AN EVOLVING COMPUTER SIMULATION (ECOSIM) OF MOSQUITOES TO SUPPORT A LARVAL CONTROL PROGRAM IN ALAMEDA COUNTY, CALIFORNIA

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Introduction.

The Alameda County Mosquito Abatement District (ACMAD) conducts a comprehensive mosquito control program of physical, biological and chemical control. A computer simulation program has been developed to support decisions made in the larval treatment component of that program. The reason this area of the program was selected was because the greatest number of decisions, and perhaps the most complex decisions, are being made in the larval treatment program. A simulation to support larval treatment decisions, therefore, appears to offer the greatest potential for increasing efficiency and cost-effectiveness.

The problem of establishing an efficient larval treatment program is complicated by a number of factors. The District has approximately 1400 major mosquito sources in 815 square miles. Seven technicians are assigned the responsibility of inspecting and treating an average of about 200 major sources in zones of about 100 square miles each. During the spring and summer months, as many as six species of mosquitoes may be designated for larval treatment. The size of the District, number of mosquito sources and number of pest and vector mosquito species combine to create an enormous scheduling problem.

In recent years, environmental, safety and cost considerations have further complicated the task for technicians by increasing requirements for information. A decision whether to treat a mosquito source now entails the following information:

1. Location of the larval source.
2. Presence or absence of mosquito larvae.
3. Species of larvae present.
4. Number/dip of each developmental stage of larvae to compare to an established treatment-threshold.
5. Presence of beneficial predators.
6. Presence of wildlife (e.g. endangered species).

Ironically, at the same time that pressures were increasing to process more information about mosquito sources, financial constraints imposed by a tax reduction measure in the late 1970's caused the District to cut back the number of mosquito control technicians.

ACMAD data systems.

The District designed, developed and implemented an automated data processing system (ACMAD Data Systems) as one of a number of measures aimed at increasing efficiency to compensate for the loss of staff (Roberts 1984). The systems analysis and construction of computer programs was accomplished by a team of District employees (Rusmisel et al. 1983). All District programs have been written in BASIC programming language of Tandy computers. Our current host computer is a Tandy 4000 operating on SCO Xenix software and currently supporting six terminals at various workstations in the District offices. The center piece of the District's computer system is a data base describing the physical and biological characteristics of all major mosquito sources in the District.

A number of computer programs operating in ACMAD Data Systems directly support the larval treatment program (Fig. 1). An environmental simulation program (ESP) determines which species of mosquitoes in the District would be active in the larval stage at any given time. Each day ESP compares input information (date, tide, rainfall, maximum and minimum temperatures) to conditions coded in the program which predict the beginning or end of larval activity of each important mosquito species in the District. When a species of mosquito becomes active in the larval stage, the data base of all mosquito sources is searched by ESP to create a "hot" file of all sources where larvae of the species have been found. The "hot" files are updated each day with inspection and treatment data recorded by the technicians on the previous day. A scheduling program (ZING) searches all "hot" files on a weekly basis or upon request to create zone inspection and treatment information about the location of the mosquito sources, and the results of the most recent inspections or treatments.

The District's computer system, at the above stage of development, provided valuable assistance to mosquito control technicians. ESP provided the answer to "what" species of mosquitoes were active and "when". ZING listed the specific larval sources "where" the larvae could be expected to be found. It was felt, however, that still another increment of efficiency could be added by assisting technicians in deciding more precisely "when" a particular source in a "hot" file should be inspected. Ideally, the best time to inspect a source would be when larvae were present at the established treatment-threshold level. If high quality information were provided to the technicians predicting when threshold would be reached in each source, inspections could be more efficiently scheduled; and savings could be accrued by avoiding unnecessary inspections.

Evolving Computer Simulation of mosquitoes.

The District began construction of a computer program in 1986 with the express purpose of providing a date when threshold is reached at each active larval source. Since the major factor determining the time of threshold is the rate of larval growth, the computer program took the basic form of a simulation of larval growth. Other components have been added to the simulation as necessary to refine the output. The program is best described as an evolving computer simulation of mosquitoes designated by the acronym ECOSIM. It has been constructed by a team of District employees. The employees gained much of the technical expertise necessary to construct the simulation by assisting in the development of the computer simulation of Coyote Hills Freshwater Marsh (Schooley et al. 1982).

Description of the simulation.

ECOSIM is called up daily by a control program in ACMAD Data Systems to simulate larval growth in all "hot" sources (Fig. 1). The simulation occurs following input of the previous day's operational and weather data to insure that the most recent input data is available to the simulation. For mosquito sources that have already been inspected and found to have early instar larvae present, ECOSIM simulates the development of the instars (and pupae) and predicts a date when treatment threshold is reached. When sources are treated, found without larvae, or have not yet been inspected, oviposition is simulated. The simulation proceeds through hatching and larval growth until simulated threshold is reached. Three companion papers will describe the temperature subroutine, the oviposition subroutine and the use of the simulation in the District (Conner and Roberts 1990; Mead et al. 1990; Rusmisel and King 1990).

Behavior of the simulation.

The initial input to a larval growth component of the simulation may be provided by a field inspection of the source or by simulated oviposition. Standard inspection procedures during field inspections establish the number of larvae (and pupae) per pint dipper in each instar. All of the individuals in each instar are considered a distinct cohort to begin the simulation. Simulated oviposition may add eggs to the source each day resulting in additional cohorts as the simulation progresses.

The computer begins the simulation on day one which is the date of the last inspection, the date of the last treatment of the source, or if neither of the preceding, the date when the "hot" file was created. An increment of growth is added to each cohort for that day based upon the temperature of the source. The growth rates and the relative duration of each larval stage used in the simulation have been determined locally for each species being simulated (Mead and Conner, 1987). The growth is calculated by use of a rate summation technique and added to each cohort as a fraction of total growth from eggs to pupae (Wagner et al. 1985; Fig. 2). The grown cohorts are then transformed back to number per dip to determine if threshold has been reached. If threshold has not been reached, another day is incremented and the cohorts are processed through the growth loop again (Fig. 3).

If the simulation reaches threshold, the number of days of growth are added to the initial date of inspection and a predicted date of threshold is created. This date is then made available to each technician by placing it next to the appropriate source in the zone inspection guidelines.

Figure 3 describes the essentials of the simulation.

Method of construction.

ECOSIM has been developed by a bottom-up approach. This approach was given a substantial boost by Alan Berryman during discussions at a computer modeling workshop at the 1987 conference of the American Mosquito Control Association held in Seattle, Washington. He said that simulations are accomplished to learn about the dynamics of the system being simulated or to obtain some very practical information. He suggested that if the simulation were to be aimed at a practical application, the model should be as simple as possible, adding complexity only as necessary. Other

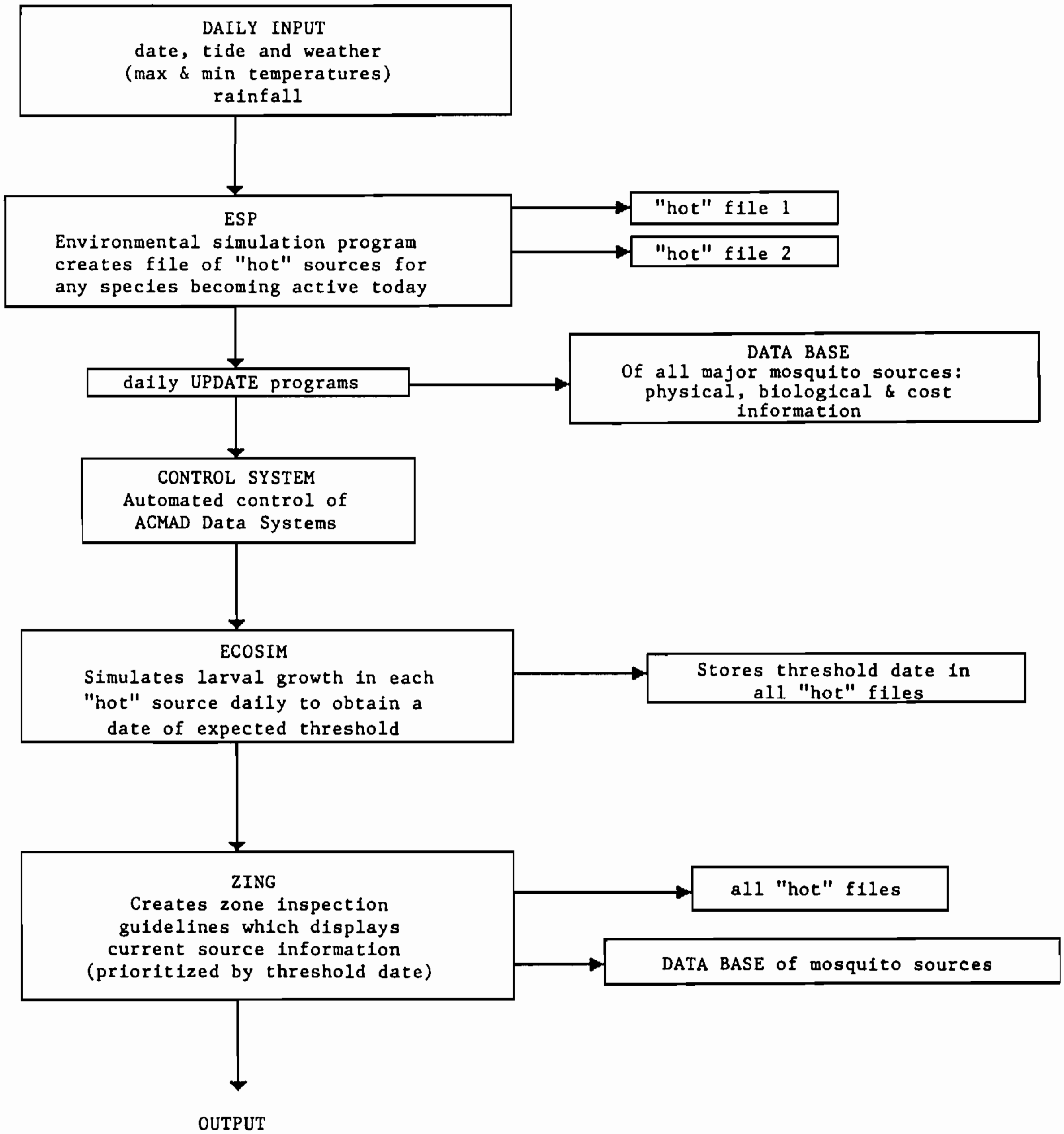
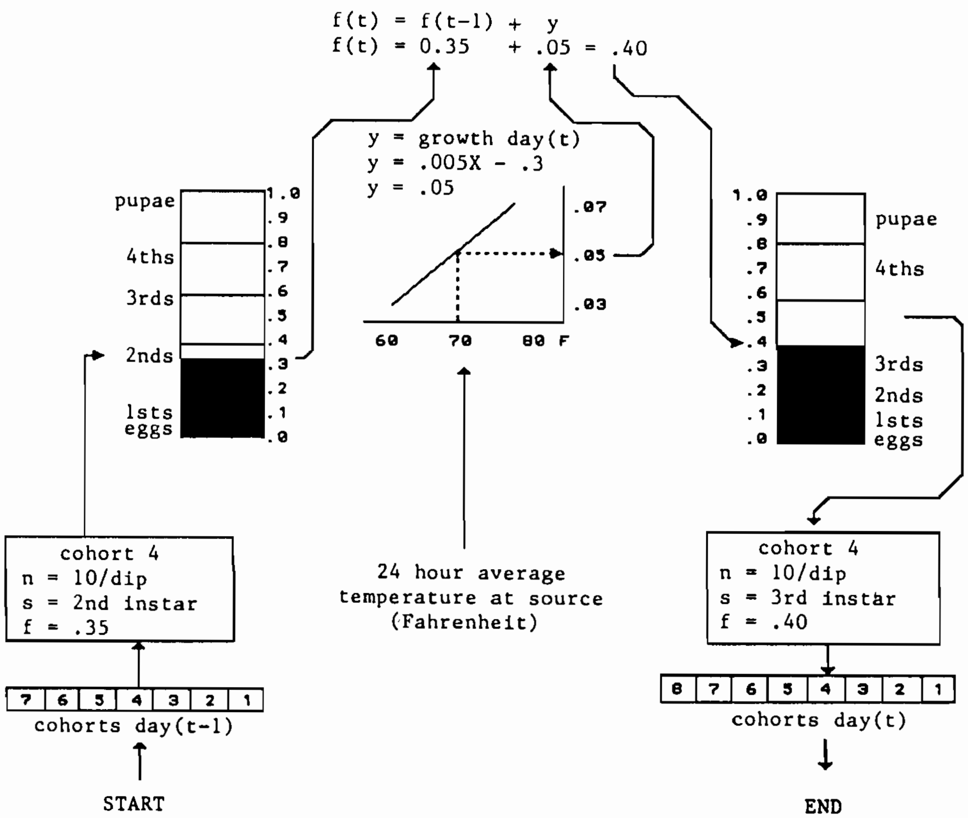


Figure 1. Flow chart of the operations of ACMAD DATA SYSTEMS emphasizing support provided to the larval control program.



Cohort = Individual mosquitoes are segregated into cohorts according to their age. Mosquitoes collected at the source and identified as distinct instars (and pupae) are segregated into separate cohorts. All subsequent oviposition occurring during the simulation creates an additional cohort (cohort #8).

n = number of individuals in a cohort

s = stage of larval development of the individuals in a cohort (eggs, larvae or pupae)

f = fraction of accumulated growth completed by a cohort between egg and emergence as adult mosquitoes

y = .005X - .3 is an equation used to determine the fraction of growth of a cohort in one day at specified temperature X. The values are for illustrative purposes only. The slope of the line below the equation graphically represents the growth rate (see Mead and Conner, 1987) and is used to estimate a solution (y = .005(70) - .3 = .05 = fraction of growth for one day).

t = current time of the simulation (in days). t-1 = yesterday.

f(t) = f(t-1) + y is the rate summation equation used to increment growth of each cohort each day.

Figure 2. An illustration of the rate summation method used to simulate one day's growth of immature mosquitoes in ECOSIM (one cohort).

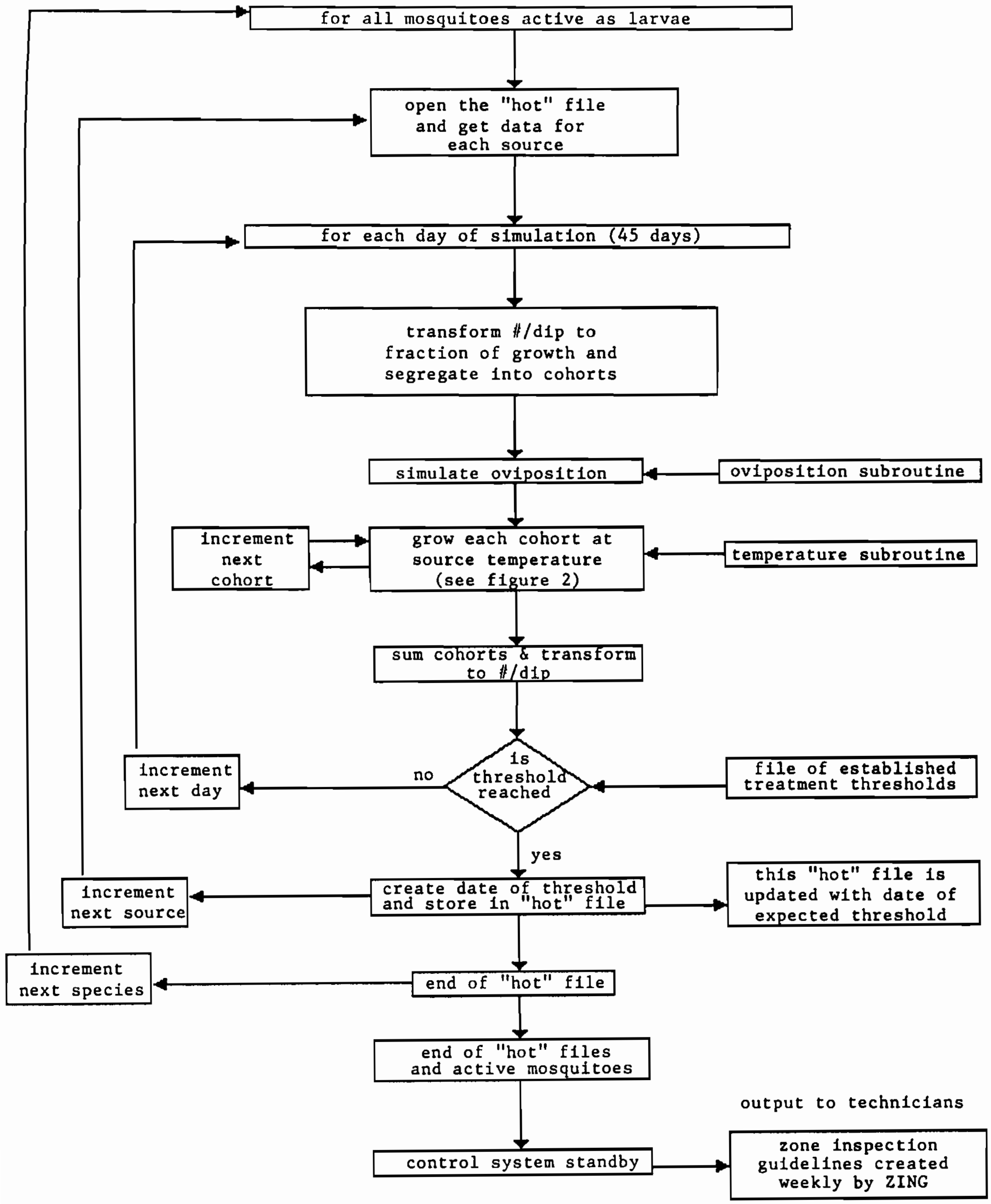


Figure 3. Flow chart of the operation of ECOSIM in ACMAD DATA SYSTEMS.

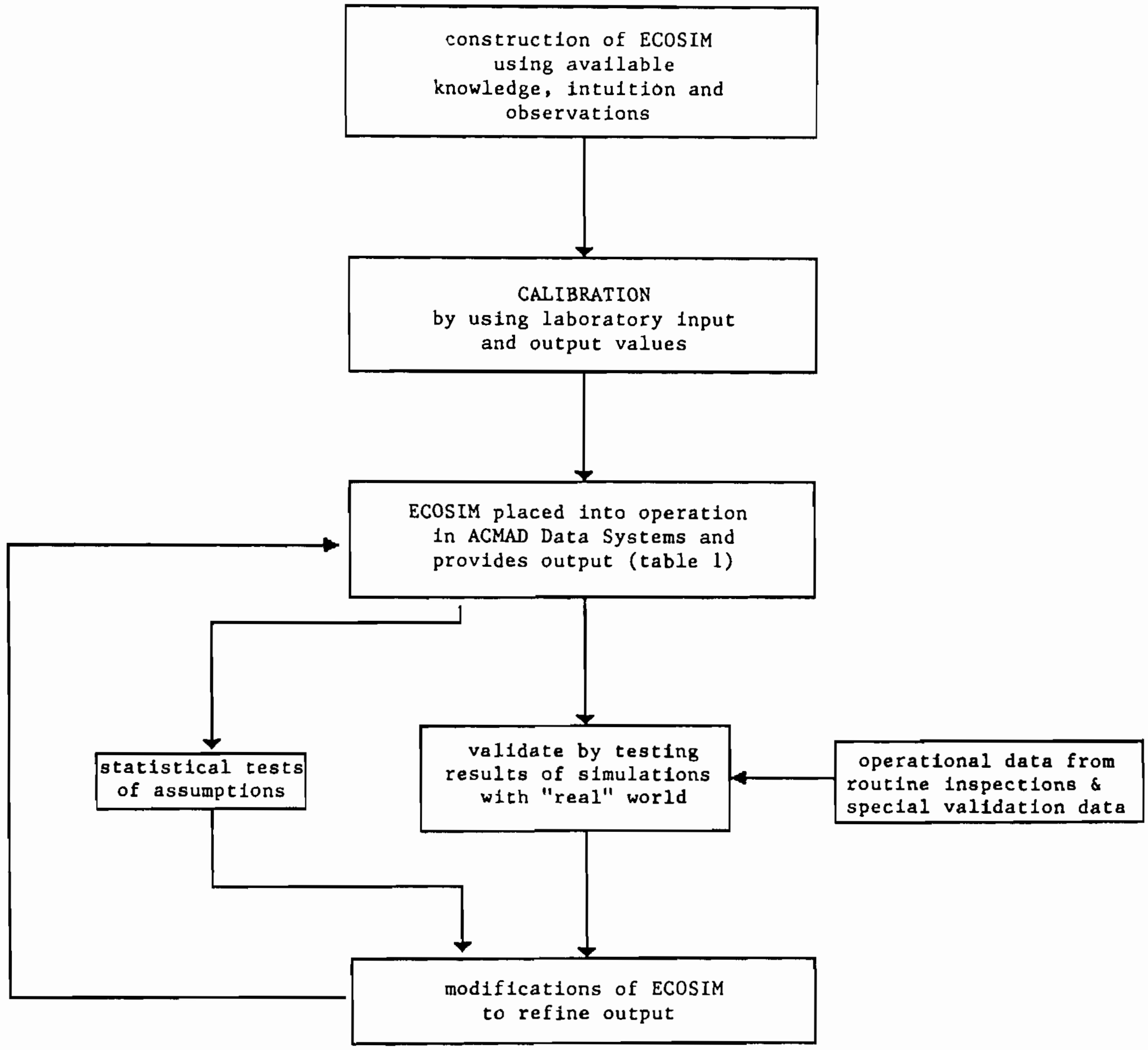


Figure 4. A flowchart of the validation procedures for ECOSIM.

wise, he felt we might waste resources dealing with an unnecessary level of complexity.

A significant advantage of developing the simulation from the bottom was that it became useful almost immediately. The basic component of the model was the simulation of larval growth. Once it had been built and was calibrated, it was providing useful information. The simulation, therefore, was placed into operation in late 1986 in a relatively primitive state of development. The simulation has continued to evolve into a more complex program as complexity was added to further refine the output (Table 1).

Validation of ECOSIM.

According the Shannon (1975) confidence in any simulation is established by repeated cycles of construction followed by verification. He suggests that verification should include statistical testing of assumptions of the model as well as comparing input-output transformations of the model to those of the real world. Our approach to validation has included an initial calibration, testing of the output with the real world and statistical analysis of assumptions. A companion paper by Mead et al. (1990) will conduct statistical analysis of the temperature subroutine.

The model was initially tested by comparing simulated growth of the larvae with growth of larvae in controlled laboratory conditions. The laboratory data used in the test was the same data used to calculate the growth rates used in the simulation. Using this data assured us that the input and expected output to the simulations were correct. The results of the simulation were then compared to the laboratory results and the simulation was modified as necessary (calibrated) to reduce error. By this method, we were able to establish a level of intrinsic error of 2.4% that was built into the simulation. It appeared that the error was primarily associated with the length of the time interval chosen in the simulation. Since a one day time interval was as small an interval as we could practically support in the simulation, we were forced to accept that level of error and would expect it to increase in warm temperatures and decreased with cooler temperatures.

An on-going system has been established to accomplish evaluation of how well the output of ECOSIM represents the real world. The "reality check" of the simulation is accomplished, for the most part, by utilizing data collected routinely in the larval treatment program (Fig. 4). Some data were also collected by frequently repeated inspections of sources made for the specific purpose of validating the simulation. These inspections were time consuming and expensive, however, causing us to rely primarily on data collected through routine inspection.

Criteria has been established to validate the simulation. The results of the simulations run in 1987, 1988 and 1989 were compared with data collected from the field by the routine larval inspections. The following validation system was established:

1. Operational data were searched to find inspections of sources where two or more inspections had indicated growth of larvae through at least two instars.

Table 1.-Evolving complexity of ECOSIM.

Program Components	Date Installed	Date Replaced	Useful Output to Technicians
Larval Development	1/87	In use	Minimum development time of larvae to threshold in inspected sources found with larvae (maximum growth rates).
Ambient Temperature Subroutine	2/87	6/87	None. No measurable improvement.
Source Temperature Subroutine	6/87	In Use	Probable actual development time of larvae to threshold in each positive source.
Temperature Related Mortality	8/87	12/87	None. Output not validated. To be installed in the future.
Oviposition Subroutine	12/88	In Use	Probable development time egg to threshold in sources not inspected or without larvae.
Predation Subroutine	future ?		Refinement of predicted #/dip to trigger threshold.
Stochastic Component	future ?		Determine probabilities for predicted thresholds.
Adult Population	future ?		Determine numbers of adult mosquitoes based on simulated larval development in all sources. (Predict complaints).

Table 2.-Results of validation tests on ECOSIM.

Parameter Measured	Year 1987	1988	1989
Successful Simulations *	48.0% n=33	79.3% n=29	80.8% n=43
Average Number of Days Error	5.9 days n=17	5.0 days n=6	4.3 days n=9

* Simulation predicts development within one day (see text).

2. If simulation had successfully predicted within one day the number of days required for the observed growth, the simulation was considered successful.
3. The total number of days error was established for unsuccessful simulations.

The percentage of successful simulations and the average number of days error were used as parameters to evaluate the effectiveness of the simulations (Table 2).

Results of validation tests indicate the output of the simulation is improving. A significant improvement made in the simulation between 1987 and 1988 can primarily be attributed to the implementation of a program to monitor larval source temperatures. The program is discussed in detail in a companion paper (Mead et al. 1990). It is expected that the statistical analysis accomplished on the temperature subroutines will provide the basis to gain another significant level of improvement in the simulations in 1990.

The future of ECOSIM.

Our goal in the development of ECOSIM is to increase the accuracy of the output to a level where it will be a highly reliable tool. We would like to continue the validation process to attempt to reach a 90% success level and a reduction in the average error (Table 2). The simulation, operating at the level of reliability, should be a powerful scheduling tool for the technicians. It would be expected to provide yet another increment of efficiency to the larval control program.

The desire to improve the accuracy of ECOSIM seems to require the addition of more components. This evolution toward more complexity brings ECOSIM that much closer to providing output beyond that of just predicting treatment-threshold. Table 1 lists the subroutines now being considered to be added and describes the desired output. It appears feasible in the future for ECOSIM to predict activity and numbers of adult mosquitoes based upon simulated levels of adult emergence. The structure of ECOSIM provides an opportunity to accumulate the number of emerging adults from each source during the simulation. A component to sum and store the number of emerging adults could easily be placed in the simulation loop (Fig. 3). An adult mosquito simulation could then be built to use the emergence data, as well as other available data, to provide needed information concerning adult mosquitoes.

The development of a promising new simulation may preclude the need to develop ECOSIM to the level of adult mosquito populations. A simulation of mosquito populations has been developed for Orange County, California. The simulation is accomplished by RAM, an artificial life system developed at UCLA for modeling populations (Taylor et al. 1987). Our District is in the process of putting it into operation to support the *Culex pipiens* L. control program. It is particularly appealing because it simulates mosquito populations and would support decision at the District-wide level. ECOSIM, on the other hand currently only supports individual decisions at each source. RAM and ECOSIM operating together would create valuable decision support to both the supervisor of the control programs as well as the individual mosquito control technicians in each zone. If RAM were to be easily modified to also support decisions at the individual source level, it may well replace ECOSIM altogether. It should be remembered that computer programs compete in an environment of differential selection (Beniger 1986). They either continue to evolve and remain competitive or they become extinct.

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