual basins need to be addressed. It is especially important to determine whether individual basins may be properly treated as management units.

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BOWLING GREEN STATE UNIVERSITY
JUNE 21-25, 1982

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Following is a listing of the Lake Erie Fish Community Workshop Model. Each of: the subroutines uses restricted code areas:

Walleye/White Bass	Lines 200-399 and 2000-3999
Yellow Perch	Lines 400-599 and 4000-5999
Forage and Feeding	Lines 600-799 and 6000-7999
Fisheries and Quota	Lines 800-999 and 8000-9999.

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1 DIM Z(20,20),ZM(20)
2 DIM AC(5),AD(5),AE(5),AL(5),AM(5),AN(5),AO(5),AS(5),AR(3)
3 DIM BC(5),BD(5),BE(5),BL(5),BM(5),BN(5),BO(5),BS(5),BR(3),BB(5)
4 DIM EN(6),ES(6),EM(6),EC(6),EB(6)
7 DIM PN(15),PS(15),PL(15),QN(8),QS(8),QL(8),PM(15),RS(15,8),PC(15),PB(15),QW(1
5,8),SD(6,3),ST(6,3),PA(15),PD(15)
8 DIM UA(4),UE(5),UB(4),UC(4),VC(5),XC(4)
10 NV = 20
12 PRINT "ENTER COMMANDS,THEN CONT": END
14 INPUT "SIM FROM ";A$: IF LEFTS (A$,2) = "GR" THEN 10100
15 ZS = VAL ( LEFTS (A$,2)):NT= VAL ( RIGHTS (A$,3))
16 IF NT < 1 THEN NT = VAL ( RIGHTS (A$,2))
18 FOR TIME = ZS TO NT
100 IF TI > 0 THEN GOT0 1000
105 INPUT "DO YOU WANT SAME RANDOM # Y/N ? ";A$
107 IF A$ = "Y" THEN PRINT HND ( - 1)
110 IO = 0:Il = 1:12 = 2:13 = 3:14 = 4:15 = 5:16 = 6:17 = 7:18 = 8:19 = 9:JO = 1
0:Jl = 11:J2 = 12:J3 = 13:J4 = 14:J5 = 15
120 IP = 0.1:IQ = 0.3
180 TA = 3.68E5:TV = 28
220 DATA .1,280,631,1049,1855, .01 ,19: FOR I = IO TO 14: READ AS(
I): NEXT : READ AQ,AG
230 DATA 340,34,10.3,1.02,18.7: FOR I = IO TO 14: READ AN(I): NEXT
240 DATA .307,.200,.18,.15,.05 : FOR I = IO TO 14: READ AE(1):
 NEXT
260 DATA 2,.218, .218,.218,.218 : FOR I = IO TO 14: READ AD(I): NEXT
265 AY = .30164:AX = 1.576E - 6:A3 = .6
270 AU = 45.3:AV = 0.284E - 6 * TA:AW = .215:AF = .3:AJ = 30:AI = .004
280 AS(O) = AJ
300 BX = 1.793E - 5:BY = .33954
305 DATA .3,190,278,375,577,.1,32: FOR I = IO TO 14: READ BS(1): NEXT : READ
 BQ,BG:
306 DATA 320 ,32,22,6.8,3.0: FOR I = IO TO 14: READ BN(I): NEXT
307 DATA .307,.249,.27,.22 ,.13: FOR I = IO TO 14: READ BE(I
) : NEXT
309 DATA 1 ,.14,.14,.14,.14: FOR I = IO TO 14: READ BD(1): NEXT
310 Bl = 50:B2 = .005:B3 = 1:BJ = 1.5
320 BS(0) = BJ
400 EG = .1:EP = .0152:EQ = .5398:FR = 20.2:ET = 427:EV = .07:EA(I0) = 0: FOR I
= I1.TO IS:EA(I) = 0: NEXT
```

```
405 FX = 36:FY = 101
410 GK = 1.55:GM = .05:GN = 3E5:GP = .308:FE = .0008:FF = .2:FH = 120:FI = .1:GQ
 = .2:FP = 1
420  DATA   1.5E9,8E7,59.4E6,34E6,9.8E6,1.8E6
430  FOR I = I0 TO I5: READ EN(I):EN(I) = EN(I) / TA: PRINT EN(I): NEXT
440  DATA   .1,8,41,81,102,110: FOR I = I0 TO I5: READ ES(I): NEXT
450 EB(0) = 2.5:EB(1) = 1.5:FQ = (FP * GN) ^ GP
460 EV = .01:ES(0) = FP
700 SN(0) = 5E5:SN(1) = 1E5:SN(2) = 1E5:SN(3) = 5E3:SN(4) = 5E3:QN(5) = 10E6
710 QS(0) = 0.1:QS(1) = .25:QS(2) = 1.1:QS(3) = 7.5:QS(4) = 14:QS(5) = .05
720 QL(0) = 12:QL(1) = 35:QL(2) = 65:QL(3) = 85:QL(4) = 110:QL(5) = 10
730  FOR I = 0 TO 8:QM(I) = .0: NEXT I:RV = .0075:SS = 9.0432E - 04:SA = 4.0:SB
=  - .73:SR = .25:SP = 1:TS = 240
740 RL = 1.5: FOR I = I0 TO I5:PA(I) = .5:PA(I + I5) = .5:PA(I + J0) = .5:PD(I)
=  - .0004:PD(I + I5) =  - .0007:PD(I + J0) =  - .0010: NEXT I:PA(J5) = .5:PD(J5
) =  - .0010
750 AC(0) = 933:AC(1) = 1230:AC(2) = 2322:AC(3) = 5373:AC(4) = 8000:AM(0) = .95:
AM(1) = .89:AM(2) = .91:AM(3) = .91:AM(4) = .89
760 BC(0) = 33:BC(1) = 68:BC(2) = 138:BC(3) = 185:BC(4) = 238:EC(0) = 87:EC(1) =
 46:EC(2) = 56:EC(3) = 66:EC(4) = 70:EC(5) = 72:BM(0) = .8:BM(1) = .3:BM(2) = .5
:BM(3) = .6:BM(4) = .6:EM(0) = 1.0:EM(1) = .5:EM(2) = .3:EM(3) = .3:EM(4) = .3:
762 EM(I5) = .3:P1 = 1E - 6
840  FOR I = I1 TO I4: READ UG(I),VG(I),XG(I): NEXT
845  READ VG(I5)
850  DATA      .1,.001,.001,.5,.18,.001,.8,.71,1,1,1,1,1
860  FOR I = I1 TO I4: READ UC(I),VC(I),XC(I): NEXT
865  READ VC(I5)
870  DATA      2E-9,1E-11,.1,2.15E-8,2.1E-8,1,2.15E-8,4.2E-8,1,2.15E-8,4.2E-8,1,
4.2E-8
880 UJ = .8:UK = 1.25E7:VJ = 7:VK = 7.5E7:UN = .025:VN = .05
885 U3 = 1.4E7:U4 = .4:V3 = 4E6:V4 = 1:V6 = .15
900 UZ = .2:VZ = .2:XZ = .2
910 UR = .3:VR = .3:XR = .98
925 U0 = (I1 -  EXP ( - UZ)) * TA:V0 = (I1 -  EXP ( - VZ)) * TA:X0 = (I1 -  EXP
( - XZ)) * TA:VQ = EN(I5) * V0 * TA:UQ = I0:XQ = I0
930  FOR I = I1 TO I4:UA(I) = UZ * UG(I):UB(I) = XZ * XG(I):UE(I) = VZ * VG(I):U
Q = U0 * UG(I) * AN(I) + UQ:VQ = V0 * EN(I) * VG(I) + VQ:XQ = XQ + XG(I) * BN(I)
 * X0: NEXT :EN(I5) = VZ
950 GQ = 0:A3 = 0:B3 = 0:V6 = 0
1000  REM  START
```

```
2000 REM   START
2010 AH = IO
2020 FOR I = IO To 14:AP = AD(I) + AQ * (11 - AM(I)):AZ = UA(I) + AP t UP(I):AA
 = 11 -  EXP ( - AZ):AH = AH + (UA(I) / AZ) * AA * AN(I)
2030 AN(I) = AN(I) * (I1 - AA):AS(I) = AS(I) + (AE(1) * AC(I)): NEXT
2040 AS(14) = (AS(13) * AN(13) + AS(I4) * AN(I4)) / (AN(I3) + AN(14))
2050 AN(14) = AN(14) + AN(I3)
2060 FOR I = 13 TO El STEP  - Il:AS(I) = AS(1 - Il):AN(I) = AN(1 - 11): NEXT
2400 AF = ( - 11 t AI * AS(3)):  IF AF < IO THEN AF = IO
2405 IF AF > 11 THEN AF = I1
2410 AG = AF *  AN(3)  t  AN(4)
2500 COSUB 12000
2510 AR = AU * AG *  EXP ( - AV * AG + A3 * ZR)
2530 AN(I0) = AR:AS(IO) = AJ
2610 FOR I = IO TO 14:AL(I) = (AS(I) / AX) - AY: PRINT AS(I),AN(I): NEXT
2900 Z(1,TI) = AG
2905 Z(2,TI) = AH
2910 Z(3,TI) = AN(I0)
3120 BH = IO
3130  FOR I = IO TO 14:BP = BD(1) + BQ * (I1 - BM(I)):BZ = UB(1) + BP t BD(1) t
LJP(I):BA = 11 -  EXP ( - BZ):BH = BH t (UB(1) / HZ) * BA * BN(I)
3135 PRINT BZ,BN(I)
3140 BN(I) = BN(I) * (11 - BA):BS(I) = BS(I) t (BE(I) * CC(I)): NEXT
3150 BS(I4) = (BS(I3) * BN(I3) t BS(14) * BN(I4)) / (BN(13) + BN(I4))
3160 BN(I4) = BN(14) + BN(13)
3170 FOR I = I3 TO 11 STEP - Il:BS(I) = BS(1 - Il):BN(I) = BN(1 - 11): NEXT
3190 GOSUB 12000
3200 BG = IO: FOR I = I2 TO 14:BG = BG + BN(I): NEXT
3210 BR = Bl * BG *  EXP ( - B2 * BG + ZR * B3)
3220 BN(I0) = BR:BS(IO) = BJ
3610 FOR I = IO TO I4:BL(I) = (BS(I) / BX) - BY: NEXT
3900 Z(4,TI) = BG
3905 Z(5,TI) = BH
3910 Z(6,TI) = BN(0)
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4000 EW = I0:EH = I0:FC = I0: PRINT TI: GOSUB 12000:ZR =  EXP (ZR * GQ)
4005  FOR I = I0 TO I5:EG =  - FE * ES(I) + FF: IF EG < I0 THEN EG = I0
4010 ES(I) = ES(I) + (EG * EC(I)):GJ = GK *  EXP ( - (J0 * EM(I))) + GM
4015 GT = UE(I) + UP(I) + EA(I) + EB(I) + GJ:GV = I1 -  EXP ( - GT):GW = (UE(I)
/ GT) * GV:EH = EH + (GW * EN(I) * TA):EN(I) = EN(I) * (I1 - GV): NEXT
4020 FA = EN(I5) + EN(I4):ES(I5) = (EN(I5) * ES(I5) + EN(I4) * ES(I4)) / FA:EL(I
5) = (ES(I5) * GN) ^ GP:EN(I5) = FA
4030  FOR I = I3 TO I0 STEP  - I1:EN(I + I1) = EN(I):ES(I + I1) = ES(I):EL(I + I
1) = (ES(I) * GN) ^ GP: NEXT
4050  FOR I = I0 TO I5
4055  PRINT ES(I),EN(I)
4120 EF = I0: IF ES(I) > FX THEN EF = FR * ES(I) - ET
4125 FA = 1: IF ES(I) >  = FY GOTO 4150
4130 FA = (EP * ES(I) - EQ): IF FA < I0 THEN FA = 0
4140 EF = EF * FA
4150 FZ = EV * ZR:FC = FC + EN(I) * FA
4180 EW = EW + EN(I) * EF * FZ / I2: NEXT
4800 EN(I0) = EW:ES(I0) = FP:EL(I0) = FQ
4900 Z(7,TI) = EN(I0):Z(8,TI) = EH:Z(9,TI) = ES(I3):Z(10,TI) = FC
4950 Z(11,TI) = ES(5):Z(12,TI) = AS(4)
7000  FOR I = I0 TO I4:PN(I) = AN(I):PS(I) = AS(I):PL(I) = AL(I):PN(I + I5) = BN
(I):PS(I + I5) = BS(I):PL(I + I5) = BL(I):PN(I + J0) = EN(I):PS(I + J0) = ES(I):
PL(I + J0) = EL(I): NEXT I:PN(J5) = EN(I5):PS(J5) = ES(I5):PL(J5) = EL(I5)
7010  FOR I = I0 TO I4:QN(I) = SN(I): NEXT I:QN(I6) = BN(I0):QS(I6) = BS(I0):QL(
I6) = BL(I0):QN(I7) = EN(I0):QS(I7) = ES(I0):QL(I7) = EL(I0):QN(I8) = EN(I1):QS(
I8) = ES(I1):QL(I8) = EL(I1)
7015  FOR J = I0 TO I8:QZ(J) = I0: NEXT J
7020  FOR I = I0 TO J5:RC = PA(I) + PD(I) * PL(I):QT = I0
7030  FOR J = I0 TO I8
7040 QW(I,J) = QL(J) * (RC - QL(J) / (PL(I) + P1)): IF QW(I,J) < 0 THEN QW(I,J)
= 0
7050  IF J > I5 THEN QW(I,J) = QW(I,J) * SR
7055  IF J > I7 THEN QW(I,J) = QW(I,J) * SR
7060 QT = QT + QW(I,J): NEXT J:QT = SP / (QT + P1)
7070 PM(I) = I0: FOR J = I0 TO I8
7080 RH = QS(J) * SA * PS(I) ^ SB:RC = QL(J) * RV: IF RC > RL THEN RC = RL
7090 QW(I,J) = QW(I,J) * QT:RS(I,J) = QW(I,J) * SS * PL(I) * RC * RC:PM(I) = PM(
I) + RS(I,J) * QN(J) * RH:RS(I,J) = RS(I,J) * TS
```

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7110 PB(I) = I1 / (I1 + PM(I)): FOR J = I0 TO I8:QZ(J) = QZ(J) + RS(I,J) * PB(I)
 * PN(I): NEXT J
7120  NEXT I
7130  FOR J = I0 TO I8:QA(J) = (I1 -  EXP ( - QZ(J))) * QN(J) * QS(J) / (QZ(J) +
 P1): NEXT J
7135  FOR I = I0 TO J5:PC(I) = I0:PM(I) = PM(I) / (I1 + PM(I)): FOR J = I0 TO I8
7140 PC(I) = PC(I) + RS(I,J) * QA(J): NEXT J:PC(I) = PC(I) * PB(I): NEXT I
7150  FOR I = I0 TO I4:AM(I) = PM(I):AC(I) = PC(I):BM(I) = PM(I + I5):BC(I) = PC
(I + I5):EM(I) = PM(I + J0):EC(I) = PC(I + J0): NEXT I:EM(I5) = PM(J5):EC(I5) =
PC(J5)
7160  FOR I = I0 TO I4:SZ(I) = QZ(I): NEXT I:BB(I0) = QZ(I6):EB(I0) = QZ(I7) - Q
M(I7):EB(I1) = QZ(I8) - QM(I8)
7170  FOR I = 0 TO 15: PRINT PC(I),PM(I): NEXT I: PRINT
8000 UQ = UQ + 1:VQ = VQ + 1:XQ = XQ + 1
8210 Z(16,TI) = AH * TA / UQ:Z(17,TI) = BH * TA / XQ:Z(18,TI) = EH / VQ
8300 UD = 0:VD = 0:XD = 0
8310  FOR I = I1 TO I4:UD = (UG(I) * UR + (I1 - UR) * UC(I) / UC(I4)) * AN(I) *
TA + UD:VD = VD + (VG(I) * VR + (I1 - VR) * VC(I) / VC(I5)) * EN(I) * TA:XD = XD
 + (XG(I) * XR + (I1 - XR) * XC(I) / XC(I4)) * BN(I) * TA:UA(I) = 0:UE(I) = 0
8311  NEXT
8320 VD = VD + (VG(I5) * VR + (I1 - VR)) * EN(I5) * TA
8330 UQ = (I1 -  EXP ( - UZ)) * UD:VQ = (I1 -  EXP ( - VZ)) * VD:XQ = (I1 -  EXP
 ( - XZ)) * XD:UF =  -  LOG (I1 - UR * UQ / UD):VF =  -  LOG (I1 - VR * VQ / VD)
:XF =  -  LOG (I1 - XR * XQ / XD)
8450 UE(I5) = VG(I5) * VF: FOR I = I1 TO I4:UA(I) = UG(I) * UF:UE(I) = VG(I) * V
F:UB(I) = XG(I) * XF: NEXT
8470 UA(I1) = UA(I1) + VN * UE(I1) + UN * UA(I1)
8500 UI = UJ * UD / (UK + UD):VI = VJ * VDK / (VK + VD)
8510 U0 = UI * UI:U2 = U3 * U0 / (U0 + U4 * U4):U0 = VI * VI:V2 = V3 * U0 / (U0
+ V4 * V4): GOSUB 12000:V5 = V6 * ZR:U2 = U2 + V5 * U2:V2 = V2 + V5 * V2
8520  FOR I = I1 TO I4:UA(I) = UA(I) + UC(I) * (I1 - AM(I)) * U2:UE(I) = UE(I) +
 VC(I) * (I1 - EM(I)) * V2:UB(I) = UB(I) + XC(I) * (XZ - XF): NEXT :UE(I5) = UE(
I5) + VC(I5) * (I1 - EM(I5)) * V2
8600  PRINT "HR: ";AH * TA / UQ;"               ";EH / VQ
```