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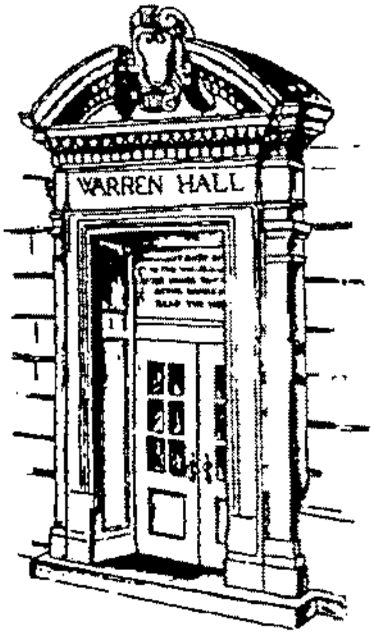


# Staff Paper

Department of Applied Economics and Management
Cornell University, Ithaca, New York 14853-7801 USA

# Brown Tide, Bay Scallops and the Location of Spawner Sanctuaries in the Peconic Bays, New York

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# Brown Tide, Bay Scallops, and the Location of Spawner Sanctuaries in the Peconic Bays, New York

*by*

Jon M. Conrad and Kevin C. Heisey*

Jon Conrad is Professor of Resource Economics and Kevin Heisey is a Ph.D. student, both at Cornell University, Ithaca, New York 14853. Correspondence may be sent to Jon Conrad at 455 Warren Hall, or by email to jmc16@cornell.edu The authors thank New York Sea Grant for financial support and Chris Smith for advice and patience. Neither necessarily share the views or conclusions found in this paper, and the authors are responsible for any remaining errors.

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*ABSTRACT*

A model is developed to determine the optimal location of spawner sanctuaries to hasten the re-establishment of the bay scallop fishery in the Peconic Bays of eastern Long Island, New York. The bay scallop suffered high mortality rates as a result of a series of brown tides (dense algae blooms) that occurred from 1985 through 1988, and in 1991, and 1995. The model has three components: (1) transport probabilities, $p_{i,j}$, from source site i to settlement site j, (2) eggs spawned per net house at source site i, $L_i$, and (3) year-one survival rates at settlement sites j, $S_j$. Current information did not allow us to differentiate between source sites on the basis of a variation in $L_i$, nor could we differentiate between the likely survival rates $S_j$, at the six settlement sites. With $L_i = L = 1.56 \times 10^{10}$ eggs/net house, and $S_j = S = 5.0 \times 10^{-5}$, the naive optimum would be to locate all net houses at the source site with the highest summed settlement probability. In our model this was Source Site #2 with all scallop larvae settling in Settlement Site #1 (Flanders Bay). This would be a high risk strategy, particularly if a brown tide appeared after deployment and spring spawning. By spreading net houses across the top 12 sites, there was only an 11.2% decline in expected year-one survival compared to the naive optimum, and there was a 31.2% increase in expected survival over the actual deployment in 1999. In years with a brown tide, adaptive strategies would include the relocation of seed transplant programs and spawner sanctuaries to bays at the eastern end of the Peconic system and delaying the opening of the commercial bay scallop season until November 15th, to take advantage of any autumn spawn.

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## I. Introduction and Overview

The Peconic Bays are a system of bays between the north and south forks of eastern Long Island (Figure 1). In June of 1985 these waters turned a coffee brown as the result of a large algae bloom by the phytoplankton *Aureococcus anophagefferens.* The bloom, which also appeared in the south shore bays of Long Island, in Narragansett Bay, Rhode Island, and in Barnegat Bay, New Jersey, was quickly named the "Brown Tide." It soon became clear that the brown tide was having a devastating effect on the ecosystem and tourist industry in the Peconic Bays. Large expanses of eelgrass died because of the shading effect caused by the algae bloom. Bay scallops, mussels, and oysters stopped feeding, and literally starved to death. Tourists went elsewhere, viewing recreation in coffee-colored water as undesirable.

Because of its life history, the bay scallop, *Argopecten irradians irradians,* was perhaps the most adversely affected species. Bay scallops in the northeastern U.S. have a lifespan of 20 to 26 months (Belding 1910). Spawning occurs in spring (typically late May through early June), triggered by an increase in water temperature. The bay scallop is a functional hermaphrodite and eggs are fertilized externally in the water column. Following fertilization, the scallop larvae drift for about 10 to 14 days, during which time they develop a small shell and eventually settle to the bottom. In the Peconics, some adults may spawn a second time in September or October (Tettelbach *et al.* 1999). This later spawn, though considerably smaller than the spawn which takes place in late spring, may have been critical to the survival of the bay scallop in the Peconic system.

After settling, the bay scallop must survive predation by starfish, crabs, and whelks, and severe winter weather, when cold water and storms can induce significant mortality. Those that survive will spawn in May or June (at one year of age) and, upon reaching a legal size, will be subject to harvest by "baymen" when the commercial fishery opens in mid-September. The bay scallop season in the Peconics will end in March of the following year and is based almost entirely on a single cohort approaching a period of senescence and high mortality during their second winter. The cumulative natural mortality of a cohort by the age of 24 months is usually more than 95% (Bricelj *et al.* 1987a). Very few bay scallops would "naturally" survive to age two, so a commercial fishery, based on individuals with a low probability of further "biological productivity," makes economic sense. (In a year when a brown tide appears during the summer, it may be advisable to delay the start of the commercial bay scallop season, in hopes of a second spawn during September or October. We will return to this point in our discussion of adaptive strategies in Section IV.)

This life history, where the local survival of the species depends critically on a single cohort, can result in wild, year-to-year, swings in population abundance, even without a devastating phenomenon like the brown tide. In the summer of 1985, mortality among adults ranged from 95% in Flanders Bay to only 10% in Orient Harbor [Wenczel *et al.* (1994)], but the mortality among larvae and juveniles was thought to be higher. This allowed baymen to harvest adult survivors in the fall of 1985 and winter of 1986, but the mortality of juveniles lead to the near disappearance of the spring-spawning cohort of 1986 and the virtual collapse of the commercial fishery in the fall of 1986 and winter of 1987. For the period 1970 - 1984 commercial landings in New York State averaged 318,400 pounds of meats. In 1987 and 1988 commercial harvests fell to 300 pounds (Wenczel *et al.* 1994)). To make matters worse, the brown tide returned in 1986 and 1987.

As the extent of the mortality and reproductive failure became known, baymen, Suffolk County, New York State, Cornell Cooperative Extension, the federal government, and researchers at local universities and colleges mobilized to provide (1) biological research on the brown tide and bay scallop, (2) hydrological research on circulation and larval dispersion within the Peconic Bays, and (3) strategies to aid the recovery of the bay scallop population. One of the initial strategies focused on the acquisition and transplant of seed stock into selected sites in the Peconic system. The wide-spread occurrence of the brown tide in 1985 created a scarcity of "natural set seed," and the committee in charge of the transplant program surveyed shellfish hatcheries in the northeast to determine if anyone was culturing bay scallop seed. At that time, the only hatchery capable of producing a large quantity of bay scallop seed was in Edgertown, Massachusetts. That hatchery was producing seed exclusively for the bay scallop fishery on Martha's Vineyard and was not interested in supplying seed for transplant into the Peconic Bays. The committee began working with local hatcheries and, through contracts which created a suitable financial incentive, achieved a production of almost 400,000 seed scallops (30 mm in shell height) in 1988. Transplant sites were ranked for suitability, and those receiving seed scallops were monitored. It has been estimated that 25% of the stock of Peconic bay scallops in 1989 were the progeny of hatchery scallops (Wenczel *et al.* 1994).

A second strategy, and the focus of this paper, is the "spawner sanctuary" program. In this program "net houses," containing 1,000 adult scallops, are deployed at a "source site," where warming waters will trigger a spawn. The source sites are chosen based on a dispersion model of the Peconic system, and on the expected survival rates of juveniles at various "settlement sites." Larvae may die if they are carried out of the Peconic system into the Atlantic Ocean, or if they settle at an unsuitable site within the Peconics. Suitable sites would have a firm sand bottom, eelgrass, and a water depth ranging from 5 - 10 feet (Wenczel *et al.* 1994). More difficult to predict is predator density. This will change with changes in the abundance of both predators and substitute prey species, as well as with their spatial distribution within the Peconic system. While many of the components of a model to optimize the location of spawner sanctuaries were developed in the late 1980's and 1990's, they have not been integrated into a consistent model that might optimize the location of net houses within the Peconic system. The problem is made complex by the uncertainty of transport and settlement of larvae and their survival at a particular settlement site. On top of this uncertainty, transplant or spawner sanctuary programs, like the predators that feed on bay scallops, need to be adaptive in the face of brown tides which recurred in 1986, 1987, 1988, 1991, and 1995.

This paper is organized as follows. In the next section we present a model to optimize the location of net houses containing scallops ripe for spawning. In the third section we calibrate the model and present our preliminary results. In the fourth section we critique the model and discuss certain adaptive strategies in the face of normal variations in the Peconic ecosystem and the episodic nature of the brown tide.

## II. The Model

The problem is to determine the optimal location of a finite number of net houses so as to maximize the expected survival of larvae to age one, when they would spawn. The model employs the following notation.

$i$ = a source-site index, $i=1,2,\ldots,I$. Net houses are allocated to source sites.

$j$ = a settlement-site index, $j=1,2,\ldots J$. Larvae surviving the planktonic stage would settle at a settlement site.

$p_{i,j}$ = the probability that a larva spawned at source site i will settle at site j.

$S_j$ = the one-year survival rate at site j.

$n_i$ = the number of net houses located at source-site i.

$L_i$ = the number of eggs spawned per net house at source-site i.

$N_i$ = the maximum number of net houses allowed at source-site i.

N = the total number of net houses to be allocated across the I source sites.

$\sum_{i=1}^{I} p_{i,j} n_i L_i$ = the expected number of larvae settling at site j.

$S_j \sum_{i=1}^{I} p_{i,j} n_i L_i$ = the expected number of bay scallops surviving to age one at site j.

The expected recruitment, across all settlement sites, of one-year old bay scallops would be given by the expression

$$E\{R\} = \sum_{j=1}^{J} S_j \sum_{i=1}^{I} p_{i,j} n_i L_i \qquad (1)$$

Maximization of expected recruitment, subject to constraints on the number of net houses allowed at a particular source site ($N_i$) and the total number of net houses available for deployment (N), becomes an integer programming problem which may be stated mathematically as

$$\text{Maximize} \quad E\{R\} = \sum_{j=1}^{J} S_j \sum_{i=1}^{I} p_{i,j} n_i L_i$$

$$\text{Subject to} \quad N_i \geq n_i \geq 0$$

$$N \geq \sum_{i=1}^{I} n_i$$

If there were no binding constraints on the number of net houses allowed at a particular site ($N_i \geq N$ for all i), then the linear nature of this optimization problem would lead to a "place all your eggs in one basket" solution. All net houses would be located at the source site with the highest expected recruitment given by the expression

$$E\{R_i\} = \sum_{j=1}^{J} S_j p_{i,j} L_i \qquad (2)$$

Locating all your net houses at one source site may not be feasible and, given a risky marine environment, is probably undesirable. The politics of marine resources on eastern Long Island would also lead to binding $N_i$, and possibly lower bounds, $M_i > 0$, such that $n_i \geq M_i$. A requirement to locate a certain number of net houses at certain source sites might arise because the baymen who harvest Peconic bay scallops reside in different towns (a level of municipal government below Suffolk County). The towns are active in the management of shellfish resources within "their" jurisdictions (extending into the bays in the Peconic system). The towns often hire shellfish biologists as permanent employees to administer town-run programs or participate in multi-town programs that would enhance the abundance of shellfish in town waters. While it is the dispersal, settlement, and survival of juveniles that will ultimately determine the abundance of scallops in town waters, elected officials and baymen often want to be able to point to net houses at source sites in their towns as a symbol of their efforts to re-establish the fishery. In our preliminary calibration of the model we will assume that $M_i$=0; that is, that there is no minimum number of net houses that must be located at a particular source site.

## III. Model Calibration and Results

The $p_{i,j}$ transport probabilities were obtained from a finite-element, particle-diffusion model of the Peconic system constructed by Siddall *et al.* (1986). Siddall *et al.* ran computer simulations to track the diffusion of particles (larvae) from I=46 source sites to J=6 settlement sites. The source sites are shown in Figure 2 while the six major settlement sites are shown in Figure 3.

The integer programming model of this paper uses the percentages of particles reported in Siddall *et al.*, Table 1 as estimates of $p_{i,j}$. Five source sites (27, 29, 30, 45, and 46) deposited no particles at any of the six settlement sites and were eliminated from the model. (Presumably larvae spawned at these sites would be carried out to sea or settle in areas where they would not survive.) The transport probabilities for the 41 viable source sites to the six settlement sites are contained in the block B5:G45 on the Base-Case Spreadsheet. The source sites vary considerably in the survival, dispersion, and settlement of larval (juvenile) bay scallops.

The model allows for site-specific spawning rates, $L_i$. This would permit variation in the spawning rate per net house, depending upon the source site. There was no basis on which to differentiate among source sites in our preliminary calibration. Bricelj *et al.* (1987b) estimate fecundity in the range of 12.6 to 18.6 x $10^6$ eggs/scallop. In the Base-Case Spreadsheet it was assumed that each scallop would spawn 15.6 x $10^6$ eggs and that a net house would contain 1,000 first-year scallops. This implied $L_i = L = 1.56 \times 10^{10}$ eggs/net house.

There were no published mortality rates for bay scallops at the six settlement sites. The transport probabilities, to the extent that $1 > \sum_{j=1}^{J} p_{i,j}$, capture the mortality, or disappearance, of larvae before settlement. After settlement, juveniles would be subject to predation and "winter kill." The combined effect of these two sources of mortality can vary considerably. Smith (1999) reports that over-wintering mortality in lantern nets varied from 20% to 99%. Survival rates would be much lower for juveniles on the actual bay bottom, and $S_j = S = 5.0 \times 10^{-5}$ provided more realistic numbers for scallops surviving to year one. This would be the survival rate in a non-brown-tide year. In a year with a brown tide, settlement sites in the western end of the system (like Flanders Bay, Site #1 in Figure 3) are likely to exhibit even lower survival rates.

The Base-Case Spreadsheet summarizes the numerical values for $p_{i,j}$, $L_i$ and $S_j$ used in the preliminary calibration. The Base-Case deployment of net houses is similar to the actual deployment of net houses in 1999 (Smith, personal communication, 10/18/99). These were $n_2 = 20$, $n_6 = 10$, $n_9 = 20$, $n_{14} = 10$, $n_{17} = 10$, $n_{26} = 15$, $n_{33} = 30$, and all other $n_i = 0$, for a total of $N = 115$.

In columns K - P we calculate the expected number of larvae arriving at settlement site j from source site i. At the bottom of each column, K - P, in row 47, we calculate the number of scallops expected to survive the 12-month grow-out to maturity. For example, with 20 net houses allocated to Source Site #2, Settlement Site #1 would receive $9.048 \times 10^{10}$ juveniles. In cell K47 we multiply the total number of juveniles arriving at Settlement Site #1 times the annual survival rate at Settlement Site #1 to get the expected number of one-year old scallops. With $S_j = S = 5.0 \times 10^{-5}$ this implies $4.524 \times 10^6$ one-year old bay scallops survive at Settlement Site #1.

Settlement Site #2 receives larvae (juveniles) from Source Sites #6 and #9. By coincidence, the total number of juveniles arriving at Settlement Site #2 is the same as at Settlement Site #1 and the number surviving to age one is also the same. (The probability of this happening in the real world would be "vanishingly small.") The number of year-one survivors at Settlement Sites #3 - #6 are given in cells M47 through P47, respectively.

In cell M49 we sum the number of surviving one-year old scallops across all six settlement sites. The number in cell M49, $1.7589 \times 10^7$, represents total survivorship in a non-brown-tide year and is a measure of production from the current number and location of net houses. We can use the spreadsheet to explore the implications of changing various parameters ($L_i$, $S_j$, or $p_{i,j}$) or the number and location of net houses ($n_i$). Also contained in Excel is an optimization algorithm that will permit us to maximize year-one survivorship subject to constraints on $n_i$, such as $N_i \geq n_i \geq M_i$ and

$$N \geq \sum_{i=1}^{I} n_i .$$

Suppose we wish to maximize year-one survival subject to keeping the total number of net houses at or less than the N = 115 deployed in 1999.

First we call up Excel's Solver, located under the "Tools" menu bar. We tell Solver that we want to maximize the value in cell $M$49 by changing the values in cells $I$5:$I$45 subject to the following constraints:

$I$49 >= SUM($I$5:$I$45)

$I$5:$I$45 >= 0

$I$5:$I$45 = integer

The first constraint says that the number of net houses available must exceed or equal the number allocated. The second constraint says that the number of net houses allocated to any site must be nonnegative. The third constraint says that the number of net houses allocated to any site must be an integer (i.e., you can't allocate a fraction of a net house). What is the optimal allocation of net houses in this case? The result is shown in the "Naive Optimal Spreadsheet."

As we anticipated in Section II, the solution is to place all your eggs in one basket, or in our case, to deploy all 115 net houses to Source Site #2. With $L_i = L = 1.56 \times 10^{10}$ and $S_j = S = 5.0 \times 10^{-5}$ the best source site or sites would be the one(s) having the highest transport probability, when summed over all settlement sites j. In other words, Solver will rank source sites according to which site has the largest value for

$$\sum_{j=1}^{J} p_{i,j} \qquad (3)$$

Source Site #2 has the highest combined transport probability of 0.29, with all the larvae from Source Site #2 settling at Settlement Site #1. The total number of one-year old scallops expected to survive at Settlement Site #1 is

$2.601 \times 10^7$, greater than the $1.7589 \times 10^7$ on the Base-Case Spreadsheet. This result is regarded as naive because it does not take into account (1) density-dependent survival that is likely to exist at all the settlement sites, (2) Settlement Site #1, Flanders Bay, is especially vulnerable to mortality during a brown-tide year, and (3) equity and the political reality that a deployment strategy must take into account the participation and contribution of individual towns in both the location of net houses and ultimately in the location of harvestable bay scallops.

What if there were a constraint on the number of net houses that could be allocated at any one source site? Suppose no more than $N_i = 10$ net houses could be located at any single source site. We could introduce this constraint by adding

```
$I$5:$I$45 <= 10
```

With N = 115 available net houses, this constraint will force Solver to allocate 10 net houses to top 11 source sites and 5 net houses to the 12th site. Source sites with the same sum for transport probabilities, across settlement sites, will be viewed as equally desirable by Solver. The results are shown in the spreadsheet entitled "Top Twelve Source Sites."

Source Site #2 gets the first 10 net houses. Source Sites #15 and #16 are tied for second with summed transport probabilities equal to 0.28. Sites #1, #7, #10 and #34 are tied for third at 0.27, while Source Sites #6 is alone in fourth at 0.26. Source Site #9 is ranked in fifth place, by itself, with a summed probability of 0.25. Source Sites #32 and #33 are tied for sixth place, with a summed probability of 0.21 and Source Site #11 is by itself in 7th place with a probability of 0.20. This gives us the top 12 source sites and an expected survival to year one by $2.3088 \times 10^7$ scallops. This is only

11.2% below the naive optimum, which placed all net houses at Source Site #2, and "placing our eggs in 12 baskets" provides a much more diverse portfolio against predation, winter kill, and brown tide.

**IV. Critique and Adaptive Strategies**

This model is a first attempt at optimizing the location of net houses, containing adult (ready-to-spawn) bay scallops, at various source sites in the Peconic Bays on eastern Long Island. The model was a simple linear characterization of a complex stochastic problem. Sometimes simplicity is a virtue. This model had three components: (1) the transport (or dispersion) probabilities, $p_{i,j}$, (2) eggs per net house at source site i, $L_i$, and (3) the year-one survival rate at settlement sites j, $S_j$. Current information did not allow us to differentiate between source sites on the basis of a variation in $L_i$, nor could we differentiate between the likely survival rates at the six settlement sites, based on $S_j$. With identical $L_i = L = 1.56 \times 10^{10}$ eggs/net house, and survival rates $S_j = S = 5.9 \times 10^{-5}$, the naive optimum would be to locate all net houses at the source site with the highest summed settlement probability. In our model this was Source Site #2 with all larvae settling in Settlement Site #1 (Flanders Bay). This would be a high risk strategy, particularly if a brown tide appeared after placement and spring spawning. By spreading net houses across the top 12 sites, there was only an 11.2% decline in expected year-one survival from the naive ("all-eggs-in-one-basket") optimum, but a 31.2% increase in expected survival over the actual deployment in 1999.

Of the three components, survival at the settlement sites, $S_j$, is the most uncertain. When $L_i = L$ and $S_j = S$, the ranking of source sites will be determined by the sum of the transport probabilities, $\sum_{j=1}^{J} p_{i,j}$, with the most productive site having the largest summed probability. This analysis presumed a "no show" for the brown tide. Since its "debut" in 1985, it has reprised in 1986, 1987, 1988, 1991, and 1995. Brown tides have reached their highest concentrations, and induced the highest scallop mortality, in the western bays of the Peconic system. From our reading of the literature, there would appear to be two adaptive strategies that might be adopted should a brown tide occur in June or July.

First, net houses and seed transplant programs should be moved to the best sites (based on predator density) in the eastern end of the Peconic system. In 1988 a small harvest of 300 pounds was obtained from natural set in Napeague Harbor. By relocating seed transplant and spawner sanctuaries (net houses) to the eastern bays you are likely to maximize survival, spawning and commercial harvest in the following year.

Second, in a year that a brown tide occurs, it is probably optimal to delay the start of the commercial bay scallop season until November 15th, in hopes of catching a significant autumn spawn from those 15 to 18 month-old adults that survived the brown tide. In non-brown-tide years the season can be opened at the usual time, in mid-September.

With better information on survival (more confident estimates of $S_j$), the frequency of future brown-tide events, and the effectiveness of adaptive strategies, it would be possible to conduct a cost-benefit analysis of seed transplant and spawner sanctuary programs. Such an analysis might identify the relative efficiency of the two programs and better justify investments to re-establish the bay scallop fishery in the Peconics.

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**Figure 1. The Peconic Bay System**

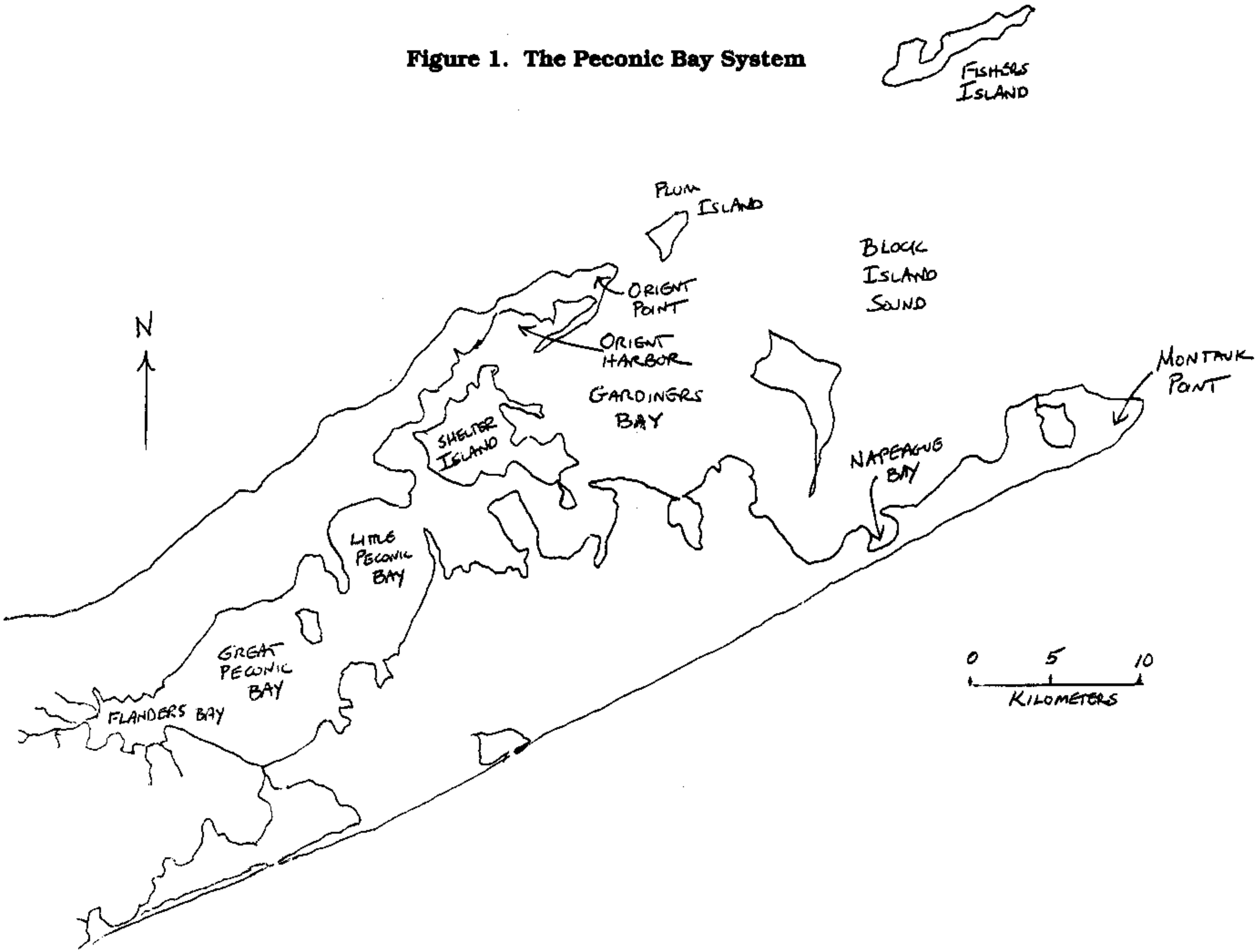


**Figure 2. Location of Source Sites**

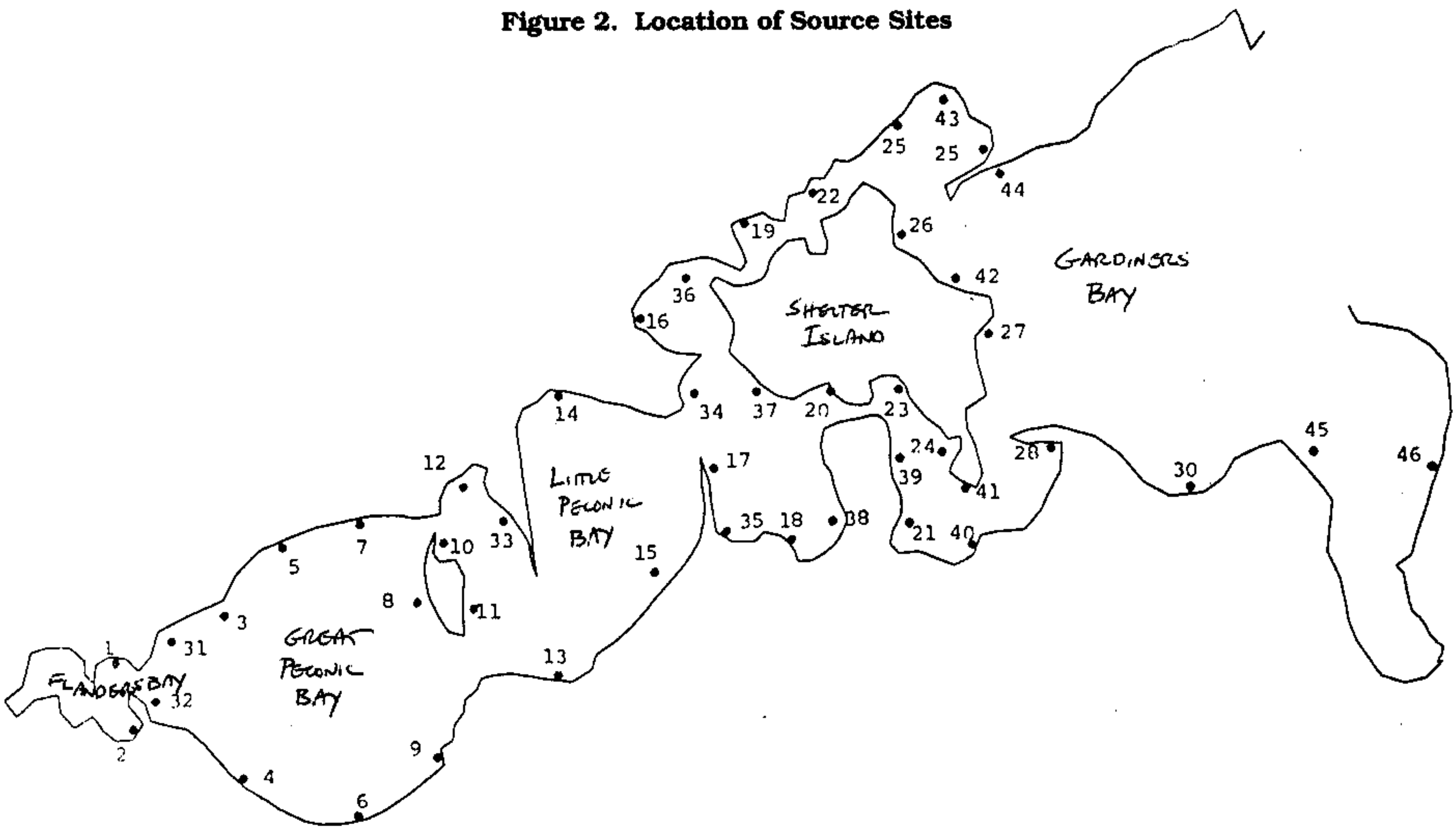
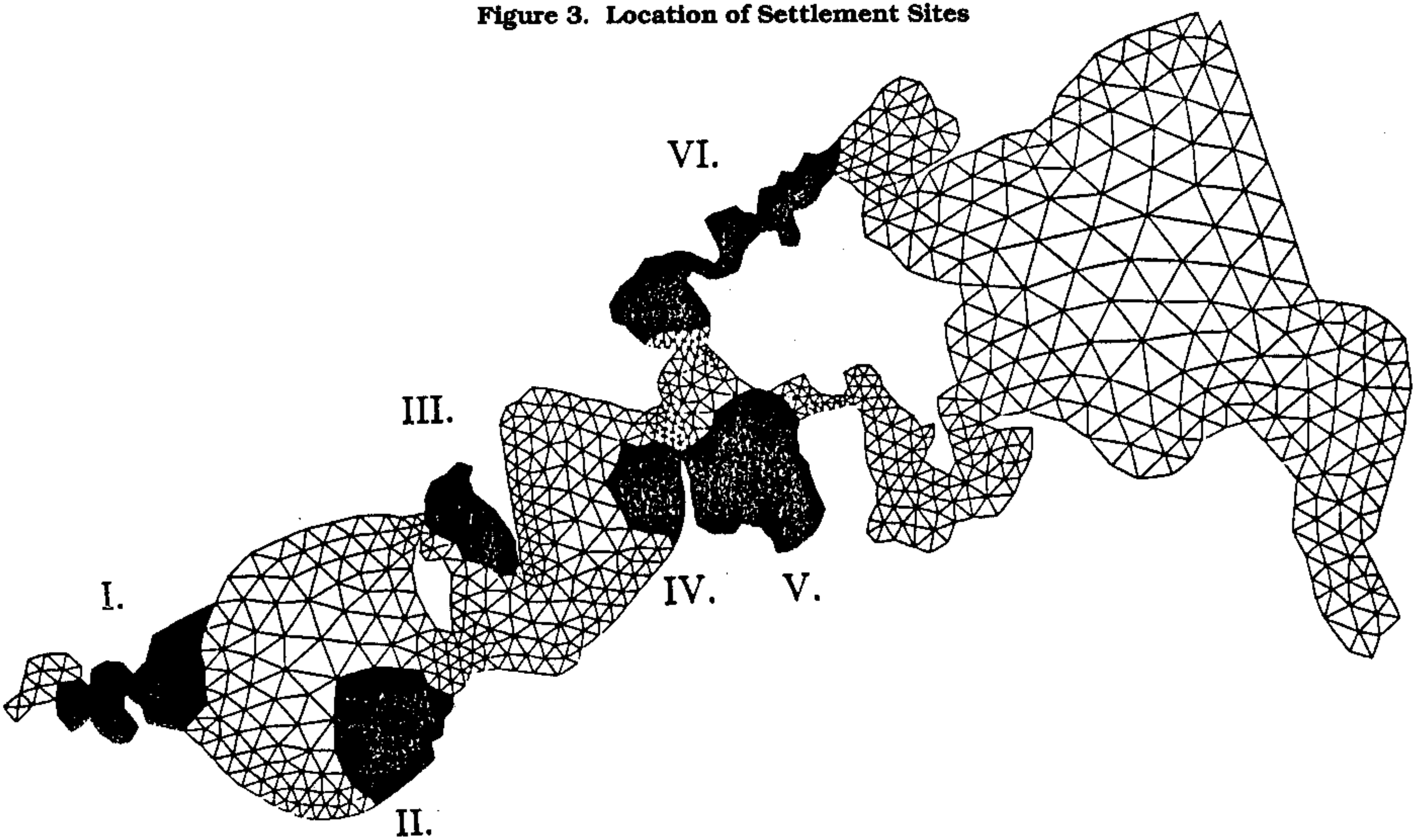


**Figure 3. Location of Settlement Sites**



# Base-Case Spreadsheet

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Base-Case Allocation of Bay Scallop Net Houses | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | |
| 3 | Transport Probabilities | | | | | | | | | | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 |
| 4 | Source Site | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 | Sum pi,j | ni | Li | p(i,1)*ni*Li | p(i,2)*ni*Li | p(i,3)*ni*Li | p(i,4)*ni*Li | p(i,5)*ni*Li | p(i,6)*ni*Li |
| 5 | 1 | 0.27 | | | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 2 | 0.29 | | | | | | 0.29 | 20 | 1.56E+10 | 90480000000 | 0 | 0 | 0 | 0 | 0 |
| 7 | 3 | 0.04 | | | | | | 0.04 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 4 | 0.03 | 0.02 | | | | | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 5 | | 0.01 | 0.01 | | | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 6 | | 0.22 | 0.04 | | | | 0.26 | 10 | 1.56E+10 | 0 | 34320000000 | 6.24000E+09 | 0 | 0 | 0 |
| 11 | 7 | | 0.06 | 0.21 | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 8 | | 0.19 | | | | | 0.19 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 9 | | 0.18 | 0.07 | | | | 0.25 | 20 | 1.56E+10 | 0 | 56160000000 | 21840000000 | 0 | 0 | 0 |
| 14 | 10 | | 0.08 | 0.19 | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 11 | | 0.08 | 0.12 | | | | 0.2 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 12 | | 0.06 | 0.12 | | | | 0.18 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 13 | | 0.09 | 0.01 | | | | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 14 | | | | 0.13 | | | 0.13 | 10 | 1.56E+10 | 0 | 0 | 0 | 20280000000 | 0 | 0 |
| 19 | 15 | | | | 0.2 | 0.01 | 0.07 | 0.28 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 16 | | | | 0.17 | 0.03 | 0.08 | 0.28 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 17 | | | | 0.03 | 0.1 | 0.01 | 0.14 | 10 | 1.56E+10 | 0 | 0 | 0 | 4.68000E+09 | 1.56000E+10 | 1.56000E+09 |
| 22 | 18 | | | | | 0.06 | 0.07 | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 19 | | | | 0.03 | 0.05 | 0.07 | 0.15 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 20 | | | | | 0.07 | | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 21 | | | | | 0.01 | 0.1 | 0.11 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | 22 | | | | | 0.05 | 0.05 | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | 23 | | | | 0.03 | 0.1 | | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 28 | 24 | | | | 0.03 | 0.02 | 0.04 | 0.09 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | 25 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 26 | | | | | | 0.01 | 0.01 | 15 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 2.34000E+09 |
| 31 | 28 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 32 | 31 | 0.16 | | | | | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 33 | 32 | 0.2 | | 0.01 | | | | 0.21 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 34 | 33 | | | 0.21 | | | | 0.21 | 30 | 1.56E+10 | 0 | 0 | 98280000000 | 0 | 0 | 0 |
| 35 | 34 | | | | 0.23 | 0.04 | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 36 | 35 | | | | 0.03 | 0.08 | 0.03 | 0.14 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 37 | 36 | | | | | 0.01 | 0.11 | 0.12 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 38 | 37 | | | | 0.1 | 0.06 | 0.01 | 0.17 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 39 | 38 | | | | | 0.16 | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 39 | | | | | 0.06 | 0.01 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 41 | 40 | | | | | 0.02 | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 42 | 41 | | | | | 0.05 | 0.02 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 43 | 42 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 44 | 43 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 44 | | | | | | 0.05 | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 46 | | | | | | | | | | | | | | | | |
| 47 | Survival at j | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | | Expected Bay Scallops Site j | | 4.52400E+06 | 4.52400E+06 | 6.31800E+06 | 1.24800E+06 | 7.80000E+05 | 1.95000E+05 |
| 48 | | | | | | | | | | | | | | | | |
| 49 | | | | | | | Total Net Houses Available= | | 115 | | Total Expected Bay Scallops | | 1.75690E+07 | | | |

# Naive Optimal Spreadsheet

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Base-Case Allocation of Bay Scallop Net Houses | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | |
| 3 | Transport Probabilities | | | | | | | | | | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 |
| 4 | Source Site | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 | Sum pi,j | ni | Li | p(i,1)*ni*Li | p(i,2)*ni*Li | p(i,3)*ni*Li | p(i,4)*ni*Li | p(i,5)*ni*Li | p(i,6)*ni*Li |
| 5 | 1 | 0.27 | | | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 2 | 0.29 | | | | | | 0.29 | 115 | 1.56E+10 | 5.2026E+11 | 0 | 0 | 0 | 0 | 0 |
| 7 | 3 | 0.04 | | | | | | 0.04 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 4 | 0.03 | 0.02 | | | | | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 5 | | 0.01 | 0.01 | | | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 6 | | 0.22 | 0.04 | | | | 0.26 | 0 | 1.56E+10 | 0 | 0 | 0.00000E+00 | 0 | 0 | 0 |
| 11 | 7 | | 0.06 | 0.21 | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 8 | | 0.19 | | | | | 0.19 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 9 | | 0.18 | 0.07 | | | | 0.25 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 10 | | 0.08 | 0.19 | | | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 11 | | 0.08 | 0.12 | | | | 0.2 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 12 | | 0.06 | 0.12 | | | | 0.18 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 13 | | 0.09 | 0.01 | | | | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 14 | | | | 0.13 | | | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 15 | | | | 0.2 | 0.01 | 0.07 | 0.28 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 16 | | | | 0.17 | 0.03 | 0.08 | 0.28 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 | 17 | | | | 0.03 | 0.1 | 0.01 | 0.14 | 0 | 1.56E+10 | 0 | 0 | 0 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 |
| 22 | 18 | | | | | 0.06 | 0.07 | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 19 | | | | 0.03 | 0.05 | 0.07 | 0.15 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 20 | | | | | 0.07 | | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 21 | | | | | 0.01 | 0.1 | 0.11 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | 22 | | | | | 0.05 | 0.05 | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | 23 | | | | 0.03 | 0.1 | | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 28 | 24 | | | | 0.03 | 0.02 | 0.04 | 0.09 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | 25 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 26 | | | | | | 0.01 | 0.01 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0.00000E+00 |
| 31 | 28 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 32 | 31 | 0.16 | | | | | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 33 | 32 | 0.2 | | 0.01 | | | | 0.21 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 34 | 33 | | | 0.21 | | | | 0.21 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 35 | 34 | | | | 0.23 | 0.04 | | 0.27 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 36 | 35 | | | | 0.03 | 0.08 | 0.03 | 0.14 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 37 | 36 | | | | | 0.01 | 0.11 | 0.12 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 38 | 37 | | | | 0.1 | 0.06 | 0.01 | 0.17 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 39 | 38 | | | | | 0.16 | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 39 | | | | | 0.06 | 0.01 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 41 | 40 | | | | | 0.02 | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 42 | 41 | | | | | 0.05 | 0.02 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 43 | 42 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 44 | 43 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 44 | | | | | | 0.05 | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 46 | | | | | | | | | | | | | | | | |
| 47 | Survival at j | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | | Expected Bay Scallops Site j | | 2.60130E+07 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 |
| 48 | | | | | | | | | | | | | | | | |
| 49 | | | | | | | Total Net Houses Available= | | 115 | | Total Expected Bay Scallops | | 2.60130E+07 | | | |

## Top Twelve Source Sites

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Base-Case Allocation of Bay Scallop Net Houses | | | | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | | | | | |
| 3 | Transport Probabilities | | | | | | | | | | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 |
| 4 | Source Site | Settle Site 1 | Settle Site 2 | Settle Site 3 | Settle Site 4 | Settle Site 5 | Settle Site 6 | Sum pi,j | ni | Li | p(i,1)*ni*Li | p(i,2)*ni*Li | p(i,3)*ni*Li | p(i,4)*ni*Li | p(i,5)*ni*Li | p(i,6)*ni*Li |
| 5 | 1 | 0.27 | | | | | | 0.27 | 10 | 1.56E+10 | 42120000000 | 0 | 0 | 0 | 0 | 0 |
| 6 | 2 | 0.29 | | | | | | 0.29 | 10 | 1.56E+10 | 45240000000 | 0 | 0 | 0 | 0 | 0 |
| 7 | 3 | 0.04 | | | | | | 0.04 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 4 | 0.03 | 0.02 | | | | | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 5 | | 0.01 | 0.01 | | | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 6 | | 0.22 | 0.04 | | | | 0.26 | 10 | 1.56E+10 | 0 | 34320000000 | 6.24000E+09 | 0 | 0 | 0 |
| 11 | 7 | | 0.06 | 0.21 | | | | 0.27 | 10 | 1.56E+10 | 0 | 9360000000 | 32760000000 | 0 | 0 | 0 |
| 12 | 8 | | 0.19 | | | | | 0.19 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 9 | | 0.18 | 0.07 | | | | 0.25 | 10 | 1.56E+10 | 0 | 28080000000 | 10920000000 | 0 | 0 | 0 |
| 14 | 10 | | 0.08 | 0.19 | | | | 0.27 | 10 | 1.56E+10 | 0 | 12480000000 | 29640000000 | 0 | 0 | 0 |
| 15 | 11 | | 0.08 | 0.12 | | | | 0.2 | 5 | 1.56E+10 | 0 | 6240000000 | 9360000000 | 0 | 0 | 0 |
| 16 | 12 | | 0.06 | 0.12 | | | | 0.18 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 13 | | 0.09 | 0.01 | | | | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 18 | 14 | | | | 0.13 | | | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 15 | | | | 0.2 | 0.01 | 0.07 | 0.28 | 10 | 1.56E+10 | 0 | 0 | 0 | 31200000000 | 1560000000 | 10920000000 |
| 20 | 16 | | | | 0.17 | 0.03 | 0.08 | 0.28 | 10 | 1.56E+10 | 0 | 0 | 0 | 26520000000 | 4680000000 | 12480000000 |
| 21 | 17 | | | | 0.03 | 0.1 | 0.01 | 0.14 | 0 | 1.56E+10 | 0 | 0 | 0 | 0.00000E+00 | 0.00000E+00 | 0.00000E+00 |
| 22 | 18 | | | | | 0.06 | 0.07 | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 19 | | | | 0.03 | 0.05 | 0.07 | 0.15 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 24 | 20 | | | | | 0.07 | | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 21 | | | | | 0.01 | 0.1 | 0.11 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 26 | 22 | | | | | 0.05 | 0.05 | 0.1 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | 23 | | | | 0.03 | 0.1 | | 0.13 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 28 | 24 | | | | 0.03 | 0.02 | 0.04 | 0.09 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 29 | 25 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 26 | | | | | | 0.01 | 0.01 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0.00000E+00 |
| 31 | 28 | | | | | | 0.07 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 32 | 31 | 0.16 | | | | | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 33 | 32 | 0.2 | | 0.01 | | | | 0.21 | 10 | 1.56E+10 | 31200000000 | 0 | 1560000000 | 0 | 0 | 0 |
| 34 | 33 | | | 0.21 | | | | 0.21 | 10 | 1.56E+10 | 0 | 0 | 32760000000 | 0 | 0 | 0 |
| 35 | 34 | | | | 0.23 | 0.04 | | 0.27 | 10 | 1.56E+10 | 0 | 0 | 0 | 35880000000 | 6240000000 | 0 |
| 36 | 35 | | | | 0.03 | 0.08 | 0.03 | 0.14 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 37 | 36 | | | | | 0.01 | 0.11 | 0.12 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 38 | 37 | | | | 0.1 | 0.06 | 0.01 | 0.17 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 39 | 38 | | | | | 0.16 | | 0.16 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40 | 39 | | | | | 0.06 | 0.01 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 41 | 40 | | | | | 0.02 | | 0.02 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 42 | 41 | | | | | 0.05 | 0.02 | 0.07 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 43 | 42 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 44 | 43 | | | | | | 0.08 | 0.08 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 44 | | | | | | 0.05 | 0.05 | 0 | 1.56E+10 | 0 | 0 | 0 | 0 | 0 | 0 |
| 46 | | | | | | | | | | | | | | | | |
| 47 | Survival at j | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | 5.00E-05 | | Expected Bay Scallops Site j | | 5.92800E+06 | 4.52400E+06 | 6.18200E+06 | 4.68000E+06 | 6.24000E+05 | 1.17000E+06 |
| 48 | | | | | | | | | | | | | | | | |
| 49 | | | | | | | Total Net Houses Available= | | 115 | | Total Expected Bay Scallops | | 2.30880E+07 | | | |