FINAL REPORT

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Linking climate change and walleye population dynamics in Lake Erie: an age-structured modeling approach

Elizabeth Marschall and Zhengda Shen

Aquatic Ecology Laboratory

The Ohio State University

1314 Kinnear Road

Columbus OH 43212-1156

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Walleye (*Stizostedion vitreum*) has been a valuable commercial and sport fish species in Lake Erie. The Lake Erie walleye population is composed of both river-spawning and reef-spawning stocks (Colby et al. 1979). Over the past century, walleye abundance in Lake Erie has varied in two ways: 1) within a small range of years, there has been great year-to-year variability in recruitment success and total population size; and 2) as biotic and abiotic conditions in the lake have changed over time (e.g., reduction in phosphorus in the last 25 years), there have been *trends* in walleye recruitment success and total abundance. Addressing both types of variation can allow us to distinguish between natural variation and trends. In this project, the impacts of climate change on walleye population dynamics are the main focus, although changes in the quality of spawning habitats, water quality, and colonization of reefs by exotic species are also important.

Using existing data and our current understanding of Lake Erie sportfish ecology, we have built a model to help us differentiate between 1) population variation that arises as a natural result of variation in abiotic conditions (e.g., weather) and natural variation in resources and predators and 2) population trends arising from directional changes in the environment and indicative of a long-term change.

Timing of spring storms can be important in determining survival of walleye eggs and larvae. In river-spawned walleye, storms that occur after walleye have hatched and while they are moving downstream as larvae can cause great mortality via high river discharge (Mion et al. 1998). In reef-spawned walleye, storms that occur during the egg stage can cause great mortality via abrasive wave action (Busch et al. 1975; Roseman et al. 1996). Although the lifestage of greatest vulnerability differs between river and reef, these lifestages probably occur at about the same time because river spawning occurs a couple of weeks before reef spawning (Parrish et al. 1989). Thus, recruitment of the whole population may be affected by a given storm (Mion et al 1998). Whether a large wave- and discharge- producing storm occurs during this vulnerable period in a given year really can be considered a matter of chance. Thus, we began by characterizing the historical timing of large storms relative to the timing of egg deposition.

Our overall goal in this modeling approach is to interpret the meaning of variation and trends in Lake Erie walleye population dynamics such that we can separate effects of management actions and other changes in the lake from effects of random patterns in weather, and thereby increase the credibility of management decisions. Using a model such as this, we can simulate many possible states of the system under a given set of weather and prey distributions (derived from historical data) combined with assumptions of their effects on population vital rates. This allows us to generate a frequency distribution of states of the population under a given set of assumptions. Thus, we are taking an approach analogous to "risk assessment" as used by conservation biologists, but rather than looking at likelihoods of population extinction, we are looking at likelihoods of a variety of other states of Lake Erie walleye population dynamics. Not only is it useful to see the distribution of population sizes that might arise from a given set of inputs, but it may be more important to see the distribution of population *trajectories* that might arise. For example, if a single set of climate and demographic inputs easily can give rise to both longterm increase and longterm declines in a given species, due only to random timing of weather patterns (for example), then making management decisions to change an observed increase or decline seems somewhat futile.

Initial Goals

1. Develop a model framework to investigate the effect of annual variation in weather on longterm trends in walleye populations
2. Gather walleye demographic data and Lake Erie weather data from published literature, agencies, and individual researchers for use as model input
3. Build a flexible Visual Basic computer program to run the model
4. Produce model output to illustrate the approach and its potential use in understanding what drives longterm variation in Lake Erie fish population dynamics

ACCOMPLISHMENTS

Model structure

The model begins with a simple age-structured representation of a hypothetical population. For simplicity in this illustration, we modeled the population as consisting of age 0, 1, 2, 3, 4, 5, 6, and age 7+. We assumed that 80% of age 2 females and 100% of age 3 and older females were adults. For adult walleye, we assumed that the male:female ratio was 1:1.

The initial population sizes and survival rates for age 2 and older were developed from the catch-at-age analysis (CAGEAN, Ohio Division of Wildlife, Ohio Department of Natural Resources). For age-1 walleye, we assumed the annual survival rate was 0.6 and the initial size was extrapolated from the age-2 population size of the next consecutive year.

We built age-structured models for both reef- and river-spawning populations of walleye in Western Lake Erie. We assumed that the proportion of the reef- and river-spawning walleye population were 60 and 40 percent of total population size, respectively.

Young-of-year (YOY) Dynamics

We modeled fecundity (F) as a function of body mass (W, in grams) (Wolfert 1969):

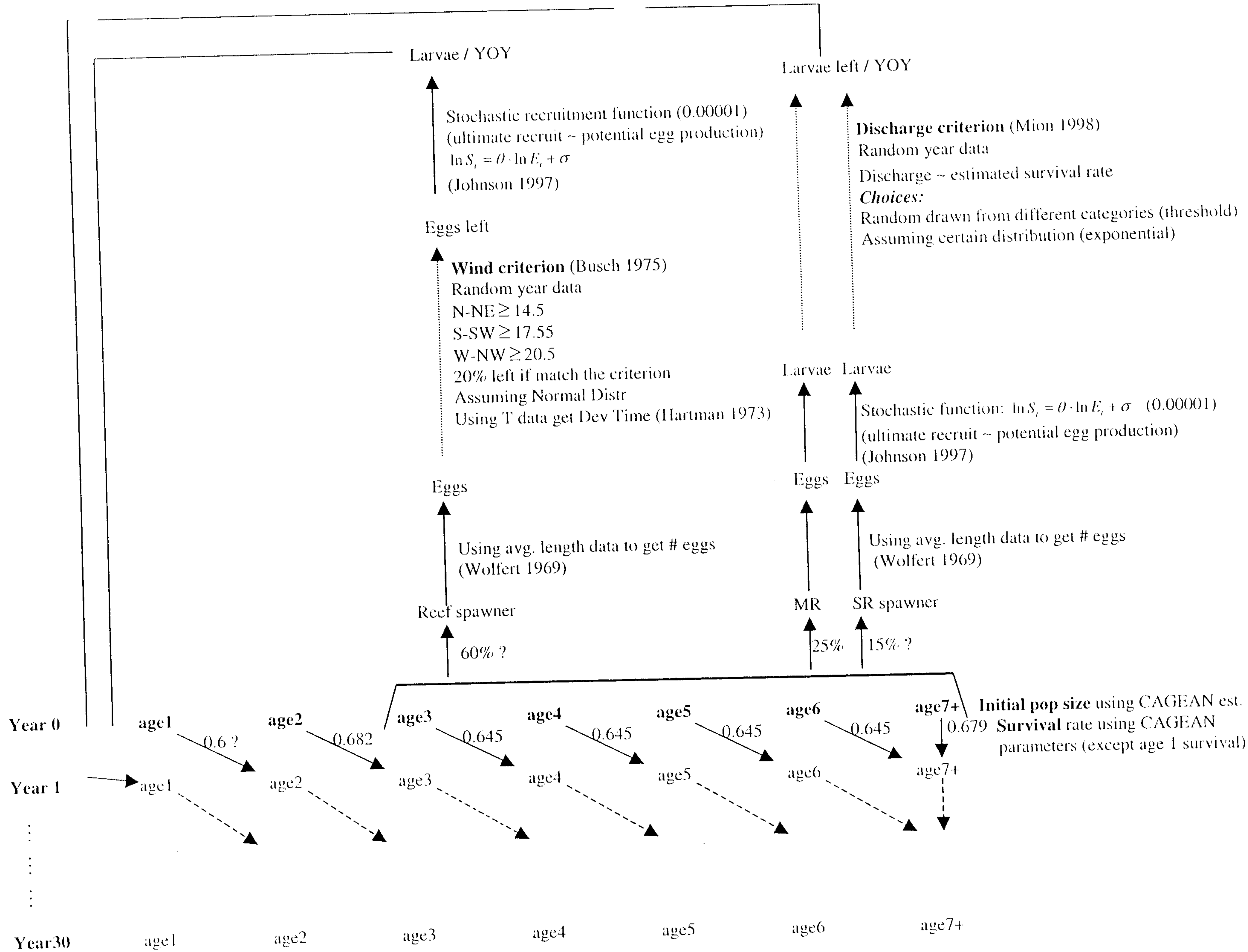
$$\log F = 1.541 + 1.111 \log W$$

Reef-spawning walleye

In reef-spawned walleye, storms that occur during the egg stage can cause great mortality via abrasive wave action (Busch et al. 1975; Roseman et al. 1996). We used the criteria developed by Busch et al (1975) to determine when wind conditions were severe enough to cause egg mortality. When the wind direction and intensity data matched one of the following criteria, we assumed 80% mortality of eggs present in that day: N-NE $\geq$ 14.5 km/h, S-SW $\geq$ 17.55 km/h, or W-NW $\geq$ 20.5 km/h (Bush et al.1975). We used 1960-1999 Toledo windspeed data from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA).

Water temperatures that rise steadily and quickly in the spring during the time of spawning and incubation of eggs produce rapid egg and larval development (Busch et al. 1975, Hartman 1972). This leads to good survival through the spring and has been correlated with strong walleye year classes in Lake Erie (Madenjian et al. 1996). We assumed that eggs are deposited over time according to a normal probability distribution function, with mean egg deposition date set to the midpoint of the average of the first and last spawning days and the standard deviation equal to the number of days between first

Simulated Walleye Population Dynamic Model Structure



Simulation: Probability distribution of the slopes (including the last 5 years for each simulation)
Global warming simulation (randomly draw warmer year) etc.

and last divided by 1.96. We assumed that spawning begins and ends on the days when water temperature first exceeds 5 and 11°C, respectively (Jones et al. 1998). The hatching time of eggs for each spawning date is estimated from Hartman (1973),

$$Y = -5.481 + 1.062 \cdot T$$

where Y is average percentage of development per day towards hatching, and T is mean daily incubation temperature. The eggs will survive and hatch to become larvae if and only if the total percentage of development time equals or exceeds 100 percent before a storm occurs.

A stock recruitment function determines the ultimate recruitment (S_t) from potential egg production (E_t):

$$\ln S_t = \theta \cdot \ln E_t + \sigma ,$$

where $\sigma = .00025$ sets the upper limit of survival and $\theta = -.169$ reduces the survival to 0.00001 at an egg density of 10^8. (Johnson and Henderson 1997 p7) (parameters can be adjusted according to model sensitivity).

River-spawning walleye

We separated the river-spawning population into a Sandusky River population (35% of total spawning population) and a Maumee River population (5% of total).

We used the same stock recruitment function as that for reef-spawning walleye, but with different parameters, to model the ultimate recruitment (S_t) from potential egg production (E_t).

Down-river transport of larval walleye is passive. Mion et al. 1998 found that survival during transport is always low when average river velocity (computed from daily discharge/cross-sectional area) was larger than 0.2 m/s, but can be very high when velocity was less than 0.2 m/s. Thus low discharge (velocity) is a necessary although not sufficient condition for high survival during transport. At the same time, if river transport is too slow, starvation may become a factor if larvae do not reach habitats with sufficient prey before their yolk reserves are depleted. For simplicity in this prototype model, we used relationships only between river velocity and survival (Mion et al. 1998) to estimate river-transport survival. We selected survival estimates from one of two groups, based on the river velocities the cohort experienced. If the velocity was less than 0.2 m/s, we randomly selected a survival estimate from group I; otherwise, we used a negative exponential function describing survival as a function of river velocity (Mion et al. 1998). We used US Geological Survey 1960-1999 discharge data from the Sandusky River and Maumee River in the simulations.

Population Dynamics

We modeled $N_{y,a}$ the number of fish in age-class a in year and y as:

$$N_{y,a} = \begin{cases} N_{y-1,a-1} * Z_{y-1} & \text{if } 1 \le a < 7 \\ N_{y-1,a-1} * Z_{y-1} + N_{y-1,a} * Z_{y-1} & \text{if } a = 7 \end{cases}$$

where Z_y is the annual survival estimated by the Ohio Division of Wildlife.

The computer model we have developed simulates the short-term and long-term trends in walleye population dynamics. The model itself is written in Visual Basic (Appendix I). The input data are stored in an MS Access file, which is dynamically linked with the program code.

Current Status

The current model is a prototype. The model structure, program, and linkage to the database are all complete, but the input data require modification and completion before we will have a realistic representation of the Lake Erie walleye population. For example, we are currently unsatisfied with the way in which survival is driven by river discharge. We continue to work with Joe Mion to use his data to derive a more realistic representation of this process. Because this interaction between discharge (which is driven by rain) and larval survival in the rivers drives much of the population dynamics in this model, it is vital that we represent it as accurately as possible.

References

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Appendix 1 Visual Basic code for Walleye Population Dynamics Model

```
'*****************************
'*****General Declarations*****
'*****************************

Dim numYears As Integer, maxSize As Double
Dim iter As Single, year As Integer

Dim rndYear As String
Dim DBase As Database
Dim length(1 To 7) As Single
Dim lag(0 To 100) As Single
Dim para(1 To 50, 1 To 50) As Single

Dim ini_rv As Single, ini_rf As Single

Dim rf_abund(1 To 50) As Single, mr_abund(1 To 50) As Single, sr_abund(1 To 50) As Single
Dim rf_sum As Single, mr_sum As Single, sr_sum As Single, rv_sum As Single

Dim reef(1 To 50) As Double, river(1 To 50) As Double, total(1 To 50) As Double

Const pi = 3.1415926
'##########################################################################################

'****************************************************************
'*****Subroutine for Sandusky river spawned walleye population*****
'****************************************************************

Sub SR_Spawn()

'~~~get abiotic data for the random year from climate.mdb~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim SQLquery As String, rstSRiver As Recordset

Debug.Print "sr_rndYear="; rndYear

SQLquery = "SELECT sand.date, sand.discharge FROM sand WHERE sand.Year = '" & rndYear & "' AND
sand.date > 45 AND sand.date < 85 AND sand.discharge > 5000"

Set rstSRiver = DBase.OpenRecordset(SQLquery)
   rstSRiver.MoveLast
   rstSRiver.MoveFirst

ReDim srDate(rstSRiver.RecordCount) As Integer
ReDim Discharge(rstSRiver.RecordCount) As Single

dayi = 0
Do While Not rstSRiver.EOF
   srDate(dayi) = rstSRiver("Date")
   Discharge(dayi) = rstSRiver("discharge")

'  Debug.Print "discharge="; Discharge(dayi); "**"; srDate(dayi)
'  Debug.Print "Rivday="; srDate(dayi)
```

```
  dayi = dayi + 1
  rstSRiver.MoveNext
Loop

'~~~Calculate total number of eggs/LARVAL survived~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim AvgEggs(1 To 7) As Double, sr_Eggs As Double
Dim Eggs_by_class(1 To 7) As Double

'~~~~~~~~~~~~~~~~
Call length_distr   'get length data from climate.female_l
'~~~~~~~~~~~~~~~~

sr_Eggs = 0
For agei = 3 To 7
'  Debug.Print ":"; length(agei)

   AvgEggs(agei) = 10 ^ (-5.293 + 3.829 * log10(length(agei)))
'  Debug.Print "AvgEggs"; agei; "="; AvgEggs(agei)

'  Debug.Print "sr_abund"; agei; "="; sr_abund(agei)
   Eggs_by_class(agei) = sr_abund(agei) * AvgEggs(agei)
   sr_Eggs = Eggs_by_class(agei) + sr_Eggs
'  Debug.Print "sr_Eggs="; sr_Eggs
Next agei
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

'~~~eggs to larve in river (before consider the dishcarge influence)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Let sr_larve = sr_Eggs * 0.00001     'eggs survival rate = 0.0001

'~~~Calculate normally distributed Larva left~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim larve(1 To 365) As Single
For i = 45 To 85
mean = (45 + 85) / 2
var = (85 - mean) / 2.58

   badyear = 0          'blocked!
   For j = 0 To dayi - 1
      If i = srDate(j) Then badyear = 1
   Next j

      If badyear = 1 Then
         larve(i) = 0
      Else
         larve(i) = NormPDF(i, mean, var) * sr_larve
      End If

'  Debug.Print "larve"; i; "="; larve(i)

Next i

sr_larve = 0
For i = 45 To 85
```

```
   sr_larve = sr_larve + larve(i)      'total larve left
Next i
'  Debug.Print "sr_larve="; sr_larve

'~~~Survival rate (CAGEAN 1997 estimates, except age 1 walleye)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For m = 1 To 7
   For n = 1 To 7
      para(m, n) = 0
   Next n
Next m

para(2, 1) = 0.6       'Survival of age 1
para(3, 2) = 0.682     'Survival of age 2
para(4, 3) = 0.645     'Survival of age 3
para(5, 4) = 0.645     'Survival of age 4
para(6, 5) = 0.645     'Survival of age 5
para(7, 6) = 0.645     'Survival of age 6
para(7, 7) = 0.679     'Survival of age 7+

'~~~Reproductivity of walleye from age 3 to 7+~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For agei = 3 To 7
   Let para(1, agei) = AvgEggs(agei)
'  Debug.Print "para(1,"; agei; ")="; para(1, agei)
Next agei

'~~~show the matrix~~~
'~~~~~~~~~~~~~~~~~~~~~~
Picture3.Print
For i = 1 To 7
'  For j = 1 To 7
'  Picture3.Print para(i, j),
'  Next j: Picture3.Print
Next i
'~~~~~~~~~~~~~~~~~~~~~~~

'~~~Calculate reef population size~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim sr_Y(1 To 50) As Single

For i = 1 To 7

   sr_Y(i) = 0
   For j = 1 To 7
      sr_Y(i) = sr_Y(i) + para(i, j) * sr_abund(j)
   Next j
Next i

For i = 1 To 7
   sr_abund(i) = sr_Y(i)
   sr_abund(1) = sr_larve    'all larve survived will be the age 1 fish of next year

'  Debug.Print "sr_E_yr"; i; "="; sr_abund(i)
Next i
```

```
sr_sum = 0
For i = 1 To 7
   sr_sum = sr_sum + sr_abund(i)
Next i
'   Debug.Print "rv_sum="; sr_sum

End Sub
'#################################################################################################


'**************************************************
'*****Egg development time from Hartman (1973)*****
'**************************************************

Sub dev_date()

'~~~extracts the data for the randomly picked year~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Set DBase = OpenDatabase("d:\zs\climate.mdb")
Dim SQLqq As String, rstDevT As Recordset

SQLqq = "SELECT wind.date,wind.temp FROM wind WHERE wind.Year = '" & rndYear & "' AND wind.date >
103 AND wind.date < 180"  'actual date of 170 is 150

Set rstDevT = DBase.OpenRecordset(SQLqq)
   rstDevT.MoveLast
   rstDevT.MoveFirst

ReDim DevDay(rstDevT.RecordCount) As Integer
ReDim Temp(rstDevT.RecordCount) As Double
ReDim Propeggdev(rstDevT.RecordCount) As Single

'Let a = -5.481: b = 1.062
dayi = 0
Do While Not rstDevT.EOF
   DevDay(dayi) = rstDevT("Date")
   Temp(dayi) = rstDevT("Temp")
   Propeggdev(dayi) = (-5.481 + 1.062 * Temp(dayi)) / 100

   If Propeggdev(dayi) < 0 Then Propeggdev(dayi) = 0

'   Debug.Print "Temp="; Temp(dayi); "Date="; DevDay(dayi)
'   Debug.Print "Day"; dayi; "Prop="; PropEggDev(dayi)

   dayi = dayi + 1
   rstDevT.MoveNext
Loop

'~~~the hatch date for eggs spawned on dayi~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Debug.Print "How much record?"; rstDevT.RecordCount
Debug.Print

For i = 0 To rstDevT.RecordCount - 1

'   Debug.Print "Day"; i; "Prop="; Propeggdev(i)
```

```
  SumEggDev = 0
  hatchday = i
  Do While SumEggDev < 1# And i < 70
    SumEggDev = SumEggDev + Propeggdev(hatchday)
    hatchday = hatchday + 1
  Loop

  lag(i) = hatchday - i

'  Debug.Print "hatchday"; i; "="; hatchday - i
'  Debug.Print "***"; lag(i)

Next i

End Sub
'##########################################################################################

'************************************
'*****Female length distribution*****
'************************************

Sub length_distr()

Dim SQL As String, rstLen As Recordset
SQL = "SELECT female_l.year, female_l.age, female_l.length FROM female_l WHERE female_L.Year=" & 1986
& ""
Set rstLen = DBase.OpenRecordset(SQL)
  rstLen.MoveLast
  rstLen.MoveFirst

ReDim RivDay(rstLen.RecordCount) As Integer
ReDim age(rstLen.RecordCount) As Single
ReDim leng(rstLen.RecordCount) As Single

Debug.Print "How much records?"; rstLen.RecordCount

di = 0
Do While Not rstLen.EOF
  RivDay(di) = rstLen("Year")
  age(di) = rstLen("age")
  leng(di) = rstLen("length")

'  Debug.Print "age="; age(di); "length="; leng(di)

  length(di + 1) = leng(di)
'  Debug.Print "()"; length(di + 1)
  di = di + 1
  rstLen.MoveNext
Loop

End Sub
'##########################################################################################

'*************************************
'*****Normal probability function*****
```

```
'***********************************

Function NormPDF(x, mean, var)
   NormPDF = ((var * Sqr(2 * pi)) ^ (-1)) * Exp(-(x - mean) ^ 2 / (2 * var ^ 2))
End Function
'#####################################################################################################

'***********************
'*****Log10 function*****
'***********************

Static Function log10(x)
   log10 = Log(x) / Log(10#)
End Function
'#####################################################################################################

'**************************************************
'*****extracts the years, and randomly picks one*****
'**************************************************

Sub RanYear()

Set DBase = OpenDatabase("d:\zs\climate.mdb")
Dim rstYearDist As Recordset

Set rstYearDist = DBase.OpenRecordset("wind")
   rstYearDist.MoveLast
ReDim YearDist(rstYearDist.RecordCount)
   rstYearDist.MoveFirst

yeari = 0
Do While Not rstYearDist.EOF
   YearDist(yeari) = rstYearDist("Year")
'   Debug.Print YearDist(yeari)
   yeari = yeari + 1
   rstYearDist.MoveNext
Loop
'   Debug.Print rstYearDist.RecordCount

Randomize
rndYear = YearDist(Int(rstYearDist.RecordCount * Rnd))

Debug.Print "Random year"; year; "="; rndYear

End Sub
'#####################################################################################################

'***********************************
'*****Draw X-Y axes using maxsize*****
'***********************************

Sub DrawAxes()
Let maxSize = 150000000

Picture1.Scale (-0.5, 1.2 * maxSize)-(numYears + 1, -0.2 * maxSize)
Picture1.Line (-0.1, 0)-(numYears + 1, 0)
```

```
Picture1.Line (0, -0.02 * maxSize)-(0, 1.2 * maxSize)
End Sub
'####################################################################################################

'******************************
'*****Draw date in Picture1*****
'******************************

Sub DrawData(reef() As Double, river() As Double, total() As Double)

   Let ini_sum = ini_rf + ini_rv
   Picture1.Circle (0, ini_rf), 0.006 * numYears
   Picture1.Circle (0, ini_rv), 0.006 * numYears
   Picture1.Circle (0, ini_sum), 0.006 * numYears

Dim i As Integer
For i = 1 To numYears
   If i < numYears Then
      Let Picture1.DrawStyle = 2
      Picture1.Line (i, reef(i))-(i + 1, reef(i + 1))

      Let Picture1.DrawStyle = 1
      Picture1.Line (i, river(i))-(i + 1, river(i + 1))

      Let Picture1.DrawStyle = 0
      Picture1.Line (i, total(i))-(i + 1, total(i + 1))
   End If

   Picture1.Circle (i, reef(i)), 0.004 * numYears
   Picture1.Circle (i, river(i)), 0.004 * numYears
   Picture1.Circle (i, total(i)), 0.004 * numYears
Next i

End Sub
'####################################################################################################

'******************************
'*****Locate X Y in Picture1*****
'******************************

Sub Locate(x As Single, y As Single)
Let Picture1.CurrentX = x
Let Picture1.CurrentY = y
End Sub
'####################################################################################################

'**************************************************
'*****Read data (simulation results) from database*****
'**************************************************

Sub ReadData(label() As Integer, reef() As Double, river() As Double, total() As Double)

Dim i As Integer
Dim a As Single, b As Single    'Stuck here!!!

Open "d:\zs\walleye.txt" For Input As #4
```

```
For iter = 1 To Text2.Text

Let maxSize = 0
For i = 1 To numYears
   Input #4, label(i), reef(i), river(i)
      total(i) = (reef(i) + river(i))
   If total(i) > maxSize Then
      maxSize = total(i)
   End If
Next i

sig = 10
If numYears >= 5 Then
   For j = numYears - 4 To numYears

   ndata = 5

   sx = 0
   sy = 0
   st2 = 0
   b = 0
      If mwt <> 0 Then
      ss = 0
         For i = numYears - 4 To numYears
         wt = 1 / sig ^ 2
         ss = ss + wt
         sx = sx + label(i) * wt
         sy = sy + total(i) * wt
         Next i
      Else
         For i = numYears - 4 To numYears
         sx = sx + label(i)
         sy = sy + total(i)
         Next i
      ss = CSng(ndata)
      End If

      sxoss = sx / ss

      If mwt <> 0 Then
         For i = numYears - 4 To numYears
            t = (label(i) - sxoss) / sig
            st2 = st2 + t * t
            b = b + t * total(i) / sig
         Next i
      Else
         For i = numYears - 4 To numYears
            t = label(i) - sxoss
            st2 = st2 + t * t
            b = b + t * total(i)
         Next i
      End If

      b = b / st2
      a = (sy - sx * b) / ss
```

```
   Next j

Else
End If

Open "d:\zs\we_slope.txt" For Append As #2
Write #2, b
Close #2

'Debug.Print "Intercept="; a
Debug.Print "slope="; b

Next iter

Close #4

End Sub
'#########################################################################################

'*****************************************************
'*****Subroutine for reef spawned walleye population*****
'*****************************************************

Sub Rf_Spawn()

'~~~get abiotic data for the random year from climate.mdb~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim SQLquery As String, rstReef As Recordset
'Debug.Print "rf_rndYear="; rndYear
'Let rndYear = 1989

SQLquery = "SELECT wind.date, wind.speed, wind.direction FROM wind WHERE wind.Year = '" & rndYear & "' AND wind.date > 53 AND wind.date < 100 AND wind.speed >= 14.5 AND wind.direction >=0 AND wind.direction < 9 or wind.Year = '" & rndYear & "' AND wind.date > 53 AND wind.date < 100 AND wind.speed >= 17.5 AND wind.direction >= 18 AND wind.direction <27  or wind.Year = '" & rndYear & "' AND wind.date > 53 AND wind.date < 100 AND wind.speed >= 20.5 AND wind.direction >= 27 AND wind.direction <36"      'need to rewrite year and date

Set rstReef = DBase.OpenRecordset(SQLquery)
   rstReef.MoveLast
   rstReef.MoveFirst

ReDim RfDate(rstReef.RecordCount) As Integer
ReDim speed(rstReef.RecordCount) As Single
ReDim Direction(rstReef.RecordCount) As Single

dayi = 0
Do While Not rstReef.EOF
   RfDate(dayi) = rstReef("Date")
   speed(dayi) = rstReef("Speed")
   Direction(dayi) = rstReef("Direction")

'  Debug.Print "Speed="; speed(dayi); "Direction="; Direction(dayi)
'  Debug.Print "dayi="; dayi; "RfDate="; RfDate(dayi)
dayi = dayi + 1
   rstReef.MoveNext
```

```
Loop

'~~~test~~~~
For j = 0 To dayi - 1
'   Debug.Print "Should Delete..."; RfDate(j)
Next j

'~~~Calculate total number of eggs available~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim AvgEggs(1 To 7) As Double, Rf_Eggs As Double
Dim Eggs_by_class(1 To 7) As Double

'~~~~~~~~~~~~~~~~
Call length_distr   'get length data from climate.female_l
'~~~~~~~~~~~~~~~~

Rf_Eggs = 0
For agei = 3 To 7
    AvgEggs(agei) = 10 ^ (-5.293 + 3.829 * log10(length(agei)))
'   Debug.Print ":"; length(agei)
'   Debug.Print "AvgEggs"; agei; "="; AvgEggs(agei)

'   Debug.Print "Rf_abund"; agei; "="; rf_abund(agei)
   Eggs_by_class(agei) = rf_abund(agei) * AvgEggs(agei)
   Rf_Eggs = Eggs_by_class(agei) + Rf_Eggs
'   Debug.Print "Rf_Eggs="; Rf_Eggs
Next agei

'~~~~~~~~~~~~
Call dev_date
'~~~~~~~~~~~~

For i = 1 To 50
'   Debug.Print "lag"; i + 52; "="; lag(i)
Next i

'~~~Normally distributed eggs~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim eggs(1 To 365) As Single

For i = 53 To 100
mean = (53 + 100) / 2
var = (100 - mean) / 2.58

'~~~first idea to calculate the dev time
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
'   badyear = 0
'   For j = 0 To dayi - 1
'       If i = RfDate(j) Then badyear = 1
'   Next j
'   If badyear = 1 Then    'blocked! change 0 and 1
'Debug.Print "**"; lag(i - 52)
'       eggs(i) = 0
'       eggs(i - 1) = 666
'       eggs(i - lag(i - 52)) = 888
'   Else
```

```
'      eggs(i) = NormPDF(i, mean, var) * Rf_Eggs
'   End If
'Debug.Print "~~~~"; lag(i - 52)     'give all lag days

    badyear = 0
    For j = 0 To dayi - 1
       If i + lag(i - 52) > RfDate(j) And i < RfDate(j) Then badyear = badyear - 1
    Next j

'   Debug.Print "badyear"; i; "="; badyear

    If badyear < 0 Then
       eggs(i) = 0.2 * NormPDF(i, mean, var) * Rf_Eggs   '80% eggs will be lost
    Else
       eggs(i) = NormPDF(i, mean, var) * Rf_Eggs
    End If

Next i

'For i = 53 To 100
'Debug.Print "eggs"; i; "="; eggs(i)     'blocked again, move outside!!!
'Next i

'~~~total egg left~~~
'~~~~~~~~~~~~~~~~~~~~
Rf_Eggs = 0
For i = 45 To 85
   Rf_Eggs = Rf_Eggs + eggs(i)
Next i
'Debug.Print "rf_eggs="; rf_Eggs

'~~~eggs to larve in reef (after consider the wind influence)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Let rf_larve = Rf_Eggs * 0.00001     'eggs survival rate = 0.00001
'Debug.Print "rf_larve="; rf_larve

'~~~Survival rate (CAGEAN 1997 estimates, except age 1 walleye)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For m = 1 To 7
   For n = 1 To 7
      para(m, n) = 0
   Next n
Next m

   para(2, 1) = 0.6      'Survival of age 1
   para(3, 2) = 0.682    'Survival of age 2
   para(4, 3) = 0.645    'Survival of age 3
   para(5, 4) = 0.645    'Survival of age 4
   para(6, 5) = 0.645    'Survival of age 5
   para(7, 6) = 0.645    'Survival of age 6
   para(7, 7) = 0.679    'Survival of age 7+

'~~~Reproductivity of walleye from age 3 to 7+~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For agei = 3 To 7
   Let para(1, agei) = AvgEggs(agei)
```

```
'   Debug.Print "para(1,"; agei; ")="; para(1, agei)
Next agei

'~~~show the matrix~~~
'~~~~~~~~~~~~~~~~~~~~~~
Picture2.Print
For i = 1 To 7
'   For j = 1 To 7
'   Picture2.Print para(i, j),
'   Next j: Picture2.Print
Next i

'~~~Calculate reef population size~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim rf_Y(1 To 50) As Single

For i = 1 To 7
   rf_Y(i) = 0
   For j = 1 To 7
      rf_Y(i) = rf_Y(i) + para(i, j) * rf_abund(j)
   Next j
Next i

For i = 1 To 7
   rf_abund(i) = rf_Y(i)
   rf_abund(1) = rf_larve    'all larve survived will be the age 1 fish of next year
'   Debug.Print "Rf_E_yr"; i; "="; rf_abund(i)
Next i

rf_sum = 0
For i = 1 To 7
   rf_sum = rf_sum + rf_abund(i)
Next i
'   Debug.Print "rf_sum="; reef_sum

End Sub
'##########################################################################################

'*************************************************************
'*****Subroutine for Maumee river spawned walleye population*****
'*************************************************************

Sub MR_Spawn()

'~~~get abiotic data for the random year from climate.mdb~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim SQLquery As String, rstMRiver As Recordset

Debug.Print "mr_rndYear="; rndYear

SQLquery = "SELECT maumee.date, maumee.discharge FROM maumee WHERE maumee.Year = " & rndYear &
"' AND maumee.date > 45 AND maumee.date < 85 AND maumee.discharge > 5000"

Set rstMRiver = DBase.OpenRecordset(SQLquery)
   rstMRiver.MoveLast
   rstMRiver.MoveFirst
```

```
ReDim mrDate(rstMRiver.RecordCount) As Integer
ReDim Discharge(rstMRiver.RecordCount) As Single

dayi = 0
Do While Not rstMRiver.EOF
   mrDate(dayi) = rstMRiver("Date")
   Discharge(dayi) = rstMRiver("discharge")

'   Debug.Print "discharge="; Discharge(dayi); "**"; mrDate(dayi)

   dayi = dayi + 1
   rstMRiver.MoveNext
Loop

'~~~Calculate total number of eggs/LARVAL fish survived~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim AvgEggs(1 To 7) As Double, mr_Eggs As Double
Dim Eggs_by_class(1 To 7) As Double

'~~~~~~~~~~~~~~~~
Call length_distr   'get length data from climate.female_l
'~~~~~~~~~~~~~~~~

mr_Eggs = 0
For agei = 3 To 7
'   Debug.Print ":"; length(agei)

   AvgEggs(agei) = 10 ^ (-5.293 + 3.829 * log10(length(agei)))
'   Debug.Print "AvgEggs"; agei; "="; AvgEggs(agei)
'   Debug.Print "mr_abund"; agei; "="; mr_abund(agei)
   Eggs_by_class(agei) = mr_abund(agei) * AvgEggs(agei)
   mr_Eggs = Eggs_by_class(agei) + mr_Eggs
'   Debug.Print "mr_Eggs="; mr_Eggs
Next agei
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

'~~~eggs to larve in river (before consider the dishcarge influence)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Let mr_larve = mr_Eggs * 0.00001      'eggs survival rate = 0.00001

'~~~Calculate normally distributed Larva left~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim larve(1 To 365) As Single
For i = 45 To 85
mean = (45 + 85) / 2
var = (85 - mean) / 2.58

   badyear = 0            'blocked!
   For j = 0 To dayi - 1
      If i = mrDate(j) Then badyear = 1
   Next j

      If badyear = 1 Then
         larve(i) = 0
      Else
```

```
        larve(i) = NormPDF(i, mean, var) * mr_larve
      End If

'   Debug.Print "larve"; i; "="; larve(i)

Next i

mr_larve = 0
For i = 45 To 85
   mr_larve = mr_larve + larve(i)      'total larve left
Next i
'   Debug.Print "mr_larve="; mr_larve

'~~~Survival rate (CAGEAN 1997 estimates, except age 1 walleye)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For m = 1 To 7
   For n = 1 To 7
      para(m, n) = 0
   Next n
Next m

para(2, 1) = 0.6      'Survival of age 1
para(3, 2) = 0.682    'Survival of age 2
para(4, 3) = 0.645    'Survival of age 3
para(5, 4) = 0.645    'Survival of age 4
para(6, 5) = 0.645    'Survival of age 5
para(7, 6) = 0.645    'Survival of age 6
para(7, 7) = 0.679    'Survival of age 7+

'~~~Reproductivity of walleye from age 3 to 7+~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
For agei = 3 To 7
   Let para(1, agei) = AvgEggs(agei)
'   Debug.Print "para(1,"; agei; ")="; para(1, agei)
Next agei

'~~~show the matrix~~~
'~~~~~~~~~~~~~~~~~~~~~
Picture3.Print
For i = 1 To 7
'  For j = 1 To 7
'  Picture3.Print para(i, j),
'  Next j: Picture3.Print
Next i
'~~~~~~~~~~~~~~~~~~~~~~

'~~~Calculate reef population size~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Dim mr_Y(1 To 50) As Single

For i = 1 To 7

   mr_Y(i) = 0
   For j = 1 To 7
      mr_Y(i) = mr_Y(i) + para(i, j) * mr_abund(j)
   Next j
```

```
Next i

For i = 1 To 7
   mr_abund(i) = mr_Y(i)
   mr_abund(1) = mr_larve    'all larve survived will be the age 1 fish of next year

'   Debug.Print "mr_E_yr"; i; "="; mr_abund(i)
Next i

mr_sum = 0
For i = 1 To 7
   mr_sum = mr_sum + mr_abund(i)
Next i
'   Debug.Print "mr_sum="; mr_sum

End Sub
'##########################################################################################################

'*********************************************
'*****Show labels of the figure in Picture1*****
'*********************************************

Sub ShowLabels(label() As Integer)

   Dim i As Integer, lbl As Double, lblWid As Single
   Dim lblHght As Single, tickFactor As Single

   For i = 1 To numYears Step 1
      Let lbl = Right(label(i), 2)
      Let lblWid = Picture1.TextWidth(lbl)
      Let tickFactor = 0.01 * maxSize
      Picture1.Line (i, -tickFactor)-(i, tickFactor)
      Call Locate(i - lblWid / 2, -tickFactor)
      Picture1.Print lbl
   Next i

   Let lbl = Int(maxSize)
   Let lblWid = Picture1.TextWidth(lbl)
   Let lblHght = Picture1.TextHeight(lbl)
   Let tickFactor = 0.005 * numYears
   Picture1.Line (-tickFactor, maxSize)-(tickFactor, maxSize)
   Call Locate(tickFactor, maxSize - lblHght)
   Picture1.Print lbl

End Sub
'##########################################################################################################

'*********************************************
'*****Show legend of the figure in Picture1*****
'*********************************************

Sub ShowLegend()
   Let Picture1.DrawStyle = 2
   Picture1.Line (5.9, 1.1 * maxSize)-(6.8, 1.1 * maxSize)
   Call Locate(6.8, 1.12 * maxSize)
   Picture1.Print "Reef"
```

```
   Let Picture1.DrawStyle = 1
   Picture1.Line (3, 1.1 * maxSize)-(3.9, 1.1 * maxSize)
   Call Locate(3.9, 1.12 * maxSize)
   Picture1.Print "River"

   Let Picture1.DrawStyle = 0
   Picture1.Line (0.1, 1.1 * maxSize)-(1, 1.1 * maxSize)
   Call Locate(1, 1.12 * maxSize)
   Picture1.Print "Total"

End Sub
'########################################################################################################

'*********************************************
'*****Show title of the figure in Picture1******
'*********************************************

Sub ShowTitle()
Call Locate(year / 2 - 1, -0.07 * maxSize)
Picture1.Print "Simulation year"
Call Locate(0.1, 1.2 * maxSize)
Picture1.Print "Population size"

End Sub
'########################################################################################################

'*****************************************************************
'*****The simulated walleye population (river and reef spawner)*****
'*****************************************************************

Sub SimuPopu()

'~~~Extract the initial population size (CAGEAN)~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

Set DBase = OpenDatabase("d:\zs\climate.mdb")
Dim SQLquery As String, rstIni As Recordset
Dim x(1 To 7) As Double

SQLquery = "SELECT * FROM abund WHERE abund.Year='" & 1996 & "'"

Set rstIni = DBase.OpenRecordset(SQLquery)
   rstIni.MoveLast
   rstIni.MoveFirst

ReDim fYear(rstIni.RecordCount) As Integer
ReDim age1(rstIni.RecordCount) As Double
ReDim age2(rstIni.RecordCount) As Double
ReDim age3(rstIni.RecordCount) As Double
ReDim age4(rstIni.RecordCount) As Double
ReDim age5(rstIni.RecordCount) As Double
ReDim age6(rstIni.RecordCount) As Double
ReDim age7(rstIni.RecordCount) As Double

di = 0
```

```
Do While Not rstIni.EOF
  fYear(di) = rstIni("Year")
  age1(di) = rstIni("1")
  age2(di) = rstIni("2")
  age3(di) = rstIni("3")
  age4(di) = rstIni("4")
  age5(di) = rstIni("5")
  age6(di) = rstIni("6")
  age7(di) = rstIni("7")

  Let x(1) = age1(di): x(2) = age2(di): x(3) = age3(di): x(4) = age4(di): x(5) = age5(di): x(6) = age6(di): x(7) =
age7(di)

  di = di + 1

  rstIni.MoveNext
Loop

Let rf_r = 0.7     'the percentage of initial reef population
ini_rf = 0
ini_rv = 0
For i = 1 To 7
'  Debug.Print "age1*"; x(1)
'  Debug.Print "age2*"; x(2)

   rf_abund(i) = x(i) * rf_r
   mr_abund(i) = x(i) * (1 - rf_r) * 0.6
   sr_abund(i) = x(i) * (1 - rf_r) * 0.4

   ini_rf = ini_rf + rf_abund(i)
   ini_rv = ini_rv + mr_abund(i) + sr_abund(i)
Next i

'~~~Call the subroutes~~~
'~~~~~~~~~~~~~~~~~~~~~~~~~
Open "d:\zs\walleye.txt" For Output As #1

For iter = 1 To Text2.Text
Let year = 1
Do While year <= numYears

   Call RanYear

   Call MR_Spawn
   Call SR_Spawn
   Call Rf_Spawn

   popsum = 0
   popsum = popsum + rf_sum + mr_sum + sr_sum
   Debug.Print "yr"; year; "="; popsum
   Debug.Print "************"

   Let rv_sum = mr_sum + sr_sum
   Write #1, year, rf_sum, rv_sum
   year = year + 1
 Loop
```

```
Next iter

Close #1

End Sub
'################################################################################################

'*********************************
'*****Command1 - Run the model*****
'*********************************

Private Sub Command1_Click()

'~~~simulation years~~~
'~~~~~~~~~~~~~~~~~~~~~~
Let numYears = Text1.Text

'~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
ReDim label(1 To numYears) As Integer

Picture1.Cls   'Graphical display of results
Picture2.Cls   'Show the reef Matrix
Picture3.Cls   'Show the river Matrix

'Call ranYear

Call SimuPopu
'   Sub SR_Spawn()
'   Sub MR_Spawn()
'   Sub Rf_Spawn()
'      Sub length_distr()
'      Sub dev_date()

Call ReadData(label(), reef(), river(), total())
Call DrawAxes
Call DrawData(reef(), river(), total())
Call ShowTitle
Call ShowLabels(label())
Call ShowLegend
'   Sub Locate()

'   Function log10()
'   Function NormPDF()

End Sub
'################################################################################################
Private Sub Data1_Validate(Action As Integer, Save As Integer)

End Sub
```