The Lake Trout Rehabilitation Model:

Program Documentation

by

Carl J. Walters

Lawrence D. Jacobson

and

George R. Spangler

Special Publication No. 86-1

Great Lakes Fishery Commission

1451 Green Road
Ann Arbor, Michigan 48105
September 1986

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GREAT LAKES FISHERY COMMISSION
1451 Green Road
Ann Arbor, MI 48105
USA

August, 1986

1 institute of Animal Resource Ecology
University of British Columbia
Vancouver, B. C. V6T 1W5
Canada

2 Department of Fisheries and Wildlife
University of Minnesota
200 Hodson Hall
1980 Folwell Avenue
St. Paul, MN 55108
USA

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FOREWORD

The purpose of this report is to describe and document a computer simulation model known as "The Lake Trout Rehabilitation Model" written by Carl Walters. The Lake Trout Rehabilitation Model has its roots in the work Of Walters et al. (1980) and in the Sea Lamprey International Symposium (SLIS) that was sponsored by the Great Lakes Fishery Commision and Convened in 1979. Over time, and with the help Of numerous individuals, the Lake Trout Rehabilitation Model evolved into its present form. Unlike the models described by Koonce et al. (1982) and Spangler and Jacobson (1985), the Lake Trout Rehabilitation Model was not written by a large team of experts during an adaptive management workshop.

The Lake Trout Rehabilitation Model simulates most aspects of lake trout population biology, including factors that are thought to contribute to delayed rehabilitation of Great Lakes lake trout stocks: 1) mortality due to predation by sea lamprey, 2) fishing mortality, 3) reproductive incompetence of stocked fish and 4) time lags due to the relatively late age at maturity in lake trout. The model is realistic in that it includes the essential features of an age structured population and important biological characteristics of lake trout. It is important to remember, however, that the model does not include some aspects of lake trout biology that may be crucial to the problem of lake trout rehabilitation, notably changes in growth of lake trout due to forage base limitations. Furthermore, the true functional relationships between some of the entities in the model (e.g. mortality of lake trout and abundance of sea lamprey, abundance of sea lamprey and dollars spent for sea lamprey control) are unknown and are represented in the model by "best guesses". For these reasons results obtained using the Lake Trout Rehabilitation Model should be interpreted qualitatively rather than quantitatively.

The Lake Trout Rehabilitation Model simulates rehabilitation of a trout stock from an initial condition of no fish. Rehabilitation is achieved through control of sea lamprey, lake trout stocking and limitations on fishing effort. The rate of rehabilitation depends on how much money is spent on lamprey control, the number of yearling lake trout stocked and the amount of fishing effort; these policy variables are controlled by the person using the model. The model runs quickly (2 1/4 minutes to simulate 30 years) and plots the status of the simulated trout Stock and fishery on the screen at the end of every simulated year. The user can interrupt the simulation at any time in order to Chang8 the policy variables. These features are important because they allow the user to experiment with a variety of different policies for lake trout rehabilitation and to continuously monitor the effects of those policies as the Simulation progresses. The potential for interactive use of the program and the degree of realism that was obtained make use of the Lake Trout Rehabilitation Model an interesting exercise.

The Lake Trout Rehabilitation Model is written in Applesoft™ BASIC and will run under Disk Operating System 3.3 (DOS 3.3) on any Apple II™ series microcomputer with at least 64K of memory. The model can be obtained on a 5 1/4 inch floppy disk from the Great Lakes Fishery Commission or from George

Spangler. There are two versions of the program: “INTERACTIVE TROUT. ORIGINAL” and “INTERACTIVE TROUT”. INTERACTIVE TROUT. ORIGINAL is the original version written by Walters. INTERACTIVE TROUT is a version that was modified by the junior authors. The modifications were made to correct a minor bug and to enhance the readability of the computer code (see Appendix E). The original and modified VerSiOns are both useable and will give similar, though not identical, results.

Functional relationships used in the Lake Trout Rehabilitation Model are described in the main body of this document. Policy analysis (using the modified version) is illustrated in Appendix A. Appendix B gives instructions for running the models. A flow chart and listing of the computer code are given for INTERACTIVE TROUT in Appendices C and D, respectively. Appendix E describes the differences between INTERACTIVE TROUT and INTERACTIVE TROUT.ORIGINAL.

The Lake Trout Rehabilitation Model:

Program Documentation

Overview

The objective of the Lake Trout Rehabilitation Model is to simulate changes in lake trout abundance using an age structured population model that realistically accounts for: 1) known time lags (between birth, stocking, maturity and recruitment to the fishery), 2) stocking policy, 3) differences in the reproductive capability of wild and stocked fish, 4) natural limits to recruitment (the stock-recruitment relationship and juvenile habitat capacity) and 5) mortality due to natural factors, lamprey predation and fishing. Not included in the model are a number of more controversial relationships such as changes in the forage base, changes in the abundance of alternate hosts for sea lamprey and changes in lake trout habitat due to pollution. The “slow dynamic” of spawning habitat recolonization and adaptation of local stocks is not considered; instead, it is assumed that all major spawning shoals are simultaneously recolonized as abundance of lake trout increases. The model starts from an initial condition of no fish. Abundance of lake trout increases as fish are stocked and as stocked fish begin to reproduce naturally. Thirty years of lake trout rehabilitation are simulated.

Functional Relationships

The following are detailed descriptions of the important functional relationships in the Lake Trout Rehabilitation Model. Values for constants and initial values of variables are given in parentheses after the quantity is defined.

Age Structure

The number of fish age a in year t is related to the number of fish age $a+1$ in year t+1 by:

$$N_{a+1,t+1} = N_{a,t}\ exp(-M - v_a\, q\, E_t - \lambda_t\, L_t\, p / V_t). \qquad [1]$$

Where: $N_{a,t}$ = number of trout age a in year t,

M = natural mortality rate in the absence of sea lamprey (constant = 0.3),

v_a = relative vulnerability to fishing for trout at age a (constant, see Table 1),

q = catchability coefficient for fully recruited fish (6.0×10^{-7}),
E_t = fishing effort in year t (see below),

λ_t = number of trout attacked per lamprey in year t (see below),
L_t = lamprey abundance in year t (see below),
p = probability of a lake trout surviving one lamprey attack (0.4),
V_t = total number of trout vulnerable to lamprey attack at the start of year t (all trout age 4-15).

Note that the instantaneous rates for fishing and lamprey induced mortality in [1] are $v_a\, q\, E_t$ and $\lambda_t L_t p / V_t$, respectively. The maximum age for lake trout is 15 years.

Table 1. Relative vulnerability to fishing by age for lake trout.

Age (a)	v_a
1	0.0
2	0.0
3	0.0
4	0.1
5	0.3
6	0.7
7-15	1.0

Lamprey mortality

The number of attacks per lamprey in year t is given by:

$$\lambda_t = \alpha V_t / (\beta + V_t). \qquad [2]$$

Where: λ_t = the number of attacks per lamprey in year t,
α = the maximum number of attacks per lamprey (10),
β = density of lake trout at which λ_t is half the maximum (3000),
V_t = abundance of lake trout that are vulnerable to lamprey (all trout age 4-15 in year t).

Natural reproduction

Stocked and wild fish are assumed to mate randomly. Total effective egg deposition is given by:

$$E_t = \sum_{a=m \text{ to } j} N_{a,t}\, f_a \{R_{t-a} [S_t\, \varpi_{WW} + (1 - S_t)\, \varpi_{WS}] + (1 - R_{t-a}) [S_t\, \varpi_{WS} + (1 - S_t)\, \varpi_{WW}]\}. \quad [3]$$

Where: E_t = effective egg deposition in year *t*,
R_t = the ratio of wild yearlings to total yearlings in year *t*,
S_t = the ratio of wild fish to stocked fish in year *t*,
f_a = the average fecundity for fish age a,
= proportion mature x proportion female X eggs per female (Table 2),
ϖ_{WW} = relative reproductive success for mating between two wild fish (1.0),
ϖ_{WS} = relative reproductive success for mating between a wild and a stocked fish (0.75),
ϖ_{SS} = relative reproductive success for mating between two stocked fish (0.5),
m = the age of maturity (7),
j = the maximum age for lake trout (15).

All fish that result from spawning in the lake are assumed to be wild type at spawning time.

Table 2. Average fecundity by age for lake trout.

Age (a)	f_a
1-6	0
7	100
8	1000
9	2000
10	3000
11	4,000
12	5,000
13	6,000
14	7,000
15	8,000

Limits to recruitment

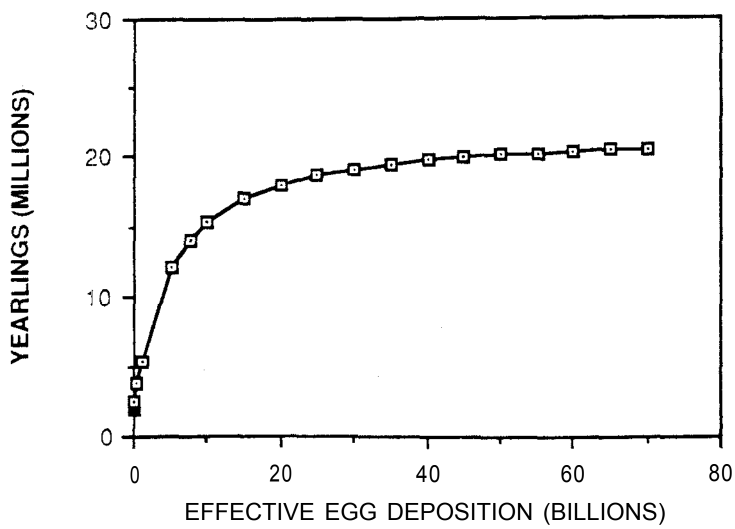
The number of yearling recruits in year t+1 is given by:

$$N_{1,t+1} = S_{t+1} + s_0 E_t / (1 + s_0 E_t / K). \qquad [4]$$

Where: $N_{1,t+1}$ = total number of yearlings in year $t+1$,
S_{t+1} = number of yearlings stocked in year $t+1$ (2 million),
E_t = effective egg deposition in year t,
K = maximum number (carrying capacity) of wild yearlings (20 million),
s_0 = maximum survival rate from egg to yearling under uncrowded conditions (0.004).

The relationship between egg deposition and yearlings is illustrated in Figure 1.

Figure 1. Number of yearlings produced as a function of effective egg deposition (assuming 2 million stocked yearlings).



Fishing Effort

Fishing effort is a constant fraction of the vulnerable stock until a maximum value is reached:

$$E_t = 0.2\,V_t \qquad \{if\ 0.2\,N_v \leq E_{max}\}$$
$$E_t = E_{max} \qquad \{if\ 0.2\,N_v > E_{max}\}, \qquad [5]$$

where E_t is the fishing effort in year t, V_t is the number of fish vulnerable to fishing in year t ($V_t = \Sigma v_i N_{i,t}$) and E_{max} is the maximum effort (1 million boat days).

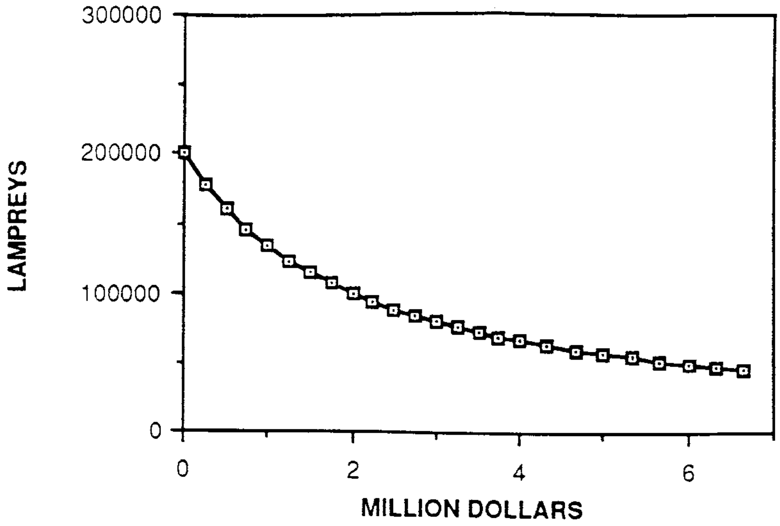
Lamprey control by expenditure of money

The relationship between lamprey abundance and dollars spent on lamprey control (Figure 2) is given by:

$$L_t = 200000 / (1 + D_t / 2000000). \qquad [6]$$

Where Lt is the number of lamprey in year t and Dt is dollars spent on lamprey control in year t (6 million dollars). Expenditure of six million dollars gives 50,000 lamprey, expenditure of zero dollars gives 200,000 lampreys.

Figure 2. Number of lamprey as a function of dollars spent on lamprey control.



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APPENDIX A

POLICY Analysis

The following examples illustrate the way in which the Lake Trout Rehabilitation Model can be used to investigate the effects Of stocking, harvest and sea lamprey control on rehabilitation of lake trout stocks. There are four examples. The first is a “baseline” scenario in which the number of fish stocked, maximum fishing effort and dollars spent on lamprey control are kept at their initial values (2 million fish, 6 million dollars and 1 million boat days, respectively) through the entire simulation. In the second scenario the amount of money spent for lamprey control is reduced to 2 million dollars (one-third the value used in the baseline case) in order to examine the effects of reduced sea lamprey control on lake trout rehabilitation. Rehabilitation of lake trout in a refuge is depicted in the third example; fishing effort was zero boat days per year through the entire simulation. In the fourth scenario the number of fish stocked is temporarily reduced in year 15 to zero. The effects of a one year interruption in the stocking program are illustrated. Most of these examples are taken from the recommendations by Eshenroder et al. (1985) for large scale field experiments. The axes in the following figures keep the same scale from one scenario to the next in order to facilitate comparison of results from different simulations.

Figure AI. Simulation results for baseline scenario (2 million fish stocked annually, 6 million dollars spent annually for lamprey control, and 1 million boat days per year as the maximum fishing effort). After 30 years of rehabilitation the number of 10 year old fish is negligible, wild fish constitute 50% of the mature stock and the annual catch is 400,000 fish.

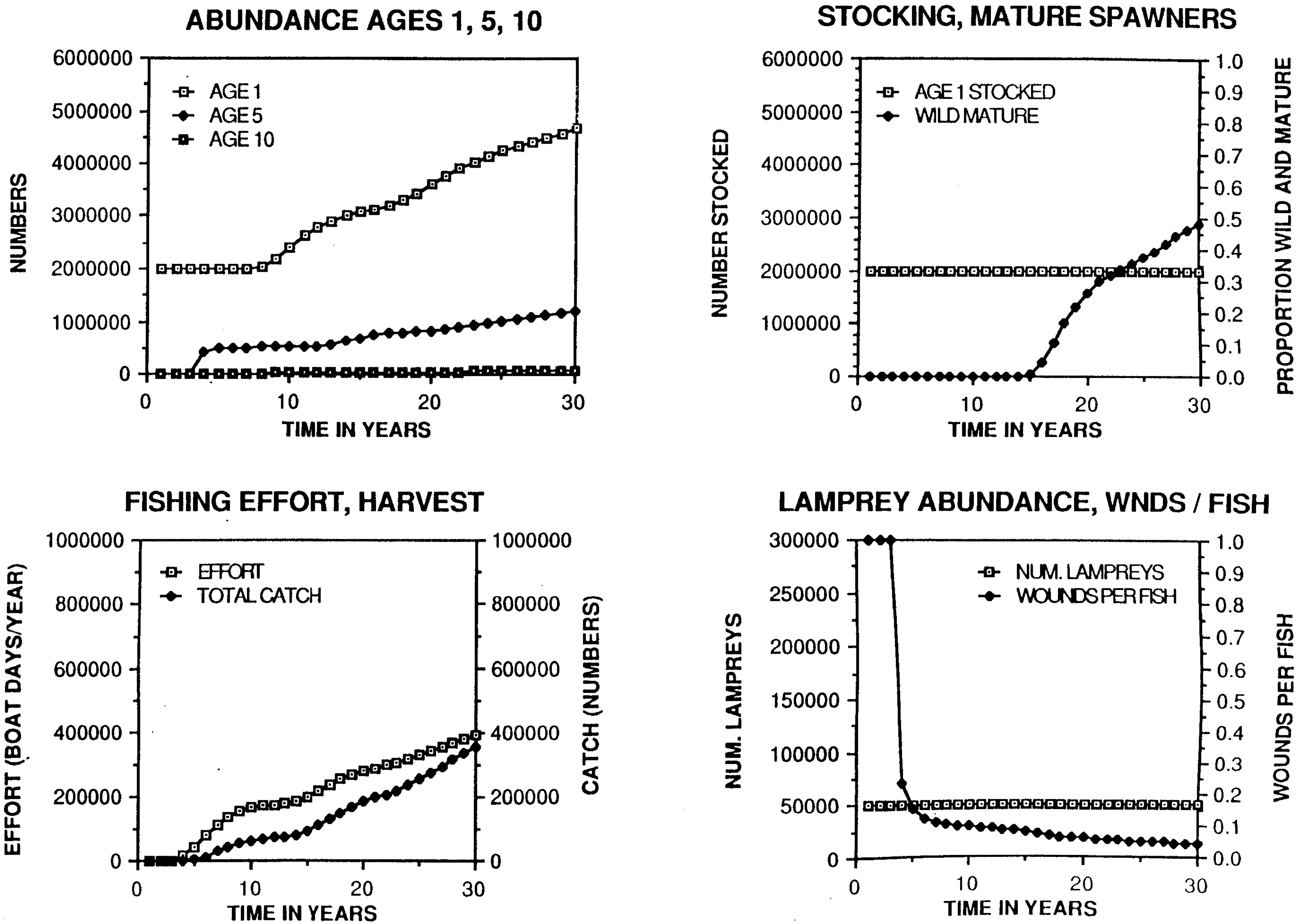
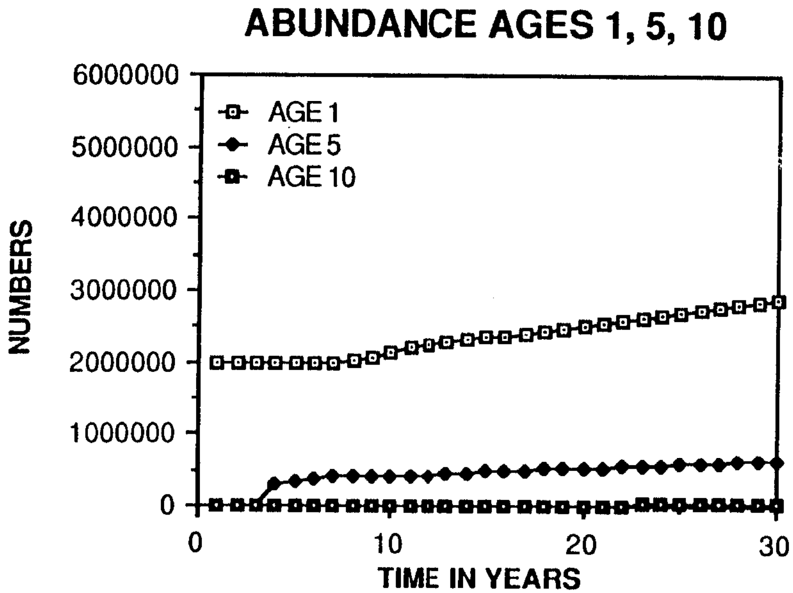
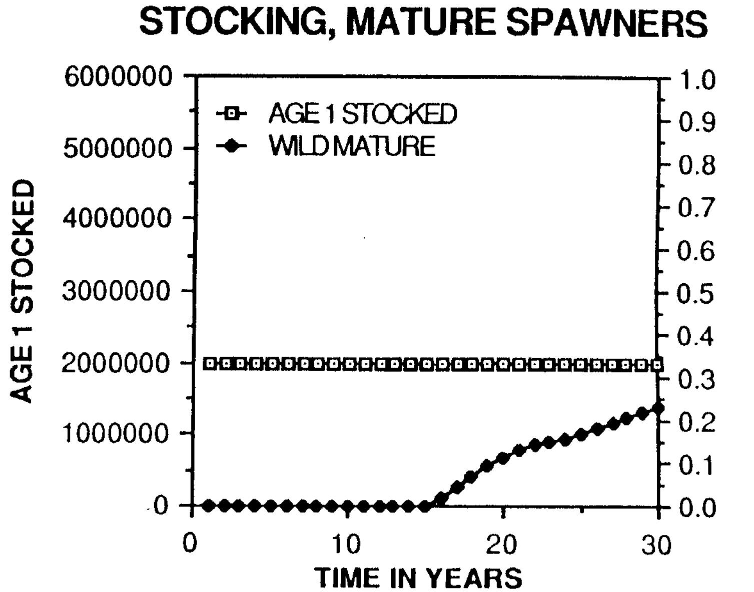
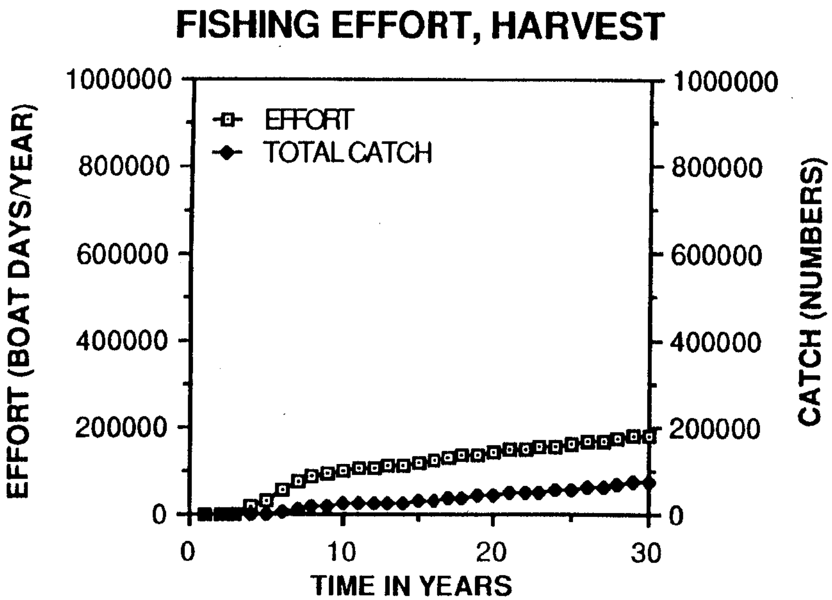

ABUNDANCE AGES 1, 5, 10
6000000
5000000
4000000
3000000
2000000
1000000
0
NUMBERS
AGE 1
AGE 5
AGE 10
0
10
20
30
TIME IN YEARS
STOCKING, MATURE SPAWNERS
6000000
5000000
4000000
3000000
2000000
1000000
0
NUMBER STOCKED
AGE 1 STOCKED
WILD MATURE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
PROPORTION WILD AND MATURE
0
10
20
30
TIME IN YEARS
FISHING EFFORT, HARVEST
1000000
800000
600000
400000
200000
0
EFFORT (BOAT DAYS/YEAR)
EFFORT
TOTAL CATCH
CATCH (NUMBERS)
0
10
20
30
TIME IN YEARS
LAMPREY ABUNDANCE, WNDS / FISH
300000
250000
200000
150000
100000
50000
0
NUM. LAMPREYS
NUM. LAMPREYS
WOUNDS PER FISH
WOUNDS PER FISH
0
10
20
30
TIME IN YEARS

Figure A2. Simulation results for scenario with reduced budget for lamprey control (2 million dollars annually for sea lamprey control, other control variables as in baseline scenario). Note that the rate of rehabilitation is much reduced and that total catch in year 30 is about 1/4 the value obtained in the baseline scenario.


ABUNDANCE AGES 1, 5, 10
NUMBERS
6000000
5000000
4000000
3000000
2000000
1000000
0
AGE 1
AGE 5
AGE 10
0
10
20
30
TIME IN YEARS


STOCKING, MATURE SPAWNERS
AGE 1 STOCKED
6000000
5000000
4000000
3000000
2000000
1000000
0
AGE 1 STOCKED
WILD MATURE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS


FISHING EFFORT, HARVEST
EFFORT (BOAT DAYS/YEAR)
1000000
800000
600000
400000
200000
0
EFFORT
TOTAL CATCH
CATCH (NUMBERS)
1000000
800000
600000
400000
200000
0
0
10
20
30
TIME IN YEARS

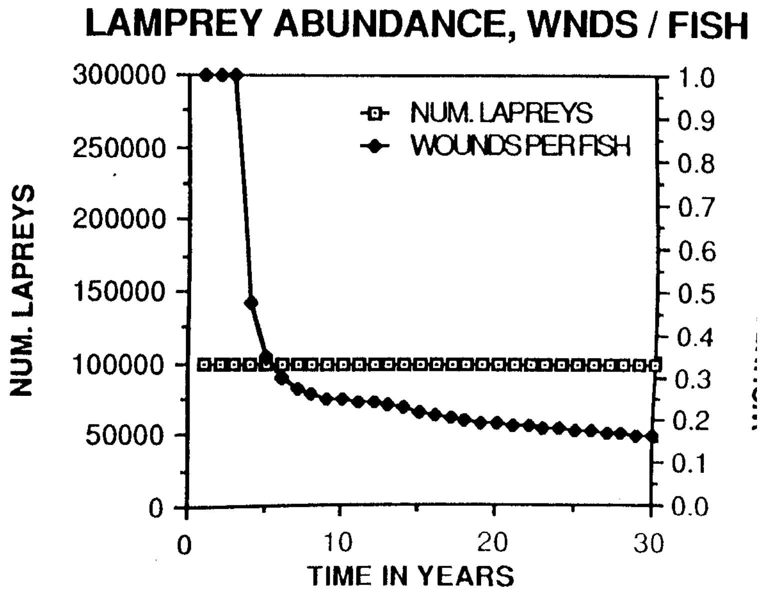
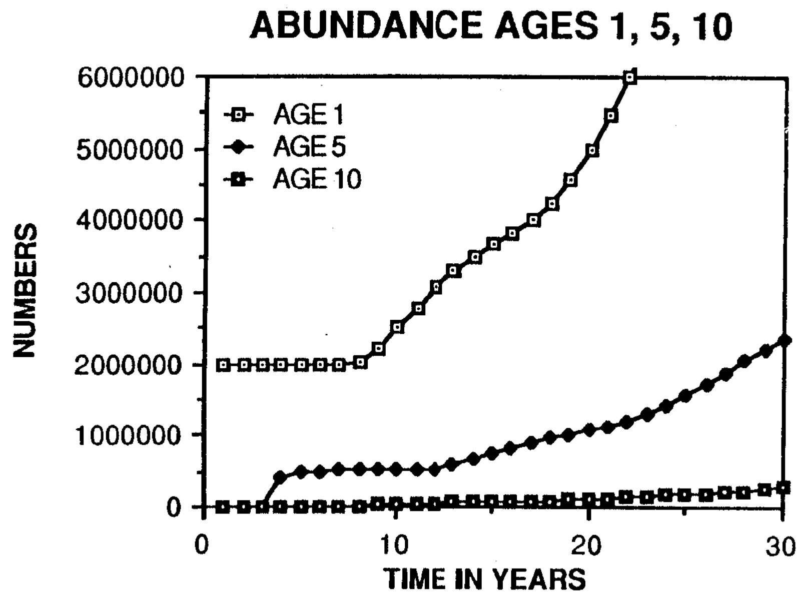
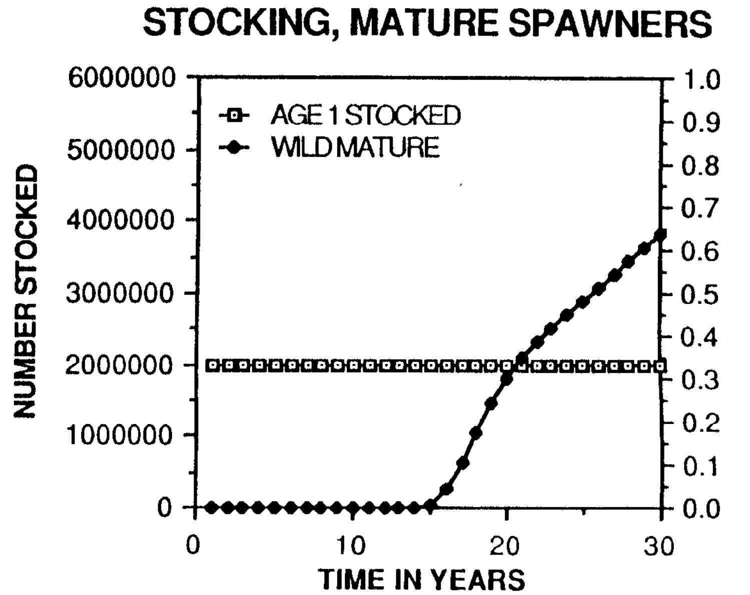
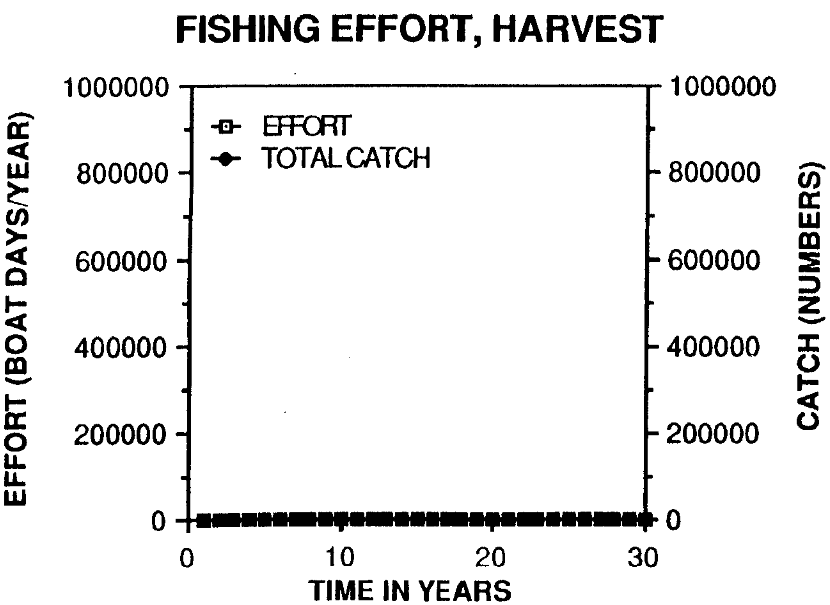

LAMPREY ABUNDANCE, WNDS / FISH
NUM. LAPREYS
300000
250000
200000
150000
100000
50000
0
NUM. LAPREYS
WOUNDS PER FISH
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS

Figure A3. Simulation results for scenario with no fishing effort. This is the only scenario that (gives an appreciable number of 10 year old fish and more than 50% wild fish in the mature stock by year 30.


ABUNDANCE AGES 1, 5, 10
NUMBERS
AGE 1
AGE 5
AGE 10
6000000
5000000
4000000
3000000
2000000
1000000
0
0
10
20
30
TIME IN YEARS


STOCKING, MATURE SPAWNERS
NUMBER STOCKED
AGE 1 STOCKED
WILD MATURE
6000000
5000000
4000000
3000000
2000000
1000000
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS


FISHING EFFORT, HARVEST
EFFORT (BOAT DAYS/YEAR)
CATCH (NUMBERS)
EFFORT
TOTAL CATCH
1000000
800000
600000
400000
200000
0
1000000
800000
600000
400000
200000
0
0
10
20
30
TIME IN YEARS

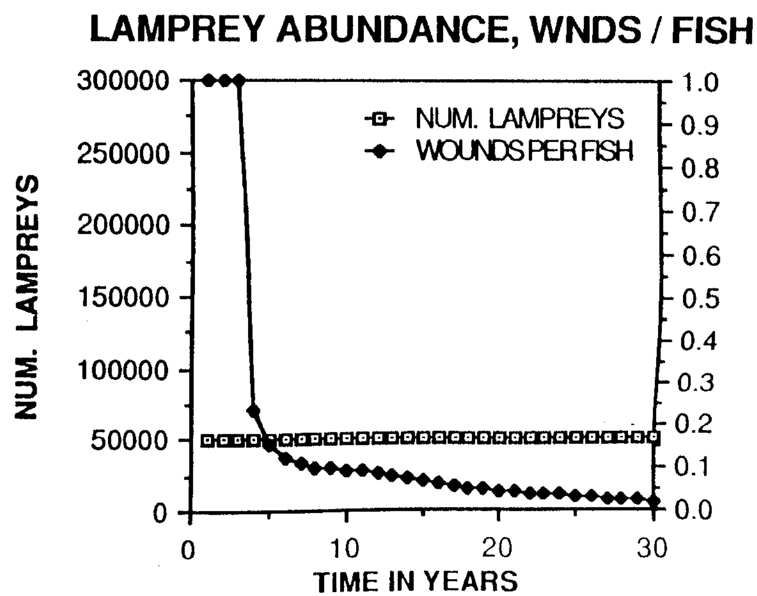
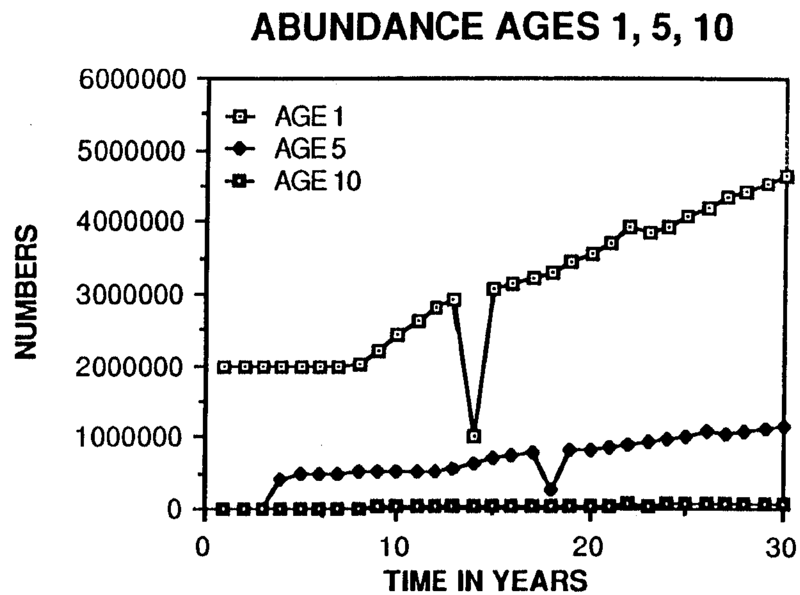

LAMPREY ABUNDANCE, WNDS / FISH
NUM. LAMPREYS
NUM. LAMPREYS
WOUNDS PER FISH
300000
250000
200000
150000
100000
50000
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS

Figure A4. Simulation results for scenario with no fish stocked in year 15 (other policy variables same as for baseline scenario). Note that the number of yearlings in year 16 produced from natural reproduction in year 15 can be clearly seen in the upper right panel. By the end of the simulation, most variables are not much different from the levels obtained in the baseline scenario.


ABUNDANCE AGES 1, 5, 10
NUMBERS
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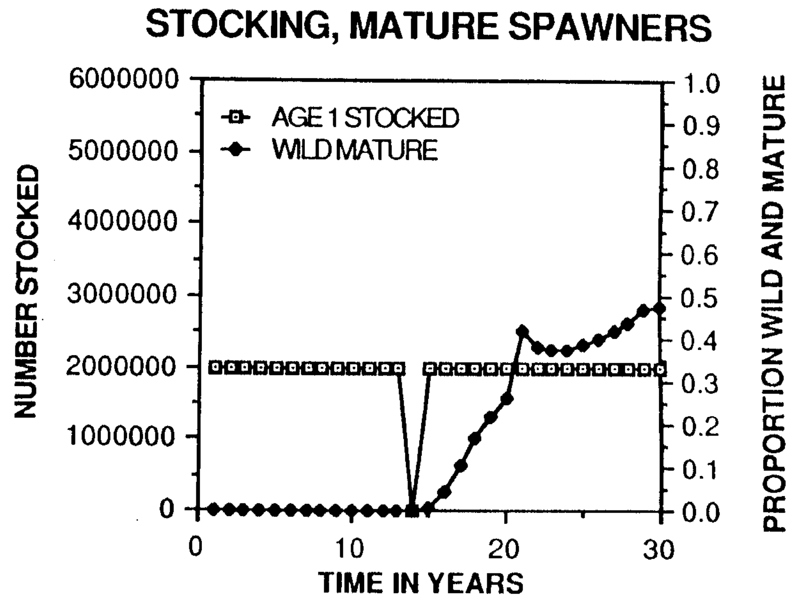
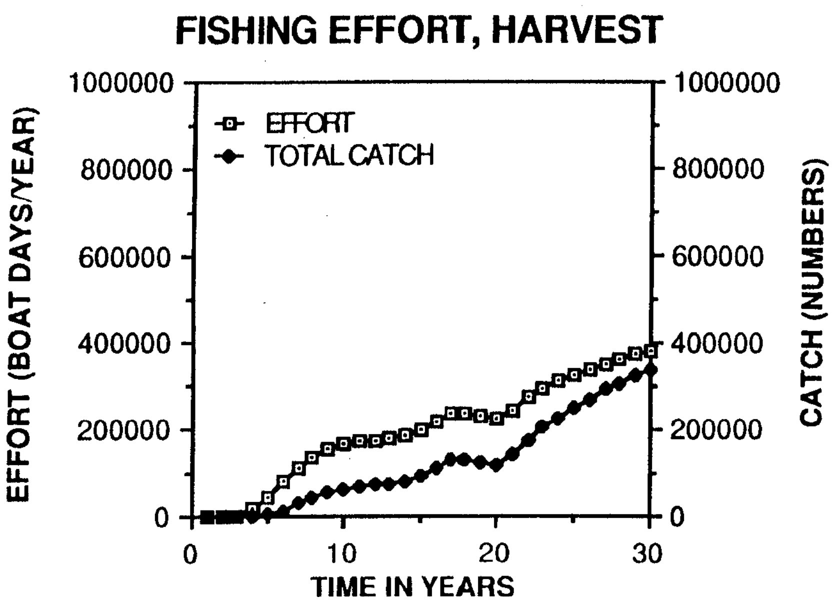
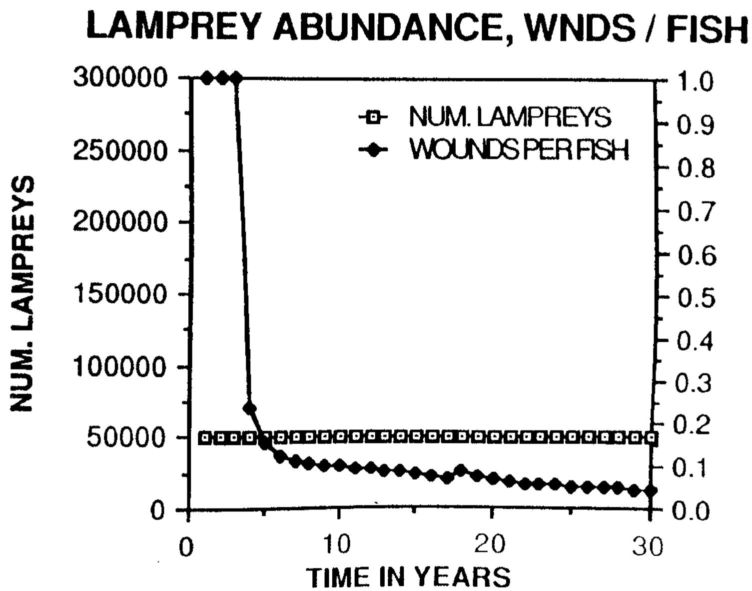
5000000
4000000
3000000
2000000
1000000
0
AGE 1
AGE 5
AGE 10
0
10
20
30
TIME IN YEARS


STOCKING, MATURE SPAWNERS
NUMBER STOCKED
6000000
5000000
4000000
3000000
2000000
1000000
0
AGE 1 STOCKED
WILD MATURE
PROPORTION WILD AND MATURE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS


FISHING EFFORT, HARVEST
EFFORT (BOAT DAYS/YEAR)
1000000
800000
600000
400000
200000
0
EFFORT
TOTAL CATCH
CATCH (NUMBERS)
1000000
800000
600000
400000
200000
0
0
10
20
30
TIME IN YEARS


LAMPREY ABUNDANCE, WNDS / FISH
NUM. LAMPREYS
300000
250000
200000
150000
100000
50000
0
NUM. LAMPREYS
WOUNDS PER FISH
WOUNDS PER FISH
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
TIME IN YEARS

APPENDIX B

INSTRUCTIONS FOR RUNNING THE LAKE TROUT REHABILITATION MODEL

Both versions of the Lake Trout Rehabilitation Model (INTERACTIVE TROUT and INTERACTIVE TROUT.ORIGINAL) are written in Applesoft[M] BASIC and run under Disk Operating System 3.3 (DOS 3.3) on an Apple II™ series microcomputer with at least 64K of memory. To run either model do the following:

1) Insert the disk into the internal disk drive.

2) Turn the computer on. When the disk drive stops turning a greeting message is displayed.

3) Type "RUN" plus the name of the program plus a carriage return to load a program and run it (e.g. "RUN INTERACTIVE TROUT" followed by a carriage return). You can type "CATALOG" to see the names of the files on the disk.

4) The program will ask you to press a key in order to start the simulation.

5) If you are using the original version (i.e. INTERACTIVE TROUT.ORIGINAL) then the simulation will commence immediately. If you are using the modified version (i.e. INTERACTIVE TROUT) then the program will give you the opportunity to change the policy variables before the simulation begins. To change a policy variable type the new value plus a carriage return in response to the appropriate prompt. For example, if you type 10000 plus a carriage return in response to the prompt "ANNUAL PLANTING (2000000):" then the number of yearling lake trout planted annually will be changed from the old value (2000000) to the new value (10000). Typing a carriage return only in response to a query will leave a value unchanged. A new value, once entered, is used for the remainder of the simulation or until it is changed again.

6) Once the simulation begins, you can interrupt the simulation in order to change the policy variables at any time by pressing the space bar. The program will stop within a few seconds and give you the opportunity to specify new values for the policy variables. Follow the instructions in the instruction above to change a policy variable.

7) The numbers of fish in ageclasses l-9 are printed (in thousands of fish) at the bottom of the screen at the end of every simulated year.

8) A number of variables are plotted on the screen at the end of each simulated year. If you have a Color monitor then the plots for different variables will be in different colors. The variables are described in Table B1.

9) The model will simulate 30 years of lake trout rehabilitation. At the end of the simulation the program will prompt you to either quit or start a new simulation. Press “Q” to quit or any other key will start a new simulation. If you press “Q” accidentally or change your mind about quitting then type “RUN” or “RUN” plus the version name followed by a carriage return.

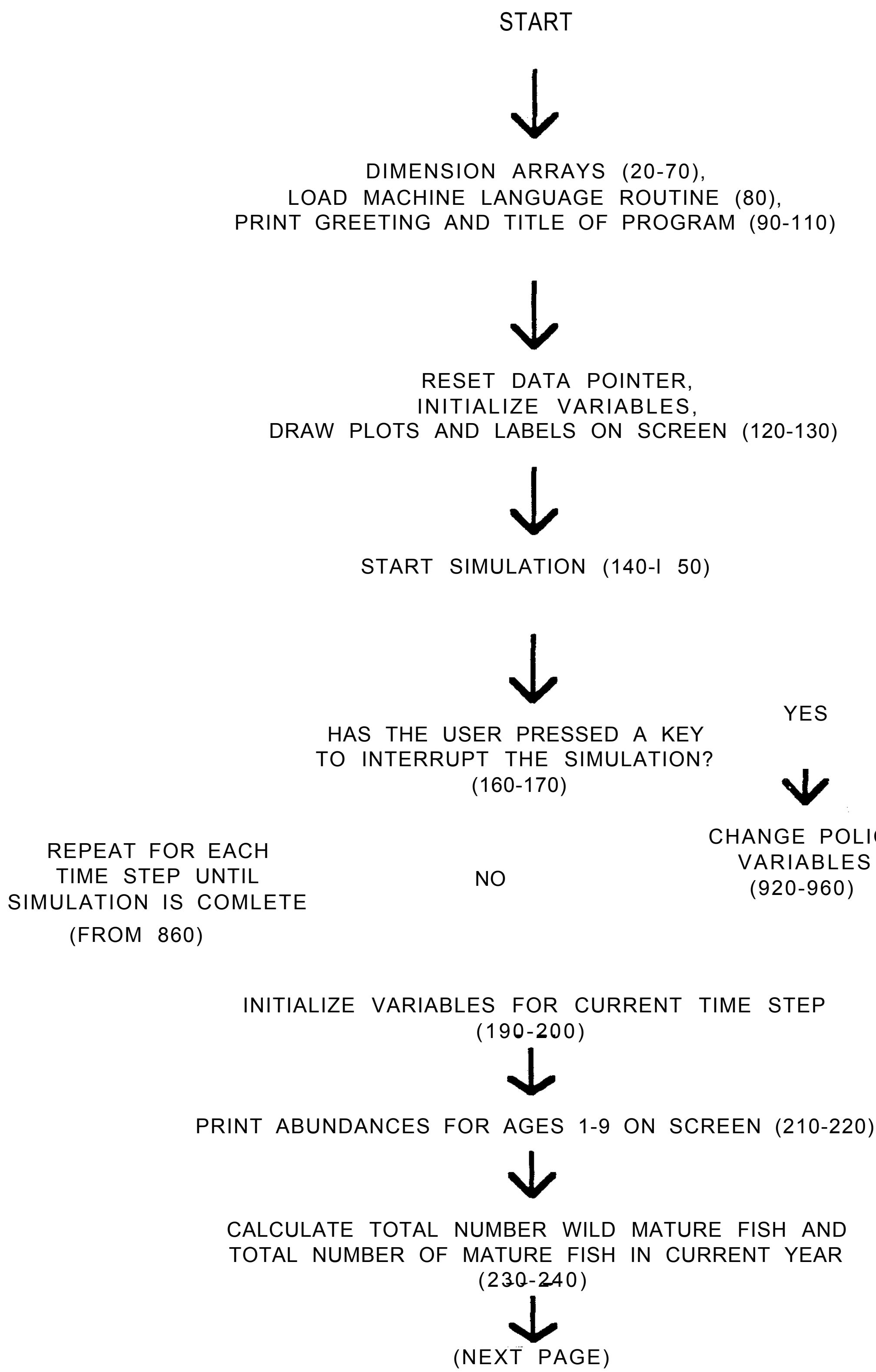
Table B1. Description, plotting color and maximum value for the variables plotted by the Lake Trout Rehabilitation Model.

Description	Color	Maximum Value
Panel 1 (upper left)		
number age 1	white	6 million fish
number age 2	green	6 million fish
number age 3	orange	6 million fish
Panel 2 (upper right)		
% wild yearlings	white	100%
% wild fish age >=5	green	100%
number yearlings stocked	orange	6 million fish
Panel 3 (lower left)		
sport effort	white	10^6 boat days/year
total catch	green	1 million fish
catch of wild fish	orange	1 million fish
Panel 4 (lower right)		
lamprey wounds per fish	white	1 wound per fish
number sea lamprey	orange	300,000

APPENDIX C

FLOWCHART

The following is an informal flowchart that describes the order of computations in the simulation program INTERACTIVE TROUT. Sections of the computer code that draw the graphic images on the screen are omitted from the flowchart for simplicity. The line numbers in the computer program at **which** computations occur are indicated in parentheses.


START
DIMENSION ARRAYS (20-70),
LOAD MACHINE LANGUAGE ROUTINE (80),
PRINT GREETING AND TITLE OF PROGRAM (90-110)
RESET DATA POINTER,
INITIALIZE VARIABLES,
DRAW PLOTS AND LABELS ON SCREEN (120-130)
START SIMULATION (140-I 50)
HAS THE USER PRESSED A KEY
TO INTERRUPT THE SIMULATION?
(160-170)
YES
CHANGE POLICY
VARIABLES
(920-960)
NO
REPEAT FOR EACH
TIME STEP UNTIL
SIMULATION IS COMLETE
(FROM 860)
INITIALIZE VARIABLES FOR CURRENT TIME STEP
(190-200)
PRINT ABUNDANCES FOR AGES 1-9 ON SCREEN (210-220)
CALCULATE TOTAL NUMBER WILD MATURE FISH AND
TOTAL NUMBER OF MATURE FISH IN CURRENT YEAR
(230-240)
(NEXT PAGE)

↓

CALCULATE PROPORTION WILD MATURE FISH IN CURRENT YEAR (250-260)

↓

CALCULATE TOTAL EFFECTIVE EGG DEPOSITION (270-280)

↓

CALCULATE NUMBER OF YEARLINGS PRODUCED FROM EGGS LAID IN CURRENT YEAR (290.310)

↓

CALCULATE TOTAL NUMBER OF YEARLINGS (NATURAL REPRODUCTION + STOCKING) AND THE PROPORTION WILD YEARLINGS FOR CURRENT YEAR (320-330)

↓

CALCULATE ABUNDANCE OF TROUT VULNERABLE TO LAMPREY (340-350)

↓

CALCULATE THE NUMBER OF TROUT VULNERABLE TO FISHING (360-370)

↓

CALCULATE FISHING EFFORT FOR CURRENT YEAR (380-390)

↓

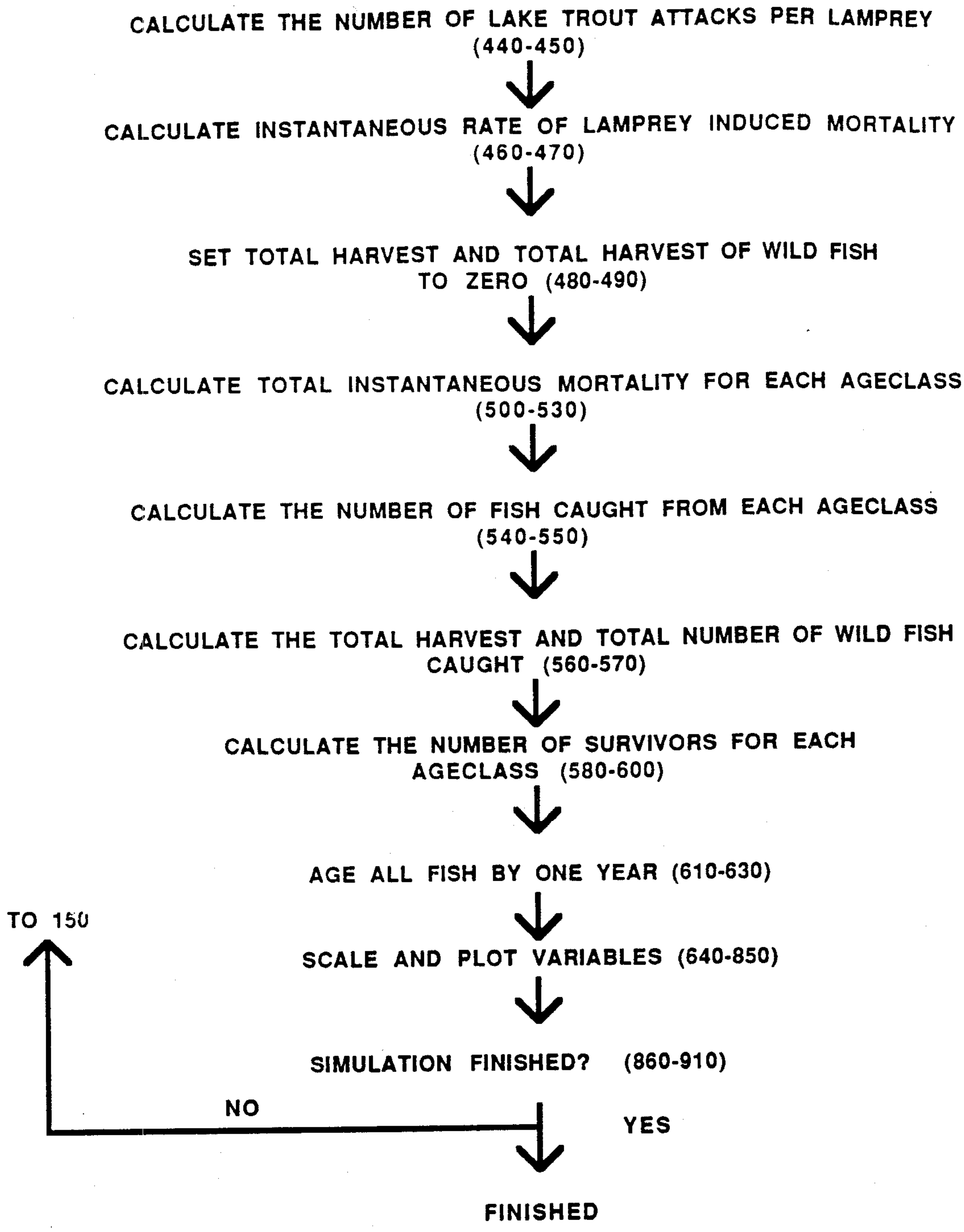
CALCULATE INSTANTANEOUS FISHING RATE FOR FULL RECRUITED AGECLASSES (400-410)

↓

CALCULATE THE NUMBER OF LAMPREY FROM DOLLARS SPENT ON LAMPREY CONTROL (420-430)

↓

(NEXT PAGE)


CALCULATE THE NUMBER OF LAKE TROUT ATTACKS PER LAMPREY (440-450)
CALCULATE INSTANTANEOUS RATE OF LAMPREY INDUCED MORTALITY (460-470)
SET TOTAL HARVEST AND TOTAL HARVEST OF WILD FISH TO ZERO (480-490)
CALCULATE TOTAL INSTANTANEOUS MORTALITY FOR EACH AGECLASS (500-530)
CALCULATE THE NUMBER OF FISH CAUGHT FROM EACH AGECLASS (540-550)
CALCULATE THE TOTAL HARVEST AND TOTAL NUMBER OF WILD FISH CAUGHT (560-570)
CALCULATE THE NUMBER OF SURVIVORS FOR EACH AGECLASS (580-600)
AGE ALL FISH BY ONE YEAR (610-630)
TO 150
SCALE AND PLOT VARIABLES (640-850)
SIMULATION FINISHED? (860-910)
NO
YES
FINISHED

Appendix D

Listing of Computer Code

The following is a complete listing of the Lake Trout Rehabilitation Model named INTERACTIVE TROUT. The dashed lines between lines of computer code are meant to improve readability; they are not part of the code.

```
INTERACTIVE TROUT-VERSION 8   10 JULY 86

---------------------
10     REM  PROGRAM INTERACTIVE TROUT BY
                 CARL WALTERS, VERSION 8
---------------------
20     REM   Z() ARE VALUES TO BE
                 PLOTTED,ZM() ARE MAXIMUM
                 VALUES THAT CAN BE
                 PLOTTED FOR EACH VARIABLE
---------------------
30     DIM Z(20),ZM(20)
---------------------
40     REM        N() ARE AGE SPECIFIC
                 ABUNDANCES,F() ARE AGE
                 SPECIFIC FECUNDITIES, V()
                 ARE THE PROPORTION OF
                 EACH AGECLASS THAT ARE
                 VULNERABLE TO FISHING,
                 R() HOLDS THE PROPORTION
                 WILD YEARLINGS FOR EVERY
                 COHORT IN THE SIMULATION
---------------------
50     DIM N(20),F(20),V(20),R(50)
---------------------
60     REM   HC() HOLDS THE INTEGER
                 VALUES THAT DESIGNATE THE
                 COLORS USED TO PLOT THE
                 VARIABLES, ZO() HOLDS THE
                 ORDINATE VALUE FOR FOR
                 THE POINTS PLOTTED IN THE
                 LAST TIME STEP
---------------------
70     DIM HC(11),ZO(11)
---------------------
80     PRINT CHR$ (4);"BLOAD
                 S.T.UPPER/LOWER
                 CASE,A$800"
     : POKE 232,00
     : POKE 233,08
---------------------
90     REM  PRINT GREETING AND TITLE OF
                 PROGRAM
---------------------
100    TEXT
     : HOME
     : VTAB 10
     : PRINT "    LAKE TROUT
                 REHABILITATION MODEL"
     : PRINT
     : PRINT "TO CHANGE POLICY IN ANY
                 YEAR, SIMPLY   HIT SPACE
                 BAR"
     : PRINT
     : PRINT "TO BEGIN, HIT ANY KEY"
     : GET A$
     : PRINT
---------------------
110    VTAB (24)
---------------------
120    REM    RESET DATA POINTER TO
                 FIRST ELEMENT IN DATA
                 LIST, INITIALIZE
                 VARIABLES, DRAW PLOTTING
                 RECTANGLES AND LABELS ON
                 SCREEN, THEN GIVE USER A
                 CHANCE TO CHANGE
                 MANAGEMENT VARIABLES
---------------------
130    RESTORE
     : GOSUB 1150
     : GOSUB 970
     : GOSUB 920
---------------------
140    REM   START LOOP FOR YEARS 1 TO
                 30
---------------------
150    FOR TI = 0 TO 30
---------------------
160      REM    CHECK AND SEE IF THE
                 USER HAS HIT ANY KEYS, IF
                 SO THEN ASK USER TO
                 MODIFY POLICIES
---------------------
170      X = PEEK ( - 16384)
     :   POKE - 16368,0
     :   IF X > 127 THEN GOSUB 920
---------------------
180      REM       TP = THE CURRENT TIME
                 STEP + NUMBER OF
                 AGECLASSES, R(TP) HOLDS
                 THE PROPORTION WILD
                 YEARLINGS IN THE CURRENT
                 TIME STEP
---------------------
190      REM  W IS THE NUMBER OF MATURE
                 WILD FISH IN THE CURRENT
                 YEAR , T IS THE TOTAL
                 NUMBER OF MATURE FISH IN
                 THE CURRENT YEAP
---------------------
200      TP = TI + NA
     :   W = O
     :   T = 0
---------------------
210      REM    PRINT ABUNDANCES OF
                 FIRST 9 AGECLASSES AT
                 BOTTOM OF SCREEN (SCALED
                 TO UNITS OF 1000 FISH)
---------------------
220      FOR I = 1 TO 9
     :     PRINT INT (N(I) / 1000);" ";
     :   NEXT
     :   PRINT
---------------------
230      REM     CALCULATE TOTAL NUMBER
                 OF YEARLINGS IN CURRENT
                 YEAR (NATURAL
                 REPRODUCTION + STOCKING)
                 THEN STORE THE PROPORTION
                 WILD YEARLINGS IN CURRENT
                 YEAR
---------------------
240      N1 = W1 + ST
     :   R(TP) = W1 / N1
---------------------
```

```
250     REM  CALCULATE TOTAL NUMBER OF
              WILD MATURE FISH AND
              TOTAL NUMBER OF MATURE
              FISH FOR CURRENT YEAR
---------------------
260     FOR A = M TO NA
  :       W = W + R(TP - A) * N(A)
  :       T = T + N(A)
  :     NEXT
---------------------
270     REM  CALCULATE PROPORTION WILD
              MATURE FISH IN CURRENT
              YEAR
---------------------
280     PW = W / (T + 1)
  :     IF PW > 1 THEN PW = 0
---------------------
290     REM  CALCULATE TOTAL EFFECTIVE
              EGG DEPOSITION (E = EGG
              DEPOSITION)
---------------------
300     RS = (1 - PW) * FS - PW * FC
  :     RW = (1 - PW) * FC - PW * FW
---------------------
310     E = 0
  :     FOR A = M TO NA
  :       TA = TP - A
  :       E = E + N(A) * F(A) * ((1 -
              R(TA)) * RS + R(TA) * RW)
  :     NEXT
---------------------
320     REM  CALCULATE THE NUMBER OF
              YEARLINGS (W1) PRODUCED
              FROM SPAWNING
---------------------
330     PM = S1 * E
  :     W1 = PM / (1 + PM / RK) + O
---------------------
340     REM  CALCULATE THE ABUNDANCE OF
              TROUT THAT ARE VULNERABLE
              TO LAMPREY (V)
---------------------
350     V = 0
  :     FOR A = L TO NA
  :       V = V + N(A)
  :     NEXT
---------------------
360     REM  CALCULATE THE NUMBER OF
              TROUT THAT ARE VULNERABLE
              TO FISHING
---------------------
370     VS = 0
  :     FOR A = 1 TO NA
  :       VS = VS + V(A) * N(A)
  :     NEXT
---------------------
380     REM  CALCULATE FISHING EFFORT
              (ES) IN YEAR, IF THE
              FISHING EFFORT IS HIGHER
              THAN THE MAXIMUM ALLOWED
              THEN SET EFFORT EQUAL TO
              THE MAXIMUM
---------------------
390     ES = AE * VS
  :     IF ES > EM THEN ES = EM
---------------------
400     REM  CALCULATE THE
              INSTANTANEOUS FISHING
              RATE FOR FULLY RECRUITED
              AGECLASSES
---------------------
410     FR = QE * ES
---------------------
420     REM  CALCULATE THE NUMBER OF
              LAMPREY (LT) AS A
              FUNCTION OF THE AMOUNT OF
              MONEY SPENT FOR LAMPREY
              CONTROL
---------------------
430     LT = L1 / (1 + LX / L2)
---------------------
440     REM  CALCULATE THE NUMBER OF
              ATTACKS PER LAMPREY
---------------------
450     LA = AL * V / (BL + V)
---------------------
460     REM  CALCULATE THE
              INSTANTANEOUS RATE OF
              MORTALITY DUE TO LAMPREY
              (LM)
---------------------
470     LM = LA * LT * (1 - PL) / V
---------------------
480     REM  INITIALIZE TOTAL HARVEST
              (H) AND TOTAL HARVEST OF
              WILD FISH (WH)
---------------------
490     H = 0
  :     WH = 0
---------------------
500     REM  CALCULATE HARVEST AND
              SURVIVAL FOR EACH
              AGECLASS
---------------------
510     FOR A = 1 TO NA
---------------------
520       REM  CALCULATE TOTAL
              INSTANTANEOUS MORTALITY
              AS NATURAL MORTALITY +
              FISHING MORTALITY +
              LAMPREY MORTALITY
---------------------
530       FA = FR * V(A)
  :       Z = MR + FA
  :       IF A > = L THEN Z = Z + LM
---------------------
540       REM  CALCULATE THE AGE
              SPECIFIC SURVIVAL RATE
              (SU) AND NUMBER OF FISH
              CAUGHT FROM EACH AGECLASS
              (HA)
---------------------
550       SU = EXP ( - Z)
  :       HA = FA * N(A) * (1 - SU) / Z
---------------------
```

```
560        REM  CALCULATE THE TOTAL
                HARVEST (H) AND THE TOTAL
                NUMBER OF WILD FISH
                CAUGHT (WH)
---------------------
570        H = H + HA
   :       WH = WH + HA * R(TP - A)
---------------------
580        REM  CALCULATE THE NUMBER OF
                SURVIVORS IN EACH
                AGECLASS
---------------------
590        N(A) = N(A) * SU
---------------------
600        NEXT
---------------------
610        REM  AGE ALL THE FISH BY ONE
                YEAR
---------------------
620        N(NA) = N(NA) + N(NA - 1)
---------------------
630        FOR A = NA - 1 TO 2 STEP - 1
   :         N(A) = N(A - 1)
   :       NEXT
   :       N(1) = N1
---------------------
640        REM  CALCULATE POSITION ON X-
                AXES FOR PLOTTING CURRENT
                VALUES (Z1 FOR PLOTS ON
                RIGHT SIDE OF SCREEN AND
                Z2 FOR PLOTS ON LEFT SIDE
                OF SCREEN) AND STORE
                OUTPUT VARIABLES IN Z()
                FOR PLOTTING
---------------------
650        REM  Z(1) IS THE NUMBER OF 1
                YEAR OLDS, Z(2) IS THE
                NUMBER OF 5 YEAR OLDS,
                Z(3) IS THE NUMBER OF 10
                YEAR OLDS, Z(4) IS THE
                NUMBER OF YEARLINGS
                STOCKED, Z(5) IS THE
                PROPORTION WILD MATURE
                FISH
---------------------
660        Z1 = TI * ZX
   :       Z2 = Z4 + TI * ZX
   :       Z(1) = N(1)
   :       Z(2) = N(5)
   :       Z(3) = N(10)
   :       Z(4) = ST
   :       Z(5) = PW
---------------------
670        REM  Z(6) IS THE PROPORTION
                WILD YEARLINGS IN CURRENT
                YEAR, Z(7) IS THE SPORT
                EFFORT, Z(8) IS THE
                HARVEST, Z(9) IS THE
                HARVEST OF WILD FISH,
                Z(10) IS THE NUMBER OF
                LAMPREYS, AND Z(11) IS
                LAMPREY WOUNDS PER FISH
---------------------
680        Z(6) = R(TP)
   :       Z(7) = ES
   :       Z(8) = H
   :       Z(9) = WH
   :       Z(10) = LT
   :       Z(11) = LA * LT * PL / V
---------------------
690        REM  IF THERE ARE NO FISH
                VULNERABLE TO LAMPREY
                THEN SET WOUNDS PER FISH
                TO 1
---------------------
700        IF V < 1 THEN Z(11) = 1
---------------------
710        REM  SCALE THE VALUES BEFORE
                PLOTTING
---------------------
720        FOR I = 1 TO 6
   :         Z(I) = Z7 * (UN - Z(I) /
                ZM(I))
   :         IF Z(I) < 0 THEN Z(I) = 0
---------------------
730        NEXT
---------------------
740        FOR I = 7 TO 11
   :         Z(I) = Z8 + Z7 * (UN - Z(I) /
                ZM(I))
   :         IF Z(I) < Z8 THEN Z(I) = Z8
---------------------
750        NEXT
---------------------
760        REM  PLOT THE VALUES
---------------------
770        IF TI = 0 THEN FOR I = 1 TO 3
 * :         HPLOT Z1,Z(I)
 * :       NEXT
 * :       FOR I = 4 TO 6
 * :         HPLOT Z2,Z(I)
 * :       NEXT
 * :       FOR I = 7 TO 9
 * :         HPLOT Z1,Z(I)
 * :       NEXT
 * :       FOR I = 10 TO 11
 * :         HPLOT Z2,Z(I)
 * :       NEXT
 * :       GOTO 850
---------------------
780        FOR I = 1 TO 11
   :         HCOLOR= HC(I)
---------------------
790          ZL = Z3
   :         ZU = Z1
---------------------
800          IF I < 4 THEN 840
---------------------
810          IF I > 3 AND I < 7 THEN ZL =
                Z9
 * :         ZU = Z2
---------------------
820          IF I > 6 AND I < 10 THEN 840
---------------------
830          IF I > 9 THEN ZL = Z9
```

```
 * :     ZU = Z2
---------------------
840     HPLOT ZL,ZO(I) TO ZU,Z(I)
    :   NEXT
---------------------
850     FOR I = 1 TO 11
    :     ZO(I) = Z(I)
    :   NEXT
    :   Z3 = Z1
    :   Z9 = Z2
---------------------
860   NEXT TI
---------------------
870   PRINT "DONE: TYPE 'Q' TO QUIT,
               ANY OTHER KEY"
    : PRINT "TO BEGIN NEW SIMULATION"
    : GET Y$
---------------------
880   REM  IF Y$ <> Q THEN BEGIN AGAIN
---------------------
890   IF Y$ < > "Q" THEN PRINT
  * : PRINT
  * : PRINT
  * : GOTO 130
---------------------
900   REM  IF Y$ = Q THEN QUIT
---------------------
910   TEXT
    : HOME
    : END
---------------------
920   VTAB (24)
    : PRINT "MODIFY POLICIES OR RETURN
               TO KEEP AS IS"
---------------------
930   PRINT "ANNUAL PLANTING (";ST;
    : INPUT "):";A$
    : IF A$ < > "" THEN ST = VAL (A$)
---------------------
940   PRINT "LAMPREY CONTROL $ (";LX;
    : INPUT "):";A$
    : IF A$ < > "" THEN LX = VAL (A$)
---------------------
950   PRINT "MAX FISHING EFFORT (";EM;
    : INPUT "):";A$
    : IF A$ < > "" THEN EM = VAL (A$)
---------------------
960   RETURN
---------------------
970   HGR
    : HCOLOR= 3
    : ROT= 0
    : SCALE= 1
---------------------
980   Z7 = 75
    : Z8 = 84
    : UN = 1
    : ZX = 130 / 30
    : Z4 = 149
---------------------
990   HPLOT 0,0 TO 0,Z7 TO 130,Z7 TO
               130,0 TO 0,0
---------------------
1000  HPLOT 149,0 TO 149,75 TO 279,75
               TO 279,0 TO 149,0
---------------------
1010  HPLOT 0,84 TO 0,159 TO 130,159 TO
               130,84 TO 0,84
---------------------
1020  HPLOT 149,84 TO 149,159 TO
               279,159 TO 279,84 TO
               149,84
---------------------
1030  HPLOT 43,73 TO 43,75
    : HPLOT 43,157 TO 43,159
    : HPLOT 86,73 TO 86,75
    : HPLOT 86,157 TO 86,159
---------------------
1040  HPLOT 192,73 TO 192,75
    : HPLOT 192,157 TO 192,159
    : HPLOT 235,73 TO 235,75
    : HPLOT 235,157 TO 235,159
---------------------
1050  ZN$ = "NOS AT AGES 1,5,10"
    : X = 5
    : Y = 7
    : GOSUB 1440
---------------------
1060  ZN$ = "EFFORT, CATCHES"
    : X = 5
    : Y = 90
    : GOSUB 1440
---------------------
1070  ZN$ = "PLANTING,%WILD"
    : X = 155
    : Y = 7
    : GOSUB 1440
---------------------
1080  ZN$ = "LAMPREY,WOUNDS/FISH"
    : X = 155
    : Y = 90
    : GOSUB 1440
---------------------
1090  ZN$ = "YEAR:"
    : X = 0
    : Y = 80
    : GOSUB 1440
    : X = 149
    : GOSUB 1440
---------------------
1100  ZN$ = "10"
    : X = 34
    : Y = 80
    : GOSUB 1440
    : X = 183
    : GOSUB 1440
---------------------
1110  ZN$ = "20"
    : X = 77
    : GOSUB 1440
    : X = 226
    : GOSUB 1440
---------------------
1120  ZN$ = "30"
    : X = 121
    : GOSUB 1440
```

```
    : X = 265
    : GOSUB 1440
---------------------
1130  RETURN
---------------------
1140  END
---------------------
1150  REM   THE FOLLOWING CONTAINS
            INITIAL VALUES FOR
            VARIABLES AND CONSTANTS
---------------------
1160  REM    S1 = MAX SURVIVAL RATE
             FROM EGG TO YEARLING, RK
             = CARRYING CAPACITY FOR
             WILD YEARLINGS, PL =
             PROBABILITY OF SURVIVING
             A LAMPREY ATTACK
---------------------
1170  REM   FS = RELATIVE SUCCESS FOR
             STOCKED BY STOCKED
             MATING, FC = RELATIVE
             SUCCESS FOR STOCKED BY
             WILD MATING, FW =
             RELATIVE SUCCESS OF WILD
             BY WILD MATING, AND W1 =
             NUMBER YEARLINGS IN
             CURRENT YEAR FROM EGGS
             PRODUCED LAST YEAR
---------------------
1180  S1 = .004
    : RK = 20E6
    : PL [illegible]
    : FS [illegible]
    : FC [illegible] 5
    : FW [illegible]
    : W1 [illegible]
---------------------
1190  REM   AL = MAXIMUM ATTACKS PER
             YEAR FOR ONE LAMPREY, BL
             = TROUT DENSITY NEEDED TO
             ACHIEVE 0.5 * AL, MR =
             NATURAL MORTALITY RATE
             (WITHOUT LAM PREY), O = A
             VERY SMALL NUMBER, M =
             AGE AT MATURITY, L = AGE
             AT VULNERABILITY TO
             LAMPREY
---------------------
1200  AL = 10
    : BL = 30000
    : MR = .3
    : O = 1E - 6
    : M = 7
    : L = 4
---------------------
1210  REM  INITIALIZE AGE SPECIFIC
            FECUNDITIES
---------------------
1220  DATA
             0,0,0,0,0,0,100,1000,2000
             ,3000,4000,5000,6000,7000
             ,8000
    : FOR I = 1 TO 15
    :   READ F(I)
    : NEXT
---------------------
1230  REM  INITIALIZE NUMBERS AT AGE
---------------------
1240  FOR I = 1 TO 20
    :   N(I) = 0
    : NEXT
---------------------
1250  REM  INITIALIZE AGE SPECIFIC
            VULNERABILITIES TO
            FISHING
---------------------
1260  DATA    0,0,0,.1,.3,.7,1,1,1,1
    : FOR I = 1 TO 10
    :   READ V(I)
    : NEXT
    : FOR I = 11 TO 20
    :   V(I) = 1
    : NEXT
---------------------
1270  REM   INITIALIZE NUMBER OF
             LAMPREYS (LT), MONEY
             SPENT ON LAMPREY CONTROL
             (LX), NUMBER OF LAMPREYS
             WITH NO LAMPREY CONTROL
             (L1), AND A CONSTANT USED
             TO CALCULATE THE NUMBER
             OF LAMPREY (L2)
---------------------
1280  LT = 50000
    : LX = 6E6
    : L1 = 2E5
    : L2 = 2E6
---------------------
1290  REM  INITIALIZE NUMBER OF
            YEARLINGS STOCKED
            ANNUALLY
---------------------
1300  ST = 2E6
---------------------
1310  REM  INITIALIZE INSTANTANEOUS
            FISHING MORTALITY RATE
            (FR), A CONSTANT USED TO
            CALCULATE FISHING EFFORT
            (AE), CATCHABILITY
            COEFFICIENT FOR FULLY
            RECRUITED FISH (QE)
---------------------
1320  FR = .15
    : AE = .2
    : QE = 6E - 7
---------------------
1330  REM   INITIALIZE THE MAXIMUM
             FISHING EFFORT ALLOWED
             (EM)
---------------------
1340  EM = 1E6
---------------------
1350  REM   SPECIFY THE NUMBER OF
             AGECLASSES (NA)
---------------------
1360  NA = 15
```

```
---------------------
1370  REM  INITIALIZE THE PROPORTION
             WILD YEARLINGS (R(I))
---------------------
1380  FOR I = 1 TO NA
    :   R(I) = 1E - 9
    : NEXT
---------------------
1390  REM  SPECIFY THE MAXIMUM VALUES
             THAT CAN BE PLOTTED FOR
             EACH VARIABLE
---------------------
1400  DATA   6E6,6E6,6E6,6E6,1,1,
             1E6,1E6,1E6,300000,1
    : FOR I = 1 TO 11
    :   READ ZM(I)
    : NEXT
---------------------
1410  REM   SPECIFY THE COLOR TO BE
             USED FOR PLOTTING EACH
             VARIABLE
---------------------
1420  DATA     3,1,5,5,1,3,3,1,5,5,3
    : FOR I = 1 TO 11
    :   READ HC(I)
    : NEXT
---------------------
1430  RETURN
---------------------
1440  ROT= 0
    : FOR I1 = 1 TO LEN (ZN$)
    :   II = ASC ( MID$ (ZN$,I1,1)) -
             31
    :   IF II < 1 THEN II = 1
---------------------
1450    DRAW II AT X + 6 * I1,Y
    : NEXT
    : RETURN
---------------------
1460  END
```

APPENDIX E

MODIFICATIONS BY THE EDITORS TO THE ORIGINAL MODEL

1) A comment was added to every line of code that had biological significance.

2) The code was renumbered (the first line in the new version is number 10, each line increments by 10).

3) The subscript on the vector F in line 240 of the original version (line 310 in the modified version) was changed from *A-M* to *A.* The fecundity table in line 10030 of the original model was altered to complement the subscript change (lines 1210-1220 in the modified version). As a result of these changes the fecundity table and egg deposition calculations are indexed by age. The modifications do not affect numerical results.

4) The order of calculations in the original model was changed so that the number of yearlings in year t is the sum of yearlings produced from spawning in year t-1 and yearlings stocked in year t. The relevant line numbers are 250-260 in the original version and 240 and 330 in the modified version.

GREAT LAKES FISHERY COMMISSION

SPECIAL PUBLICATIONS

79-1 Illustrated field guide for the classification of sea lamprey attack marks on Great Lakes lake trout. 1979. E. L. King and T. A. Edsall. 41 p.

82-1 Recommendations for freshwater fisheries research and management from the Stock Concept Symposium (STOCS). 1982. A. H. Berst and G. R. Spangler. 24 p.

82-2 A review of the adaptive management workshop addressing salmonid/lamprey management in the Great Lakes. 1982. Edited by J. F. Koonce, L. Greig, B. Henderson, D. Jester, K. Minns, and G. Spangler. 40 p.

82-3 Identification of larval fishes of the Great Lakes basin with emphasis on the Lake Michigan drainage. 1982. Edited by N. A. Auer. 744 p.

83-1 Quota management of Lake Erie fisheries. 1983. Edited by J. F. Koonce, D. Jester, B. Henderson, R. Hatch, and M. Jones. 39 p.

83-2 A guide to integrated fish health management in the Great Lakes basin. 1983. Edited by F. P. Meyer, J. W. Warren, and T. G. Carey. 262 p.

84-1 Recommendations for standardizing the reporting of sea lamprey marking data. 1984. R. L. Eshenroder, and J. F. Koonce. 21 p.

84-2 Working papers developed at the August 1983 conference on lake trout research. 1984. Edited by R. L. Eshenroder, T. P. Poe, and C. H. Olver.

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