ENERGY LABORATORY

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Numerical Simulation of Fish Larvae Entrainment at the Millstone Nuclear Power Station

Summary report covering period December 1989 - August 1990

by
Nadia K. Dimou, Andrew T. Obst,
Jeff Moeller, E. Eric Adams

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Acknowledgment

This report summarizes work performed between Dec. 1989 and Aug. 1990 on the project "Numerical Simulation of Fish Larvae Entrainment at the Millstone Nuclear Power Station." The work was performed by Nadia Dimou, graduate research assistant in MIT's Dept. of Civil Engineering; Andrew Obst, a graduating senior (June 1990) in MIT's Department of Mechanical Engineering; and Jeff Moeller, presently a senior at North Carolina State who spent the summer of 1990 in residence at MIT as a Parsons Summer Fellow. The work was supervised by Dr. Eric Adams of MIT's Civil Engineering Dept. Andrew Obst's senior thesis and Jeff Moeller's project report are included as Appendixes A and B. The summary is essentially as presented by Dr. Adams at the Millstone Ecological Advisory Committee, Northeast Utilities Environmental Lab, Oct. 1, 1990.

The research has been supported by Northeast Utilities Service Company. Once again we are grateful to NUSCo for their financial support and appreciate the learning opportunity for both students and staff afforded by cordial interaction with NUSCo personnel including Ernesto Lorda, Dale Miller, Bill Renfro, Don Donella, Marty Pitek, and Linda Bireley.

E. Adams
December 1990

Contents

1 Review of Past Work

Dimou and Adams (1989) describe application of a 2-D particle tracking model to simulate entrainment of winter flounder larvae at the Millstone Nuclear Power Station. Model input was based on a typical year in the interval 1984-87 and included the introduction over the season of a total of 22 million Stage 1 larvae at Stations A, B, and C in Niantic River. The total number of larvae introduced, and their distribution among stations, was in accordance with the densities of yolk-sac larvae measured by NUEL at each station. The larvae were then transported by advective and dispersive movements representing tidal and plant-induced circulation described by a regional 2-D flow model. Larval behavior (i.e., vertical migration within the water column) was simulated in accordance with larval densities measured by NUEL personnel as a function of time of day and/or phase of tide.

The model indicated that, over the year, approximately 1.5 million larvae were entrained at the station with a mean length of about 3.7 mm. In contrast, measurements indicate that about 100 million larvae are entrained at a mean length of between 5 and 6 mm. We concluded that the simulations were underpredicting entrainment numbers by a factor of 50 to 100 and underestimating larval age (hence length) at entrainment by several weeks.

Several hypotheses were developed that could explain, in whole or in part, one or both of these discrepancies:

1) The input hatching rates in Niantic River were too small.

2) The input larval mortality rates were too small.

3) Larval residence times within Niantic River were too short due to either
   - a) overestimation of hydrodynamic flushing rates, or
   - b) underestimation of larval retention mechanisms (behavior, etc.).

4) The model underestimated the percentage of larvae within the bay that were entrained.

5) Larvae are being imported from outside the Niantic River area.

These hypotheses were analyzed in turn leading to the following conclusions (Dimou and Adams, 1989):

Hypothesis 1 Because the number of larvae introduced by the model to Niantic River (22 million) is almost 5 times less than the number entrained (about 100 million), it is clear that the source of larvae in the model was too small. Based on the observed number of adult spawners, and average fecundities, NUEL estimates that 15-20 billion eggs are spawned each year in Niantic River. Furthermore, they estimate a 10% hatching rate suggesting that the number of larvae hatched within Niantic River should be in the range of 1.5 to 2 billion rather than 22 million. However, they acknowledge that the estimated hatching rate is quite uncertain (D. Miller, personal communication). Because yolk-sac larvae are negatively buoyant, it seemed possible that they resided preferentially near the bottom and hence were undersampled with the bongo sampling system used by NUEL.

Hypothesis 2 Sensitivity simulations made with the limiting assumption of zero mortality showed an increase in entrainment by a factor of 3.5 (5.2 million versus 1.5 million) and an increase in the average larval length at entrainment (4.4 mm vs 3.7 mm). While these produce the correct trends, we concluded that a discrepancy in mortality could not, by itself, explain the discrepancies between model and data.

Hypothesis 3a This hypothesis was rejected by the analysis of available salinity measurements and the results of a month long dye study conducted during November/December 1988 which indicated that the actual hydrodynamic flushing rate was faster, not slower, than simulated.

Hypothesis 3b It seemed possible that we were underestimating the role of vertical migration or other mechanisms that would allow larvae to be retained within the estuary. As mentioned under the first hypothesis, younger larvae may tend to reside near the bottom simply because their specific gravity exceeds one. Because of slower water velocities near the bottom, they would require longer times to be flushed from the river. If their residence near the bottom results in their being undersampled, this could explain both the low number and the short length distribution of entrained larvae. Support for this hypothesis was provided by the dates of peak abundance of larvae sampled in the river and in the bay which suggested that the residence time of larvae in the river was of the order of one month rather than about two weeks simulated by the model.

Hypothesis 4 This hypothesis was rejected by the results of a second dye study, conducted during January 1989, which indicated that the percentage of dye from within the bay which was entrained through the station intakes was similar (about 20%) to the simulated percentage of larvae entrained under the limiting assumption of no mortality.

Hypothesis 5 If larvae were being imported from additional spawning areas (e.g., the Connecticut River) this could explain why the actual number of larvae entrained exceeded the number simulated. Because the additional spawning areas are farther away, this would also explain why the observed lengths were generally larger than the simulated lengths. Additional support for this hypothesis comes from mass balance studies which suggest that, late in the larval season, an outside "source" must be present to explain why larval concentrations in Niantic Bay keep increasing at a time when concentrations in the bay exceed those in the river.

In view of the above conclusions, work during the period November 1989 through August 1990 was conducted in four areas:

- In support of Hypothesis 1, encouragement to NUEL to design and construct a near-bottom larval sampler and analysis of data on the vertical distribution of measured larval densities.
- In support of Hypothesis 2, modification of our model to account for density-dependent mortality.
- In support of Hypothesis 3b, sensitivity studies concerning the dependence of larval residence times within Niantic River to assumed larval behavior. (This has been the area of our greatest effort.)
- In support of Hypothesis 5), further analysis of the possible role of larval import on the number of entrained larvae.

Results have been documented in two student reports: Obst (1990) and Moeller (1990), and in presentation by Eric Adams to NUEL in June 1990 and October 1990. Conclusions from these efforts are summarized briefly below. The reports are attached as appendixes to this report.

2 Measured Vertical Larval Distributions (Hypothesis 1)

Prior to the spring 1990 season, NUEL designed and constructed a near-bottom pump sampler. Unfortunately, however, the system experienced difficulties when operated in the field. The major problem was that water was pumped through a filter at a high flow rate with severe changes in speed, which destroyed many of the delicate larvae. Many of the captured larvae were extruded through the filter, and most remaining pieces were too small to be recognized. Hence it has not yet been possible to obtain accurate measurements of larval density versus depth by pump sampling. However, refinements are being made to the system with hopes of obtaining such data for the 1991 season.

Some related data, however, have been collected by operating the bongo sampler at a fixed depth near the bottom, in addition to the step-wise oblique tows normally used. Table 1 (from Obst, 1990) compares sampling data from near bottom linear tows with corresponding depth-averaged oblique tows during March 1990. In seven of the nine samples, larval densities at the bottom were substantially higher than the average, which is a good indication that there were more larvae near the bottom.

Before proceeding, the spatial and temporal uncertainty in these measurements should be recognized. For example a bottom tow with the bongos could be sampling anywhere within about four feet of the bottom, while the surface portion of an oblique tow could be sampling anywhere within about four feet of the surface. In shallow areas, this means that bottom and surface tows could be sampling at nearly the same depth. If the interval in depth over which sampling took place could be reduced, it seems probable that the ratio of bottom to average concentrations would be higher. Also significant is the variability shown in the samples. While seven of the nine samples showed greater concentrations near the bottom, two of the samples showed lower near-bottom concentrations. On March 23 there appeared to be a substantial gradient with relatively higher bottom concentrations to the north (Station A), while six days later no such trend was apparent. And while it is not shown in the table, the larval densities varied substantially from sample to sample. This variability underscores the need to collect more data in order to improve the reliability of our conclusions.

Table 1
(from Obst, 1990)

Table 4-I: Data from March 19-29, 1990, showing ratios of near bottom to average larvae concentrations [NUEL, personal communication]

Date	Station	Bottom to Average Ratio
March 19	B	0.59
March 23	A	2.88
	B	1.56
	C	0.79
March 26	A	2.44
	B	4.55
March 29	A	2.13
	B	2.27
	C	2.17

If we assume that these measurements are representative, then we might conclude that larval concentrations near the bottom are (at least) a factor of two greater than the water column average. Thus for every three larvae found within the water column, two would be near the bottom. Furthermore, we might assume that only the fraction of larvae found above the bottom (one-third) are effectively transported by the tidal currents. Our sensitivity studies relating larval behavior to retention in the river suggest that this factor of three between total larvae and "transportable" larvae may be sufficient to explain the discrepancies between modeled and measured larval residence times. (See Section 4). However, it still does not explain the tremendous underestimation (by a factor of 50 to 100) in Niantic River larval hatching rates needed to explain the difference between measured and modeled entrainment numbers based solely on larvae hatched in Niantic River.

3 Density-Dependent Mortality (Hypothesis 2)

Substantial evidence exists in the literature that larval mortality is a function of density (concentration). And, as described above, Dimou and Adams (1989) showed sensitivity of both total entrainment and length at entrainment to assumed mortality. Accordingly, the model MILL was modified so that density-dependent calculations of mortality (or any other parameter) could be included.

It should be pointed out that one of the basic attributes of a particle tracking (random walk) model is that advective and dispersive transport is simulated by particles without ever needing to compute concentration. Indeed, this was one of the original motivations in selecting such a model, in contrast to a concentration-based model such as used by Saila (1976).

In order to compute concentrations, the model grid was sub-divided into a number of "macro-elements." For example Figure 1 shows ten such elements.. Concentrations can be computed within each macro-element by adding the number of particles within the element and dividing by the element volume. Such calculations can be made at a user-input frequency (e.g., once a week). Note that the resolution in space (ten elements) and time (once a week) can be chosen to accurately describe a given density-dependent relationship and are not tied to any criterion governing numerical accuracy, as would be the case in a concentration-based approach. For example, earlier thermal plume modeling performed at Millstone (Adams and Cosler, 1987) used a similar grid in which concentrations (temperatures) were computed at about one thousand nodes and at intervals of several hours.

Calculations of larval density with the macro-elements have been tested and indeed used to help calculate larval residence times within Niantic River (see following section). However, no density-dependent mortalities have been programmed. Use of a density-dependent mortality would undoubtedly be more realistic and technically correct. However, in view of the relatively modest sensitivity of larval entrainment to mortality, such refinements don't appear justified at present. Furthermore, until the "missing larvae" are found, computed densities would probably be too low, casting doubt on any density-dependent relationship.

4 Larval Retention in Niantic River (Hypothesis 3b)

The original MILL calculations presented by Dimou and Adams (1989) included factors to represent diel and tidal larval behavior—i.e., vertical migration as a function of time of day or phase of tide. However, the field measurements upon which the factors were calibrated suggested that these factors were not significant until larvae reached 5 mm. Because most of the simulated entrainment occurred at shorter lengths, model results were

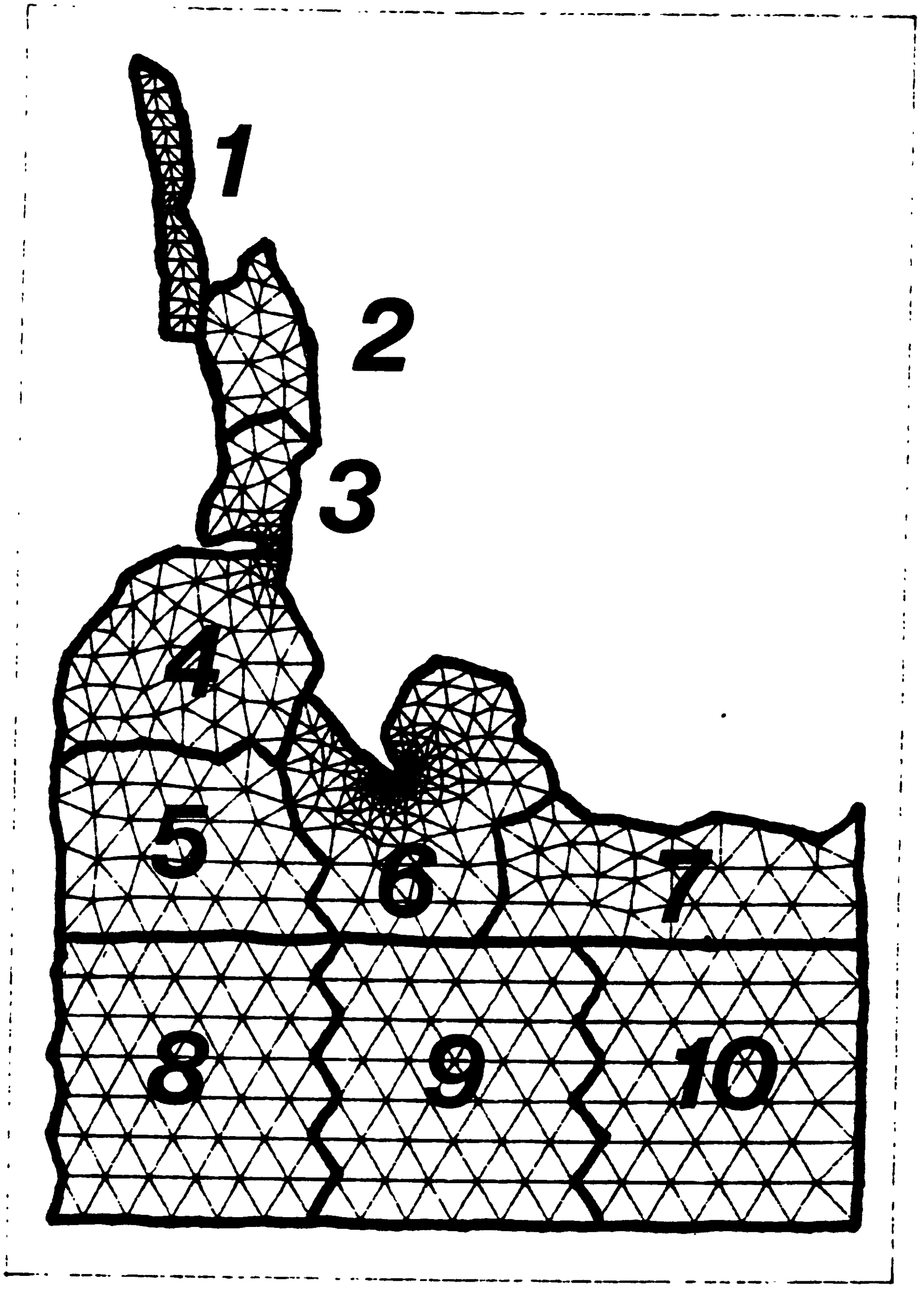

Figure 1 (from Obst, 1990)

Figure 5-1: Millstone grid macro-elements for use in determining larval concentrations.

not very sensitive to these factors. However, as discussed earlier, it appeared that the vertical distribution of larvae could be important as early as Stage 1 (due to negative-buoyancy effects), and the data on dates of peak abundance provided indication that some mechanism must be responsible for the substantially greater residence time of larvae as compared with dye.

To explore this subject, two types of sensitivity studies were conducted. The first was presented at the June 1990 meeting and involved schematizing the river as a rectangular prism. The advection-diffusion equation describing tidal-average larval transport was modified to include diel behavior (by reducing the magnitude of the diffusion term) and tidal behavior (by introducing a net upriver velocity to account for greater transport during flood tide, when more of the larvae are within the water column, than during ebb tide). The analytical solutions indicate that a modest degree of either factor was sufficient to increase larval residence times to the desired 4 or 5 weeks.

Subsequently, we have used the particle tracking model to study the effect of these factors using the real river geometry. (We should mention that we modified our model river slightly, making it symmetrical with respect to its longitudinal axis, in order to prevent particles from running into the boundaries. See Figure 2).

Figure 3 shows a histogram of residence times for particles released at Station A with no behavior, and Figure 4 plots residence time for particles emanating from Stations B and C, as well as the location of the first dye survey. We note that actual larval residence times should be in the range of 4 to 5 weeks, rather than 2 weeks as shown for Station A, in order to explain the observed dates of peak abundance.. Figures 5a and b show residence times for larvae released from Station A using diel parameters of 0.6 and 0.2 respectively, and Figure 6 plots residence times for values of the diel parameter y ranging from 0.2 to 1.0. Figures 7a and b show histograms for larvae released at Station A using values of the

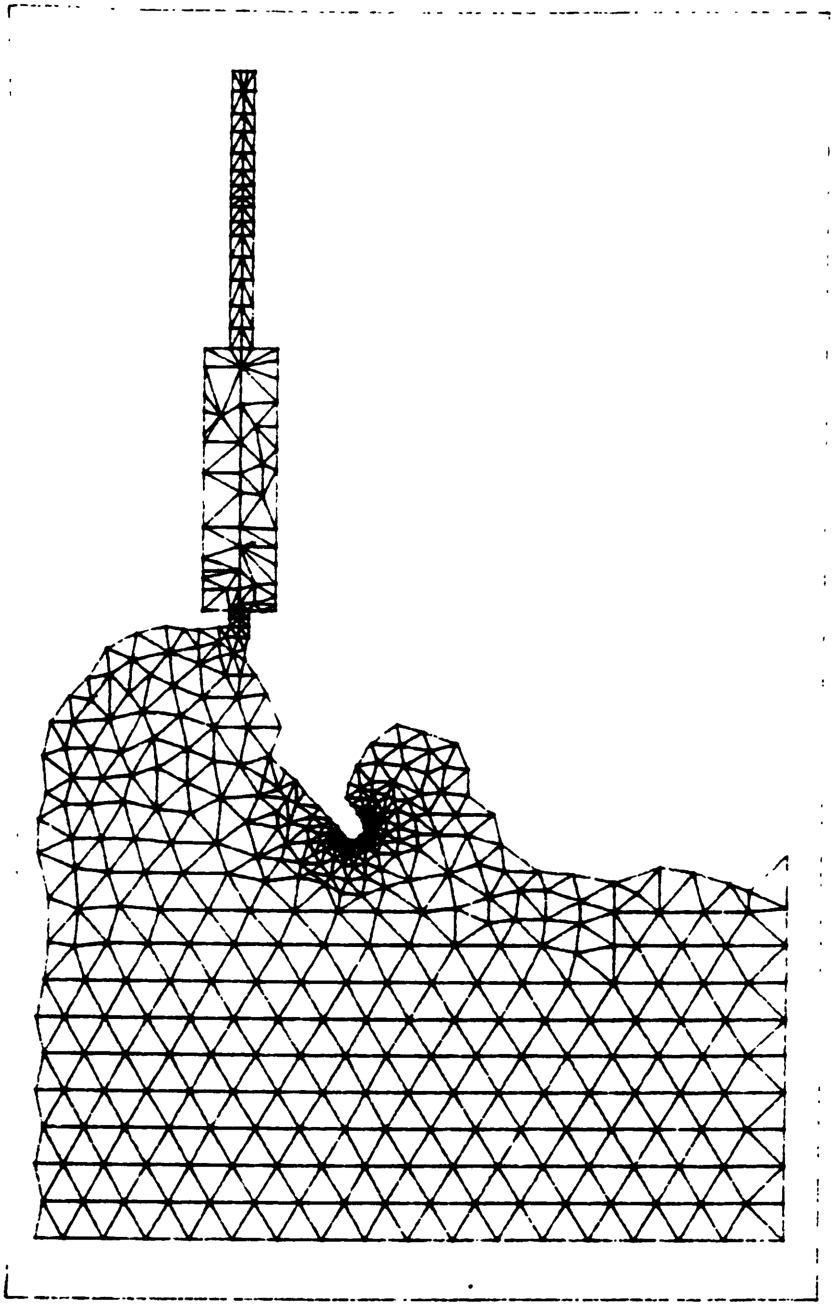

Figure 2 (from Obst, 1990)

Figure 5-4: Entire Reconfigured Grid

FIGURE 3-B: LARVAL RESIDENCE TIMES WITH NO BEHAVIOR

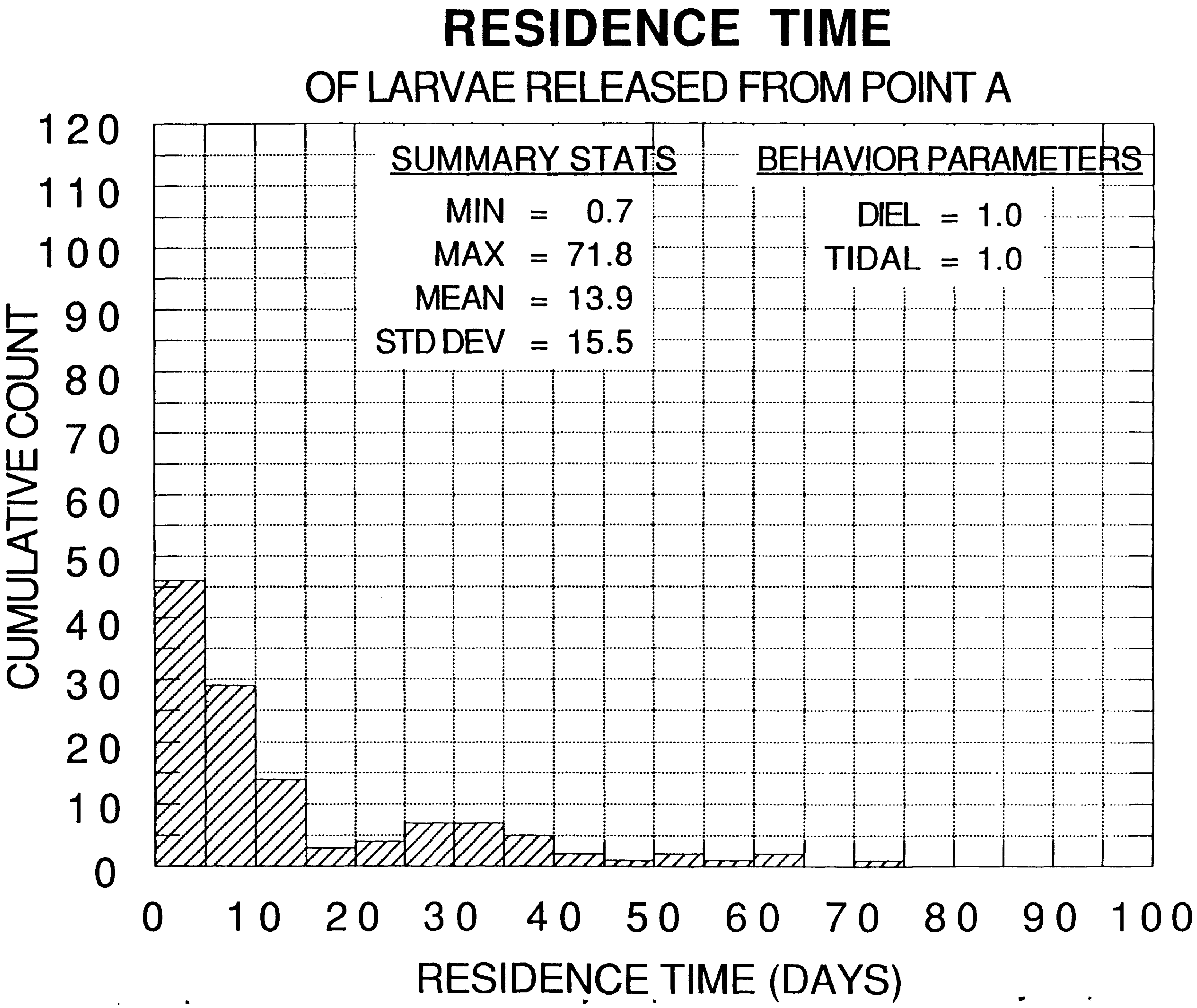

Figure 3 (from Moeller, 1990)

FIGURE 3-E: VARIATION OF RESIDENCE TIME WITH RIVER RELEASE POINT (NO BEHAVIOR)

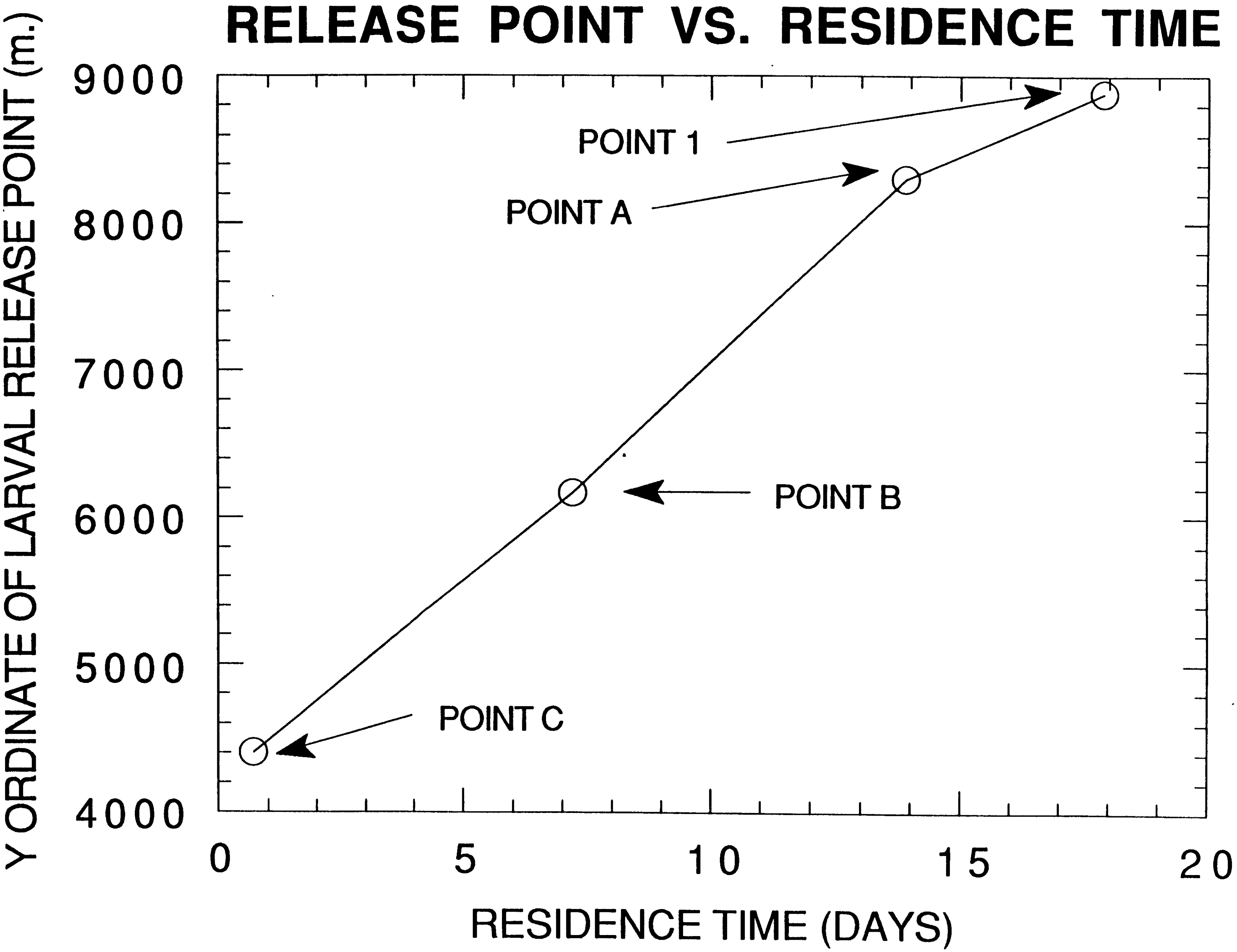

Figure 4 (from Moeller, 1990)

FIGURE 4-B: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR

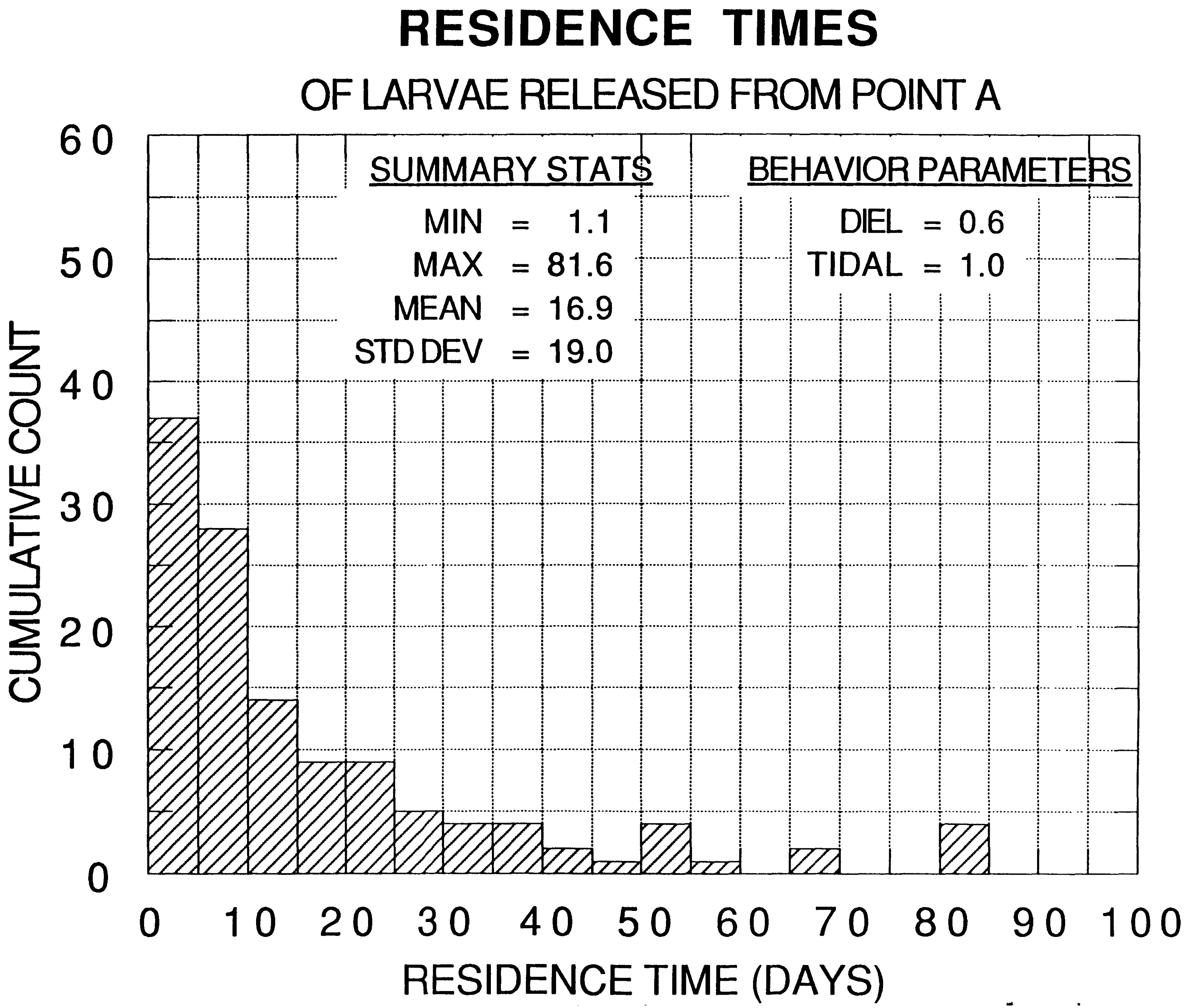

Figure 5a (from Moeller, 1990)

FIGURE 4-D: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR

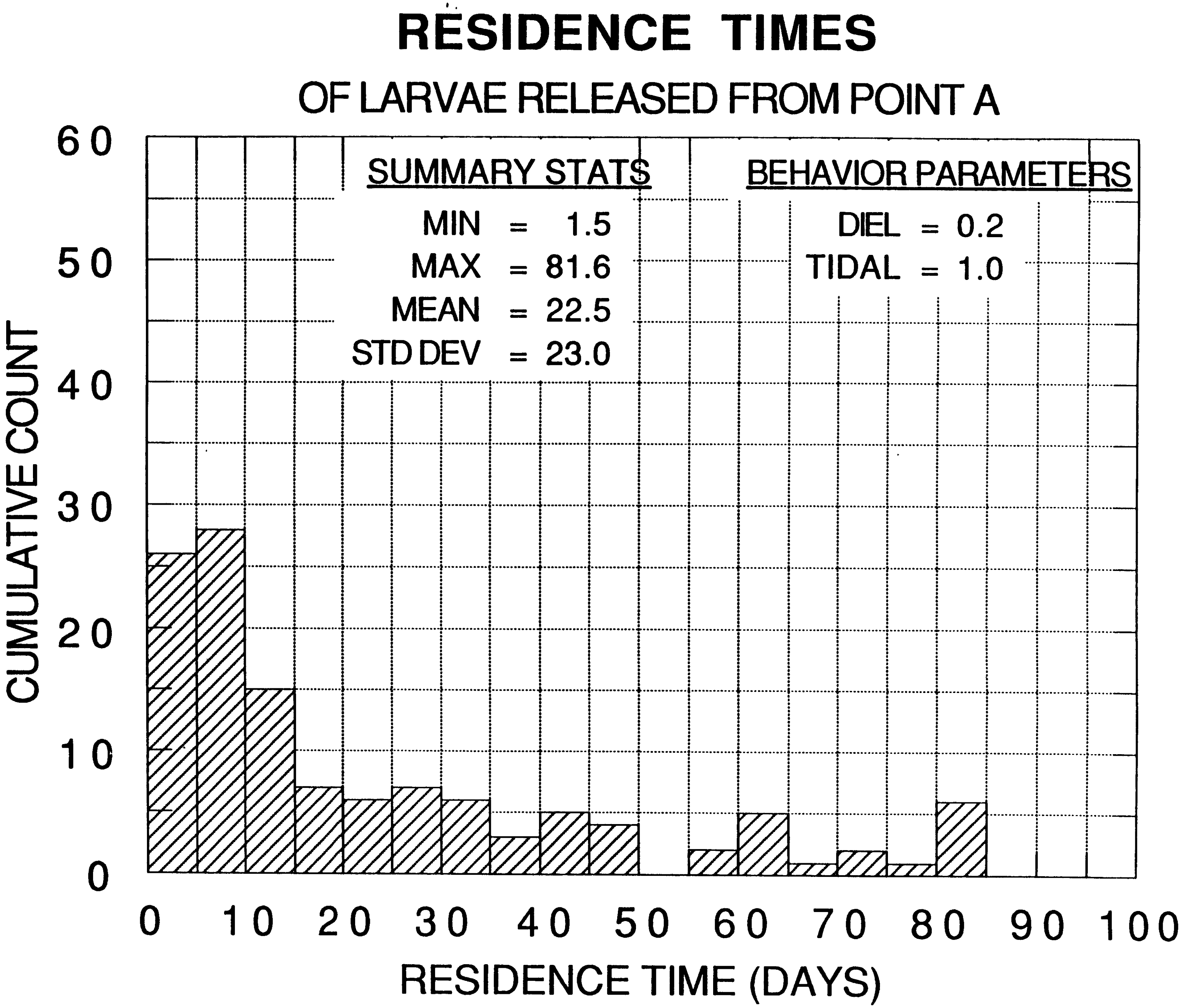

Figure 5b (from Moeller, 1990)

FIGURE 4-E: DIEL BEHAVIOR VS. RESIDENCE TIME OF LARVAE RELEASED FROM POINT A

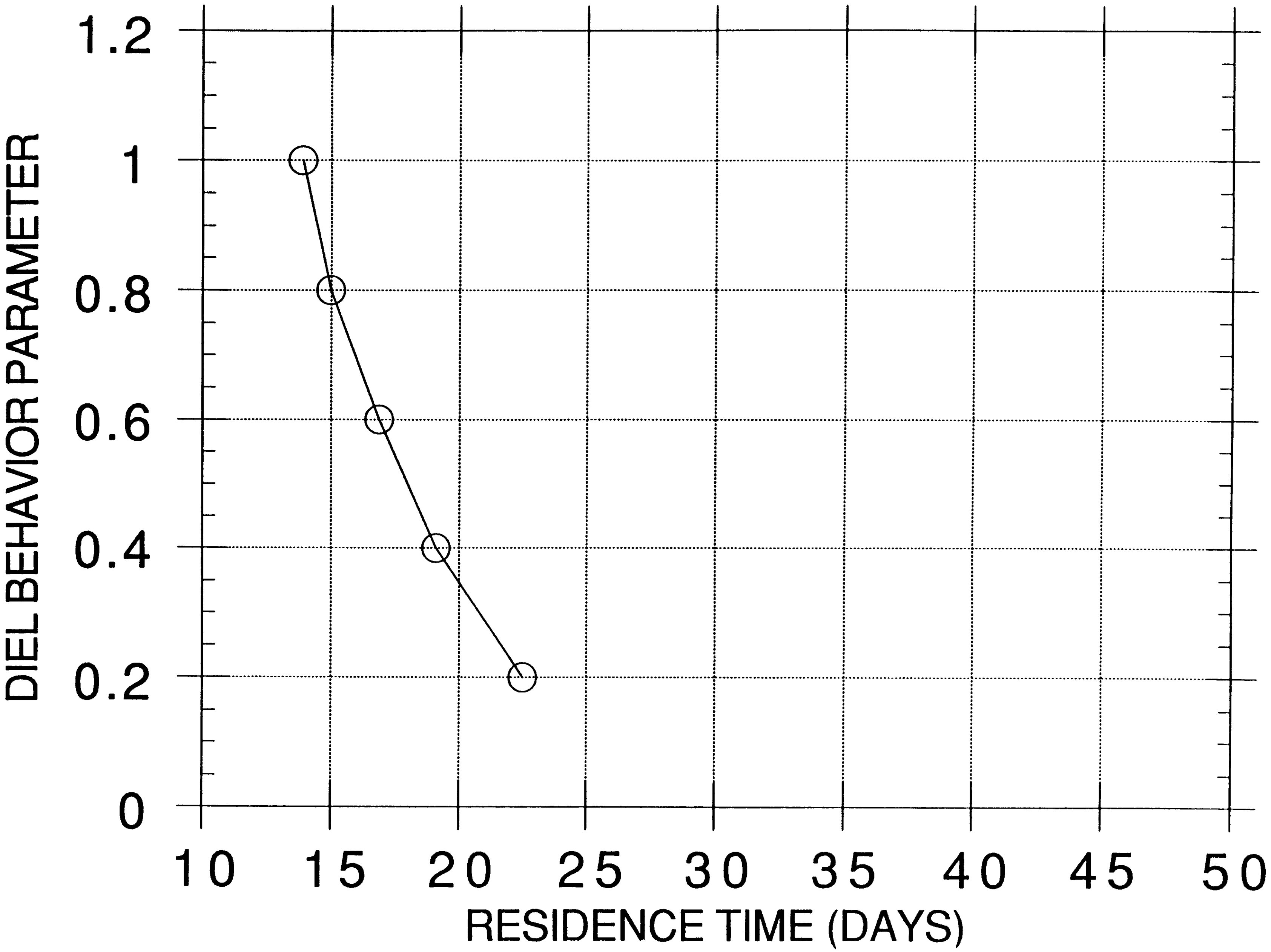

Figure 6 (from Moeller, 1990)

FIGURE 5-B: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

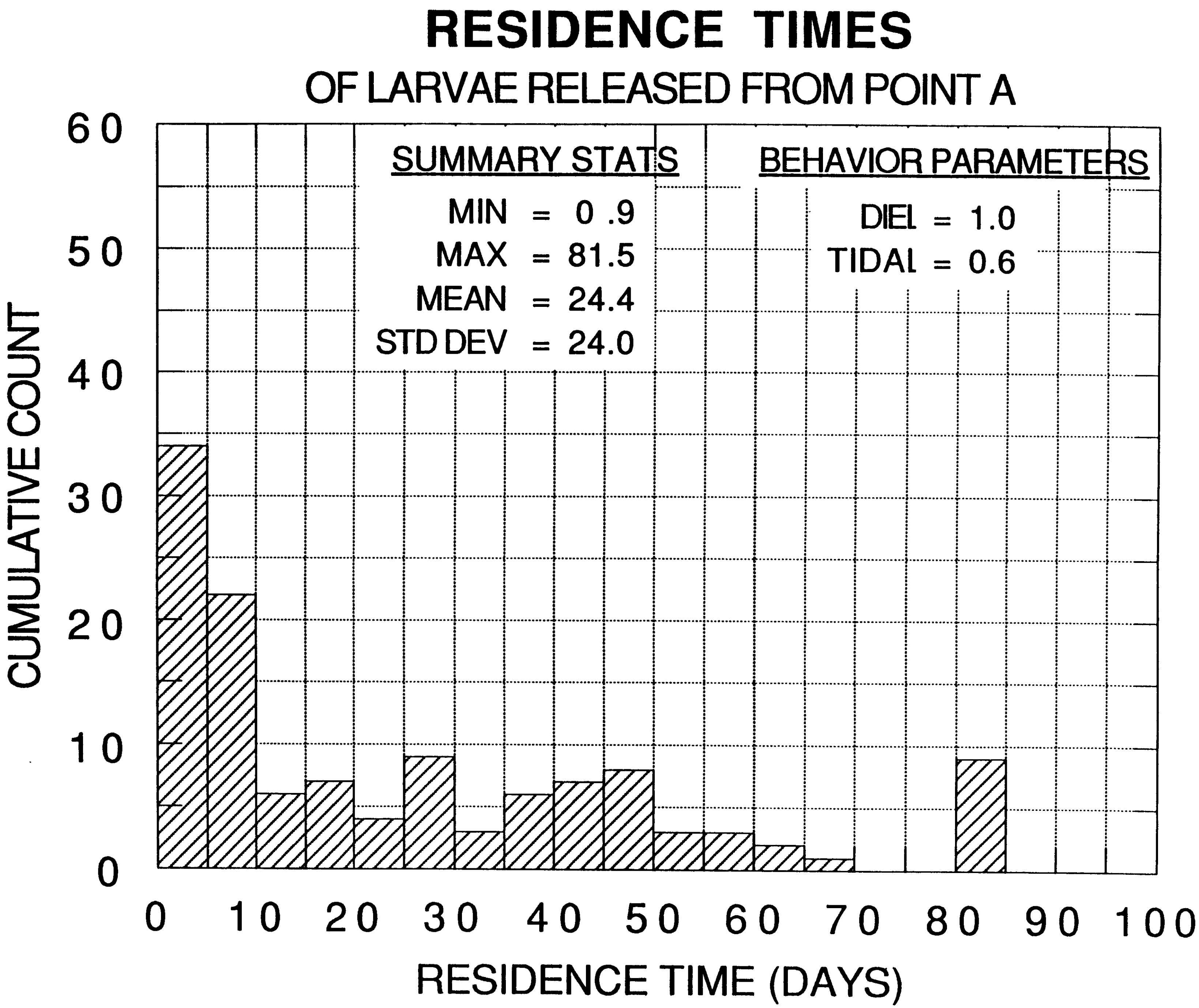

Figure 7a (from Moeller, 1990)

FIGURE 5-D: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

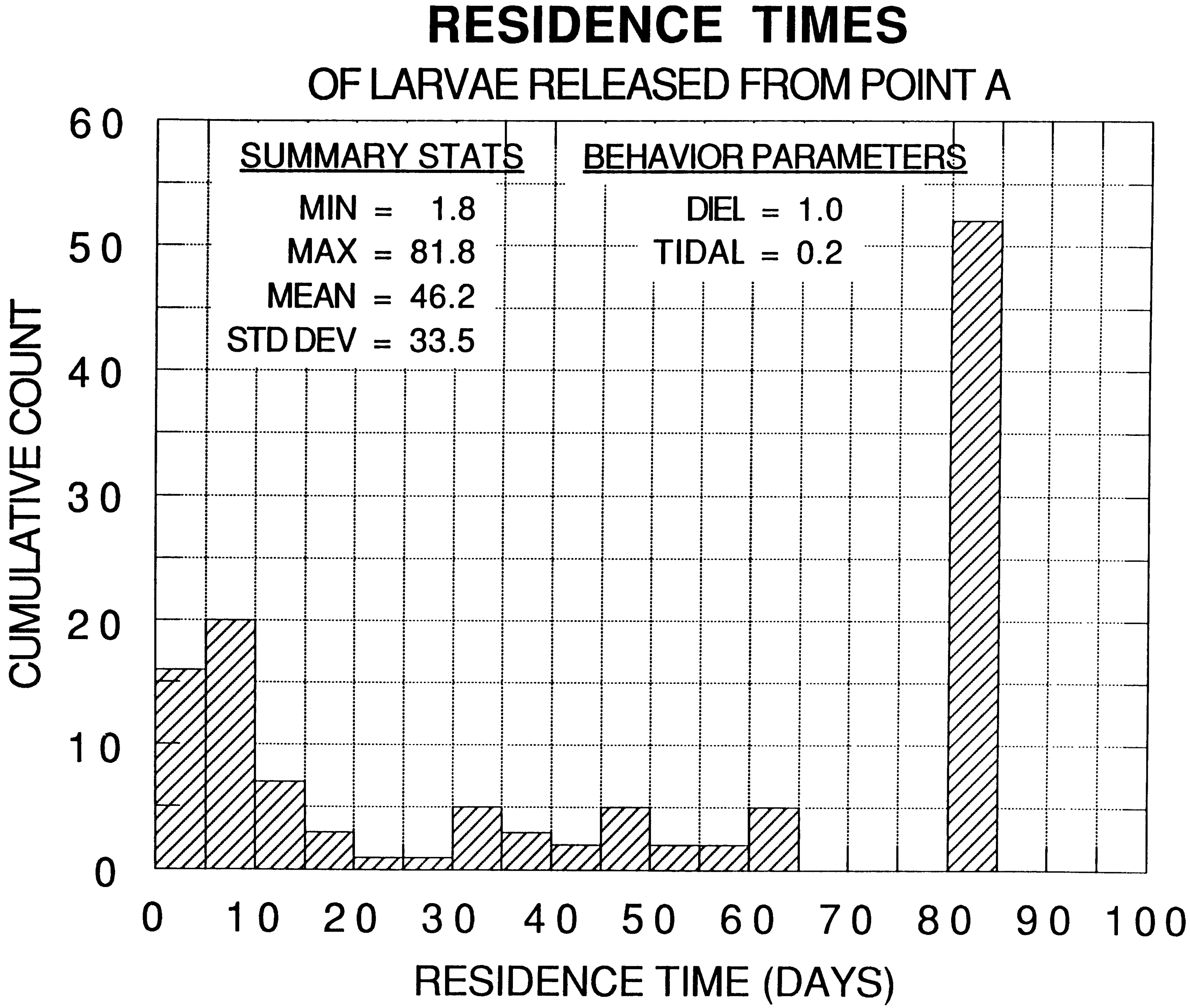

Figure 7b (from Moeller, 1990)

tidal parameter of 0.6 and 0.2 respectively, and Figure 8 plots residence times for values of the parameter ranging from 0.2 to 1.0. For both the analytical and the particle tracking models, values of the diel and tidal parameters seem to be within the range of values reported in the literature, and are consistent with the observations discussed in Section 2 concerning the higher concentration of larvae near the bottom. Thus it appears that either effect could explain the observed residence times.

For both models, larval length frequency distributions were computed corresponding to the residence time distributions. While it has been possible to match the observed residence times using behavior, it has not been possible to match the length frequency distributions at entrainment. In all cases more simulated larvae are entrained at lengths of 3 to 4 mm, followed by those of length 4 to 5 mm, etc. The explanation is that transport out of the Niantic River is by a diffusive mechanism which depends on larval density, and there is always a greater density of the younger (shorter) larvae because of 1) mortality and 2) increased growth rate with length, especially late in the season, because of the correlation between water temperature and length. In addition, if the larvae are retained for too long in the estuary (i.e., by reducing the value of either the tidal or diel behavior parameter), a significant number of simulated larvae grow to 8 mm. Indeed, the rather flat length-frequency distribution (for entrainment measurements) suggests that many of the larvae are arriving by advection, rather that diffusion. The inability to match the shape of the length frequency distribution, is a strong indication that a large fraction of entrained larvae are being imported.

5 Larval Import (Hypothesis 5)

The major evidence for import, so far, is the fact that between 50 and 100 times more larvae are being entrained than can be accounted for by the yolk-sac larvae observed in the river (assuming no behavior) and that, while modest adjustment of the behavior

FIGURE 5-E: TIDAL BEHAVIOR VS. RESIDENCE TIME OF LARVAE RELEASED FROM POINT A

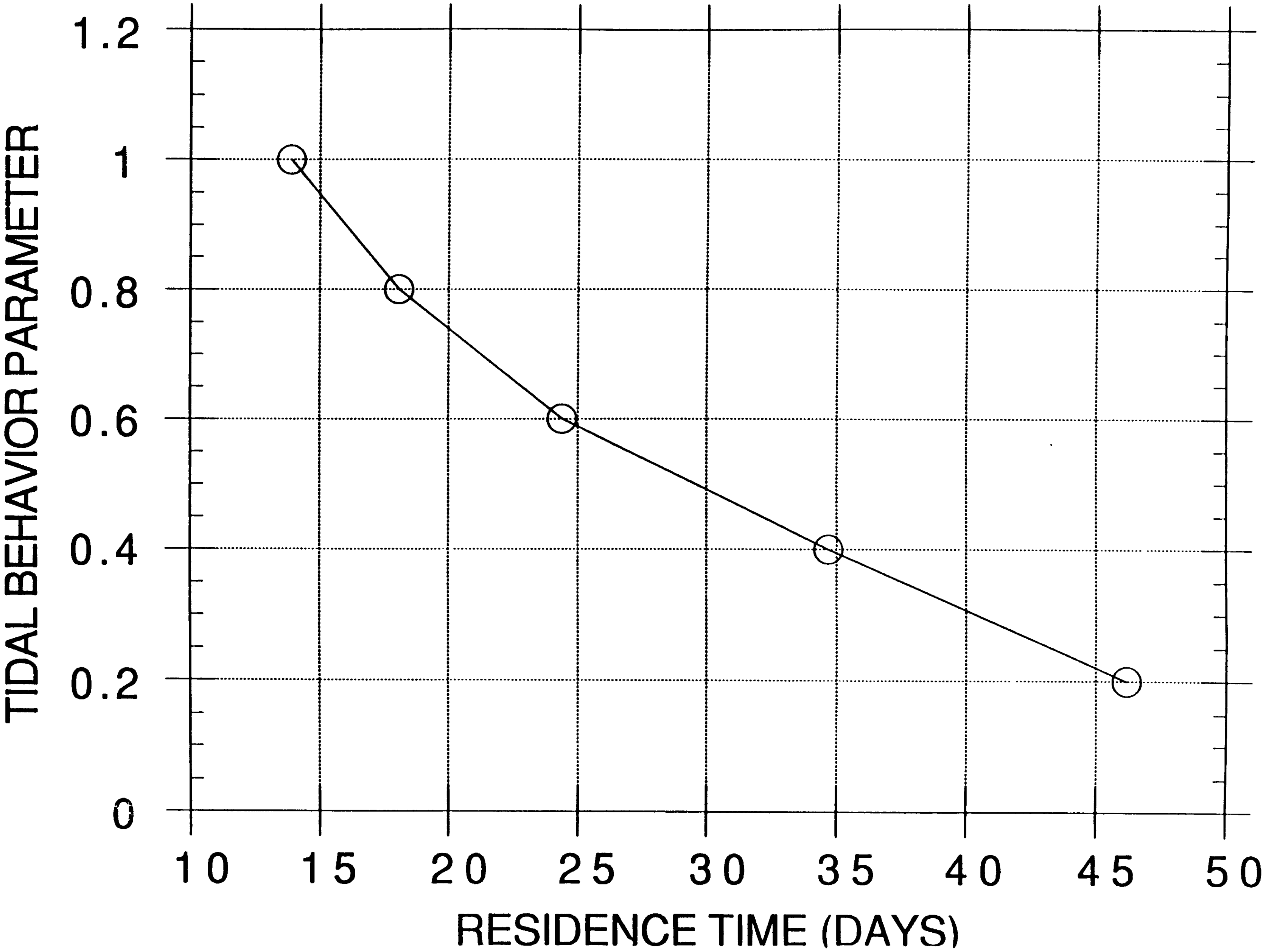

Figure 8 (from Moeller, 1990)

parameters can explain the observed residence times, they can not explain the observed length-frequency distribution. (Also note that an increase in larval residence within the river decreases the simulated number of entrained larvae for a given mortality factor.) Other evidence for import comes from mass balance calculations, mentioned previously, and from observation that the density of larvae should decrease monotonically with distance down the river and into the bay if there were no additional source. At later times of the year, the density increases.

Calculations have been made with larvae introduced along the model boundaries to show that larvae imported from outside could indeed be entrained. In addition, the fact that larval densities at the intake are similar to those in the bay suggests that the number in the bay is sufficient to support the observed entrainment.

6 Conclusions and Recommendations

1) The strongest evidence for there actually being substantially more larvae in the river than have been observed to date is the estimated hatching rate of 1.5 to 2 billion larvae per year (based on the number of adult spawners, average fecundity, and hatching rates). The assumptions behind this estimate should be reviewed to see if they still make sense.

2) If this estimate still appears reasonable, then further near-bottom sampling should be conducted with a modified pump sampler. This effort should quantify the fraction of the "missing" larvae that are within the river, with the remainder presumable being imported from outside.

3) There is strong evidence that many, if not most, larvae appear to be imported from outside because

a) the number of larvae presently accounted for from the river is too low by a factor of 50 to 100,

b) the observed length-frequency distribution at entrainment can not be matched by any simple larval retention mechanisms in the river,

c) the longitudinal distribution of larvae within the river and between the river and the bay is not consistent with the larvae coming only from the river.

4) In view of the above, further mass balance calculations should be conducted using both total larvae and larvae grouped by length or stage to try to further quantify import.

5) While we have not been able to match the observed length-frequency distribution for larvae at entrainment (based only on larvae hatched within Niantic River), our sensitivity studies indicate that a modest amount of tidal or diel "behavior" is sufficient to explain the observed longer retention times of larvae as compared with dye in the river.

7 References

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MODIFICATION OF THE MODEL MILL TO BETTER SIMULATE ENTRAINMENT OF WINTER FLOUNDER LARVAE AT THE MILLSTONE NUCLEAR POWER STATION

by

ANDREW THOMAS OBST

SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF

BACHELOR OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1990

Signature of Author ______________________________
Department of Mechanical Engineering
June 4, 1990

Certified by ______________________________
Doctor E. Eric Adams
Thesis Supervisor

Accepted by ______________________________
Professor Peter Griffith
Chairman, Department Committee

Appendix A

MODIFICATION OF THE MODEL MILL TO BETTER SIMULATE ENTRAINMENT OF WINTER FLOUNDER LARVAE AT THE MILLSTONE NUCLEAR POWER STATION

by

ANDREW THOMAS OBST

Submitted to the Department of Mechanical Engineering on June 4, 1990 in partial fulfillment of the requirements for the degree of Bachelor of Science.

Abstract

The purpose of this study is to describe recent modifications of the model MILL, which are an attempt to better simulate the entrainment of winter flounder larvae at the Millstone Nuclear Power Station (MNPS). The finite element grid used by MILL was divided into ten macro-elements in order to compute larval densities at the Niantic River hatching stations and other areas. This was done in order to accommodate future density dependent features in the model. Larval input at all three hatching stations during the same simulation was also added to the model, and the finite element grid was reconfigured to reduce the incidence of larvae exiting the model boundaries during the simulation. The model was run using both the original and reconfigured grid. In simulations with the original grid, peak larval concentrations were lower than data indicate, and time to peak concentration for macro-elements in the estuary were different than observed. Results from simulations with the reconfigured grid were inconsistent, indicating that further modifications of this grid may be required.

Thesis Supervisor:	Doctor E. Eric Adams
Title:	Principal Research Engineer

Dedication

I wish to thank Dr. Eric Adams and Nadia Dimou for their help and support in this effort. Without their contributions, I would have been unable to carry out this project.

I wish to thank the Riversiders and Associates of Scandia, Minnesota, for their continuous support during my time away from home.

I wish to thank the brothers of the Beta house for making my time at M.I.T. worthwhile.

Finally, I wish to thank my parents, Tom and Mary Jo, and my sisters, Chris, Jenny, and Katie, for their love and support.

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Chapter 1

Introduction

1.1 Purpose and Scope

The purpose of this study is to describe recent modifications of the model MILL, which are an attempt to better simulate the entrainment of winter flounder larvae at the Millstone Nuclear Power Station (MNPS). As shown in Figure 1-1, MNPS is located in Waterford, Connecticut, on the northern boundary of Long Island Sound. Winter flounder (Pseudopleuronectes americanus) spawn in the Niantic River, an estuary which empties into Niantic Bay near the intakes for the MNPS cooling station. Because of the intakes' proximity to the spawning grounds, approximately 100 million larvae are entrained and killed by the cooling station yearly [NUEL 88]. The M.I.T. model MILL [Dimou 89] was developed as a predictive population dynamics model, for impact assessment of MNPS. When compared to field data, early MILL simulations indicated that too few larvae were being entrained, and that the larvae being entrained were more immature than those observed.

1.2 Organization of Study

In Chapter 2 the model MILL is described, in particular the finite element grid used for simulations and relationships regarding larvae behavior.

Chapter 3 describes early results obtained with MILL by Dimou [1989]. Major discrepancies between simulation output and NUEL observations are described.

Factors influencing larvae numbers and length distribution at the Millstone intakes are described in Chapter 4. These factors include hatching rates and residence times in the

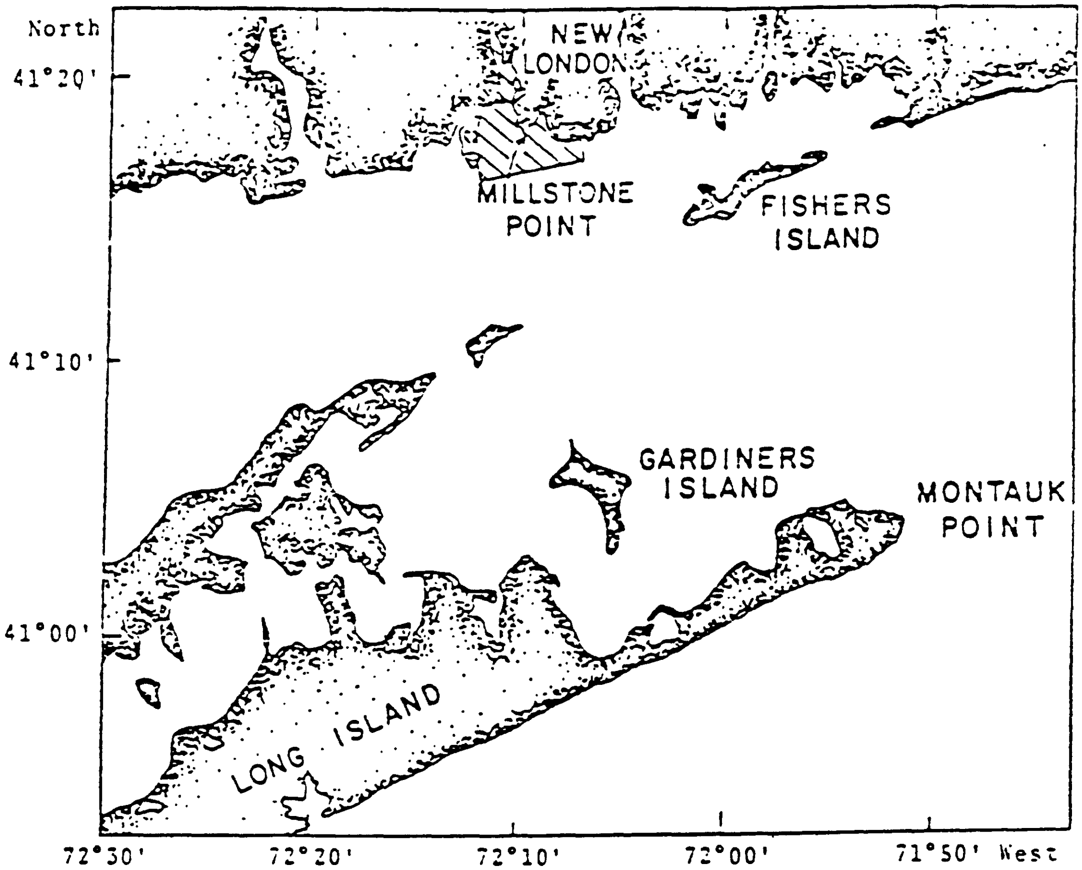


Figure 1-1: Location of Millstone Nuclear Power Station (from Saila, 1976, Figure 1)

Niantic River, larval import from other spawning grounds, and larval mortality rates. Density dependent growth and mortality are also discussed.

Modifications to the model MILL are described in Chapter 5. These modifications include division of the finite element grid into macro-elements in order to incorporate density dependent effects, altering the code to allow larval release at all three hatching stations simultaneously, and reconfiguration of the Niantic River grid to reduce the incidence of larvae exiting the model.

Chapter 6 outlines results of simulations using both the original and reconfigured Niantic River grids. The results of these simulations are then compared with observations.

Chapter 7 includes a summary of the study and conclusions.

Chapter 2

Description of the Model MILL

2.1 Background

The model MILL was developed by Dimou [1989] to simulate the transport and fate of winter flounder larvae hatched within the Niantic River. MILL is a two-dimensional random walk model based on the Eulerian-Lagrangian finite element transport model ELA [Baptista et al. 84]. Hydrodynamic circulation, required by ELA for input, is provided by the harmonic finite element circulation code TEA [Westerink et al. 84]. Other inputs to the model includes a continuous distribution of larvae hatching over time, larval mortality, and larval behavior as a function of age, time of day, and tidal stage.

2.2 Grid

The finite element grid used in this study is basically the same grid used by Dimou [1989]. The grid with the locations of the Millstone Nuclear Power Station and larval hatching stations A, B, and C is shown in Figure 2-1. The portion of the grid containing the hatching stations is the Niantic River, which empties into Niantic Bay west of MNPS.

2.3 Modeling Larval Behavior

Studies of the impact of MNPS on local marine life have been conducted since 1968, and extensive studies of the winter flounder population were initiated in 1975. From these efforts, general relationships concerning larvae behavior and growth were identified and added to the model MILL. These relationships include [Dimou and Adams 89]:

1) Estimates of hatching rates as a function of time and space

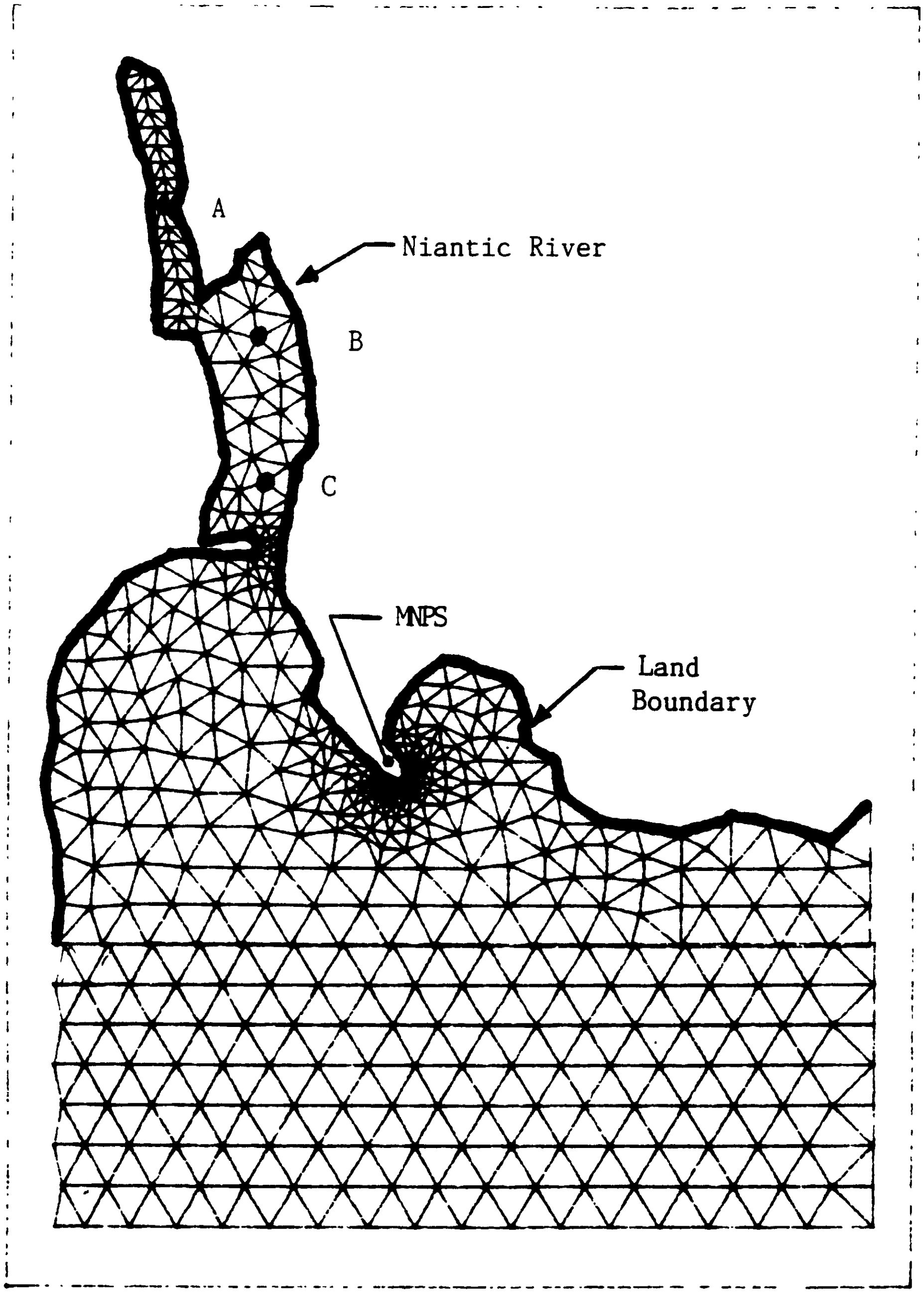


Figure 2-1: Millstone grid as developed by Dimou [1989] including locations of MNPS and hatching stations A, B, and C.

2) Daily growth rates as a function of water temperature

3) Daily larval survival rates as a function of age

4) Diel and tidal behavioral responses as a function of larvae size

5) Mortality due to entrainment as a function of larval size

2.3.1 Hatching Rates

The larval hatching distribution was estimated from the abundance of yolk-sac larvae (larvae less than 10 days old) in the Niantic River at stations A, B, and C during the years 1984-87. The average temporal abundance of yolk-sac larvae for these years is shown in Figure 2-2, where abundance is expressed as density/500 m^3.

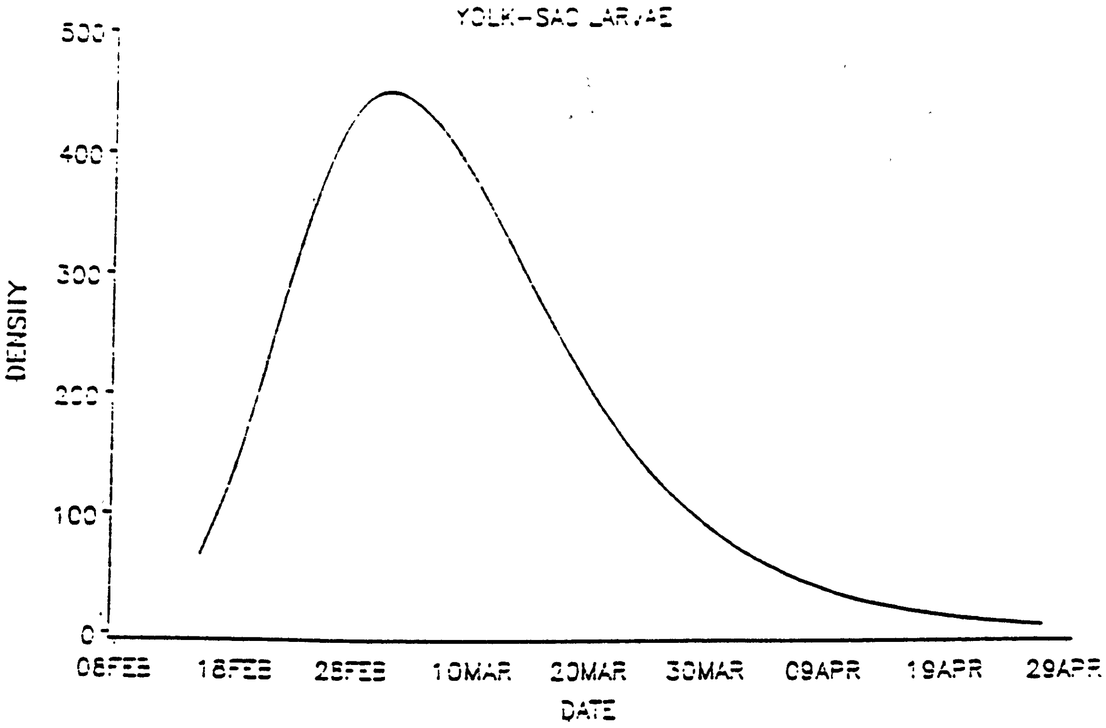


Figure 2-2: Average temporal abundance of yolk-sac larvae for the period 1984-87 for stations A, B, and C [NUEL]

Using this data, the number of larvae hatched during each three hour timestep of the simulation was calculated as:

$$b(t) = 0.0213N\,[\,[i/10 + 1]\,10] \qquad (2.1)$$

where N is the cumulative number of larvae hatched per 500 m^3 on the days j (where (i - 10) < j < i) and alive on day i [Dimou 89]. The input hatching rates at stations A, B, and C in number of larvae per day in 500 m^3 are shown in Figure 2-3.

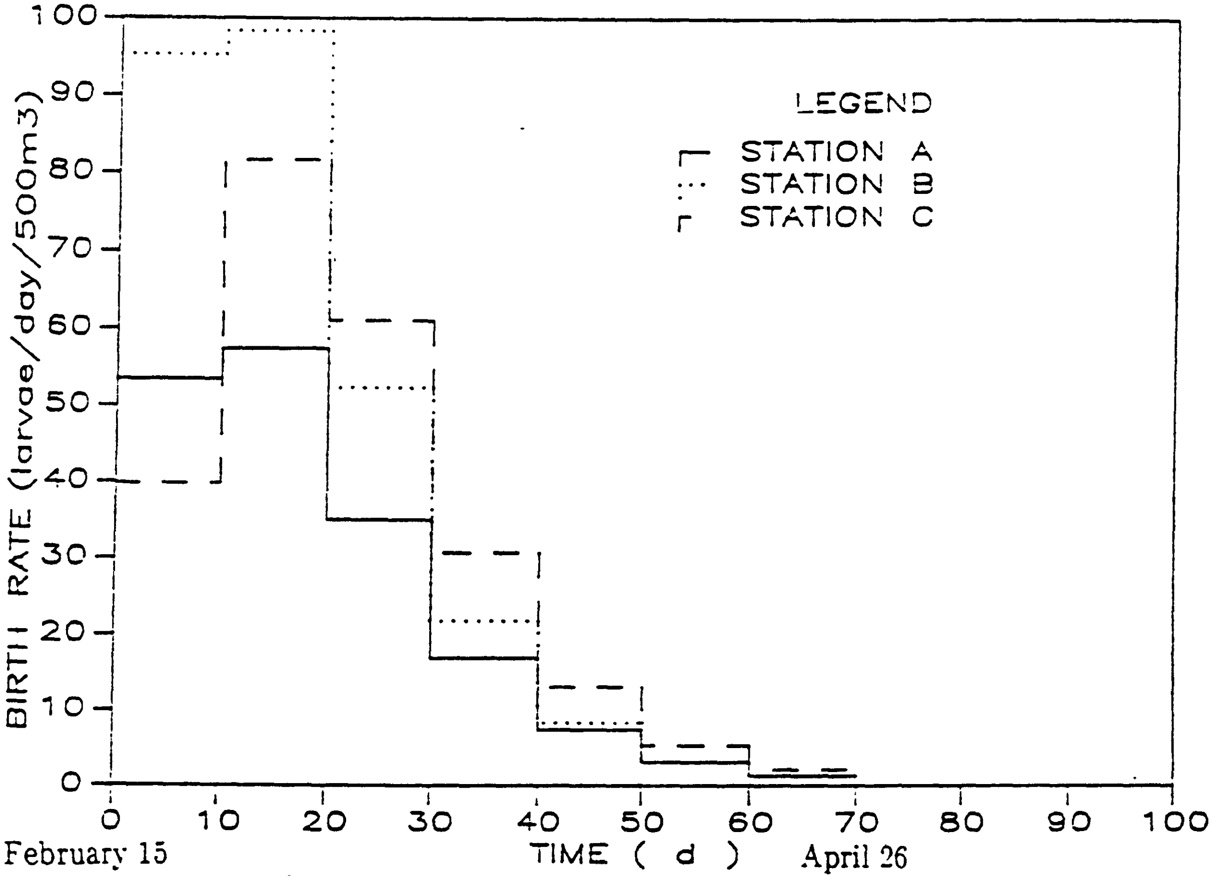


Figure 2-3: Averaged birthrates (number of larvae hatched per 3 hours in 500 m^3) for the period 1984-87 at stations A, B, and C

2.3.2 Growth and Survival Rates

Larval growth rates were calculated by the Northeast Utilities Environmental Laboratory (NUEL) from entrainment data for the years 1976-87. Data indicate that the growth rate is a function of water temperature in the estuary, and is calculated as:

$$\text{mm/day} = dL/dt = -0.0145 + 0.0134T \qquad (2.2)$$

where T is water temperature in ^{o}C. Using this relationship and average water temperature data for the Niantic River beginning February 15, larval growth was plotted in Figure 2-4.

Depicted as stage 1 in Figure 2-6, yolk-sac larvae are 3 mm in length at hatching. As they develop, the yolk-sac is absorbed and the larvae undergo metamorphosis until they reach 8 mm. At that point, the larvae have become juveniles (stage 5 in Figure 2-6) and begin to behave much like adult winter flounder [Klein-MacPhee 78]. Figure 2-4 illustrates that the larvae hatched early in the simulation require approximately 11 weeks to reach the juvenile stage, while larvae hatched near the end of the simulation require only about 5 weeks.

2.3.3 Diel and Tidal Behavior

Based on data from NUEL, MILL models larval behavior in the estuary as a function of age, time of day, and tidal stage. This behavior consists of vertical migration in the water column for larvae greater than 5mm in length [Dimou 89]. At stations A and B, the larvae exhibit diel behavior, spending more time on the bottom during the day, and migrating upward at night. To model this behavior, the proportion of larvae available for tidal transport (y) is given by Equation (2.3)

$$y = 0.985 - 0.094L \qquad (L > 5 \text{ mm}) \qquad (2.3)$$

where L is the larval length in mm.

At station C, the larvae do not exhibit diel behavior, but instead show a tidal

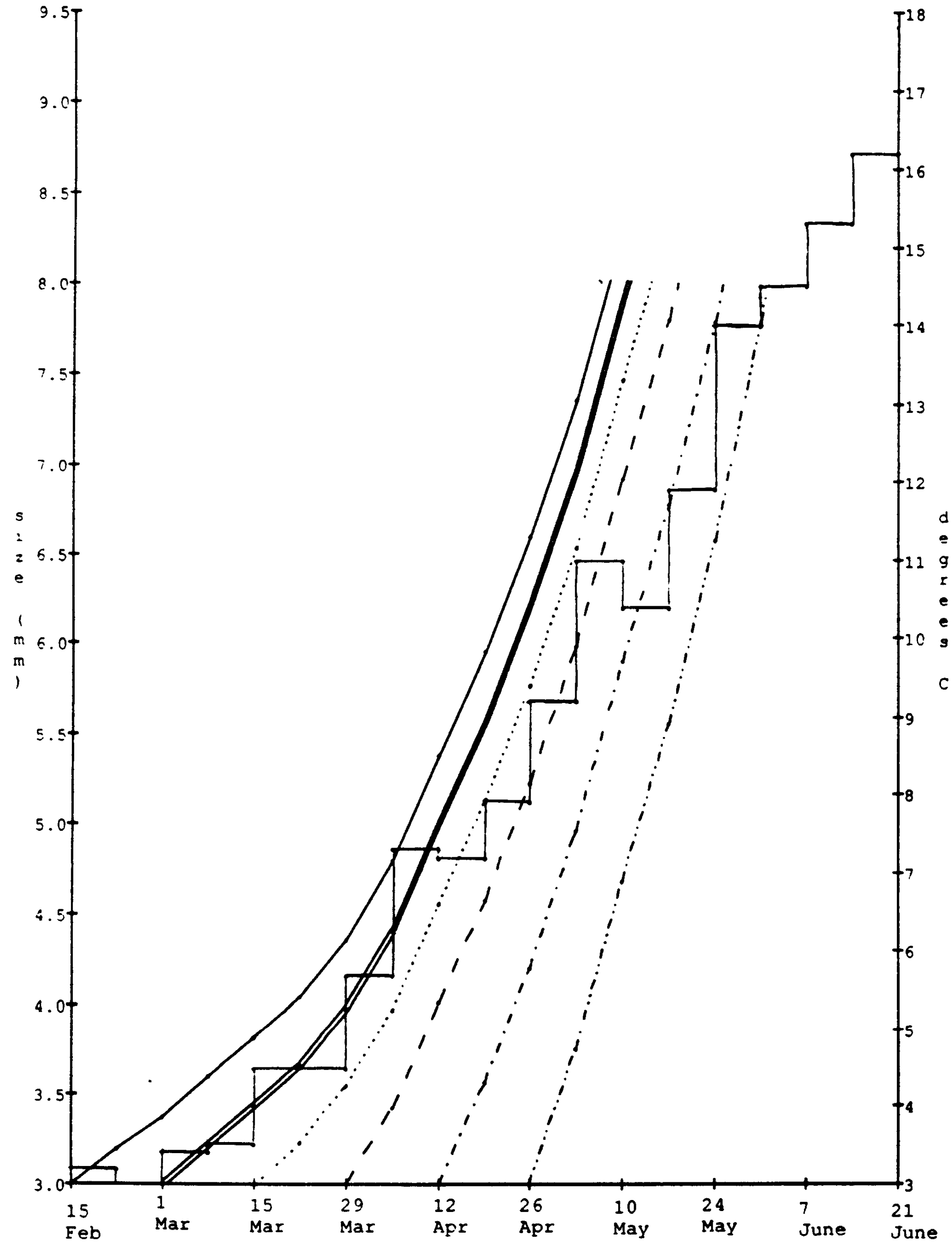
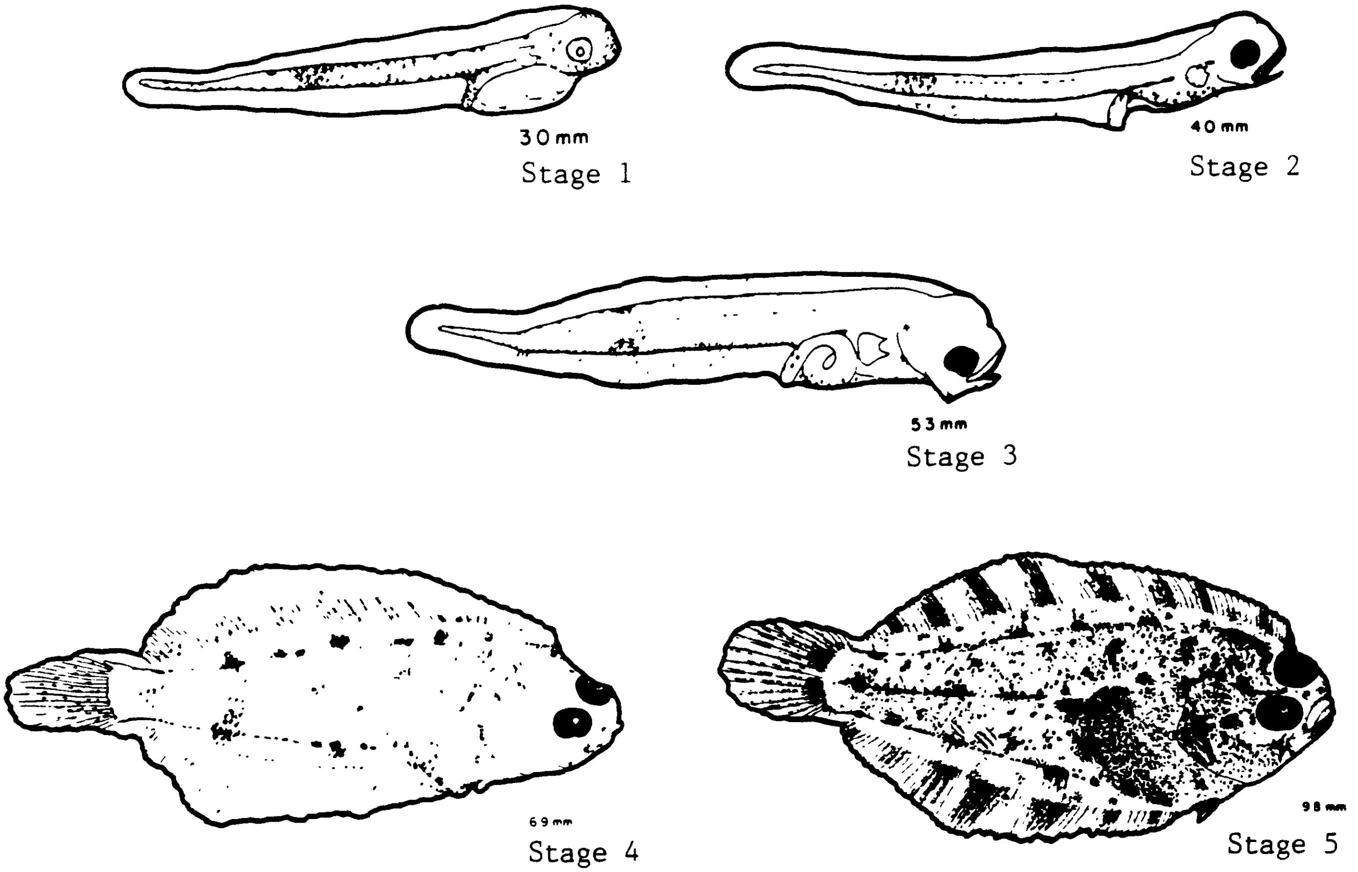


Figure 2-4: Larval growth as a function of water temperature during simulation period (water temperature plotted incrementally in °C)



Stage 1

Stage 2

Stage 3

Stage 4

Stage 5

Figure 2-5: Growth stages of winter flounder from yolk-sac larvae to juveniles [NUEL 88]

behavioral response. The larvae fall to the bottom during ebb and rise in the water column during flood tide. The proportion of larvae available for tidal transport during flood tide is given by Equation (2.4)

$$y = 1.696 - 0.221L \qquad (L > 5 \text{ mm}) \qquad (2.4)$$

MILL accounts for diel behavior at stations A and B and tidal behavior at station C by multiplying the advection and random walk components of the model by the factor y.

2.3.4 Mortality

During MILL simulations, particles are released at a fixed rate from stations A, B, and C in the finite element grid. Each particle represents a cohort of yolk-sac larvae and the number of larvae in each cohort varies according to the temporal hatching distribution. Daily survival of larvae was calculated by NUEL. For larvae 3-4 mm in length the daily survival factor was equal to 0.9, and for greater lengths it was 0.97. As the cohort is advected within the grid, it could die because of natural mortality or exit the model boundary. In these cases tracking of the particle stops. The cohort also could be entrained by the MNPS intake. If the larvae are less than 7mm in length at entrainment, 100% mortality is assumed and tracking of the particle ceases. Otherwise the cohort experiences 20% mortality, is placed in the MNPS discharge plume, and tracking resumes. Once the larvae reach 8 mm in length, they are considered juveniles and the cohort is no longer tracked.

Chapter 3

Early Model Results

The number and length distributions of entrained larvae as simulated by MILL were compared to corresponding entrainment data provided by NUEL [Dimou 89]. Table 3-I compares the simulated number of entrained larvae with the actual number entrained as calculated by NUEL [1988].

Table 3-I: Comparison of seasonal total of entrained larvae simulated by MILL (as a function of the station where hatching occurred) with measured entrainment from NUEL [Dimou 89]

Simulation	Total number ($\times 10^6$)	Percent of larvae hatched
Sta A	0.30	5.2
Sta B	0.80	6.0
Sta C	0.38	8.8
total	1.48	6.7
Measurement	98.0	450.

The model predicted that about 1.5 x 10^6 of the 22 x 10^6 larvae simulated to be hatched were entrained. This number is nearly two orders of magnitude smaller than the 98 x 10^6 larvae calculated to be entrained yearly by NUEL [1988] for the years 1984-87. The model hatching rate being less than one quarter of the actual entrainment is obviously a major problem. It is clear that not enough larvae are simulated to be hatched in the model.

Table 3-II compares entrained larval length distributions simulated by the model and observed by NUEL. A large discrepancy is found between the simulated and measured

Table 3-II: Comparison of length distributions of entrained larvae simulated by MILL (as a function of the station where hatching occurred) with measured entrainment from NUEL (percent) [Dimou 89]

	length range in mm					
Simulation	3-4	4-5	5-6	6-7	7-8	total
Sta A	85.2	5.4	7.1	2.2	0.1	100
Sta B	93.5	2.8	2.2	1.6	0.1	100
Sta C	94.6	3.0	1.2	1.1	0.1	100
ave.	91.7	3.5	3.0	1.7	0.1	100
Measurement	17.8	18.6	24.3	23.1	16.2	100

length distributions of entrained larvae. MILL calculated that about 92% of the entrained larvae were in the 3-4 mm length range, while measurements from NUEL for the years 1984-87 indicate only about 18% of the entrained larvae were in this range. The measured entrained larvae are actually well distributed in length, with each size group making up a substantial portion of the total entrained. This discrepancy appears to be the result of larvae being flushed from the Niantic River more quickly in the model than they are in reality.

In summary, there is poor agreement between the model and actual entrainment data. Not enough larvae are being entrained in the model, and those that are entrained are generally younger than data indicate.

Chapter 4

Analysis

4.1 Factors Influencing Larvae Numbers and Length Distribution

The model MILL is indicating that too few larvae are being entrained, and those that are entrained are younger on average than observations indicate. Several hypotheses were developed to help explain these discrepancies [Dimou and Adams 89]. These hypotheses, which are discussed further include:

1) The input hatching rates are too small

2) Larval residence times within the Niantic river are too short due to:
   a) Overestimation of hydrodynamic flushing rates, or
   b) Underestimation of larval retention due to larval behavior

3) Larvae are being imported from outside the Niantic River area

4) The input larval mortality rates are too high

4.1.1 Hatching Rates

Data from NUEL indicate that 98 x 10^6 larvae are being entrained yearly, while the model only simulates 22 x 10^6 larvae being hatched in the system. The fact that fewer larvae are simulated to be hatched than are actually entrained is a major discrepancy that must be rectified to achieve better results with MILL.

The input hatching rates, which are derived from NUEL data on the abundance of yolk-sac larvae, could be in error because of deficiencies in the bongo sampling method used by NUEL personnel. The bongo sampler consists of two conical nets that are towed behind a boat to capture larvae. Flowmeters installed at the center of each net determine the volume of water filtered. The sampler is towed in a stepwise oblique pattern, with equal sampling time at near the surface, mid-depth, and near the bottom [NUEL 88]. Although this method is adequate for calculating the density of many larval species, it seems to underestimate the number of winter flounder larvae in the water column. This may be due to the particular behavior of winter flounder larvae, which tend to reside on the bottom of the estuary. This behavior is discussed further in Section 4.1.2.2. NUEL has devised new methods of sampling larvae near the bottom, in an effort to obtain more accurate measurements of larval densities. The apparatus which seems to hold the most promise consists of a pump with four horizontal nozzles that are lowered together below a boat to a specific level, and operated until a large volume of water has been filtered.

During a visit to MNPS in March, 1990, I observed the operation of this new sampling device. Although the system works as it was designed, NUEL personnel have experienced some difficulties with it. The major problem is that the pump forces the sampled water through the filter at a high flow rate with severe changes in speed, which destroys the delicate flounder larvae. In preliminary tests, most of the captured larvae were extruded through the filter, and any remaining pieces were too small to be recognizable. Since that time, the flow rate has been decreased, and tests indicate that more of sampled larvae should be recovered from the filter [NUEL, personal communication]. Sampling with lower flow rates will resume in the winter of 1991, and should give better estimates of the larval population in the Niantic River.

Recent sampling by NUEL at specific depths with the bongo system seems to indicate that more larvae are located near the bottom of the Niantic River. Table 4-I compares sampling data from near bottom linear tows with corresponding depth averaged oblique tows during March, 1990. By making separate linear tows near the bottom, NUEL personnel were able to compute ratios of surface to bottom larvae concentrations. In seven of the nine samples, the larvae concentration at the bottom was substantially higher than the average, which is a good indication that there are more larvae near the bottom.

Table 4-I: Data from March 19-29, 1990, showing ratios of near bottom to average larvae concentrations [NUEL, personal communication]

Date	Station	Bottom to Average Ratio
March 19	B	0.59
March 23	A	2.88
	B	1.56
	C	0.79
March 26	A	2.44
	B	4.55
March 29	A	2.13
	B	2.27
	C	2.17

Although the results of specific depth sampling appear to support the hypothesis that more larvae reside near the bottom, it must be understood that the approach is somewhat inaccurate. This is because a bottom tow with the bongos could be anywhere within four feet of the bottom, while the surface portion of an oblique tow could be anywhere within four feet of the surface. In shallow areas (~10 feet), this means that bottom and surface tows could be sampling at nearly the same depth.

4.1.2 Larval Residence Times

The most plausible explanation for the discrepancies between the simulated and measured length distributions of entrained larvae is that the larvae actually reside in the estuary for greater periods of time than MILL simulates. Larval residence times could be underestimated due to either overestimation of hydrodynamic flushing rates or underestimation of larval retention in comparison to passive particles. Modifying either of these aspects to increase larval residence times would shift the larval length distribution toward longer lengths by allowing the larvae to age before entrainment. However, increased residence time will result in greater mortality for the larvae, reducing the overall number of larvae entrained. This could aggravate the problem addressed in the previous section of too few larvae in the system.

4.1.2.1 Hydrodynamic Effects

The hydrodynamic flushing time for the model was calibrated to Ketchum's tidal mixing model [Ketchum 1951]. In this modeling scheme, the estuary is divided into volume segments, and it is assumed that complete mixing occurs in each segment during a tidal excursion. Using this approach, Dimou [1989] calculated the flushing time to be 15 days, which agrees well with the flushing time of 14 days calculated by MILL. These flushing times were compared with tracer studies conducted during the period November 16, 1988 through January 11, 1989 to test the hypothesis that the hydrodynamic flushing rate had been overestimated. Instead, the studies indicated flushing times of between about 3 and 5 days [Dimou 89]. Plainly, the short larval residence times within the Niantic River were not due to an overestimation of the flushing rate.

4.1.2.2 Behavioral Effects

Larval residence times were most probably underestimated because of larval behavior. Although MILL models both diel and tidal larval behavior, the larvae are still being flushed out of the Niantic River too quickly during simulations. A solution to this problem would be to increase the effects of behavioral mechanisms in the model. Presently, MILL only models behavioral effects on flushing rates after larvae reach 5 mm in length. Whether or not this modeling scheme is correct is questionable, and further investigation of diel and tidal behavior is needed. A list of references for future research about tidal behavior is included in Appendix A.

For larvae less than 5 mm, the model assumes that the larvae spend a majority of the time in the water column being transported as passive particles, which in reality is probably not the case. Studies have determined that larvae have a specific gravity of 1.022 with respect to seawater with a passive sinking rate of 14 mm/s, and are usually located near the bottom [Klein-MacPhee 78]. Even while actively feeding, the larvae do not remain in the water column constantly but exhibit intermittent swimming behavior, alternating with periods of resting on the bottom [Buckley 89]. This behavior reduces the larval flushing rate, as larvae spend more time near the bottom where water velocities are lower.

The assumption that larvae are concentrated near the bottom, coupled with the fact that current sampling methods do not capture larvae that are very near the bottom, would seem to indicate that there could be a substantial population of larvae resting on the bottom at any time. It is hoped that the new methods of sampling larvae devised by NUEL will yield better estimates of the near bottom larvae densities which can be used to better approximate the effects of diel and tidal behavior on flushing rates.

4.1.3 Larvae Import

The disparities between simulated and observed larval numbers and size distributions could also be explained by larval import from other spawning sites. To reach MNPS, larvae hatched in nearby estuaries such as the Connecticut River would require long travel times, during which they would mature. Such larvae could explain the large numbers entrained at MNPS and their maturity could explain the difference between simulated and observed size distributions [Dimou and Adams 89]. Imported larvae could also help explain why observed entrainment times exceed simulated times.

Although import is a viable possibility, it is doubtful that the number of larvae required to explain the discrepancies between the model and observations could all be imported. Some evidence of larval import has been observed by NUEL, and research is currently underway to examine this alternative hypothesis [NUEL 89].

4.1.4 Mortality Rates

The number and size distribution of entrained larvae in the model MILL are both dependent on the larval mortality rate. The assumed daily survival rates of 0.9 for larvae 3-4 mm and 0.97 for longer lengths may be too high. Lower mortality would allow older larvae to survive, increasing the number of entrained larvae and shifting the size distribution toward longer lengths [Dimou and Adams 89]. Dimou [1989] tested this hypothesis by running MILL assuming zero mortality. This resulted in about a 3.5 times increase in the number of larvae entrained to 5.2×10^6, which is still much lower than NUEL data. The size distribution shifted, but about 60% of the entrained larvae were still in the 3-4 mm size range. It is clear from this test that reducing larval mortality by itself will not explain discrepancies between MILL output and actual entrainment data. However, it is evident that the total number and size distribution of entrained larvae are fairly sensitive to changes in the survival rate. Determining the survival rate is complicated by the fact that mortality is known to be density dependent, as discussed in the next section.

4.2 Density Dependent Effects

One of the primary goals of this study was to modify the model MILL to make it possible to incorporate density dependent behavior in simulations. The program was modified to compute larval densities and although no density dependent effects were added to MILL at the time of this writing, they could easily be incorporated by modifying the subroutine SCONC. The effects of greatest interest would be density dependent larval growth and mortality.

4.2.1 Density Dependent Growth

A relationship suggesting density dependent growth has been demonstrated in laboratory studies which show a decrease in larval growth as prey densities decrease

[NUEL 89]. This relationship is supported by data from NUEL, which show that two of the lowest larval growth rates were recorded in 1985 and 1988, years in which the greatest abundance of stage 2 larvae (Figure 2-4) were present at station C, while the highest growth rate was in 1986, when stage 2 abundance was lowest [NUEL 89]. Assuming prey densities remain relatively constant, this correlation between larval density and growth could be used to calculate a rough density dependent growth rate for use in MILL.

4.2.2 Density Dependent Mortality

Most mortality during larval growth seems to occur during the first feeding [NUEL 89]. The first feeding occurs about 10 or 12 days after hatching, when larvae have depleted their yolk-sac food supply [Klein-MacPhee 78]. At that point, larvae are about to graduate from stage 1 to stage 2, and must begin actively feeding, competing with other larvae for food. Larval mortality at this stage seems to be a source of compensation in the flounder population, limiting the number of larvae that survive to that which can be supported by the amount of prey in the system. In support of this hypothesis, NUEL has found a strong relationship between instantaneous mortality rates and the egg production index. Data show that for the years 1977-88, as egg production increased so did larval mortality. This relationship could form the basis for calculating larvae survival rates for MILL.

Chapter 5

Modifications to MILL

5.1 Division of Grid into Macro-Elements

As a prelude to making density dependent calculations, the model MILL was modified to compute the density of winter flounder larvae at the Niantic River hatching stations and seven other grid areas. This was achieved by dividing the grid into ten macro-elements, where macro-elements 1, 2, and 3 represented the elements associated with hatching stations A, B, and C, respectively (Figure 5-1). The volumes of the macro-elements were computed by modifying the subroutine VOLU, and the larval concentrations in the macro-elements were calculated using the volumes as input to the subroutine SCONC, which was added to MILL. During simulations, the concentrations were calculated at intervals of seven days, and written to the CASE.CON output file.

5.2 Simultaneous Hatching at Stations A, B, and C

MILL was designed to release larvae at one hatching station only during simulations. To model larvae hatching at all three stations, separate runs had to be made for each station, and the results were superimposed. In the modified version of the model, larvae are released from all three stations during the same simulation. No major modifications of the code were required, and CPU time was reduced.

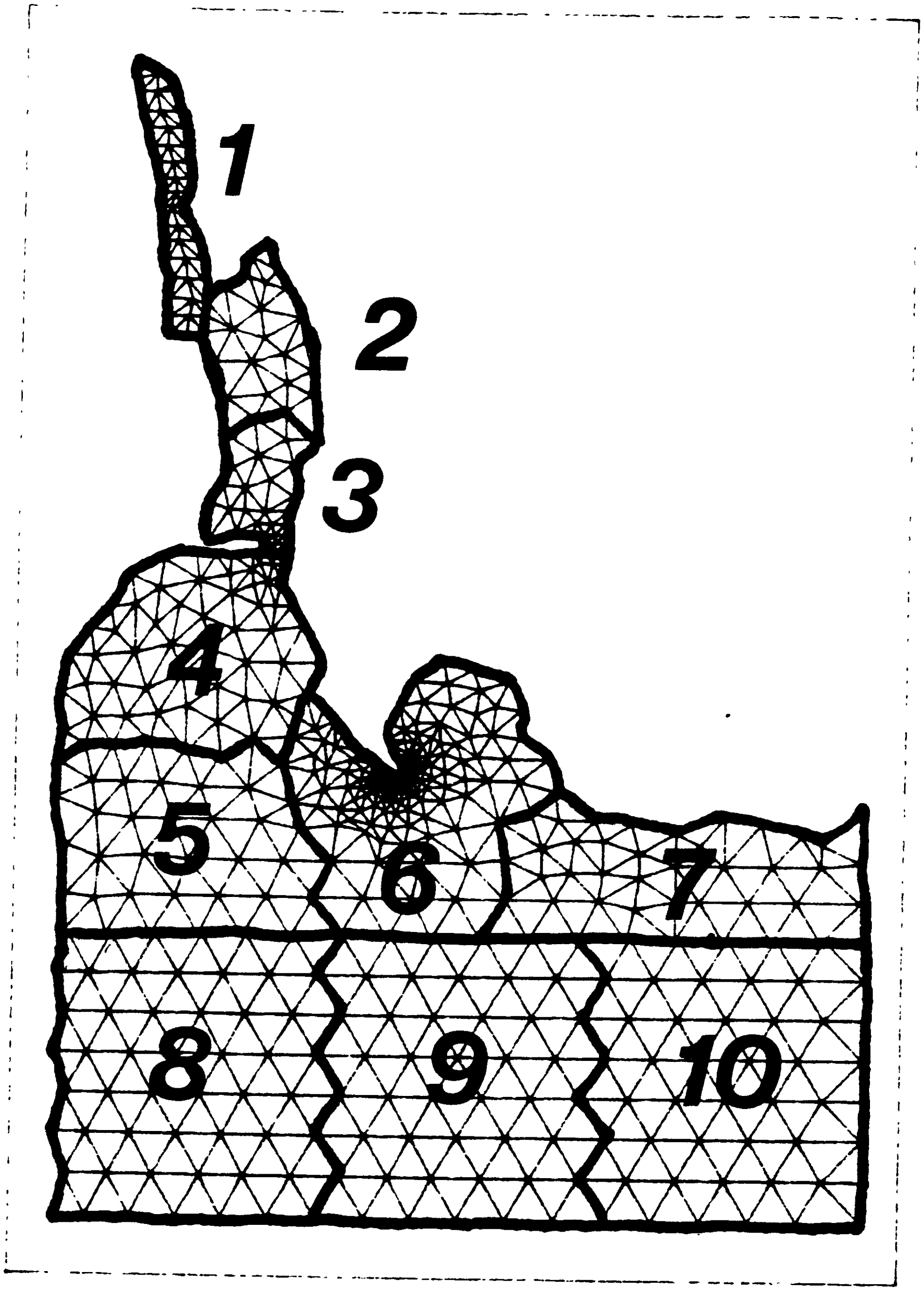


Figure 5-1: Millstone grid macro-elements for use in determining larval concentrations.

5.3 Alternative Hatching Rate Estimation

By increasing the input hatching rate by a factor n, one can force the model to yield more agreeable entrainment numbers, although the distribution of larval lengths will remain skewed toward the low end. Finding a defendable value of n is another matter entirely, and depends on future sampling by NUEL.

One alternative estimate of the actual number of larvae hatched can be made from NUEL calculations of total yearly egg production in the Niantic River. For the years 1977-88, data show an average of about 25 x 10^9 eggs were spawned [NUEL 88]. Assuming 10% of the eggs survive [Dimou and Adams 89], the number of larvae hatched would be 2500 x 10^6. This contrasts sharply with the 22 x 10^6 larvae which was extrapolated from Niantic River larvae densities sampled by NUEL using a bongo sampler.

5.4 Reconfigured Niantic River Grid

ELA is the two-dimensional Eulerian-Lagrangian finite element model upon which MILL is based. One characteristic of ELA that merits further discussion concerns particle tracking along boundaries of the grid system.

When confronted with irregular boundaries, particles that should move along the edge may drift outside of the boundary limits. Instead of stopping the tracking of a particle at the edge of the system, ELA allows the particle to drift along a small "slippery zone" which is defined as a thin band just outside of every boundary element [Kossik et al. 87]. Although it is common for this feature to be invoked in MILL simulations, its effect on the transport calculations has not been studied. It may be that this slippery zone greatly affects particle flushing time, and it certainly adds to model CPU time.

In the irregular geometry of the Niantic River estuary depicted in Figure 5-2, a large number of particles almost certainly encounter the grid boundary. In an effort to minimize

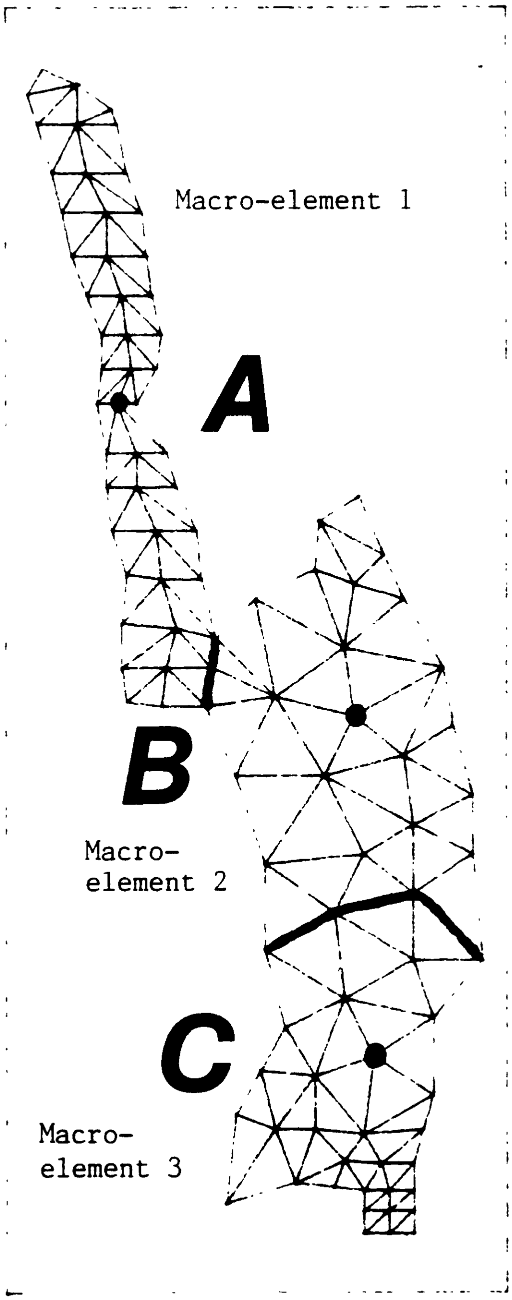


Figure 5-2: Original Niantic River Estuary Grid

the effect of particles entering the slippery zone, the section of the grid representing the Niantic River was reconfigured as shown in Figure 5-3. By making the grid symmetrical it was hoped that particles would be advected along the centerline during the simulation, avoiding the boundary limits until they entered the unchanged portion to the grid (Figure 5-4).

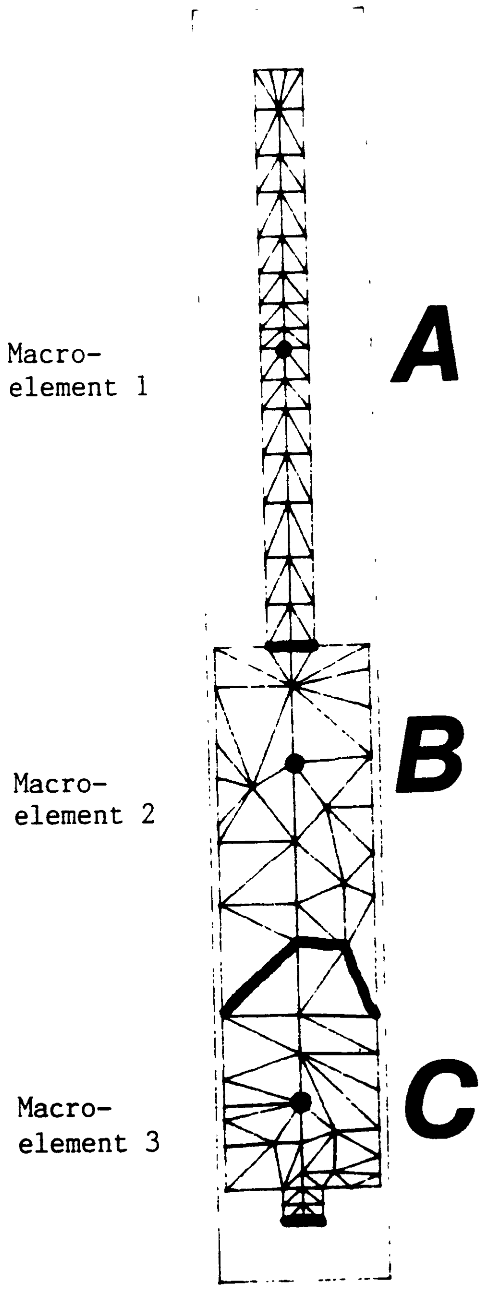


Figure 5-3: Reconfigured Niantic River Estuary Grid

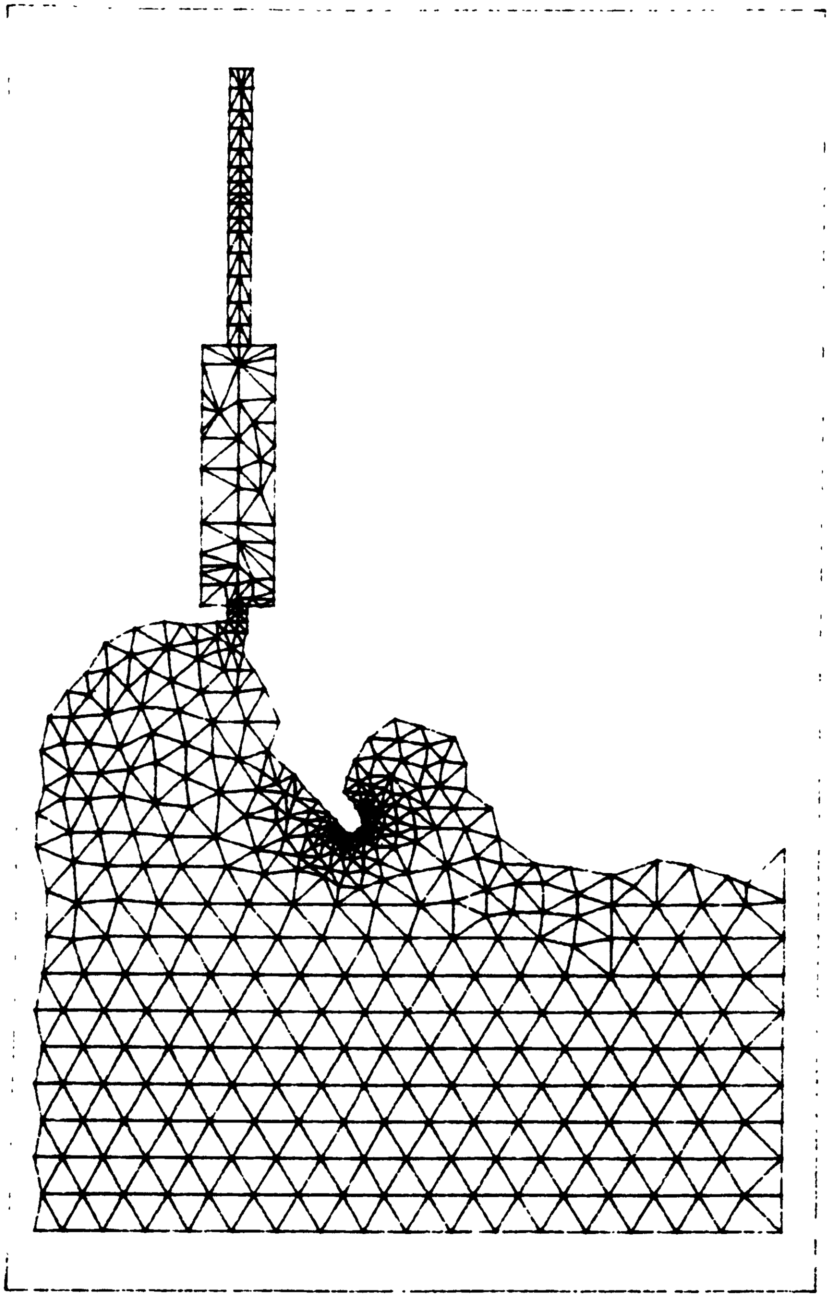


Figure 5-4: Entire Reconfigured Grid

Chapter 6

Simulation Results

6.1 Simulation with Original Grid

The concentrations from a typical run are plotted in Figure 6-1. Examination of this plot reveals that the model is simulating the larval concentration to peak at approximately the same time (March 7) in macro-elements 1, 2, and 3. The number of larvae in the Niantic River at that time can be calculated from the volumes of the macro-elements as:

$$N = [\ 1.65\text{x}10^6 C_1 + 2.35\text{x}10^6 C_2 + 9.92\text{x}10^5 C_3\ ] / 10^4 \tag{6.1}$$

where C_1, C_2, and C_3 are the larval concentrations in macro-elements 1, 2, and 3, respectively. Equation (6.1) gives a peak larval density for the Niantic River of about 320 larvae/500 m^3. This figure is somewhat small when compared to the plots in Figure 6-2, which indicate that peak larval densities ranging from about 200 to 3400 larvae/500 m^3 have been sampled in the Niantic River. Although the simulation density falls within this range and is computed from NUEL data, it is far lower than the average peak larval density of about 1500 larvae/500 m^3 calculated for the years 1981-85.

The fact that the larval densities peak at nearly the same time (about March 7) for all three stations is also a cause for concern. Table 6-I shows the dates of peak abundance at all three stations for the years 1983-88.From this data, the average dates of peak abundance can be calculated as:

Station A	March 4
Station B	March 10
Station C	March 25

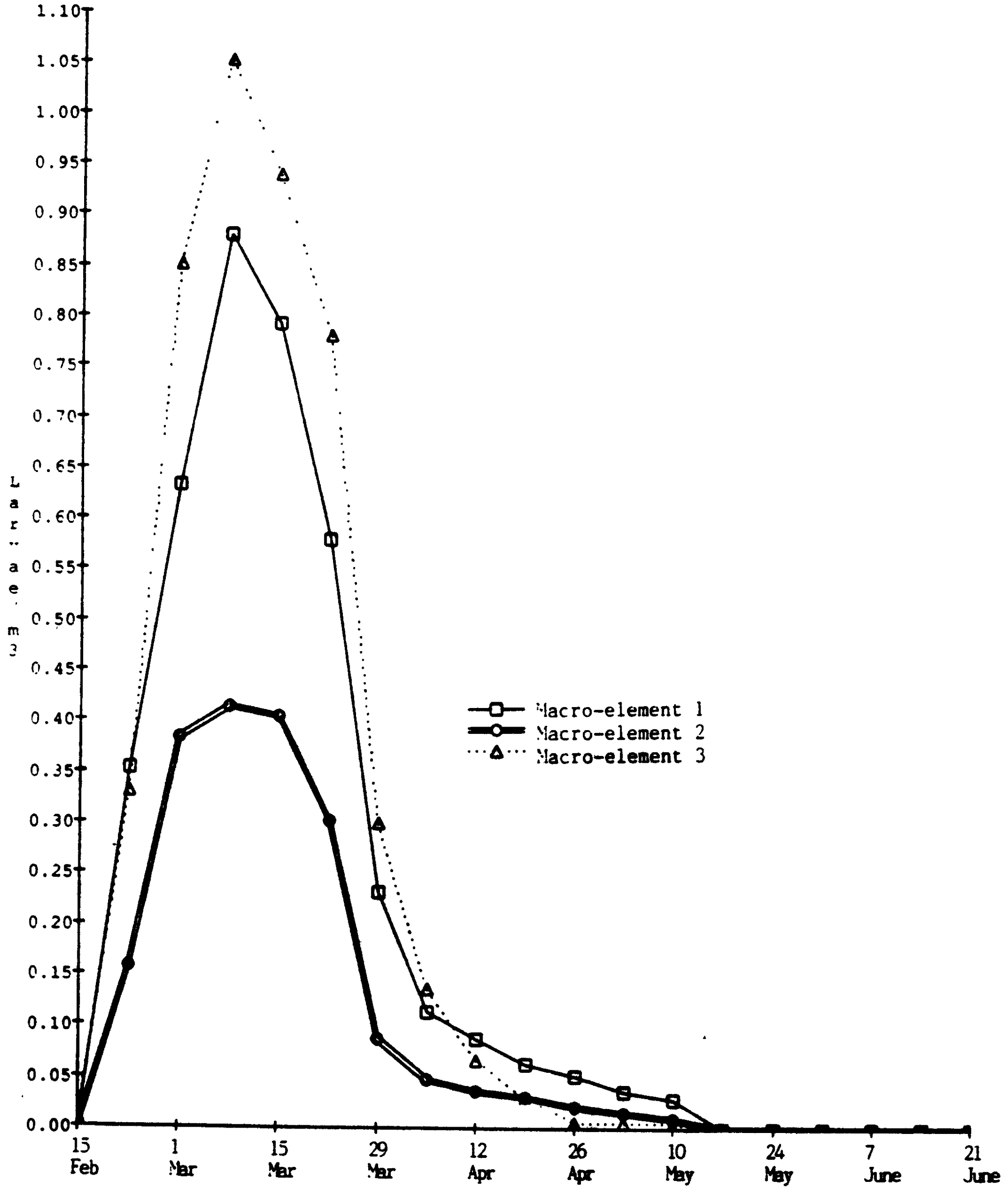


Figure 6-1: Simulated larval concentrations in larvae/m^3 in macro-elements 1, 2, and 3

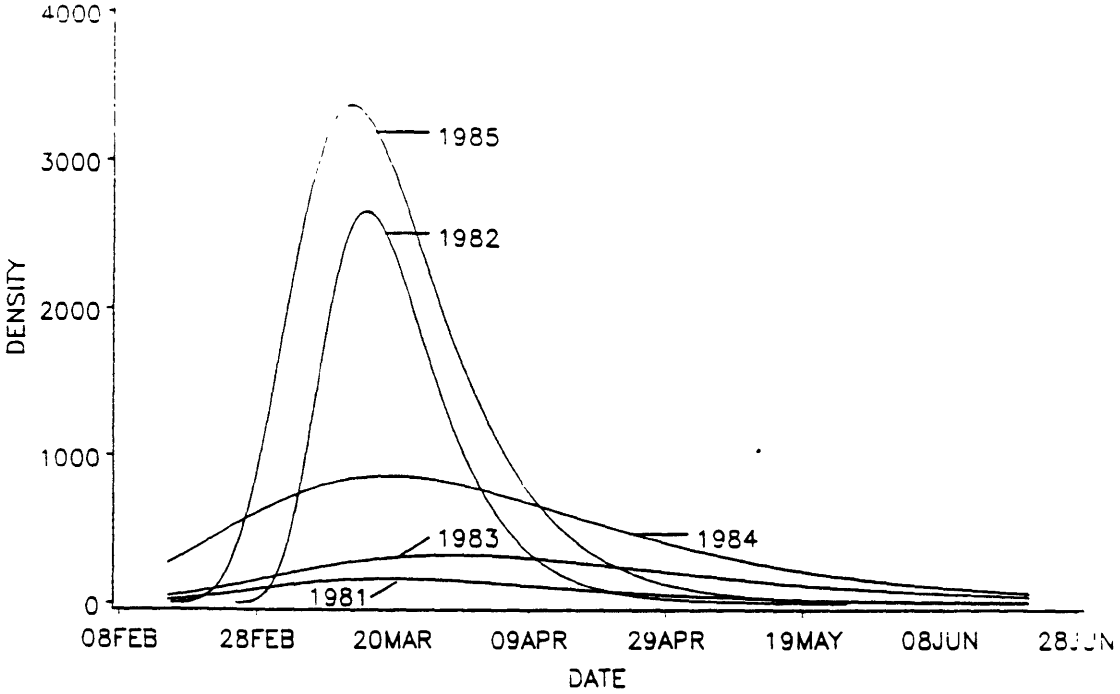


Figure 6-2: Estimated abundance curves (larvae/500 m^3) for winter flounder larvae in the Niantic River from 1981 through 1985

Table 6-1: Estimated dates of peak abundance of winter flounder larvae at Niantic River hatching stations A, B, and C [NUEL]

Year	Sta A	Sta B	Sta C
1983	Mar 6	Mar 20	Apr 9
1984	Mar 4	Mar 12	Apr 4
1985	Mar 9	Mar 14	Mar 19
1986	Feb 26	Feb 28	Apr 1
1987	Mar 8	Mar 9	Mar 17
1988	Feb 29	Mar 5	Mar 5

From these dates and predicted larval transport, one would expect the density data to plot something more like Figure 6-3, with peak larval densities increasing from macro-elements 1 to 3. Greater larval densities in the downstream portion of the river would be the result of larvae being flushed out of the estuary. If the flushing rate was more realistic, such larvae would reside in the lower reaches of the Niantic River for a longer time, increasing the larval densities there. If the larvae were retained in the river for a greater period of time during simulations, the density distributions would increase, and the dates of peak density would shift.

6.2 Simulation with Reconfigured Grid

Preliminary simulations with the reconfigured grid were run using the same input parameters as with the original grid. Results to date from these simulations are inconclusive but do indicate a need for further modifications of the new grid in order to improve the simulated flow field. Initial analysis suggests that bathymetry in the new grid may have to be changed in order to minimize several abrupt changes in depth.

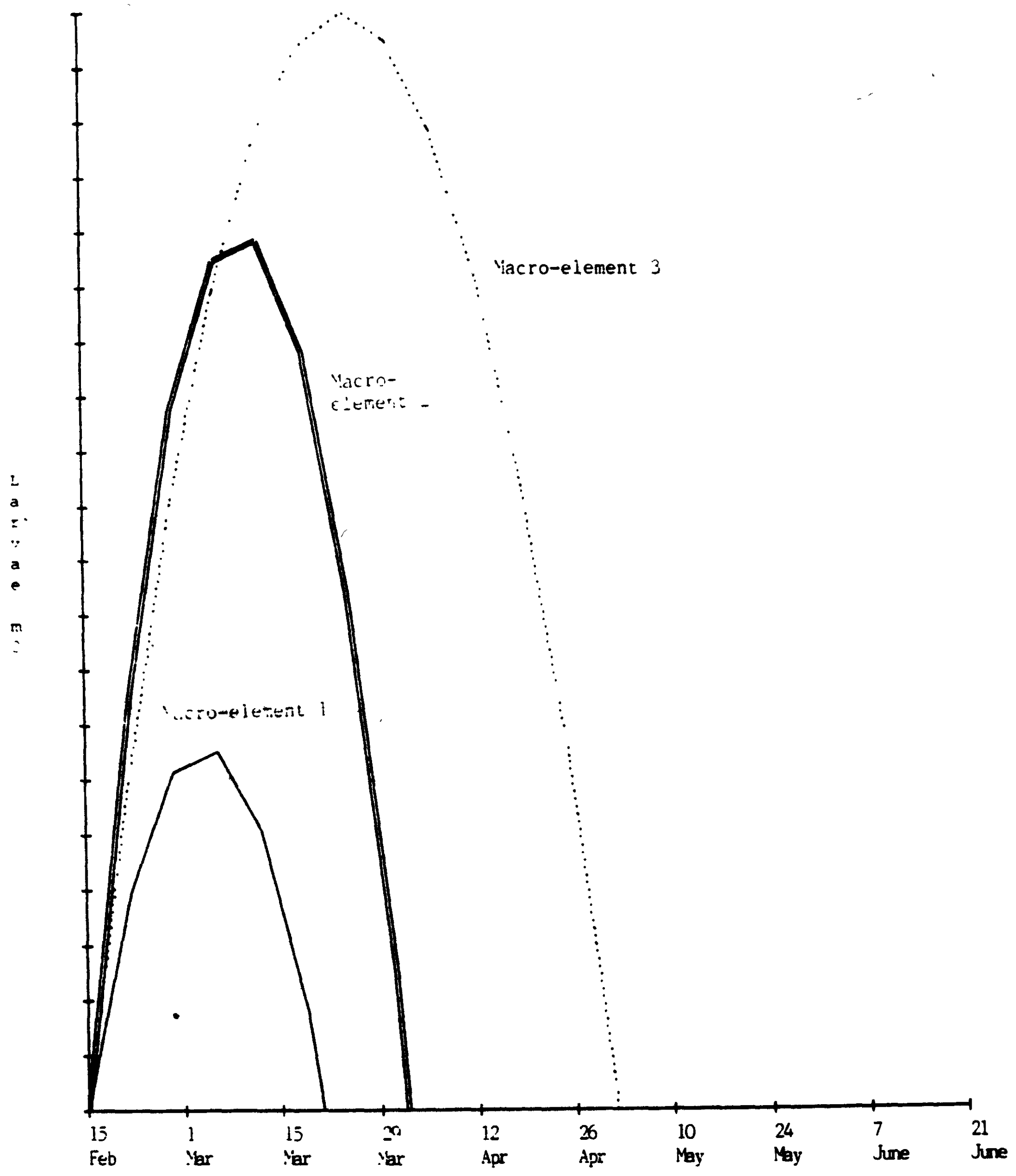


Figure 6-3: Expected distribution of larval density curves for stations A, B, and C

Chapter 7

Summary and Conclusions

The model MILL was modified in an attempt to better simulate the entrainment of winter flounder larvae at the Millstone Nuclear Power Station. The finite element grid was divided into ten macro-elements in order to compute larval densities at the Niantic River hatching stations and other areas. The purpose of this is to accommodate future density dependent features in the model. Larval hatching at all three stations during the same simulation was also added to the model, and the finite element grid was reconfigured to reduce the incidence of larvae exiting the model boundaries during the simulation. The model was run using both the original and reconfigured grid. In simulations with the original grid, peak larval concentrations were lower than data indicate, and time to peak concentration for macro-elements in the estuary were different than observed. Simulations with the reconfigured grid were inconclusive and indicated that further modifications of this grid may be required.

As with earlier simulations, the results of this study indicate that there are too few larvae in the system, and the larval flushing rate from the Niantic River is too high. This is evident in simulations with modified MILL from the low peak larvae concentrations in the estuary and the absence of a lag between peak concentrations in estuary macro-elements as the larvae progress downstream.

Future work with MILL will require better estimates of larvae hatching rates in the estuary and a more complete analysis of the degree to which larval behavior reduces the flushing rate. Improved sampling methods presently being implemented by NUEL offer some promise in these areas.

Appendix A

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Appendix B

M.I.T.

SUMMER UNDERGRADUATE RESEARCH REPORT

AUGUST 1990

BY: JEFF MOELLER

INTRODUCTION

The MILL numerical model is a 2-D tracking model of transport and diffusion. It is a derivative of the ELA numerical model. ELA is used to model passive pollution particles as they move in a body of water; however, MILL is modified to incorporate larval behavior. Thus the particles simulated by MILL are no longer passive, but instead they exhibit behavior that alters pure hydrodynamic transport and diffusion.

MILL was developed by Nadia Dimou as part of a project by the Millstone Nuclear Power Station. The goal of the project is to evaluate the impact of the power station on the local winter flounder population. The power station takes in large quantities of water from the Niantic River to cool the reactor, however many winter flounder larvae become entrained in the cooling water. The mortality rate for these entrained larvae is nearly 100%.

MILL simulations of larval transport and diffusion have been conducted to determine the quantity and characteristics of larvae entrained at the power station. MILL predictions of the number of larvae and length distributions of larvae entrained at the station were compared with corresponding field data. The model indicated that far too few larvae are being entrained and that the entrained larvae are shorter (younger) than those observed in the field.

OBJECTIVES

The purpose of the summer research project is twofold:

1) To modify the model MILL code to be more efficient, and

2) To determine the sensitivity of larval residence time in the river to varying degrees of larval behavior.

It is often time consuming and costly to make computer simulations, especially large ones, of larval transport with the model MILL. Revisions in code which eliminate unnecessary computations, increase the efficiency of calculations, or create more logical procedures will save time and money.

One possible explanation of the differences in model predicted number and length distribution of entrained larvae and actual field data is larval behavioral mechanisms are underestimated; therefore, it is important to determine the sensitivity of larval residence time to varying degrees of behavior. The sensitivity analysis can be used as a diagnostic tool to resolve discrepancies between the model and field data. For example, if increased behavioral effects result in longer residence times and thus larger lengths of entrained larvae which match collected data, then biologists will know what kind of behavioral effects to look for in the field. If this behavior can be found in the field, then some discrepancies have been resolved.

MILL CODE CHANGES

The MILL numerical model is computer coded in Fortran. The original code that was taken from the ELA model has undergone many changes by several programmers. Thus an effort was undertaken to streamline the code.

Among the major changes are:

A) *Solution of advective process with a first-order differential equation.*

The numerical model has two primary means of moving a particle: by advection (deterministic processes) and by diffusion (random processes). The diffusion component was solved with a first-order differential equation; however, the advective component was solved with a more accurate and time consuming fifth order Runge-Kutta differential equation. Since the diffusion component in the river is more dominant, it is not necessary or consistent to be so precise with the advective component. Thus the advective component was converted to a less time consuming first-order differential solution.

The Runge-Kutta solution process reduces the timestep when it is unable to find the new element location a particle has been advected to. This process is continues until the new element location is found. The first-order solution lacks this process. To circumvent this problem it was necessary to reduce the timestep from 3 hours to .3 hours so a particle would not be advected too far in any one time step, and the number of elements that are searched for the new location of the particle had to be increased from 70 to 250. Both of these solutions tend to increase the simulation time, but the time saved by using a first-order process makes this a worthy tradeoff (Table 1). Additionally the smaller timestep will result in a more accurate diffusion process (optimal accuracy is obtained as the timestep goes to zero).

Table 1

Comparison of simulations with Runge-Kutta solution and first-order solution of advection.

Simulation Characteristics

Time:	131 days
Number of Particles:	124
Release Point:	A
Behavior:	None
Timestep:	.3 hrs (first-order) 3 hrs (Runge-Kutta)
Elements Searched:	250 (first-order) 70 (Runge-Kutta)

	Avg. Simulation Time
first-order solution	30 minutes
Runge-Kutta solution	90 minutes

Since the first-order process was mainly applied to the river portion of the finite element grid, additional testing of the program in the bay is recommended.

B) *Format of the .PAR file.*

The .PAR file, a file which contains the behavior parameters including the temperature and birthrate values at every timestep, originally had to be reconstructed every time variables such as the number of timesteps, the size of the timestep, or the number of particles changed. The file was altered so it is independent of these variables; thus the file does not have to be reconstructed when these variables change. Calculations dependent on these variables are calculated in a newly created subroutine called BEHPAR (behavior parameters). This will save time in user simulation preparation.

C) *Testing of the random number generator.*

The random number generator was tested to see if it would be worthwhile to replace it with a more efficient generator. The generator was removed from the MILL program and tested in isolation. The generator produced 20,000 random Gaussian distributed numbers in under 20 seconds. It was concluded that no change of the present generator was necessary.

D) *1-D approximation of river flow.*

The original river portion of the finite element grid was modified and made symmetrical by Andrew Obst in an effort to advect particles along the centerline of the grid and avoid crossing the boundary limits until a particle entered the bay portion of the grid (Figure 1). If the river portion of the grid were highly irregular, particles advected or diffused "out of bounds" would be bounced back in. This does not duplicate reality well and has the potential for introducing large errors when the particles are bumped back into the grid. In a further effort to advect the particles along the centerline of the grid, the U-velocities (tidal and steady) at the element nodes in the river (Y >= 3800) were set to zero to prevent lateral movement. This was accomplished by revising the TEA program, a program that provides the necessary flow input to the model, into a new program called TEA-U which produces a .TOU file with U velocities set to zero in the river.

E) *Method of incorporating larval tidal behavior in tidal velocity.*

As larvae increase in size, they begin to exhibit a tidal dependent behavior in which they rise in the water column during flood tide and sink in the water column during ebb tide. Since velocities near the bottom of the water column are nearly zero, the proportion of larvae available for

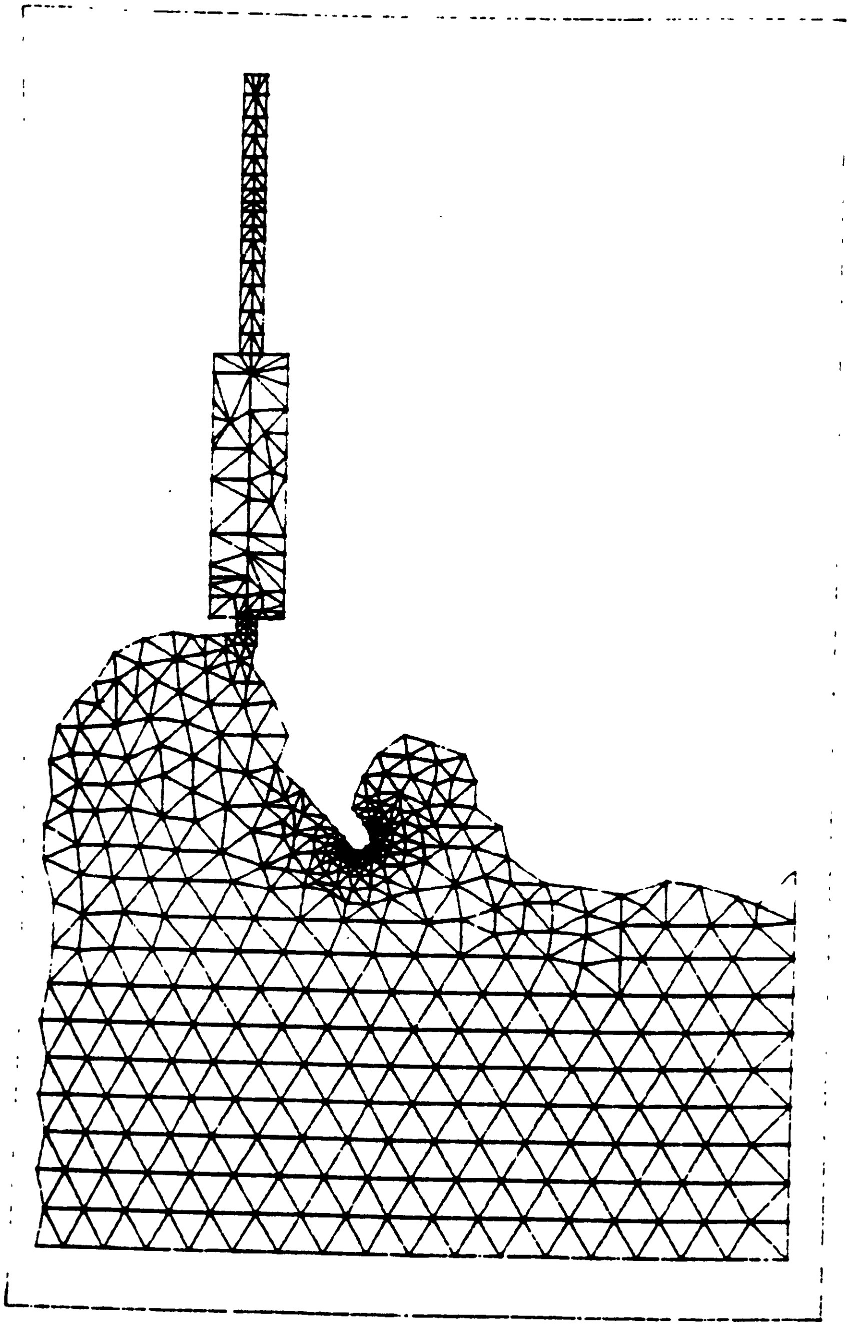


Figure 1 : Entire Reconfigured Grid

transport during ebb tide is heavily decreased (damped). The tidal velocity is set to zero in the river as the net ebb and flood velocities cancel one another out. This presents a problem for incorporating tidal behavior in the tidal velocity component. Previously the tidal velocity (zero) was multiplied by a tidal behavioral factor (damping factor) which resulted in a value of zero or no behavioral effect on the tidal velocity component in the river. A better way to incorporate tidal behavior in the tidal velocity component is to have a constant upward velocity or drift due to the difference in the flood velocity and the damped ebb velocity:

drift = (tidal velocity)*(1 - damping factor)
where: damping factor < = 1.0

The damping factor equals 1.0 in the absence of behavior resulting in the correct net tidal value of zero for a passive particle.

F) *Option for river calculations.*

The code has been modified so a user interested only in larval movement in the river can specify this option in the .EIN input file. This option sets the lower domain boundary to the mouth of the river, thus eliminating bay calculations and saving computer time.

G) *Debugging.*

Any code changes involving debugging of the original MILL program have been commented in the code version entitled INT21J.FOR.

MILL SIMULATIONS

Simulations of larval movement in the river were conducted with no behavior, with diel behavior, and with tidal behavior to determine larval residence time in the river. The residence time is defined by convention as the time between particle (larval cohort) release (birth) and the moment a particle exits the river (crosses Y-ordinate 3970). It is possible for a particle to wash back into the river; this would not be included in the residence time. If a particle grows to maturity (reaches a length of eight mm.) in the river, the residence time is the time it takes for the particle to reach this state. A negative sign is put in front of the residence times of these particles in the simulation output as a flag to indicate the particle was not flushed from the river.

Simulations were conducted using 124 particles. One particle was released per .3 hour timestep; thus the particles were released over exactly three tidal cycles (37.2 hours) to eliminate any tidal bias in the data. The simulated time was 131 days.

The extent of tidal and diel larval behavior in the simulations is controlled by input parameters in the .PAR file. The proportion of larvae (y) available for transport is a function of larval length (L) given by the expressions:

$$y = 1.0 \qquad (L < K)$$
$$y = m^*(L) + b \qquad (L > K)$$

where K = the length behavior begins to occur

Field data suggests the following values for the variables m, b, and K:

Variable	Diel	Tidal
m	-.094	-.221
b	0.985	1.696
K	5.0 mm.	5.0 mm.

To achieve no behavioral effect in the simulations, the value of K was set to 8.0 mm. so the larvae would reach maturity before they displayed any behavior. To achieve behavioral effects, the value of K was set to 3.0 (size at birth), the value of m was set to 0.0, and the value of b was set to a constant less than one (such as .2 or .6). Thus the behavior factor in these simulations was a constant value from birth.

A) No Behavior.

Eight simulations of 124 particles were run without behavior for a total of 992 particles. The results are shown in Figure 2. The mean residence time was 13.8 days. This value is close to the residence time value determined prior to the changes in the river grid geometrty and the change to a first-order advection process which is a good indication the modified code is working properly. The mean residence time of each individual run was +/- 3.5 days of the mean residence time for all eight runs. Thus 124 particles seems to be enough to give an adequate representation for residence time distribution.

Figures 3-A through 3-D show the differences in larval residence time distributions as the particles are released from different points in the river. Figure 3-E is a summary of these distributions. The residence time seems to increase nearly linearly with increasing distance from the mouth of the river.

FIGURE 2: LARVAL RESIDENCE TIME HISTOGRAM

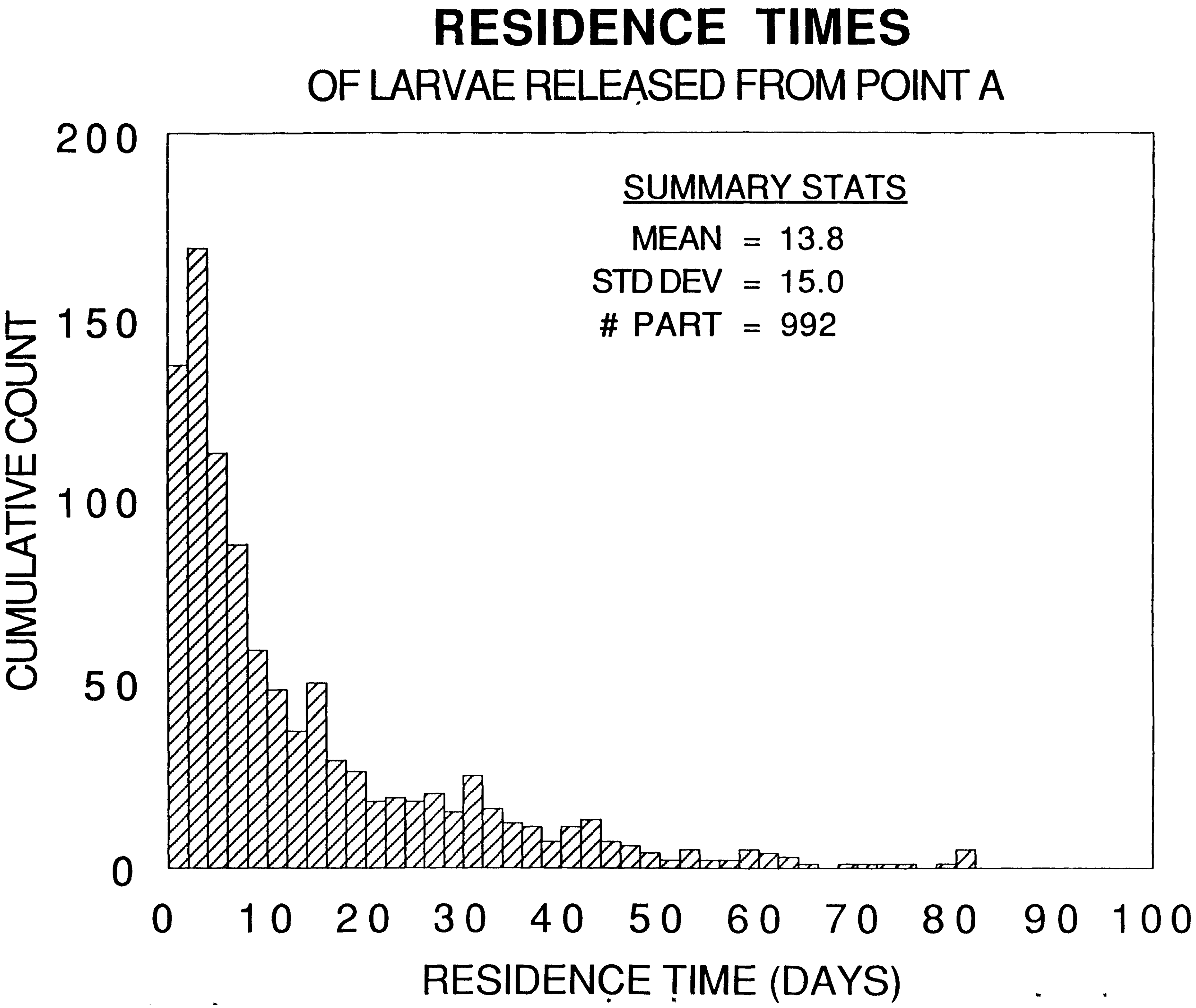


FIGURE 3-A: LARVAL RESIDENCE TIME WITHOUT BEHAVIOR

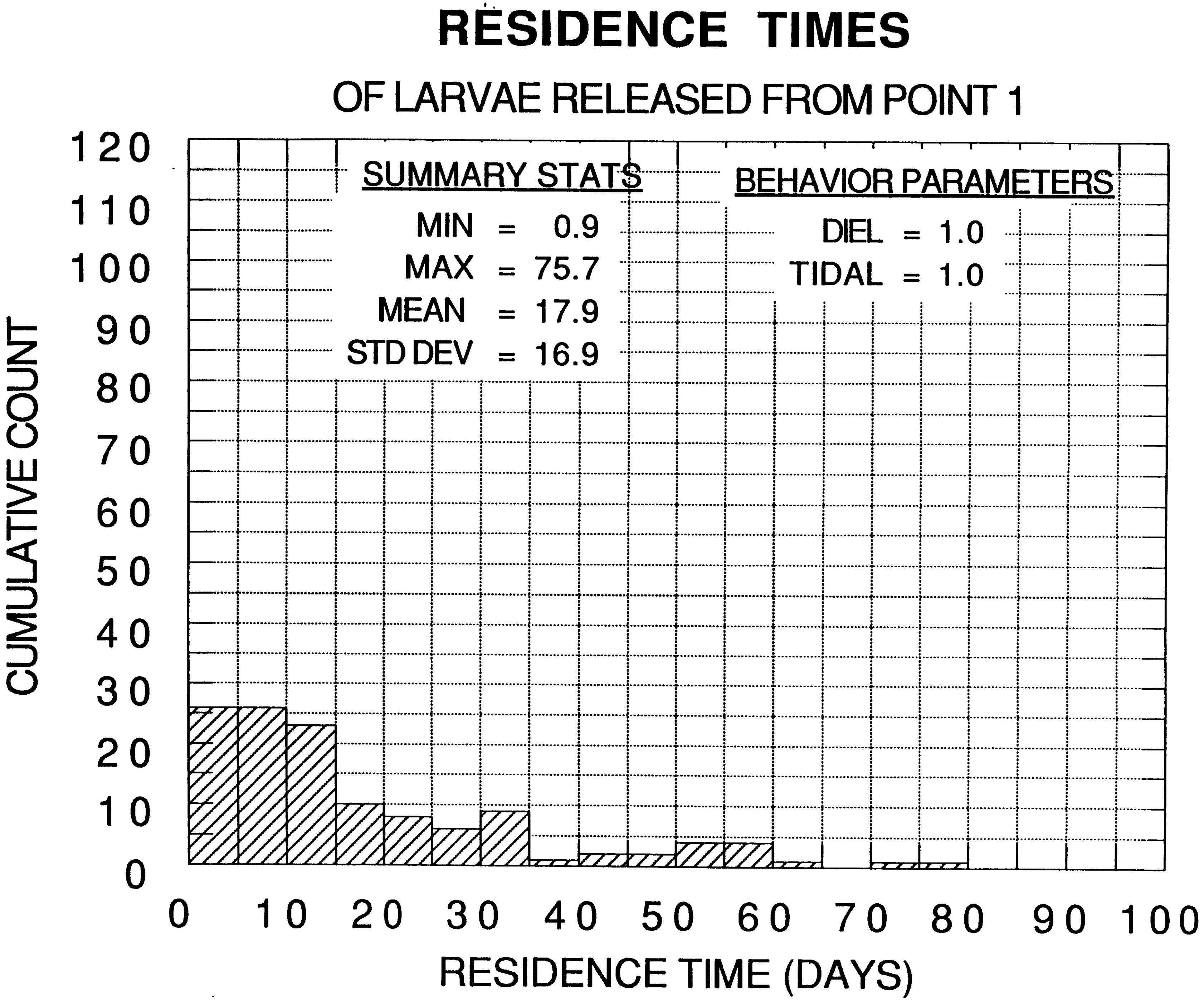


FIGURE 3-B: LARVAL RESIDENCE TIMES WITH NO BEHAVIOR

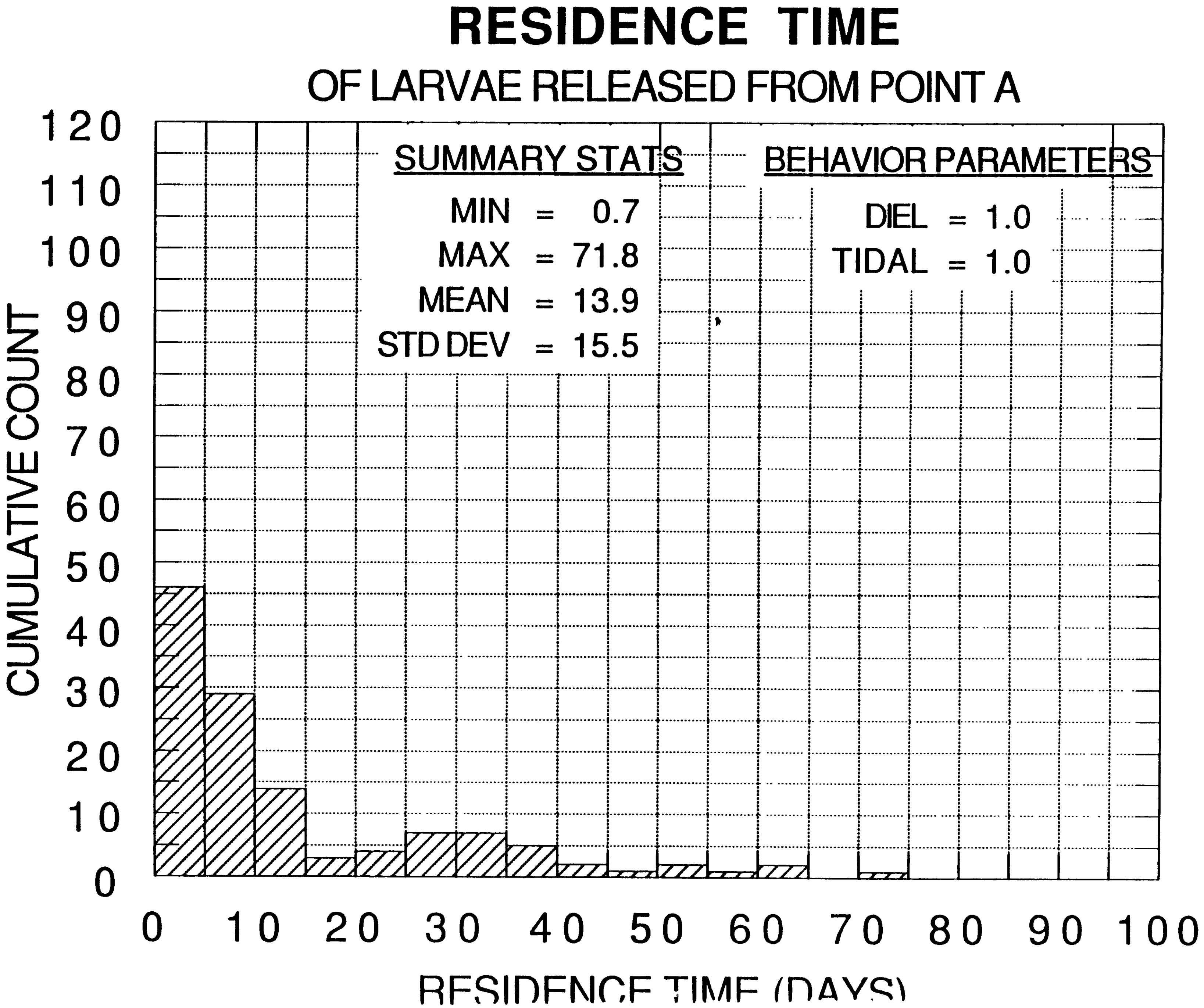


FIGURE 3-C: LARVAL RESIDENCE TIMES WITH NO BEHAVIOR

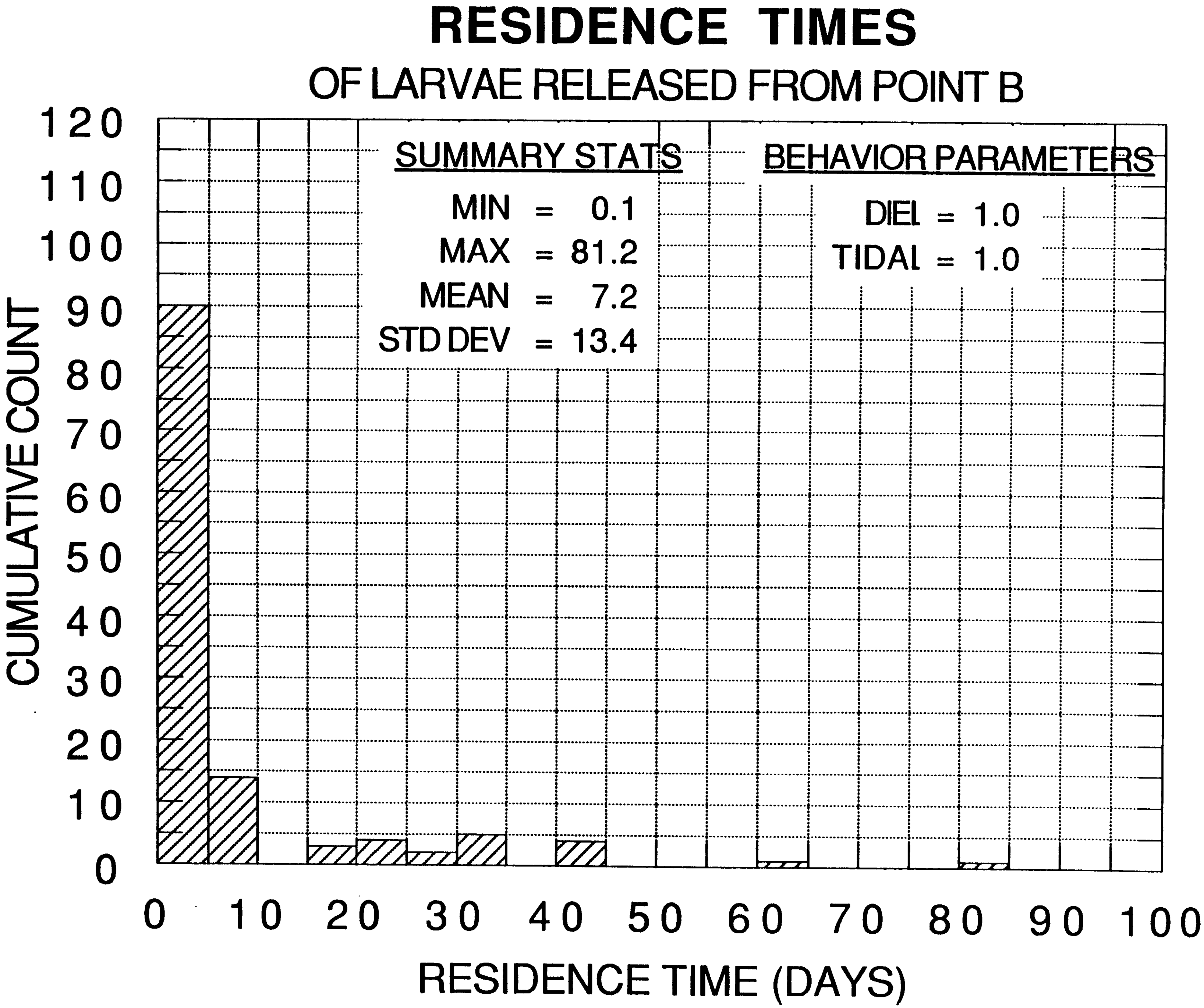


FIGURE 3-D: LARVAL RESIDENCE TIMES WITH NO BEHAVIOR

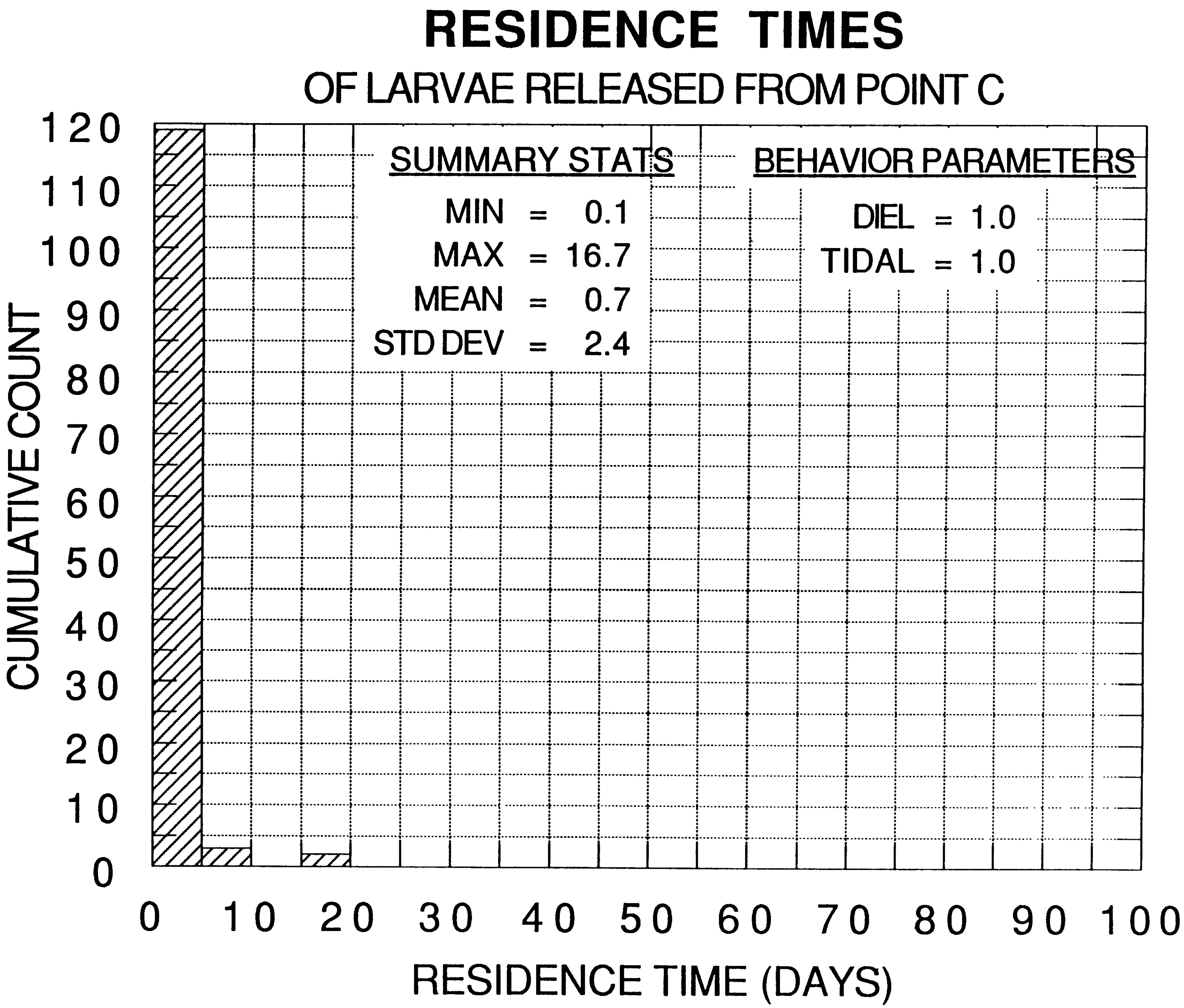
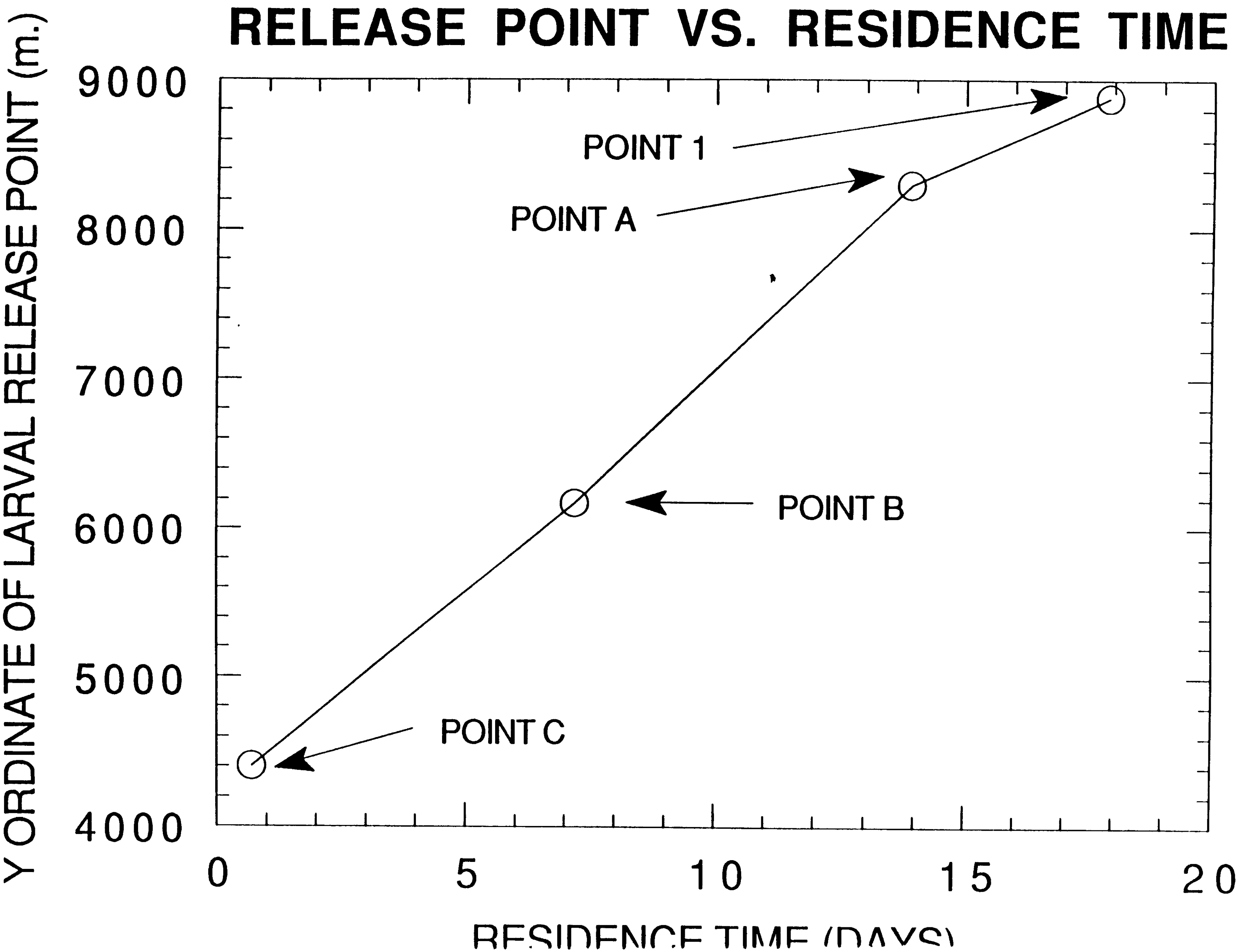


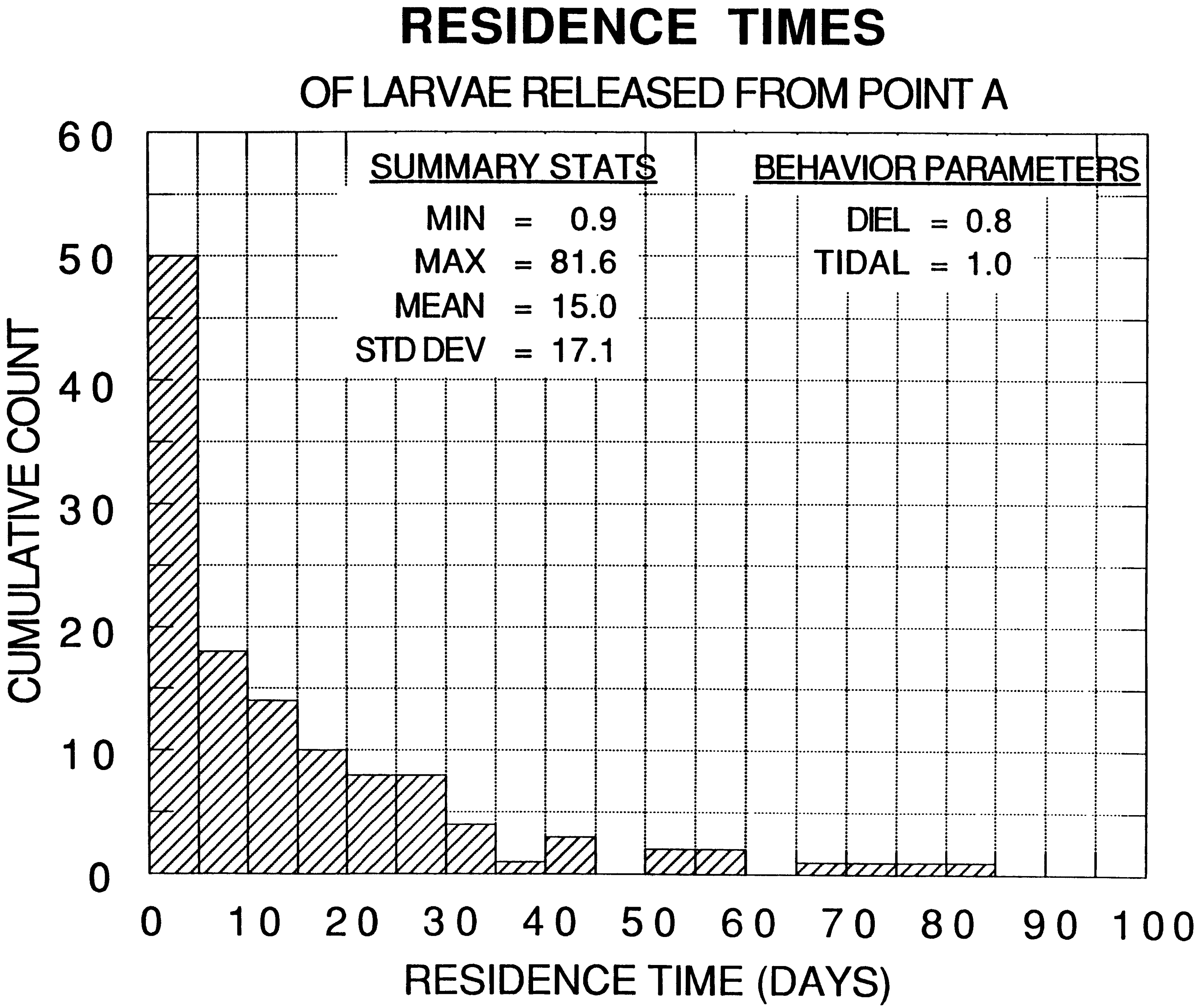
FIGURE 3-E: VARIATION OF RESIDENCE TIME WITH RIVER RELEASE POINT (NO BEHAVIOR)



B) Diel Behavior.

Figures 4-A through 4-D show the differences in larval residence time distributions as the diel behavior parameter varies (tidal behavior remains constant = 1.0). The release station is A. Figure 4-E is a summary of these distributions. As is expected, the residence time increases with increasing behavioral effect. One would expect the residence time to approach infinity as the diel behavior asymptotically approaches zero.

FIGURE 4-A: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR


RESIDENCE TIMES

OF LARVAE RELEASED FROM POINT A

FIGURE 4-B: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR

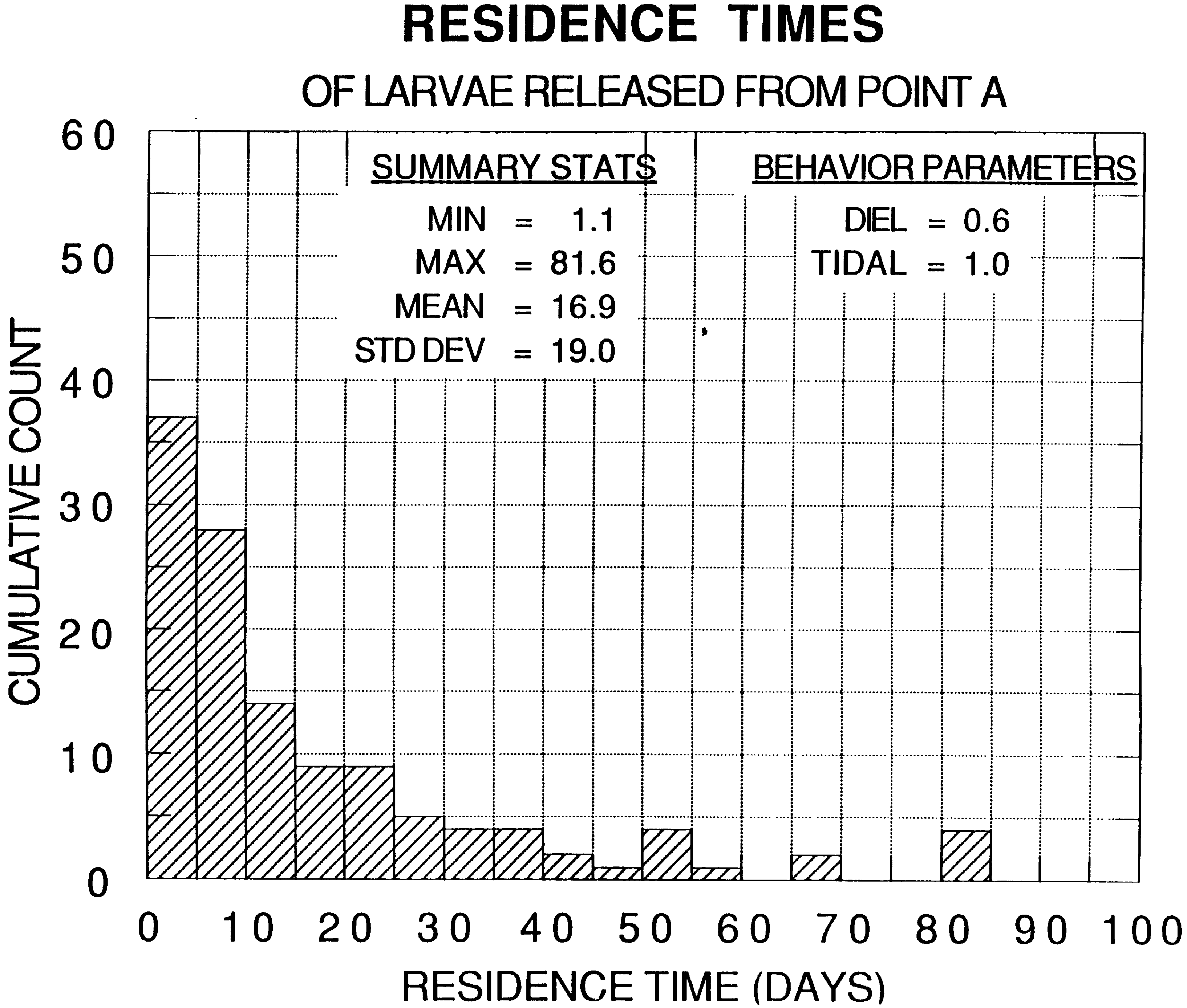


FIGURE 4-C: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR

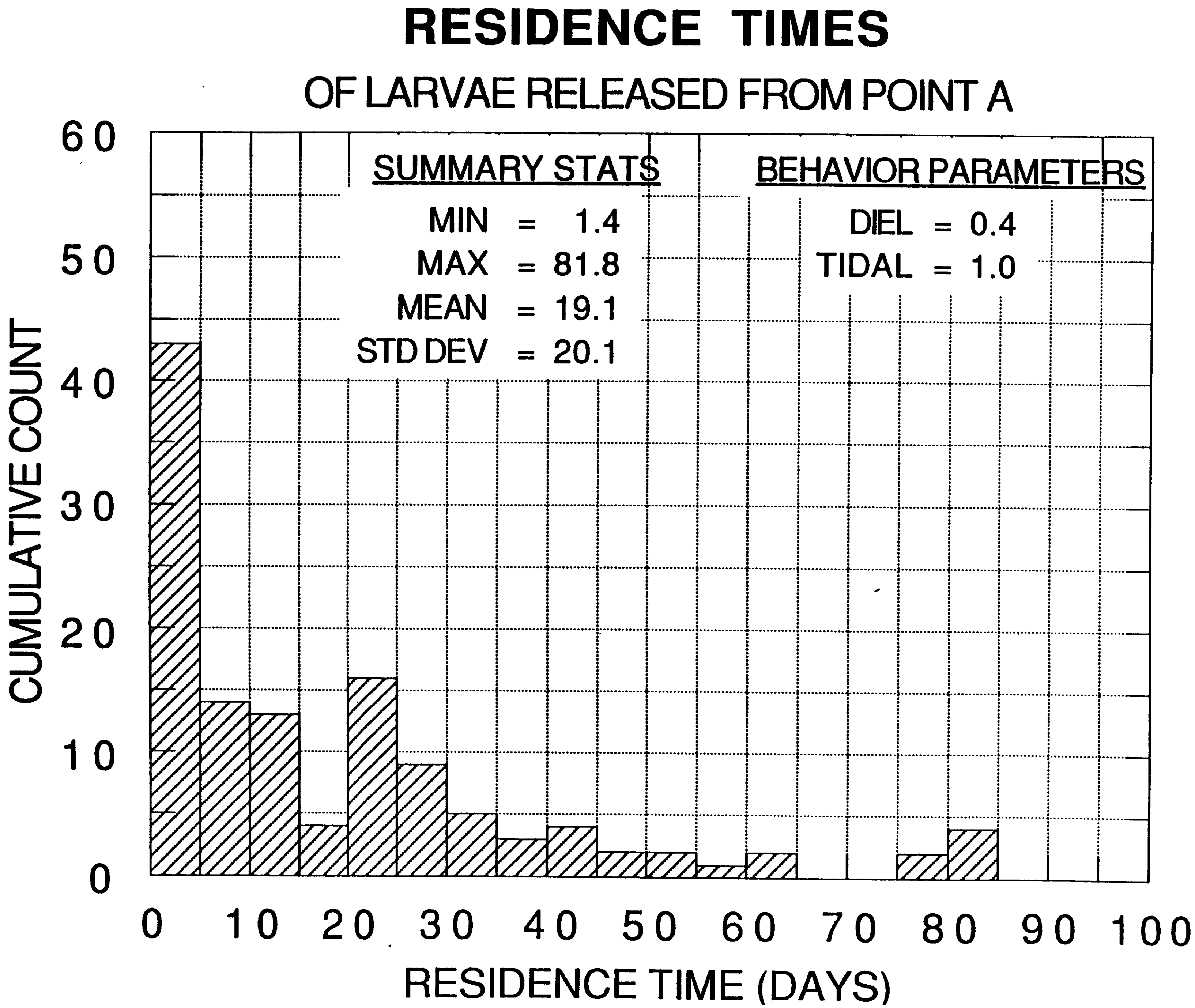
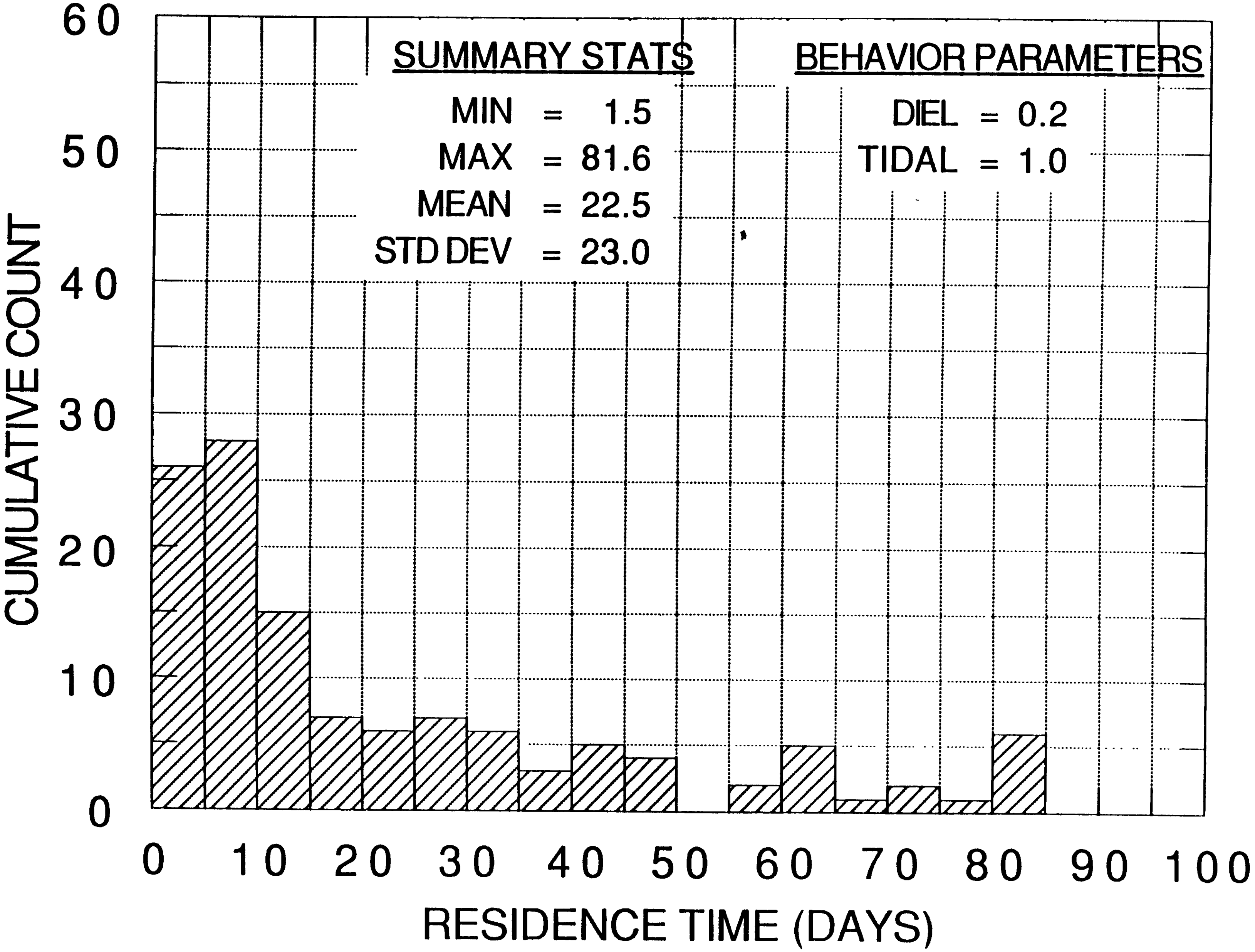


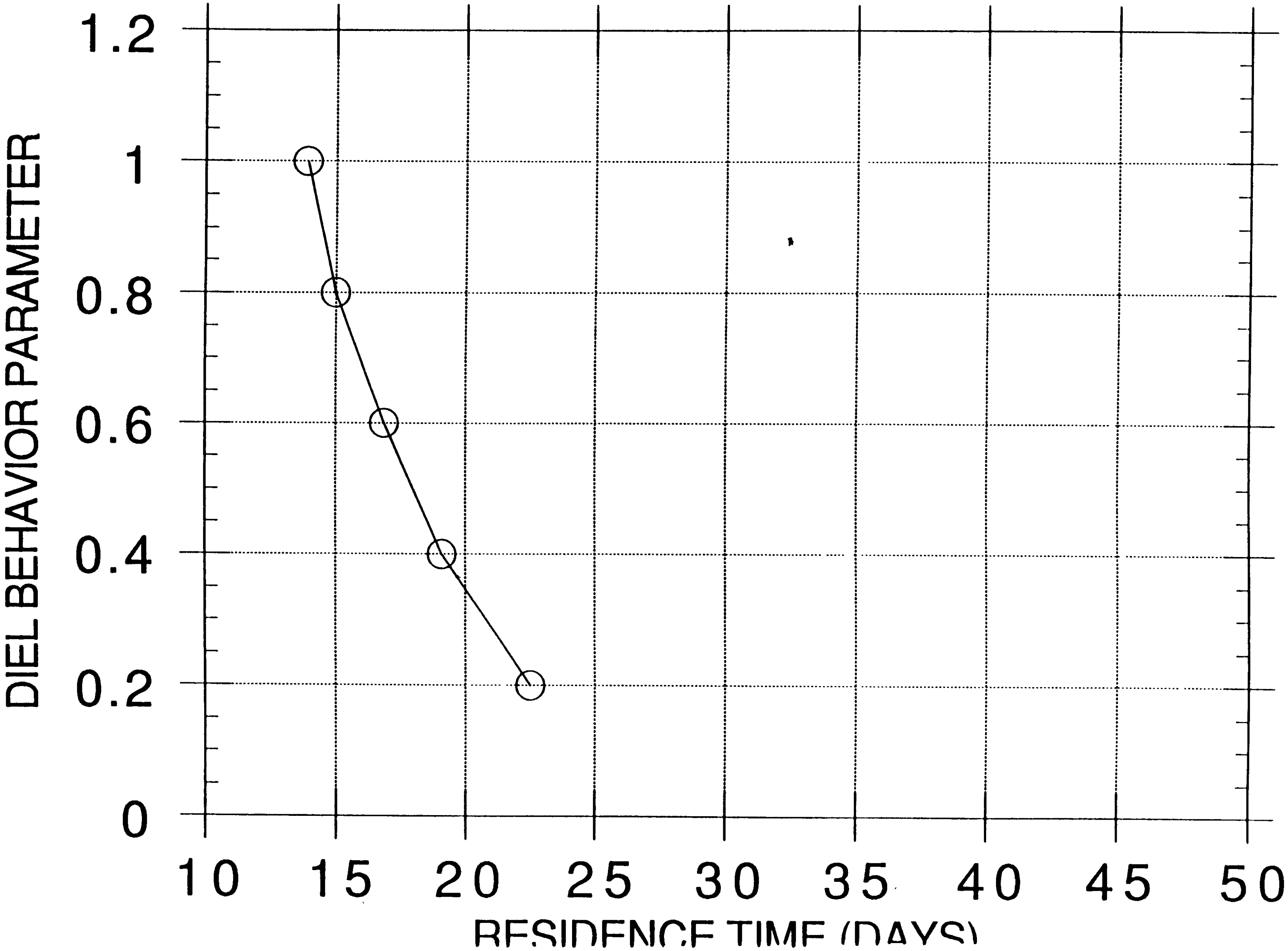
FIGURE 4-D: LARVAL RESIDENCE TIMES WITH DIEL BEHAVIOR



RESIDENCE TIMES

OF LARVAE RELEASED FROM POINT A

FIGURE 4-E: DIEL BEHAVIOR VS. RESIDENCE TIME OF LARVAE RELEASED FROM POINT A



C) Tidal Behavior.

Figures 5-A through 5-D show the differences in larval residence time distributions as the tidal behavior parameter varies (diel behavior constant = 1.0). Figure 5-E is a summary of these distributions. As is expected, the residence time increases with increasing behavioral effect. Tidal behavior has a more prominent effect on larval residence times than diel behavior because tidal behavior is more than just a damping of the velocities. Tidal behavior causes a small, steady, net upward drift that diel behavior does not include.

FIGURE 5-A: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

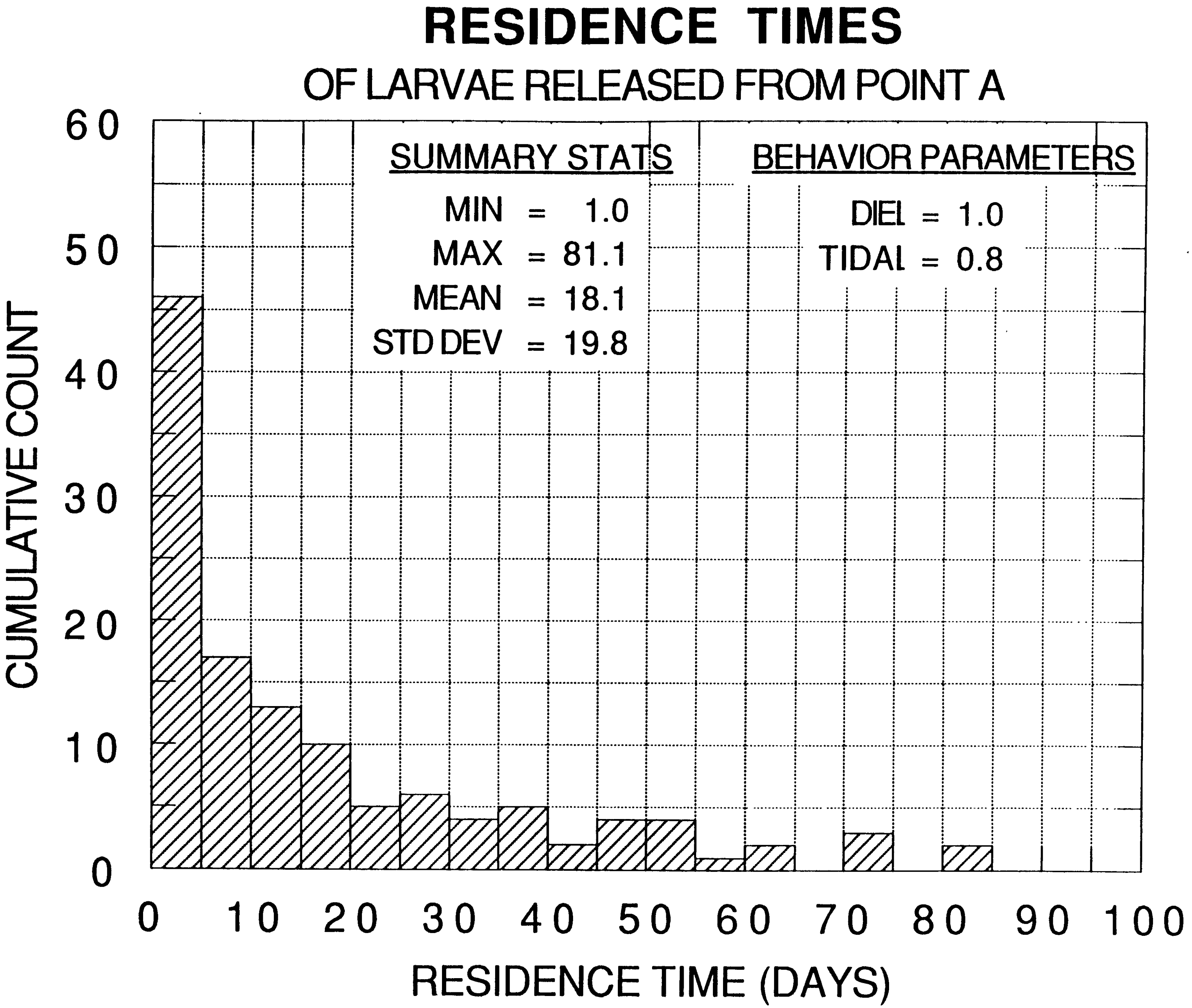


FIGURE 5-B: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

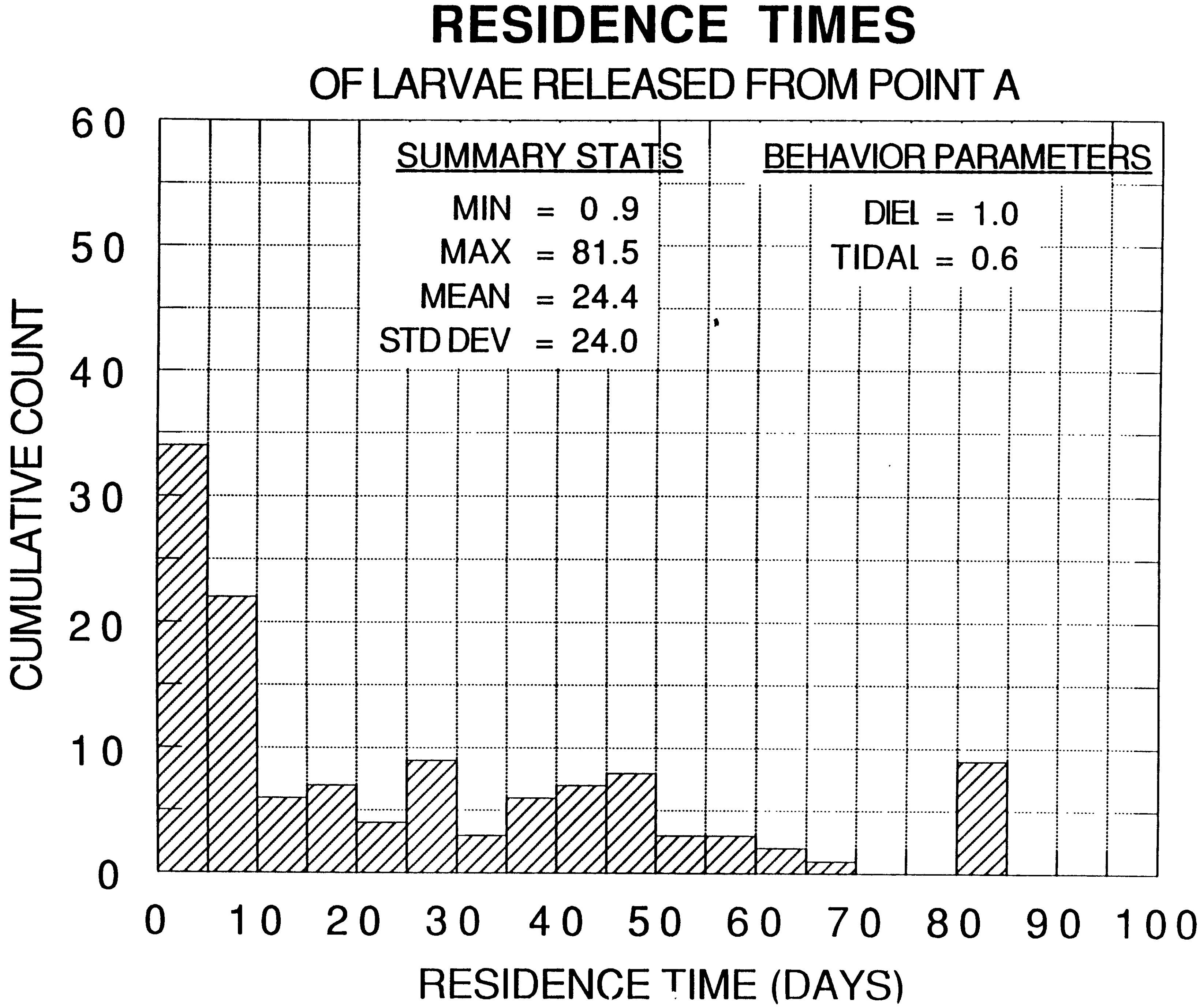


FIGURE 5-C: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

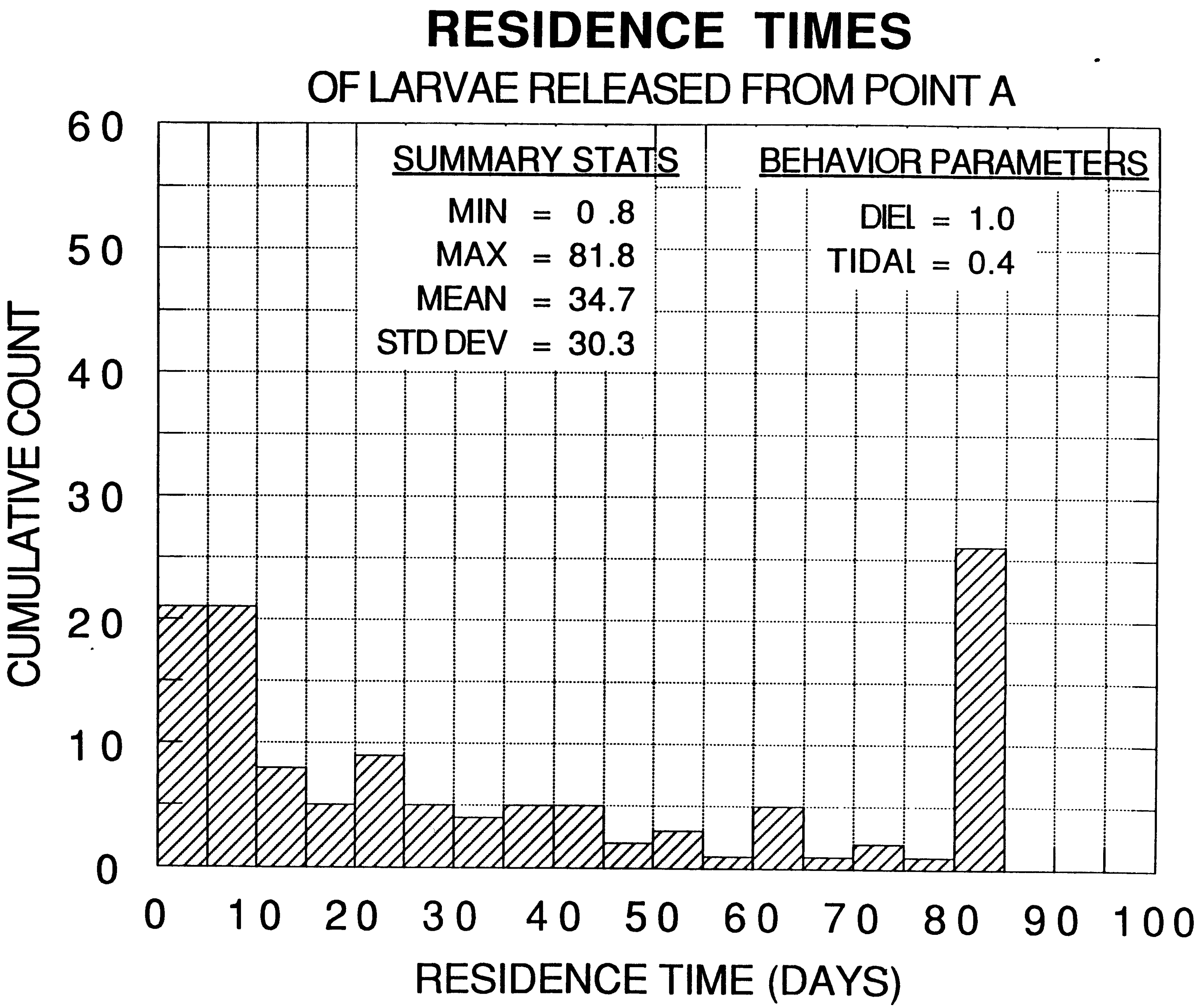


FIGURE 5-D: LARVAL RESIDENCE TIMES WITH TIDAL BEHAVIOR

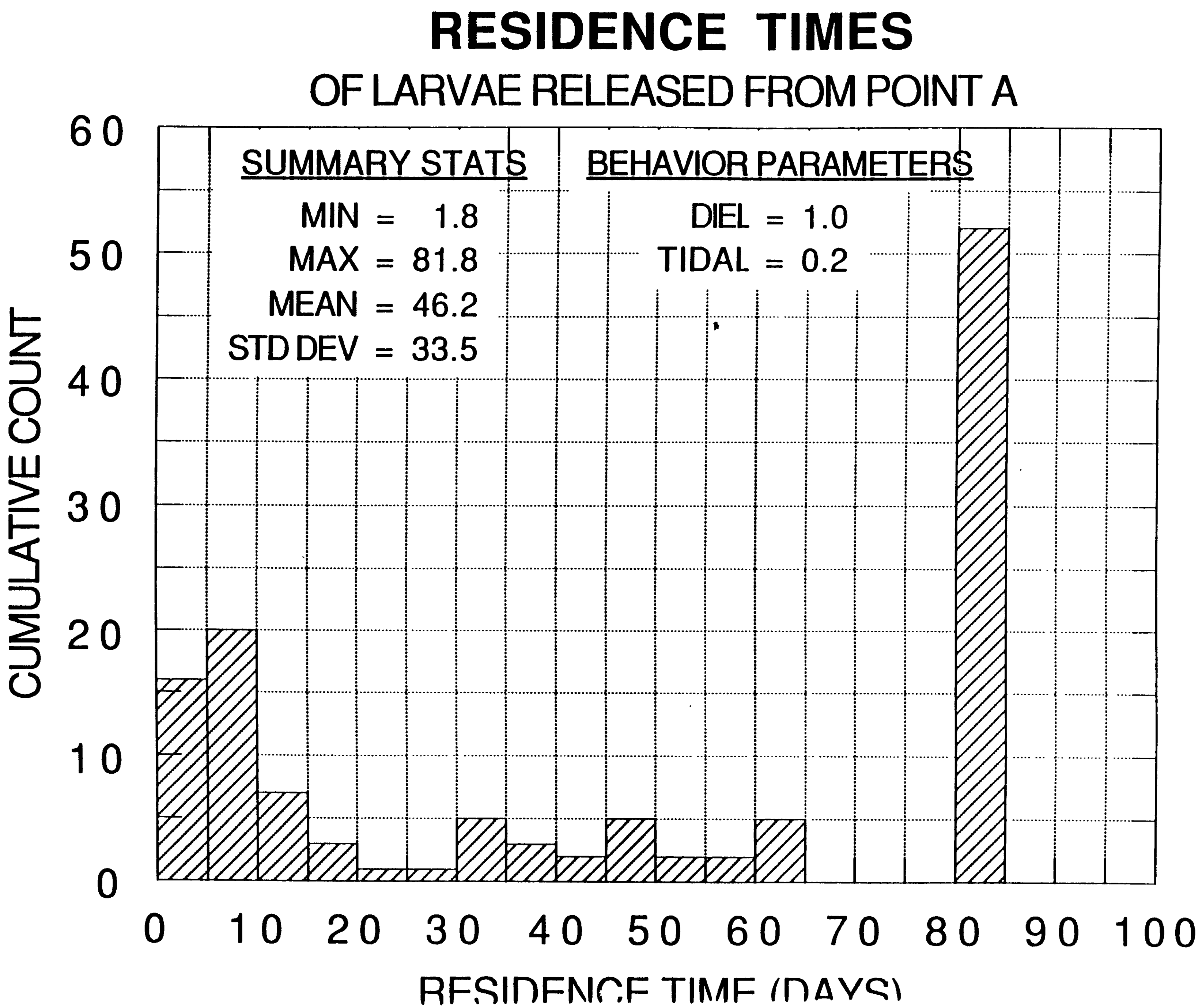
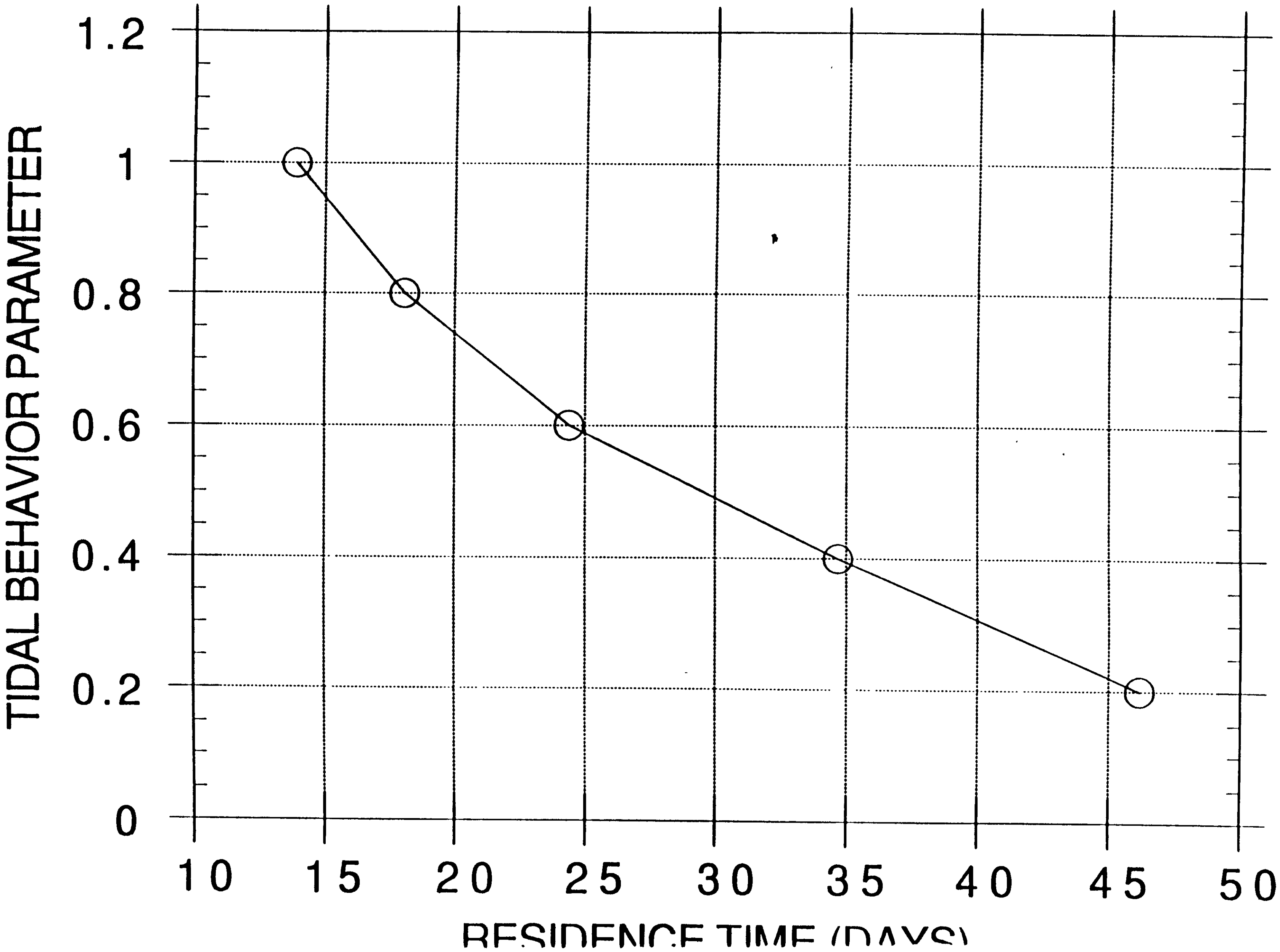


FIGURE 5-E: TIDAL BEHAVIOR VS. RESIDENCE TIME OF LARVAE RELEASED FROM POINT A



CONCLUSIONS

The residence time distributions show a gradual shift to the right (longer residence times) as behavioral effects increase. Since tidal and diel effects were examined separately, it is recommended that their combined effects be examined. It is expected that this would shift the distributions even further to the right.

If increased behavioral effects increase the residence times, then larvae reaching the intake at the power station will have longer lengths. It is recommended that a study be conducted to examine the variation of behavioral effect with length distribution of larvae at the intake. Behavioral effects could be varied until they produce length distributions similar to those observed in the field. This could better pinpoint the magnitude of behavior biologists should look for in the field.

Previous simulations showed larvae arriving significantly earlier and in smaller numbers than indicated by observations at the intake. However, if behavioral mechanisms are being underestimated, then present computer simulations indicate increased behavior will increase the residence times and consequently arrival times at the intake. Also, if larvae residence near the bottom means larvae are being undersampled, then this could explain the low number of entrained larvae in the simulations. Both of these conclusions could help explain the discrepancies between computer simulations and field data.