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OIL SPILL RESPONSE ENGINEERING AND PLANNING

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CHAPTER I

INTRODUCTION

1. Oil Spill Problem

Tanker and barge traffic associated with the five petroleum product terminals along the NH side of the Piscataqua River (see Figure 1.1) represents a constant oil spill threat to the contiguous Great Bay System, NH, an estuarine reserve. Several serious accidents have in fact taken place in the 1970's and two small spills in 1990. A major factor is that the Piscataqua channel is subject to high velocity tidal currents. Should a spill occur, problems arise in knowing where the slick will move and how to control it using booms.

In this project, these problems were addressed by developing procedures for using diversion booms in high speed current environments and in revising and implementing a previously developed Oil Spill Trajectory Model. In the diversion boom concept shown in Figure 1.2, the boom is angled to the current in order to direct a slick to one side rather than attempt to contain the oil at an apex. Boom

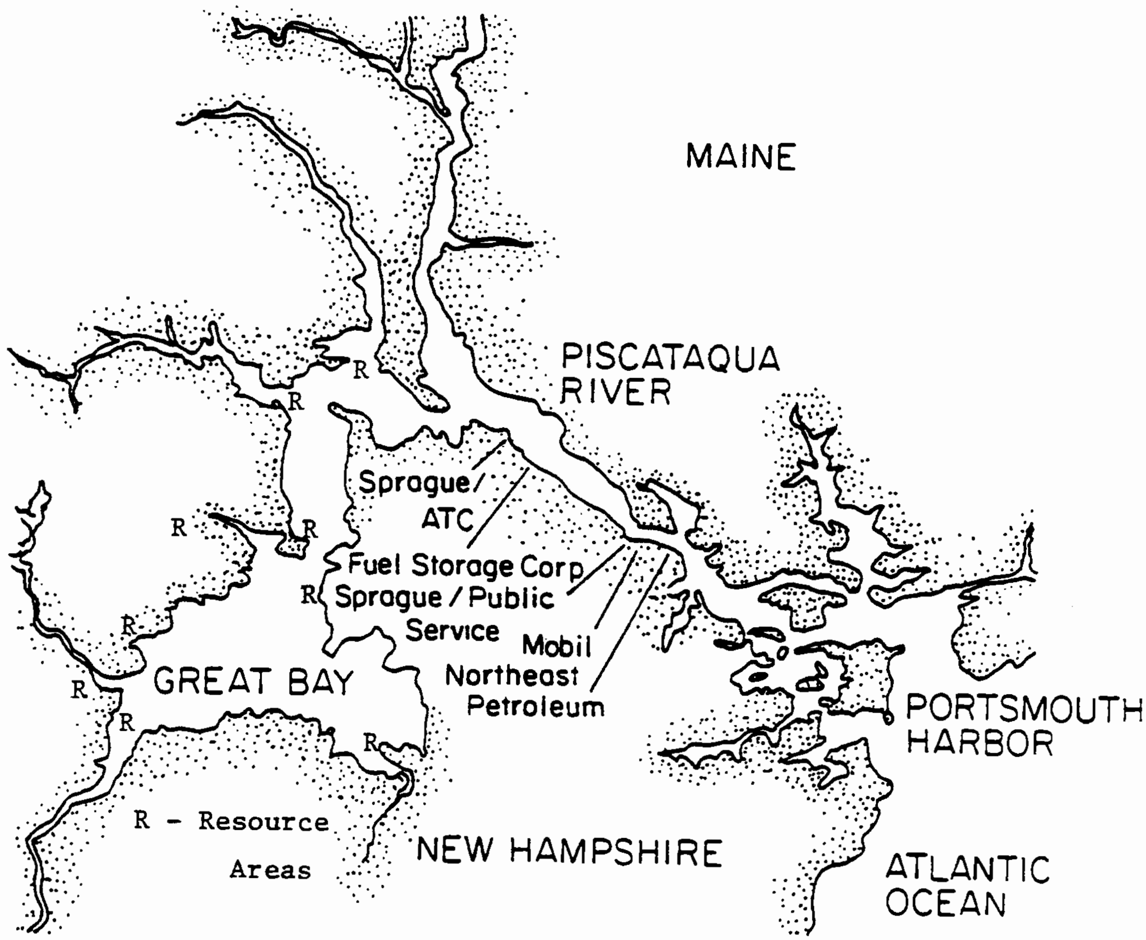

Figure 1.1: The Piscataqua River/Great Bay estuarine system.

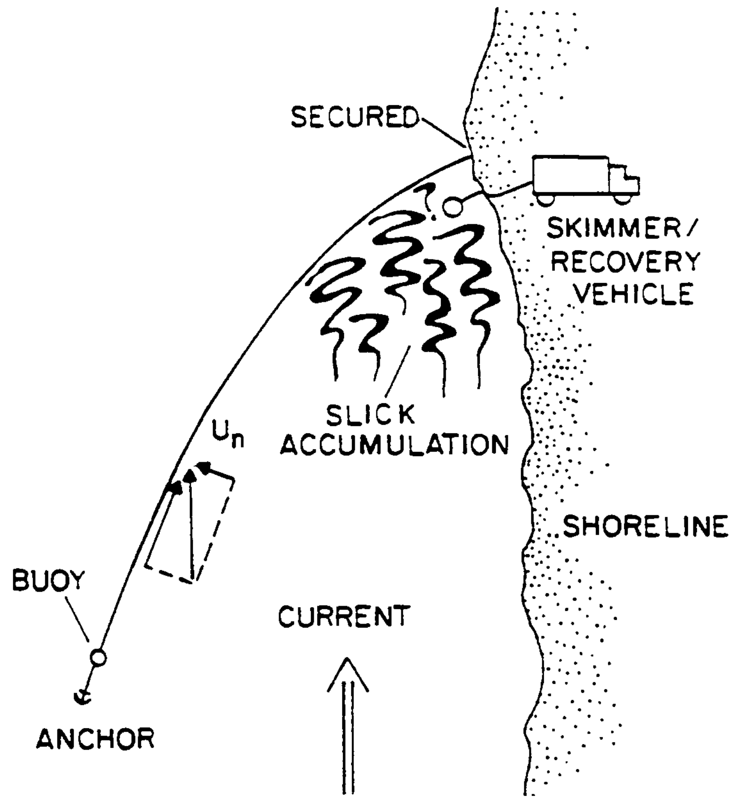

Figure 1.2: The diversion boom concept.

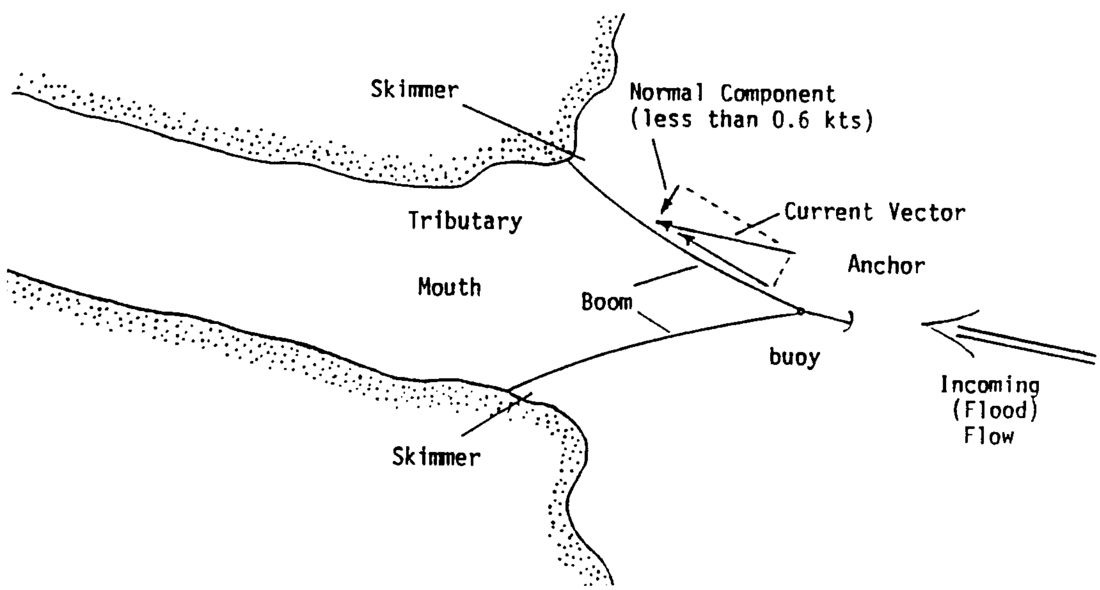

Figure 1.3: Protective booming of a tributary.

configuration (planform shape) must be designed before an emergency in order to prevent leakage when deployed. The leakage criterion used was that the normal component of current (U_n in Figure 1.2) be less than 0.6 kts. The Trajectory Model computer program makes use of surface current data to calculate the movement and spreading of spills in the Great Bay System.

2. Objectives

Tasks necessary in order to achieve these goals were to:

- Develop computer programs for boom configuration design
- Develop site-specific configurations for containing spills at the terminals
- Conduct a field program to support design development and to evaluate anchor systems
- Upgrade the Oil Spill Trajectory Model.

The study involved close cooperation between UNH and the Water Supply and Pollution Control Division (WSPCD) of the NH Department of Environmental Services (DES). Results are being incorporated into their contingency planning activities and into training exercises.

3. Methodology

In the next chapter, a boom configuration mathematical model is developed assuming that the boom is flexible and acted upon by a drag force normal to the boom. Each boom segment between anchor points is taken to be within a uniform current field. The resulting solution yields boom shape in the form on a catenary. Next, procedures are developed for extracting a diversion boom solution (without apex) from the full catenary boom (U-shaped). This involves applying new boundary conditins and solving a system of nonlinear algebraic equations. The mathematical basis and program algorithm are discussed here, while coding for a program implementing the solution is listed by Goodwin (1991). This model has been found to be satisfactory and convenient to apply to short booms and/or booms with many intermediate anchors.

The use of diversion booming at the terminals, however, has been found to necessitate long booms spanning significant variations in current speed and direction. A general boom configuration model, therefore, was developed and is discussed in Chapter III. This computer model takes into account the tangential component of drag as well as the normal component. The current speed and direction is specified by the user and can vary with position. The governing nonlinear equations are integrated numerically. The mathematical and programming steps are discussed in the report, while program code has been listed by Goodwin (1991).

The general computer model was calibrated and validated, as described in Chapter IV, using data from a field experiment conducted at Fuel Storage Corporation (see Figure 1.1) and reported by LeCompagnon (1984). Empirical coefficients were calibrated using one set of data. The model was then tested by application to an independent data set. The model was also applied to a longer boom configuration deployed at Northeast Petroleum. Though detailed measurements were not taken in this demonstration exercise, observations that were made were consistent with model predictions.

Then the general model was applied to the design of boom configurations for each of the Piscataqua terminals. Spills from vessels berthed at the terminal were considered, because most accidents occur during transfer operations. The site specific design applications made use of current data contained in Savage et al. (1982). Savage et al. (1982) and Swift et al. (1990) also discuss terminal design solutions making use of multiply-anchored boom configurations.

Subsequent field work showed that this approach is difficult to put into practice. Thus the terminal boom configurations were re-designed with the results presented here.

The upgraded boom configuration designs are summarized in Chapter V. This chapter is written so as to be self-contained. Those interested only in implementing the recommended diversion booms may turn directly to this section. Where it was possible, four designs were developed - two for the flood tide and two for the ebb. For each tidal phase a configuration plan is provided for spills on the inside of a berthed vessel and on the outside.

The logistics of boom deployment and anchoring were investigated with results presented in Chapter VI. Demonstration boom deployment exercises (without oil) were carried out by UNH. The use of portable anchors (Danforths) and screw-in type permanent systems were tested. Permanent sinker type moorings and a boom response barge were investigated. A training exercise was also conducted by the terminal operators in cooperation with the U.S. Navy.

Because response to terminal spills will involve some delay and since spills can occur from vessels not at terminals, attention was also given to protecting priority resource areas (see Figure 1.1). Since these areas consist mostly of river tributaries, protective boom configurations were considered as shown in Figure 1.3. Each side of the boom closing off the river entrance can be designed and analyzed as a diversion boom, so previus methods were applicable. Recommended boom configurations for the Squamscott River Wetlands, specifically required in this study, are presented in Chapter VII. Results for other rivers and creeks were developed in a companion study and are reported by Swift et al. (1991).

In order to determine which resource areas are threatened in the event of a released oil slick, a computer simulation was developed to track spills as they move through the Great Bay System. The Oil Spill Trajectory Model is also useful in devising other counter-measures during an emergency as well as for planning purposes. The Trajectory Model is based on a previously developed computer program that was implemented on a mainframe computer. Upgrading included transfer to a personal computer, better current data and a more realistic spreading model. A description of the Trajectory Model and directions for its use are contained in Chapter VIII.

CHAPTER II

CATENARY DIVERSION MODEL

1. Modeling Approach

This catenary diversion model is best applied to short boom segments terminating at anchoring points. A short boom or a longer boom with many intermediate anchors is an example of this. See Figure 2.1 for a schematic of this configuration.

This model (and subsequent computer solution) is developed with the designer in mind. Therefore, input includes the number of boom segments to be modeled, the length of each segment, the location of the end of each segment, and the current vectors. All other quantities are calculated by the program. Output includes the boom tension, magnitude and location of maximum normal current, and boom shape.

As previously mentioned, there are two major assumptions made in this modeling of oil booms. First, the current is restricted to being constant in both velocity and direction over a boom segment defined by two consecutive anchoring points. Current can, however, vary segment to segment. The second assumption is that the drag forces are perpendicular to the boom.

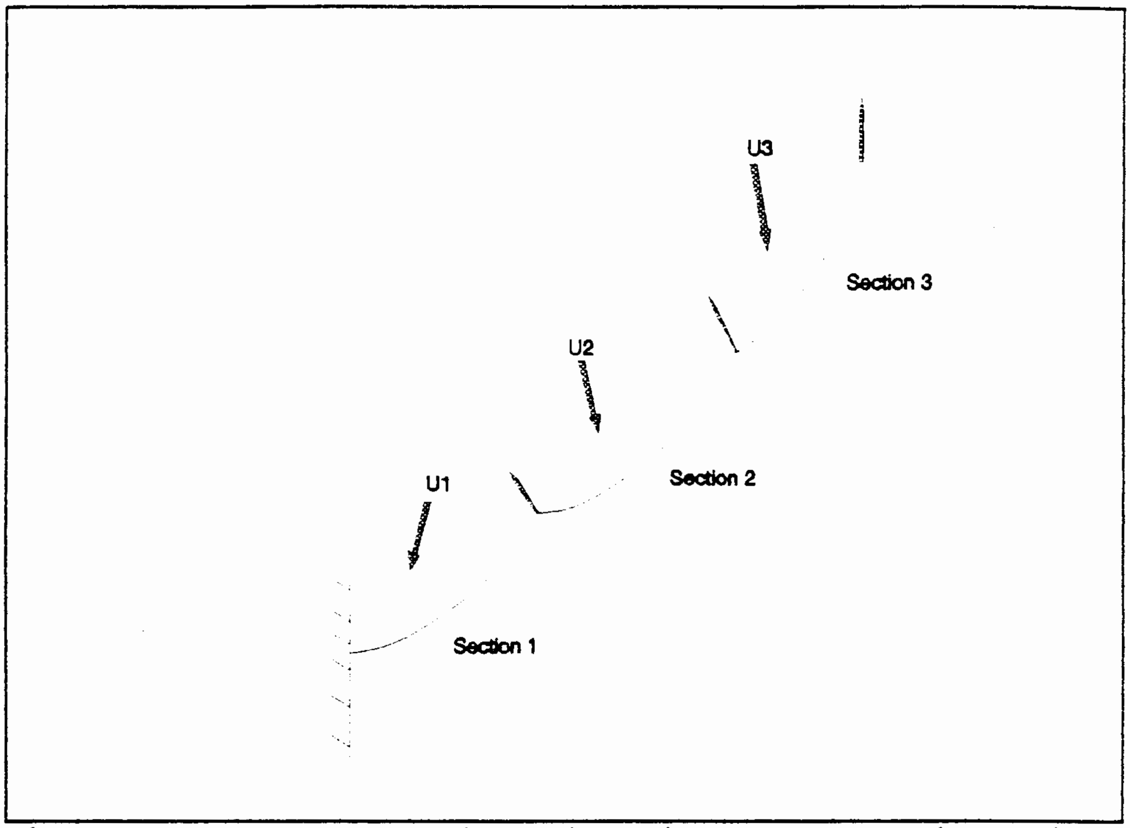

Figure 2.1: A 3-section diversion boom configuration, where $U_{1,2,3}$ = current vector for that section.

2. Catenary Containment Model

The modeling approach begins with the static equilibrium equations governing the containment system as shown in Figure 2.2. The containment (or U-shaped) boom model presented here is similar to that found in several sources, for example, Cross and Hoult (1970). When the containment model is complete, the diversion model is then obtained from the full containment solution as described in the next section.

The catenary model equations describe the equilibrium between the tension in the boom and the drag forces exerted on the boom by the current. In the tangential direction, equilibrium requires that

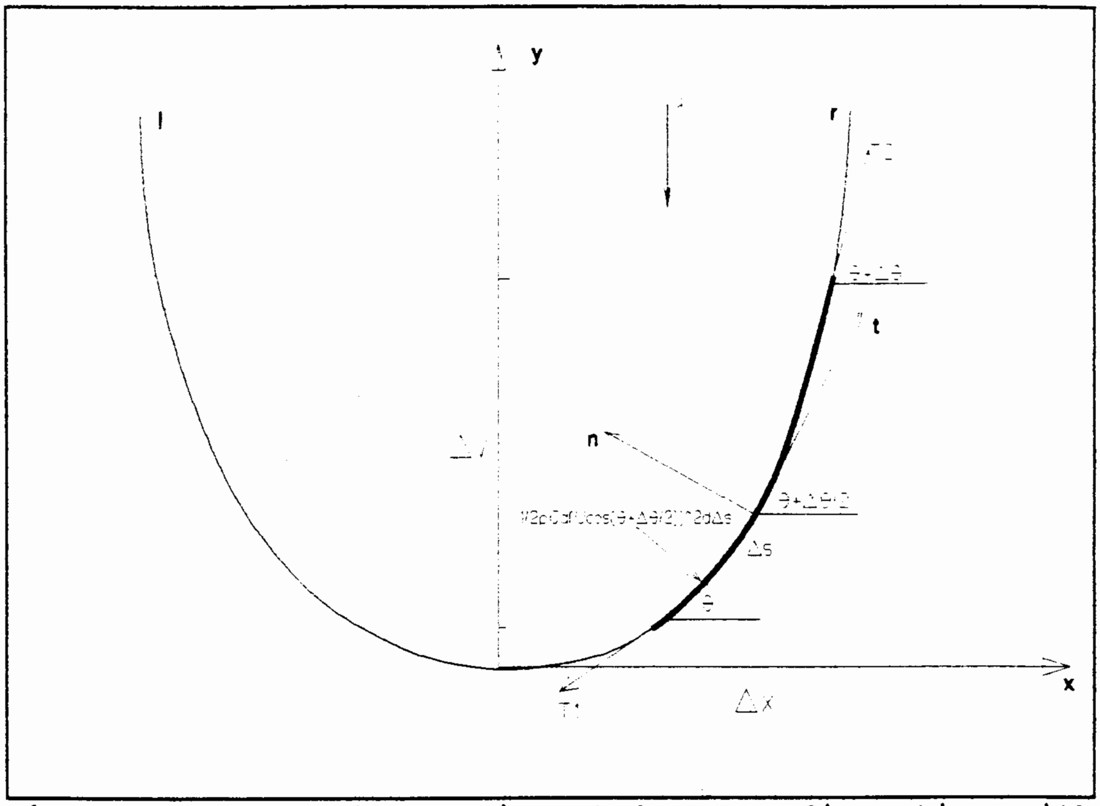

Figure 2.2: Full containment boom configuration with free body diagram shown.

$$\Sigma F_t = -T_1\cos\left(\frac{\Delta\theta}{2}\right) + T_2\cos\left(\frac{\Delta\theta}{2}\right) = 0, \qquad (2.1)$$

where

$T_{1,2}$ = tension at the respective end, and

$\Delta\theta$ = change in angle from one end of the boom section to the other.

This reduces to

$$T_1 = T_2, \qquad (2.2)$$

which says that the tension is constant throughout the boom.

In the normal direction, equilibrium is satisfied only if

$$\Sigma F_n = -\frac{1}{2}\rho C_d d\left[U\cos\left(\theta+\frac{\Delta\theta}{2}\right)\right]^2 \Delta s + T\sin\left(\frac{\Delta\theta}{2}\right) + T\sin\left(\frac{\Delta\theta}{2}\right) = 0 \quad (2.3)$$

where

ρ = density of water,

C_d = coefficient of drag,

d = boom skirt depth,

U = current magnitude,

θ = angle of boom at left end, and

Δs = length of boom section.

Dividing by Δs, taking the limit as $\Delta\theta \to 0$, the limit as $\Delta s \to 0$, and simplifying results in:

$$\cos^2\theta = \left(\frac{T\, d\theta}{\frac{1}{2}\rho C_d d U^2 ds}\right) \quad (2.4)$$

or,

$$\cos^2\theta = \frac{T}{\frac{1}{2}\rho C_d d U^2} \frac{d\theta}{dx} \frac{dx}{ds}. \quad (2.5)$$

Define the non-dimensionalized tension as

$$\lambda = \frac{T}{\frac{1}{2}\rho C_d d U^2 L}, \quad (2.6)$$

where L is the containment boom length.

From geometry,

$$\frac{d^2y}{dx^2} = \frac{d}{dx}(\tan\theta) = \frac{1}{\cos^2\theta}\frac{d\theta}{dx}, \tag{2.7}$$

and

$$\frac{dx}{ds} = \cos\theta = \frac{1}{\sqrt{1+\left(\frac{dx}{dy}\right)^2}}. \tag{2.8}$$

Combining (2.5), (2.6), (2.7), and (2.8) yields

$$\cos^2\theta = L\lambda\left[\cos^2\theta\ \frac{d^2y}{dx^2}\right]\left(\frac{1}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}\right), \tag{2.9}$$

or

$$1 = L\lambda\frac{d^2y}{dx^2}\frac{1}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}. \tag{2.10}$$

Defining the slope as

$$\frac{dy}{dx} = P, \tag{2.11}$$

substituting (2.11) into (2.10), and separating variables gives

$$\frac{dP}{\sqrt{1+P^2}} = \frac{dx}{L\lambda}. \tag{2.12}$$

Taking the coordinate system's origin at the apex of the curve (see Figure 2.2), equation (2.12) can be integrated by applying the boundary condition of

$$\frac{dy}{dx}(x=0) = P(0) = 0. \tag{2.13}$$

This yields

$$\ln\left(P+\sqrt{P^2+1}\right) = \frac{x}{L\lambda}. \tag{2.14}$$

Raising both sides as an exponential power and substituting from (2.11) results in

$$\frac{dy}{dx}+\sqrt{\left(\frac{dy}{dx}\right)^2+1} = e^{\frac{x}{L\lambda}}. \tag{2.15}$$

Rearranging and simplifying leaves

$$\frac{dy}{dx} = \tan\theta = \frac{e^{\frac{x}{L\lambda}} - e^{-\frac{x}{L\lambda}}}{2} = \sinh\left(\frac{x}{L\lambda}\right). \tag{2.16}$$

Finally, integrating using the boundary condition (see Figure 2.2)

$$y(x=0) = 0 \tag{2.17}$$

gives

$$y = L\lambda\left[\cosh\left(\frac{x}{L\lambda}\right)-1\right]. \tag{2.18}$$

This curve is plotted in Figure 2.2 and represents the full catenary containment configuration.

3. Diversion Boom Model

3.1 Analytical Approach

From the full containment model shown in Figure 2.2, a section can be used as the mathematical model for a diversion boom. The problem is that the diversion model designer will only know the relative position of the endpoints, *l* and *r*, as well as the length of boom to be used between these points. The user will not know apriori the apex location (i.e. the origin) and so cannot apply (2.18) directly. The mathematical problem, then, is to find x_l and y_l, the coordinates of the left end of the boom, and T in terms of specified x_b and y_b, the distances from the left end of the boom to the right end, and the boom length. Three equations are therefore required.

Defining $\mu = \frac{1}{2}\rho C_d U^2 d$ and using (2.6) results in the alternate form,

$$y = \frac{T}{\mu}\left[\cosh\left(\frac{x\mu}{T}\right) - 1\right]. \qquad (2.19)$$

Referring to Figure 2.3 and evaluating (2.19) at each end of the boom segment gives

$$y_l = \frac{T}{\mu}\left[\cosh\left(\frac{x_l\mu}{T}\right) - 1\right] \qquad (2.20)$$

and

$$y_r = y_l + y_b = \frac{T}{\mu}\left\{\cosh\left[\left(\frac{x_l + x_b}{T}\right)\mu\right] - 1\right\}, \qquad (2.21)$$

where x_r, y_r = coordinates of right end of boom.

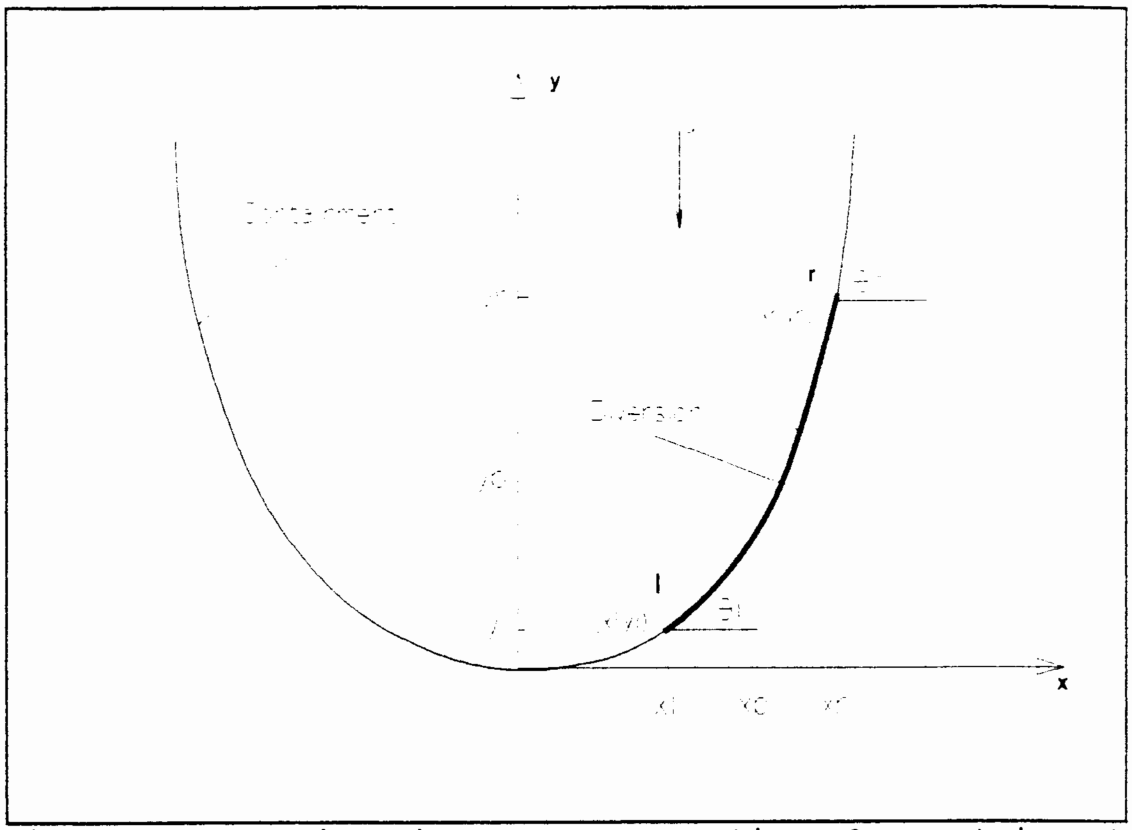

Figure 2.3: Diversion boom as a section of a containment configuration.

Combining these two equations yields

$$y_b = -\frac{T}{\mu}\left\{\cosh\left(\frac{x_l\mu}{T}\right) - \cosh\left[\left(\frac{x_l+x_b}{T}\right)\mu\right]\right\}. \tag{2.22}$$

The length of the boom segment can be obtained by rearranging and integrating (2.8).

$$\int_0^{L_b} ds = \int_{x_l}^{x_r}\sqrt{1+\left(\frac{dy}{dx}\right)^2}\,dx. \tag{2.23}$$

From (2.10) this can be rewritten as

$$L_b = \int_{x_l}^{x_r} L\,\frac{d^2y}{dx^2}\,dx. \tag{2.24}$$

Performing this integration yields

$$L_b = \left[L\lambda \frac{dy}{dx}\right]_{x_l}^{x_r} \tag{2.25}$$

or from (2.16)

$$L_b = \left[L\lambda \sinh\left(\frac{x}{L\lambda}\right)\right]_{x_l}^{x_r}. \tag{2.26}$$

Substituting $L\lambda = T/\mu$ (from (2.6)), noting that $x_r = x_l + x_b$, and evaluating gives

$$L_b = \frac{T}{\mu}\left[\sinh\left(\frac{(x_l+x_b)\,\mu}{T}\right) - \sinh\left(\frac{x_l\mu}{T}\right)\right]. \tag{2.27}$$

The problem reduces to one of solving two equations, (2.22) and (2.27), in two unknowns, T and x_l. Since the problem to be solved has a physical basis, it is possible to use the knowledge of the problem to aid in its solution.

2.2 Numerical Solution

The first part of finding the diversion configuration is finding the apex of the parent containment configuration. With this knowledge, the section being considered for diversion configuration can be taken out and analyzed.

The starting point for the solution is the tension. The tension and the length between anchoring points are physically related. The higher the tension the further apart two anchoring points will be, and vice versa. This is because higher tensions require less curvature to maintain equilibrium, and two consecutive anchoring points are therefore further apart.

To start, the tension can be estimated from the boom segment length and a physical understanding of the problem. With the tension estimated, (2.22) can be rearranged in the form

$$f(x_1) = \cosh\left(\frac{x_1\mu}{T}\right) - \cosh\left[\left(\frac{x_1+x_b}{T}\right)\mu\right] + \frac{y_b\mu}{T} = 0. \qquad (2.28)$$

and submitted to a Newton-Raphson root finding analysis to find x_1. The x_1 found by the Newton-Raphson routine is then tested in (2.27) to see if the calculated boom length is within a tolerance distance of the input boom length. If not, the tension, which is physically related to the boom length, is adjusted in (2.28) and the entire procedure repeated until the input length and the calculated lengths match.

Once this is accomplished, the information is used to calculate y_1 from (2.20). The boom's terminal angles can be found by applying (2.16) at x_1 and x_r. The maximum current normal to the boom is then evaluated as $U\cos\theta_1$, where θ_1 is the left terminal angle. Equation (2.19) can be used to plot the boom shape (from x_1 to x_r). Usually, however, it is more convenient to shift the coordinate system to point 1 which can now be done since x_1 and y_1 are known.

4. Computer Programming

Because the owners of the Piscataqua terminals use MS-DOS compatible computers, this platform was chosen. There were, however, many choices for the programming language to be used. A major criterion for this program, however, was speed. This ruled out the use of any of the interpreted languages such as BASIC. After that, the choice was made based on compactness of code, graphics, and availability of a compiler. Since the new language C had advantages in all of these categories, it was chosen.

The program is set up so that the user can easily analyze a diversion boom made up of segments with the end of each segment terminating at an anchoring point. A configuration using three such segments, for example, was shown in Figure 2.1. Each segment can have its own current definition, both magnitude and direction. Magnitude is input in knots, and direction in degrees measured positive in a counter-clockwise (ccw) direction from the negative y-axis. Each individual segment is analyzed as discussed above in numerical order from the outside anchoring point in toward shore.

The analysis automatically adjusts the coordinate system so that the end of one segment is the beginning of the next. An equilibrium analysis is also done to determine the horizontal component of the load at each mooring.

After initialization, the first of three nested loops begins (see Figure 2.4). This first, (or outside) loop moves

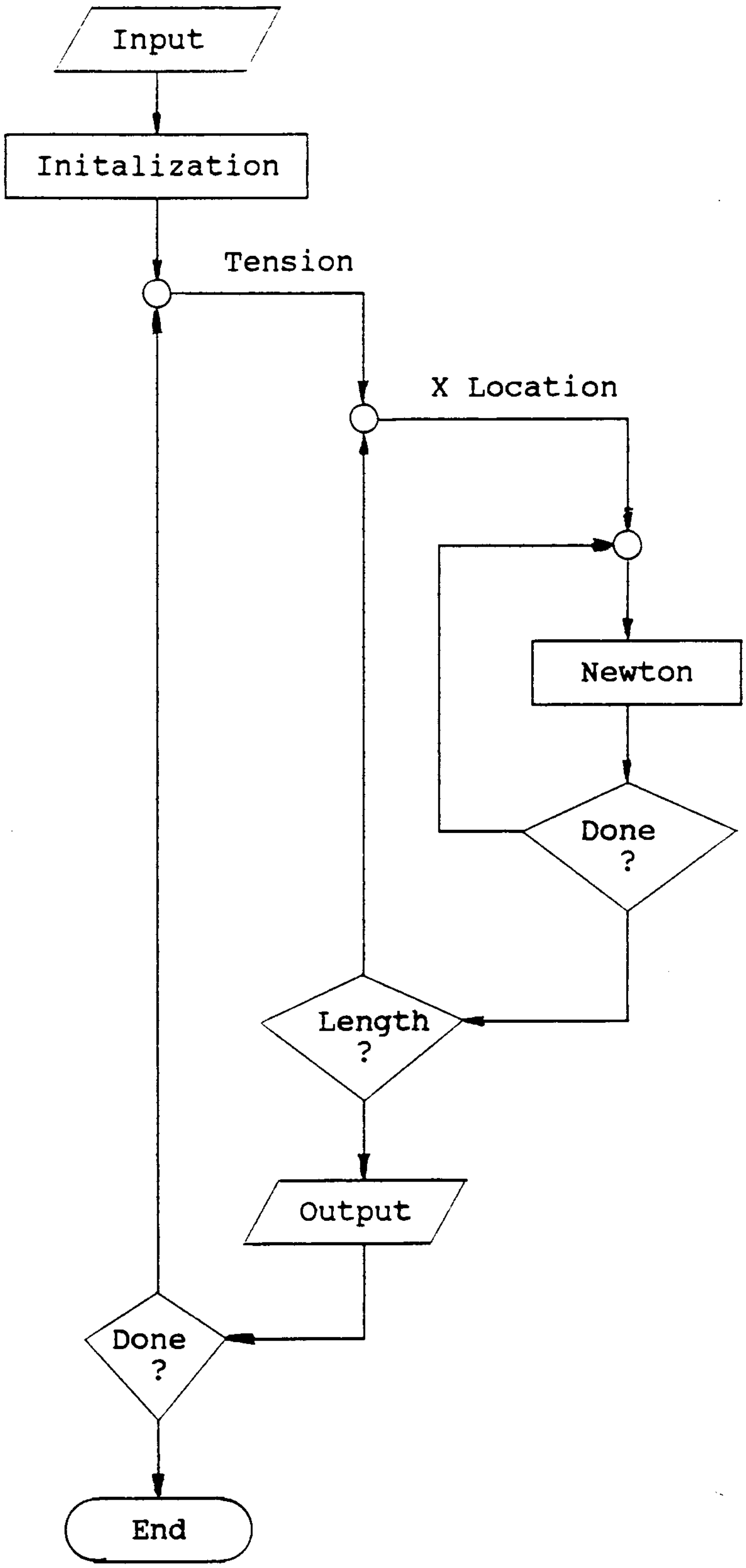

Figure 2.4: Flowchart of program DIVCAT's structure.

sequentially through the boom segments, from the outside in, as the designer would. The outer loop requests the input for the first boom segment, then enters a middle loop. This middle loop represents the finding of the boom tension by comparing the input boom length to the calculated boom length. Next, the innermost loop, representing the determination of the location of the apex of the corresponding full containment solution, x_1, begins. This inner loop calls the Newton-Raphson routine to find x_1. Control then returns to the middle loop which calculates the new boom length and compares it to the input. This loop continues until the calculated boom length matches the input boom length. After dropping out of the middle loop, the outer loop completes the calculations, prints results to the screen and asks if the results are acceptable. If not, the process is repeated with new inputs. If the results are acceptable, the program writes them to a file and continues on to the next boom segment. When all segments have been satisfactorily completed, the program gives the option of viewing graphics or exiting.

With this program implemented, the systematic approach to solving the catenary equations for a diversion boom configuration is complete. A designer can quickly and easily model a diversion boom with one or more short segments in a relatively constant current regime. To design in other environments such as long booms or variable currents, a new model needs to be developed.

CHAPTER III

GENERAL DIVERSION MODEL

1. Modeling Approach

There are two reasons why this new model is necessary. First, recent experiments have used fewer (or no) intermediate anchors, resulting in longer boom segments than originally expected. This gives rise to long sections of boom streaming with the current. This configuration introduces significant parallel drag forces which are not considered in the catenary diversion model. Second, the assumption of constant current over a boom segment is not as accurate for these longer segments. It is desirable to be able to allow the current to vary continuously over an entire boom or segment thereof. This new model addresses both of these issues.

Because the catenary model assumes no tangential drag force from the beginning, it was necessary to start the new model from scratch. Again the static equilibrium equations for an oil boom are the starting point, but this time a diversion configuration such as Figure 3.1 was considered from the start.

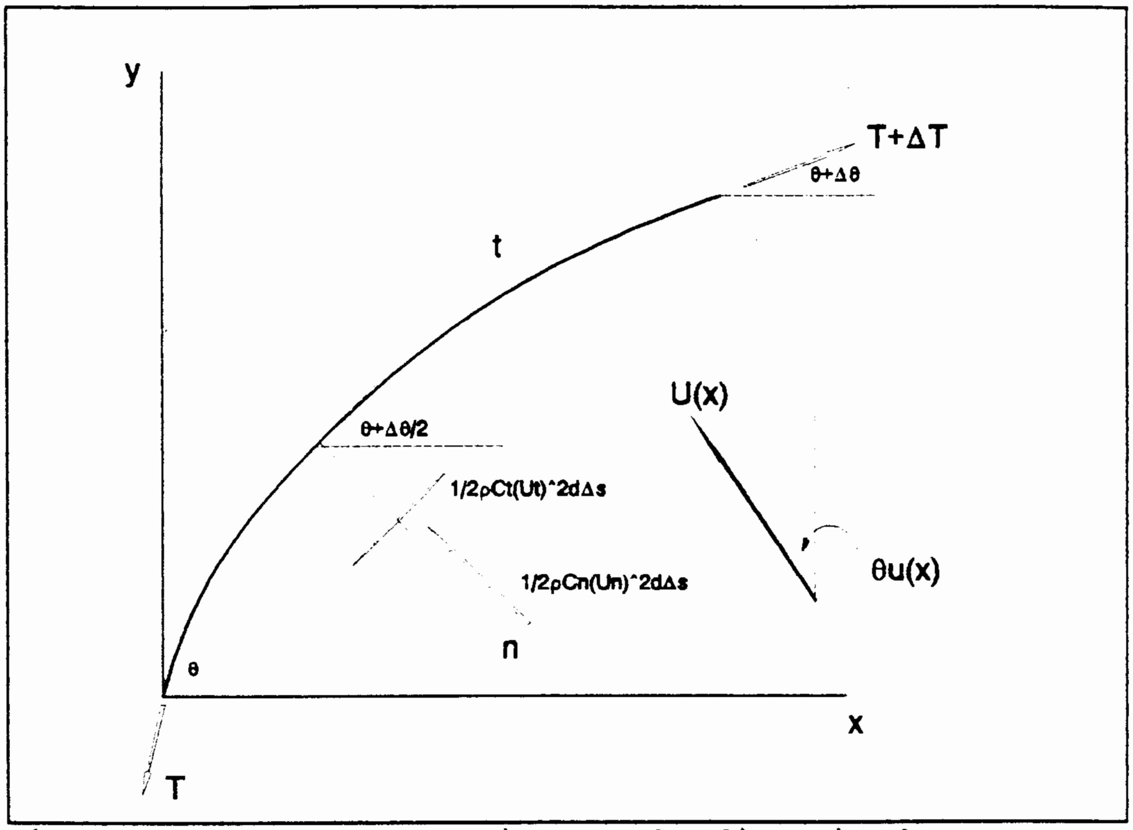

Figure 3.1: Free body diagram of a diversion boom segment with tension and drag forces exposed.

In the tangential direction, equilibrium requires that

$$\Sigma F_t = \frac{1}{2}\rho C_t d U_t^2 \Delta s - T\cos\left(\frac{\Delta\theta}{2}\right) + (T+\Delta T)\cos\left(\frac{\Delta\theta}{2}\right) = 0\,, \tag{3.1}$$

where

C_t = coefficient of drag in the tangential direction, and

U_t = component of current magnitude in the tangential direction.

Dividing through by Δs, taking the limit as $\Delta s, \Delta\theta, \Delta T \to 0$, realizing that $\cos(\Delta\theta/2)=\cos(0)=1$, and combining terms leaves

$$\frac{1}{2}\rho C_t d U_t^2 + \frac{dT}{ds} = 0\,. \tag{3.2}$$

Then, recognizing that $U_t = U\sin(\theta-\theta_U)$ leaves

$$\frac{dT}{ds} = -\frac{1}{2}\rho C_t d\,U^2 \sin^2(\theta-\theta_U)\ . \qquad (3.3)$$

In the normal direction, equilibrium will be satisfied only if

$$\Sigma F_n = -\frac{1}{2}\rho C_n d\,U_n^2 \Delta s + T\sin\left(\frac{-\Delta\theta}{2}\right) + (T+\Delta T)\sin\left(\frac{-\Delta\theta}{2}\right) = 0\ , \qquad (3.4)$$

where

C_n = coefficient of drag in the normal direction, and

U_n = component of current magnitude in the normal direction.

Combining terms and assuming a small angle approximation leaves

$$-\frac{1}{2}\rho C_n d\,U_n^2 \Delta s - (2T+\Delta T)\frac{\Delta\theta}{2} = 0\ , \qquad (3.5)$$

and taking the limit as $\Delta s, \Delta\theta, \Delta T \to 0$ gives

$$-\frac{1}{2}\rho C_n d\,U_n^2 ds - 2T\frac{d\theta}{2} = 0\ . \qquad (3.6)$$

Recognizing that $U_n = U\cos(\theta-\theta_U)$, dividing through by *ds* and simplifying leaves

$$\frac{d\theta}{ds} = -\frac{1}{2T}\rho C_n d\,U^2 \cos^2(\theta-\theta_U)\ . \qquad (3.7)$$

This gives two equations in the two dependent variables θ and T, with s as the independent variable. While both θ and T are important, it is also important to obtain the shape of the boom in terms of x and y. These can be obtained from the following equations,

$$\frac{dx}{ds} = \cos(\theta) \qquad and \qquad \frac{dy}{ds} = \sin(\theta) \qquad (3.8)$$

which were developed from Figure 3.2.

Equations (3.3),(3.7) and (3.8) form a system of four first order differential equations with T,θ,x, and y as the dependent variables, and *s* as the independent variable. Solving these four equations provides all of the information necessary to design oil diversion booms.

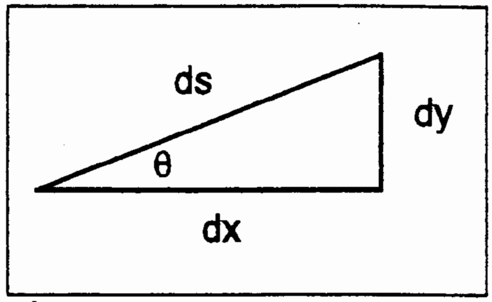

Figure 3.2: Geometry of a boom section.

2. Solution Approach

These equations describe a physical situation. Because a reasonable amount is known about this situation, it is realized that the solutions to the equations are continuous and "well-behaved". This problem is inherently a boundary value problem. This means that there were a few possible methods for attacking the solution process. The first to come to mind are finite element or finite difference type solution schemes. It was decided that these approaches would not be appropriate, however, due to the highly non-linear nature of the equations. The quasi-linearizations involved in these methods could eliminate some of the most important terms, resulting in a loss of accuracy.

The second idea is to use a stepping type solution. This involves moving along the boom in small increments, solving the equations at each step, and using those solutions as the basis for the next step. Since the equations were mathematically "well-behaved", Euler extrapolation could be used to accomplish this.

In executing this form of solution, it's the application of the boundary conditions that leads to a unique solution. In this case, the boundary conditions were of two types:

1) Known - the origin of the coordinate system would be placed at the high tension end of the boom, making the boundary conditions on x and y both zero, and,

2) Estimated - an initial boom tension and angle could be calculated based on the current profile.

With these four conditions, the program would start at the origin and step along the boom, numerically solving for the tension, angle, position and current at each step. When the end of the boom was reached, its position is compared with the desired (input) location. Based on this comparison, the initial tension and/or angle can be adjusted to provide a more accurate solution. When the desired position is reached within a tolerance, these iterations cease.

This method takes the non-linearities of the equations directly into account, but its drawback is the convergence of the solution to the desired location. Problems with stepsize versus accuracy and time needed to be addressed. It was decided, however, that these problems are easier to overcome than the loss of accuracy due to the linearizations of the other methods.

Euler extrapolation was chosen as the first numerical method to try because of its simplicity and ready adaptability to coding. Equations of the form

$$\frac{df}{dx} = f(x) \tag{3.9}$$

can be rearranged in the integral form

$$\int df = \int f(x)\,dx, \tag{3.10}$$

which can be approximated using Euler extrapolation as

$$f_{i+1} = f_i + f_i'\Delta x. \tag{3.11}$$

It was found that this method worked with these numerically "well-behaved" functions without having to resort to higher order methods.

The other part of this solution process involves finding a numerical method to allow the incorporation of continuously varying current profiles over the boom. This helps create more realistic current profiles, especially for these new boom designs which have few intermediate anchors. This current variation was accomplished using Lagrange interpolation. The current information available to the designer, usually in the form of current vectors at specific locations, are read into the program. It then interpolates smooth curves which define the current profile. This provides a much better model of the currents than the former model where currents were restricted to being constant over a boom segment.

3. Computer Approach

For the same reasons listed above, the C programming language and MS-DOS based computers were chosen to implement this model. (For a diagram of the program's structure, see Figure 3.3.) After initialization, the program receives the boom length, desired end position, and tolerances as inputs and reads the current data from a file. With these, estimates are made for the initial tension and boom angle. The program then enters the outermost of three nested loops.

The outermost loop represents the possible change in angle necessary for a solution (see Figure 3.3). The middle loop represents possible change in tension necessary for a solution, and the innermost loop is the Euler extrapolation loop over the boom length. This innermost loop is where the governing equations, (3.3), (3.7) and (3.8), are solved and the Lagrange current interpolations take place. Once the iterations reach the end of the boom, the program drops back into the middle loop.

At this point, the middle loop checks the y position of the end of the boom against the desired endpoint. If y is smaller than the desired y plus the prescribed tolerance, the program drops to the outer loop. If, however, the y position

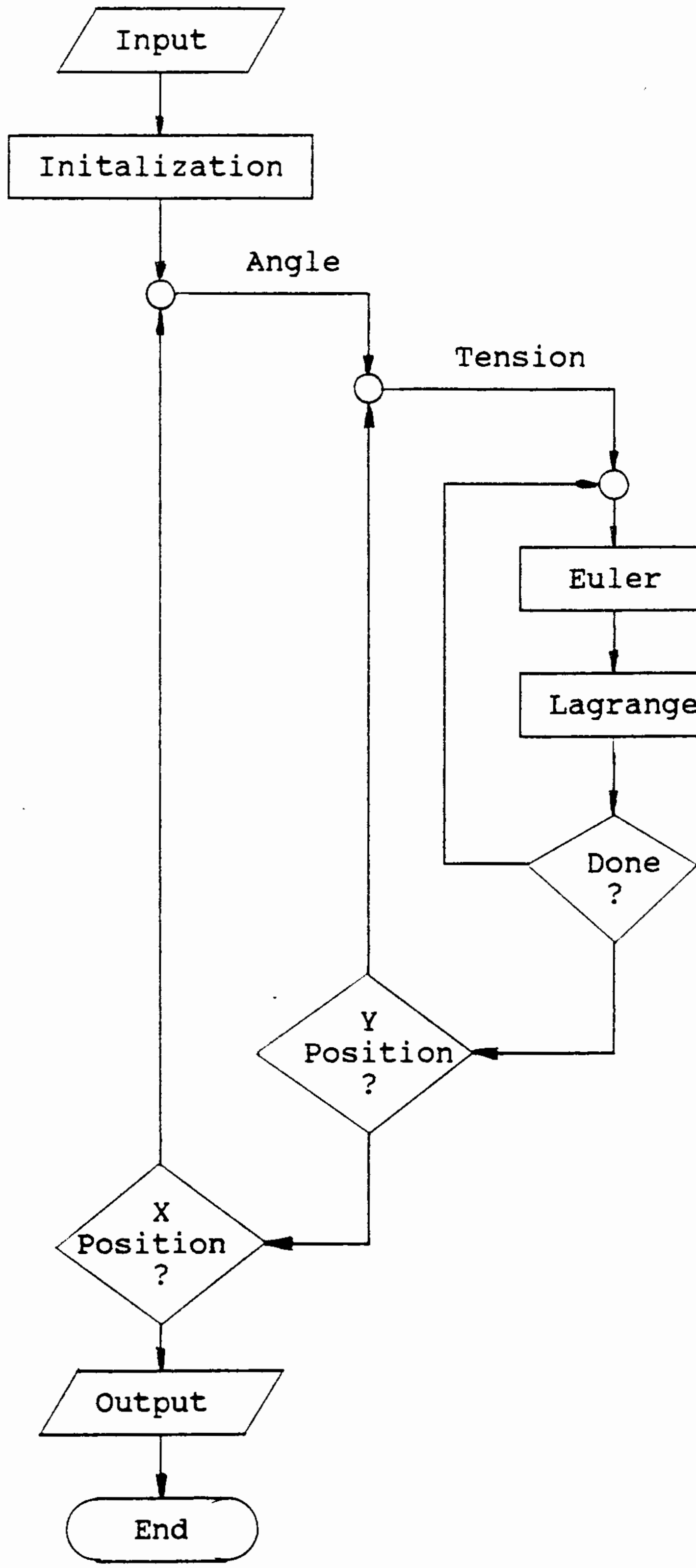

Figure 3.3: Flowchart of program LONGBOOM's structure.

is larger than y plus the tolerance, the initial tension estimate is lowered and the entire process repeated. This allows the boom to curve more, giving a smaller result for y. This continues until the y value is smaller than the desired location.

Then the program drops back to the outer loop. This loop compares the x value with the desired location and adjusts the initial angle in a similar manner. If x is too small, however, the initial angle is lowered to allow the boom to reach further in the x direction, and the entire process (both inner loops) is repeated. This continues until both the x and y coordinates for the end of the boom are within the prescribed tolerance. Finally, the program outputs the results to a file and/or screen in both tabular and graphical formats.

CHAPTER IV

CALIBRATION AND VALIDATION OF GENERAL MODEL

1. Overview

There were two general sets of data available for calibrating and validating the general model. The first was an experiment carried out at the Fuel Storage Corporation (FSC) and reported in Le Compagnon (1984). The second source was an oil boom exercise performed at Northeast Petroleum.

The FSC experiment was a test of a diversion design for the inside ebb. The design involved a boom with two intermediate anchors, therefore the boom had three distinct sections (see Figure 4.1). The data from this experiment was in the form of boom shape, end tensions, anchor tensions, and current vectors. After transforming this information to a computer compatible form it was found that part of the data was faulty. The shape of the second section was convex rather than concave. It was determined that this was due to an overlap in the measuring technique.

Figure 4.1 shows the locations of the three transits used to measure the boom shape. The outside section was measured completely by the two outer transits. The inside section was measured completely by the two lower transits. The middle section, however, was measured by all three, half from each

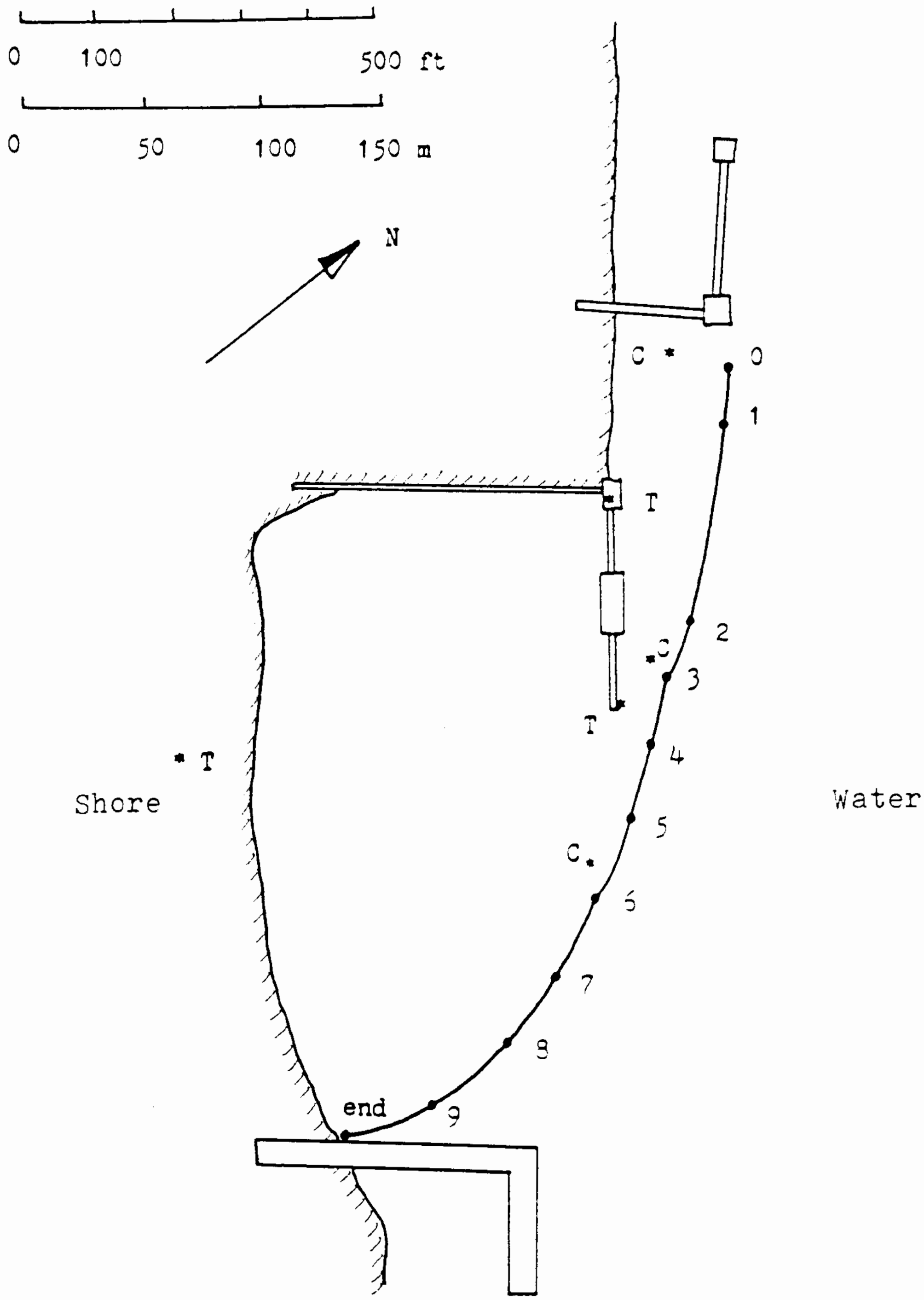

Figure 4.1: Boom configuration for the FSC experiment. Asterisks with a T indicate the position of the transits (taken from Le Compagnon, 1984).

aforementioned pair. This overlap has introduced some error. Based on this problem it was decided to use the outer section for calibration and the inner section for validation.

The exercise carried out at Northeast Petroleum formed the second source of comparison. This was a test of an outside ebb design which did not have any intermediate anchors. The data from this exercise is incomplete, however, as there was no good way to measure the end tensions. Some qualitative statements can be made, though, based on visual observations and the limited tension information.

2. Comparison With Experimental Data

2.1 Calibration

The calibration of the new model involved finding the best value for the tangential drag coefficient C_t. The normal drag coefficient C_n was studied and optimized in both Thaller (1983) and in Le Compagnon (1984).

Using the FSC outer section data (see Table 4.1) as input, the model was run using different values for C_t. The model was considered optimized when the boom shape reported by the new model most closely matched that from the experiment. It was found that a value of $C_t = 0.0289$ gave the best match. Figure 4.2 and Table 4.2 show in graphical and tabular formats all of the results of this comparison. It can be seen that boom shape closely approximates the shape measured in the experiment.

Description	Value
Outer End Tension	412.5 lbs.
Current Velocity	1.75 knots
Current Direction	150 °T

Table 4.1: Input data for the outer boom section at FSC.

FSC Experiment		Optimized Model	
x	y	x	y
feet	feet	feet	feet
0.0	0.0	0.0	0.0
8.8	92.8	12.2	99.3
56.5	391.7	56.4	396.0
86.1	491.6	86.1	491.0

Table 4.2: Comparison of boom shape between optimized model and outer boom section data.

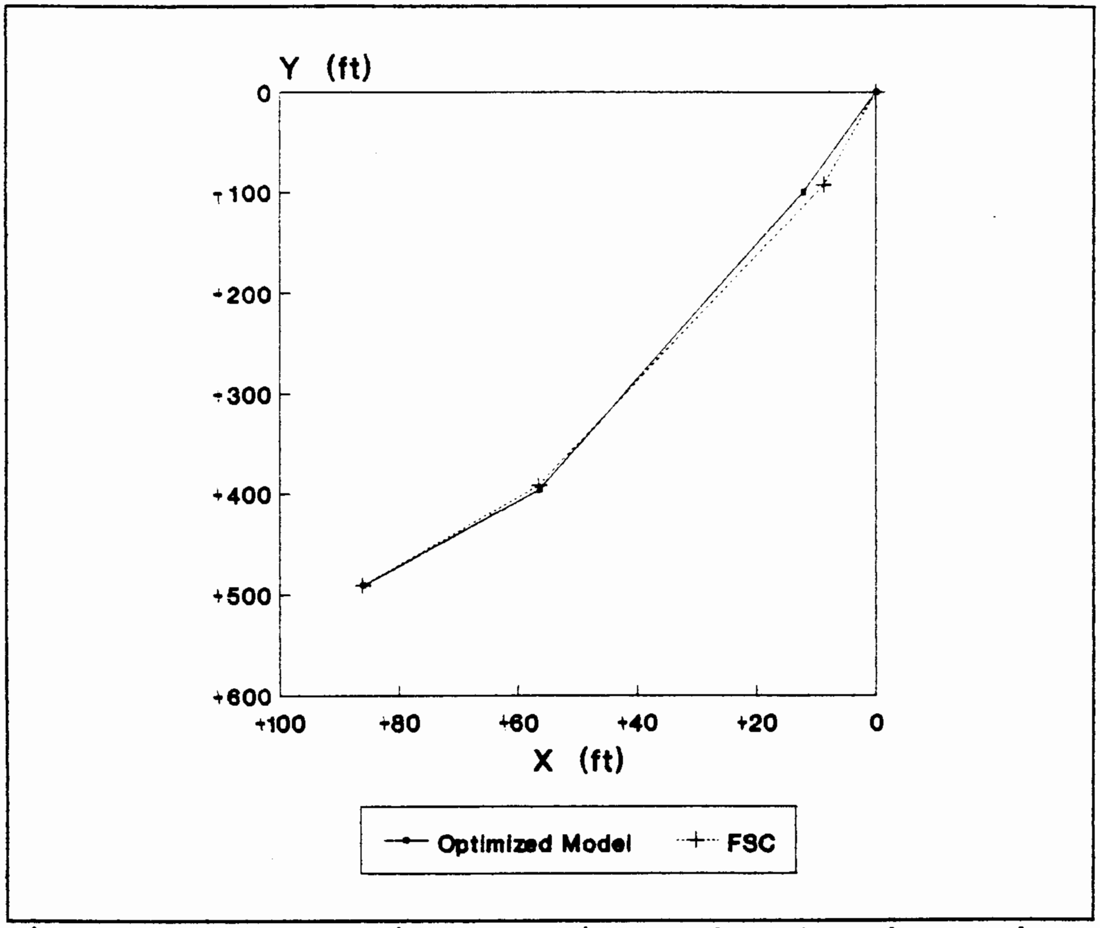

Figure 4.2: Graphic comparison of outer boom shape between new model and FSC experiment. The y-axis is directed 150°T.

The outer end boom tension in this section was 412.5 lbs. The tension dropped to 258.8 lbs. at the inner end. This corresponds to a 37 percent reduction in the boom tension. This helps to verify the necessity for including the tangential drag in the general model.

2.2 Validation

On the inner boom section it was possible to compare both the boom shape and the inner end tensions. An average current was calculated from the data and found to be 0.59 knots. Table 4.3 shows input data for the inner boom section analysis, Table 4.4 shows both the boom shape and tension comparisons, and Figure 4.3 shows the shape information graphically. As can be seen, the shape again approximates the experiment very well. The inner end tension from the experiment was 422 lbs; this was predicted within 3 percent by the model (see Table 4.4).

Description	Value	
C_n , C_t	1.80	0.0289
Current Velocity	0.59 knots	
Current Direction	155° True	

Table 4.3: Input data for the inner boom section FSC used for validation.

FSC Experiment		Optimized Model	
x	y	x	y
feet	feet	feet	feet
0.0	0.0	0.0	0.0
70.8	77.2	60.9	79.2
130.3	154.3	131.8	149.3
217.8	202.9	216.5	202.4
313.2	222.6	313.2	222.5
Tension	422 lbs.	Tension	432 lbs.

Table 4.4: Comparison of boom shape and end tension between optimized model and inner boom section data.

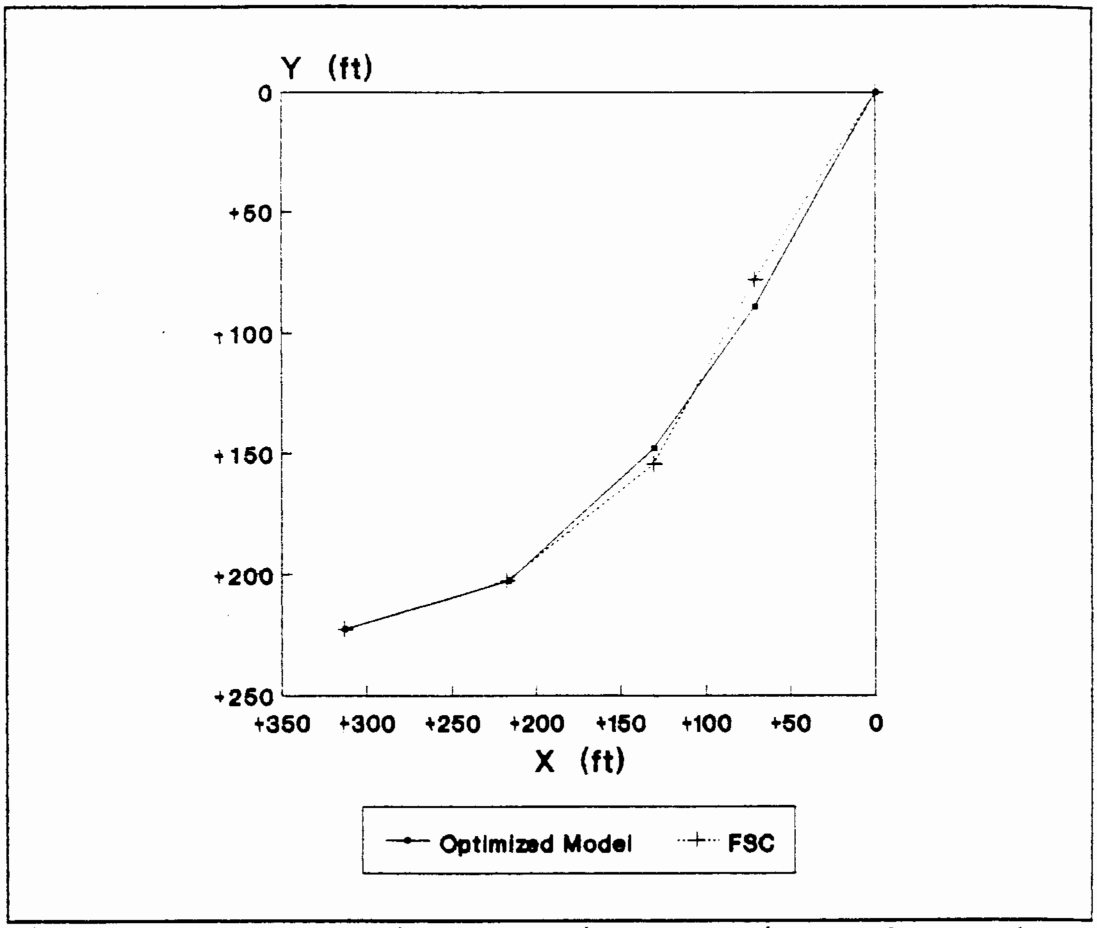

Figure 4.3: Graphic comparison of inner boom shape between new model and FSC experiment. The y-axis is directed 155°T.

3. Northeast Petroleum Exercise

This exercise was carried out during the summer of 1990, and involved the implementation of an outside ebb design at Northeast Petroleum. A 2000 ft boom was anchored outside a ship and curved into a cove downstream (see Figure 4.4).

An attempt was made to determine the outer end boom tension with a load cell, but it was found that there was no way to tell if the load cell was measuring the true tension,

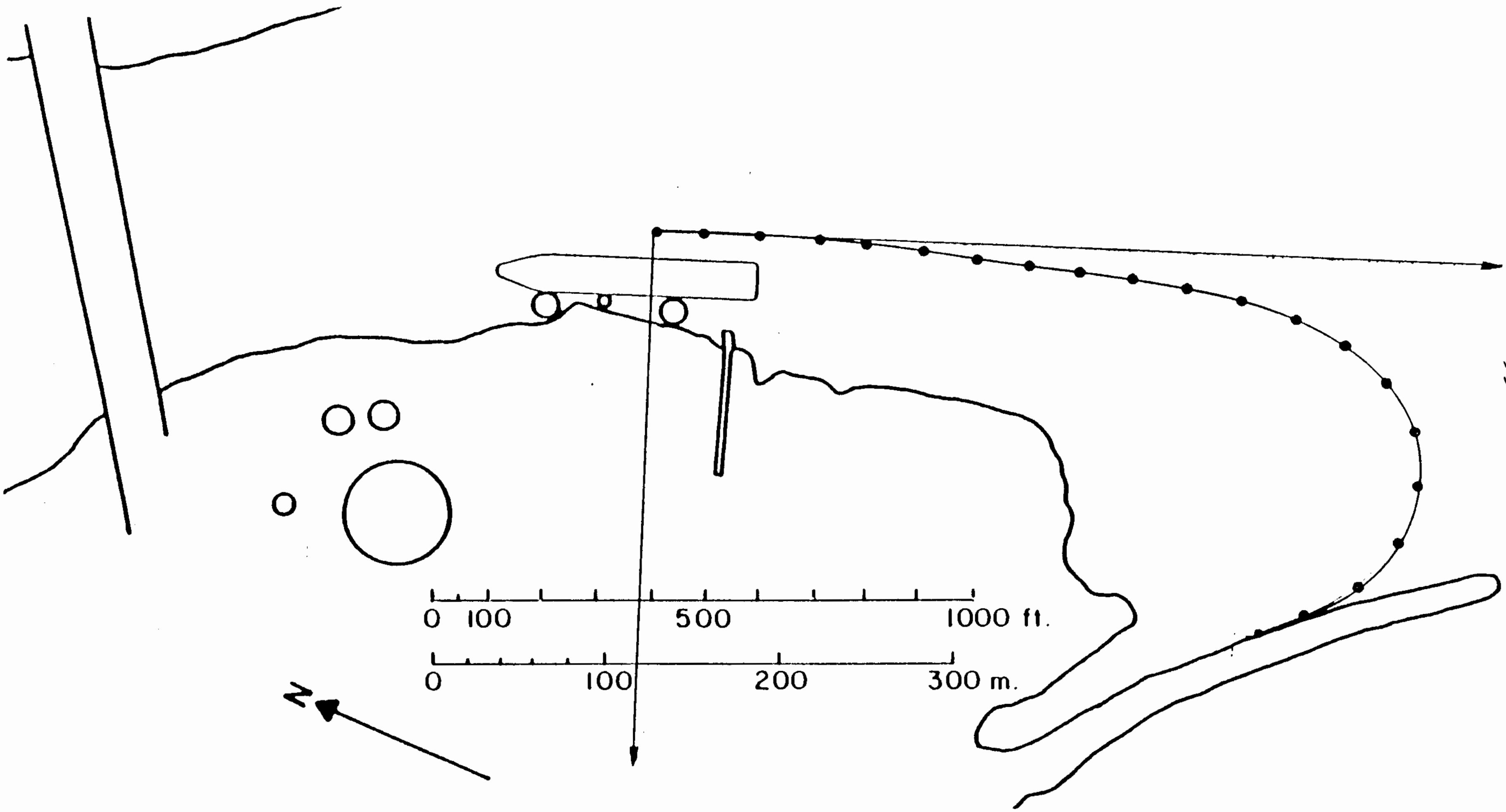

Figure 4.4: Model's prediction for Northeast Petroleum outside ebb configuration with a 2000' boom. Outer tension = 1468 lbs. Inner tension = 811 lbs.

or whether the anchor still carried some of the load. The best information available indicated that the tension was on the order of magnitude of 1000 lbs. Current measurements were also made at the outer end during the full ebb. They were found to be approximately 3.2 knots, which agreed well with the currents reported for this location in Savage et. al. (1982).

In applying the new model to this situation, it was found that very large changes in current angle combined with small current magnitudes caused problems with the program being able to accurately model the shape. This was due to tensions being very low, and the boom getting too much curvature to handle. This was remedied by adjusting the current profile slightly.

The results of applying the new model to this situation seem acceptable. Figure 4.4 shows the model's prediction for the boom shape. These shapes seem very similar to those visually observed during the exercise. Figures 4.5, 4.6 and 4.7 are pictures taken during the exercise. In the photographs the long straight outer section predicted by the model can be seen, as well as the "J" shape in the cove. Secondly, the model predicts an outer end tension of 1468 lbs. This seems very reasonable when compared with the order of magnitude measurement (1000 lbs.) mentioned earlier. Finally, it should be noted that the model predicts that this design does not meet the 0.6 knot current criteria. A redesign is therefore necessary, and this is covered in the next chapter.

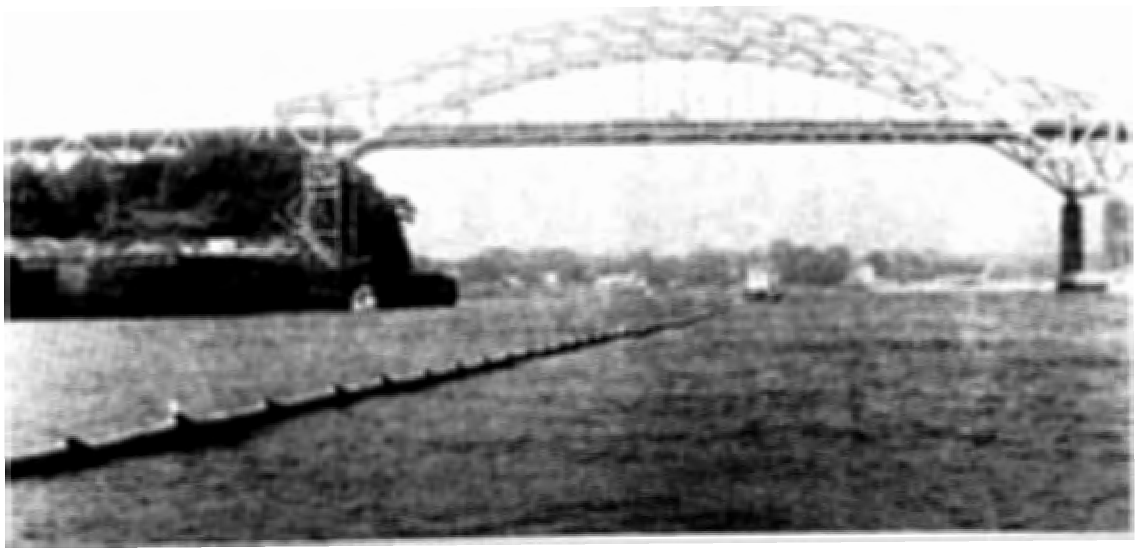

Figure 4.5: Fuel Storage Corp. exercise. This is a view upstream towards FSC. Notice the long straight boom section streaming with the current.

Figure 4.6: This is a view from further downstream along the boom. The beginning of the "J" shape is shown as the boom curves into the cove.

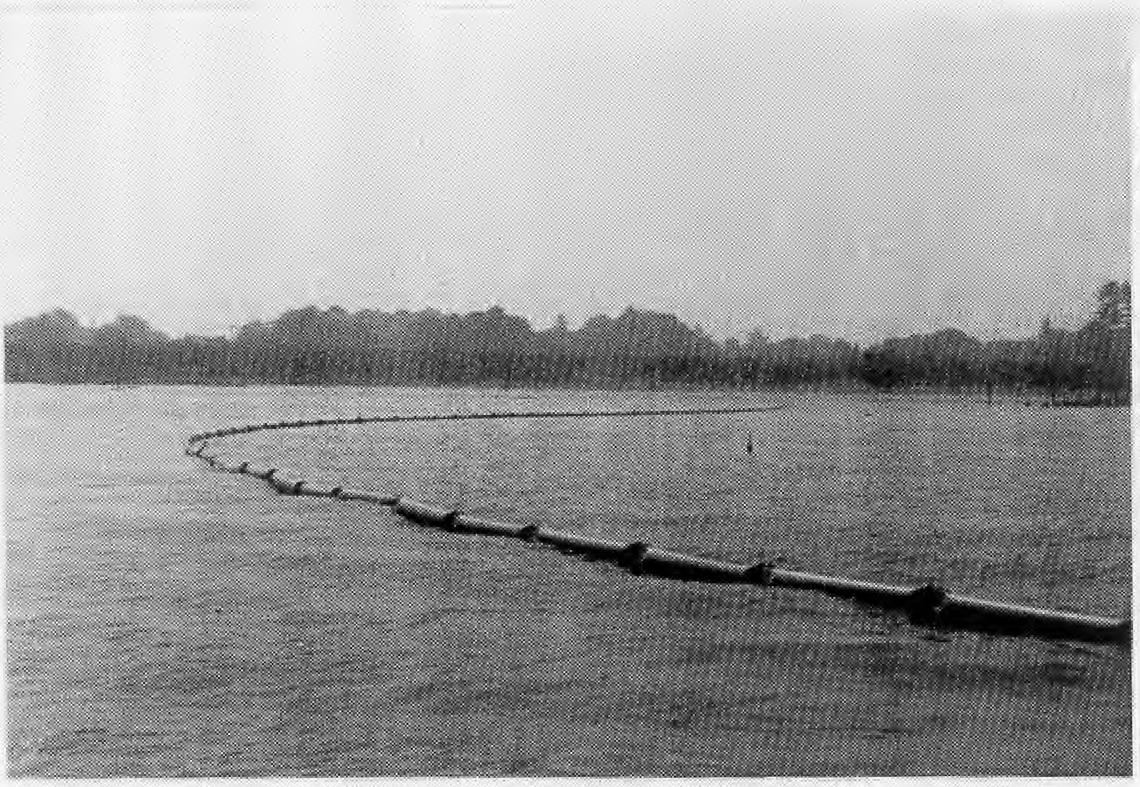

Figure 4.7: This view is downstream along the boom. It shows the general "J" shape and the shore attachment point.

CHAPTER V

DESIGNS FOR DIVERSION BOOMS AT THE PISCATAQUA RIVER TERMINALS

1. Overview

With the general model calibrated, validated, and in a useful form, it can be used to redesign the diversion boom configurations for the petroleum offloading terminals on the Piscataqua River. As previously mentioned, the designs presented in Swift et. al. (1990) and Savage et. al. (1982) assume that the boom would have intermediate anchors every 100 ft along its length. In the field this has proved to be both unnecessary and impossible. Therefore, new configurations with many fewer anchors need to be designed and analyzed.

Removing the intermediate anchors requires longer boom segments between anchors. This causes two problems in applying the previously used catenary model. First, longer booms will have a more significant tangential drag component than the previously used short-segment configurations. Second, the longer booms make the assumption of a constant current over a boom segment less satisfactory. These two problems, however, were the reasons that the general diversion boom model was developed, and why it is used for these new designs.

2. General Design Considerations

There are four general criteria which must be met by these new designs.

1) The boom designs must be able to contain all spills occurring from all possible locations on the ship. In general this requires four designs, two for the ebb tide (inside and outside the ship), and the same for the flood tide.

2) The maximum allowable normal component of current must be 0.6 knots or less to avoid leakage.

3) The booms need to be as easy to deploy as possible so that little or no oil is lost before the boom can be set up.

4) The booms must divert oil to a point, usually along the shore, where skimming or other collection and storage methods are possible.

The last two criteria were studied and reported in an earlier study. Whenever possible, the new configurations were designed to end at the same location as the previous designs as these were known to be good points for collection. In a few cases this was not possible and this fact is be noted in the specific information about those designs. The data used for the currents is taken from the Savage et. al. (1982) report. This data is reported in the form of current vectors at given locations. It is read into the program and used as the basis for a Lagrange interpolation to produce smooth continuous curves representing the current profile. Wind was not considered since this is normally of secondary importance with respect to tidal currents on the Piscataqua.

3. Diversion Boom Designs

3.1 Northeast Petroleum

Northeast Petroleum is located at the apex of a curve in the river near the I95 bridge (see Figure 1.1). The currents at this location, especially outside of a ship are quite strong (over 3 knots on the flood, and nearly that on the ebb). Berthing cells close to shore, however, cause very low velocity currents between the ship and shore, making inside spills relatively easy to control. Because of counter-currents, all of these designs require a seal between the ship and the berthing cell at the end away from the boom. This could be in the form of a short boom section with magnetic attachment points.

3.1a Inside Ebb. Figure 5.1 shows the configuration for this situation, and Figure 5.2 shows the current profile used. The currents are still large in close to shore here, but are counter-currents. This boom was designed for completeness and for security. While the indications here are that the currents are back eddies, this boom was placed to contain any oil which does try to escape downriver. The upriver cell must be sealed to the ship hull, and skimming should be done in this vicinity.

Notice in the analysis summary (Table 5.1) that this short a boom exhibits little difference in end tensions, indicating that tangential drag force is not very significant in this case. Table 5.2 shows the data used for current interpolation.

3.1b Outside Ebb. Figure 5.3 shows the configuration for the outside ebb. Figure 5.4 gives the current profile used, and Table 5.3 summarizes the boom analysis. A fairly long boom is required here, and the large current values outside of the ship make the tensions high. Notice that this configuration is an improvement on the one described in the validation exercise in Chapter IV. Shortening the boom by 500 ft. caused a 300 lb. increase in tension, but lowered the maximum normal current from 0.81 knots to 0.57 knots. This put the improved design within the 0.6 knot normal current criteria. Table 5.4 gives the current input used in the analysis.

3.1c Inside Flood. Figure 5.5 shows the recommended boom configuration for this situation. The current is profiled in Figure 5.6. The currents in this region are low, but are counter to the primary flow direction. Therefore, this boom was again designed for security and completeness. It was placed to facilitate cleanup if oil does try to escape in this direction. The downriver cell must be sealed against the hull, and oil removal can take place just inside this location. Tables 5.5 and 5.6 give the analysis summary and current input, respectively.

3.1d Outside Flood. Figure 5.7 shows the diversion boom configuration for this location. This is a very difficult situation to boom because of the very high (greater than 3 knot) outer currents. A long boom is necessary to reach around the corner and into a small cove just past the I95 bridge. The tensions on this boom are very high, 3268 lbs. at the outer end, as can be seen in Table 5.7. Figure 5.8 shows the current profile, and Table 5.8 show the current input values.

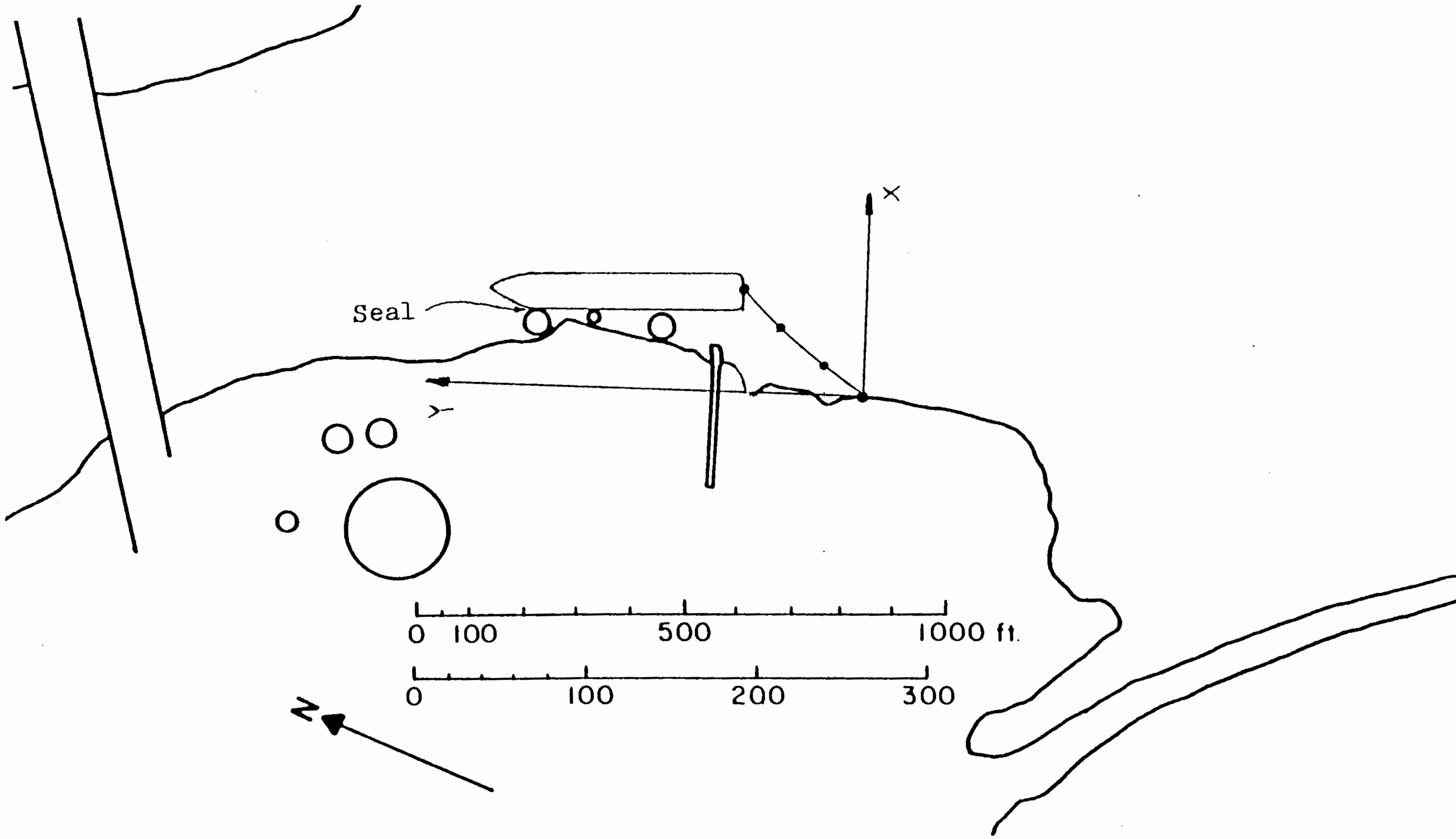

Figure 5.1: Diversion configuration for Northeast Petroleum inside ebb. Dots indicate 100' intervals. Outer tension = 1500 lbs. Inner tension = 1496 lbs.

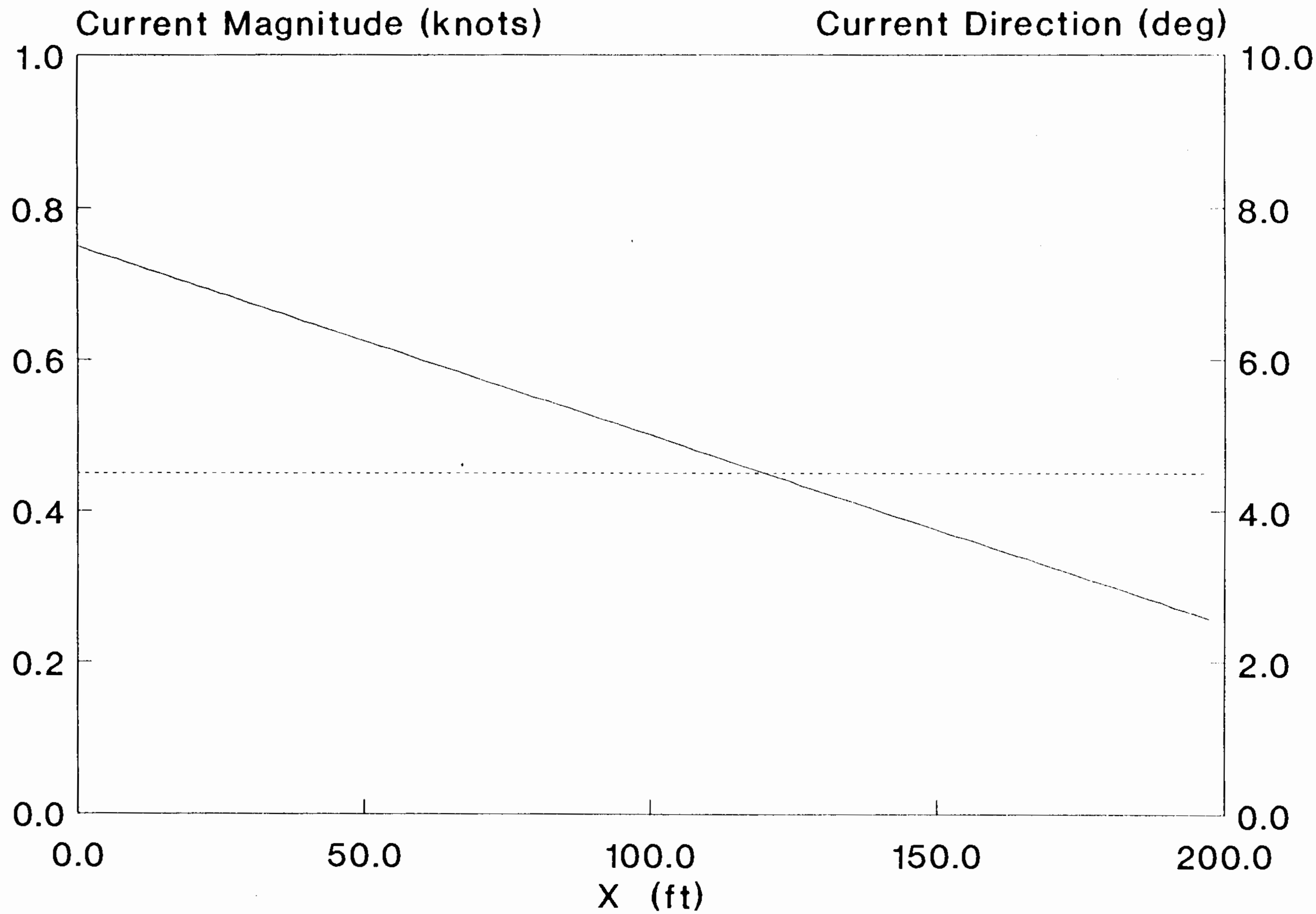

Figure 5.2: Current magnitude (———) and direction (----) for Northeast Petroleum inside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	159 °T	
Boom Length	300 ft	
Boom End Location	197 ft	225 ft
Outer, Inner Boom Tensions	1500 lbs	1496 lbs
Maximum Normal Current	0.48 knots	
Max. Normal Current Location	300 ft	

Table 5.1: Summary of Northeast Petroleum inside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0.0	0.75	4.5
100.0	0.50	4.5

Table 5.2: Current data used for Northeast Petroleum inside ebb.

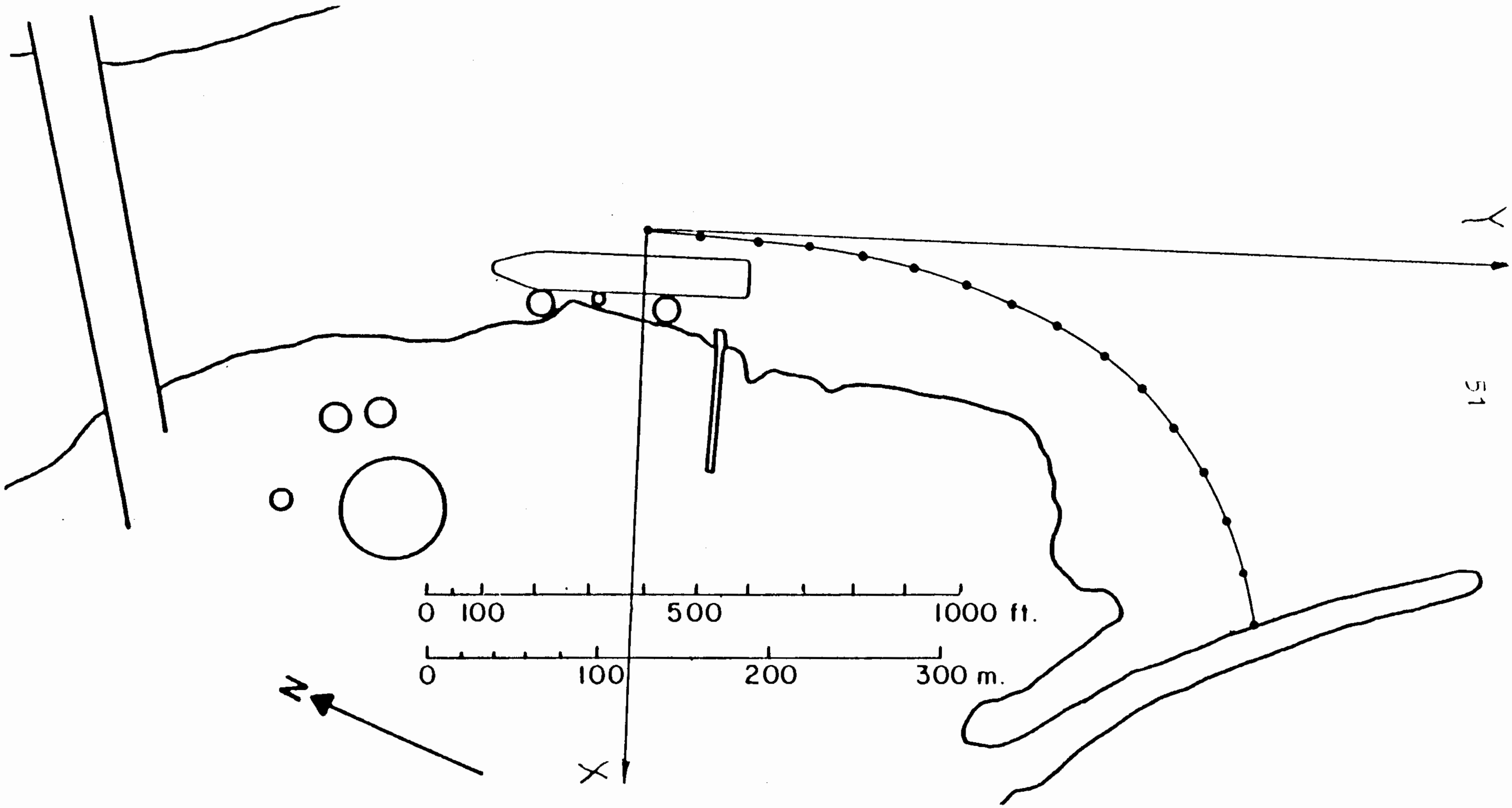

Figure 5.3: Diversion configuration for Northeast Petroleum outside ebb. Dots indicate 100′ intervals. Outer tension = 1780 lbs. Inner tension = 1381 lbs.

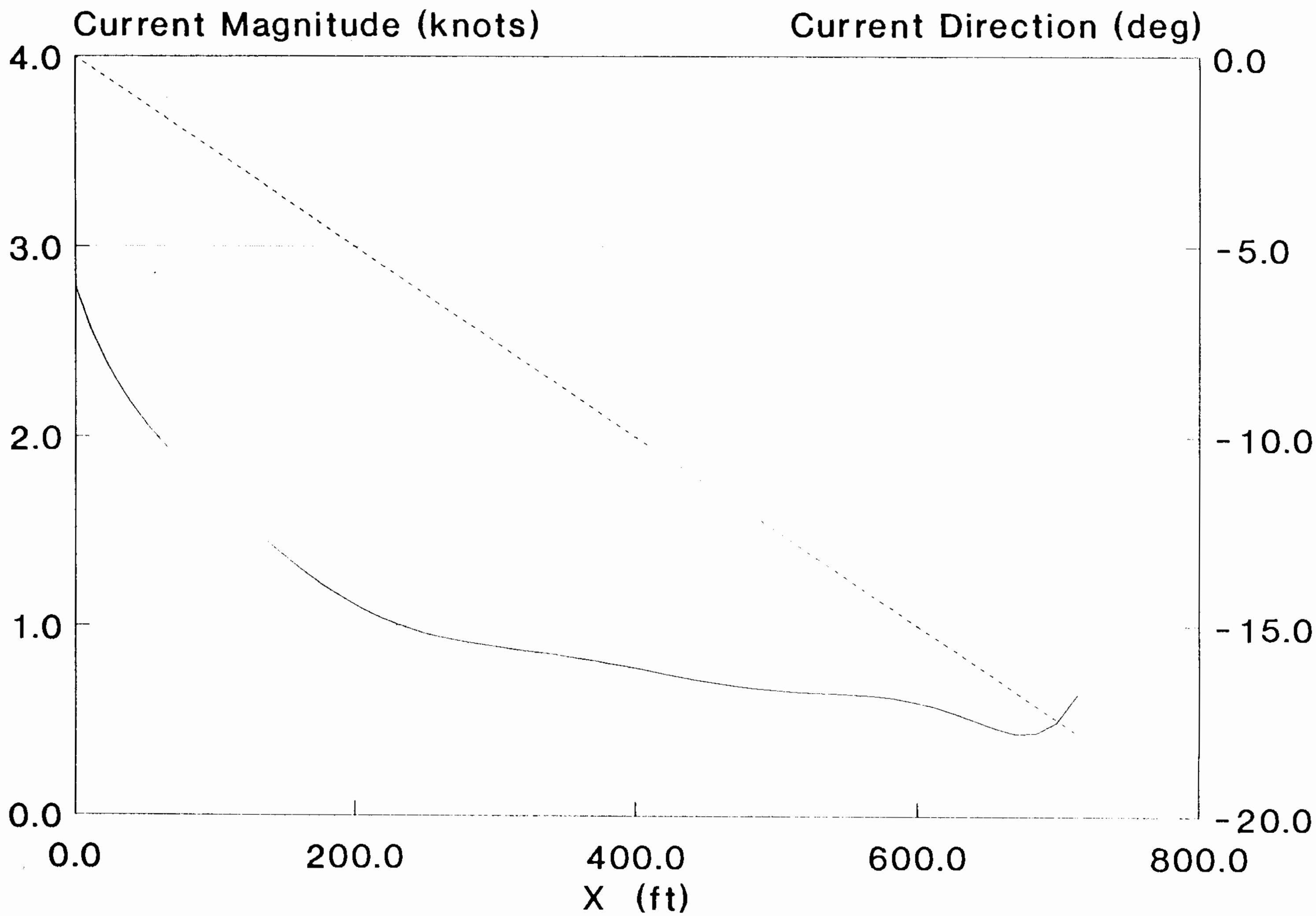

Figure 5.4: Current magnitude (——) and direction (----) for Northeast Petroleum outside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	159 °T	
Boom Length	1500 ft	
Boom End Location	714 ft	1162 ft
Outer, Inner Boom Tensions	1780 lbs	1381 lbs
Maximum Normal Current	0.57 knots	
Max. Normal Current Location	366 ft	

Table 5.3: Summary of Northeast Petroleum outside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	2.8	0.0
85	1.8	-2.125
180	1.2	-4.5
200	1.11	-5.0
300	0.889	-7.5
400	0.776	-10.0
500	0.659	-12.5
600	0.595	-15
700	0.50	-17.5

Table 5.4: Current data used for Northeast Petroleum outside ebb.

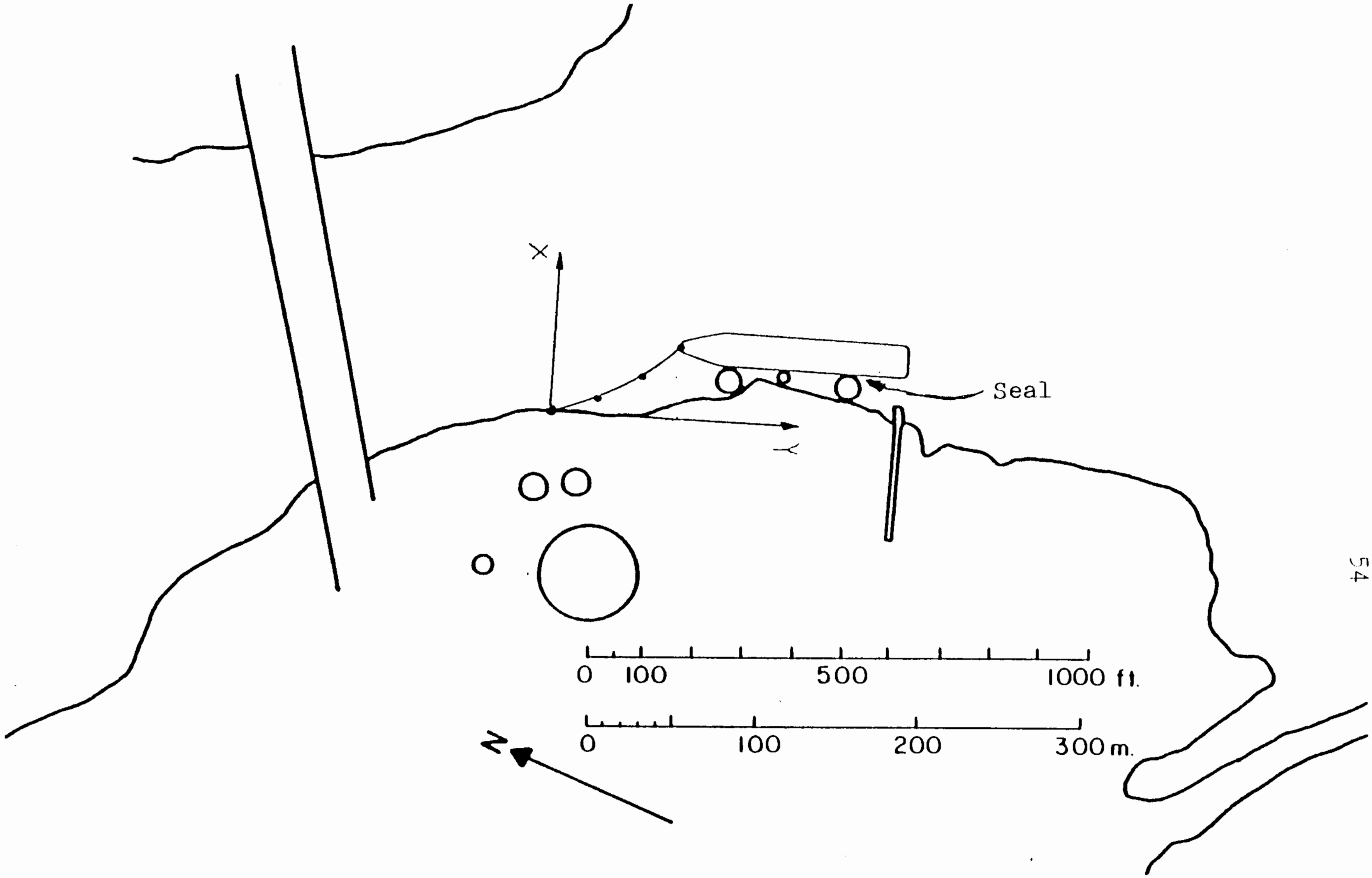

Figure 5.5: Diversion configuration for Northeast Petroleum inside flood. Dots indicate 100′ intervals. Outer tension = 103 lbs. Inner tension = 100 lbs.

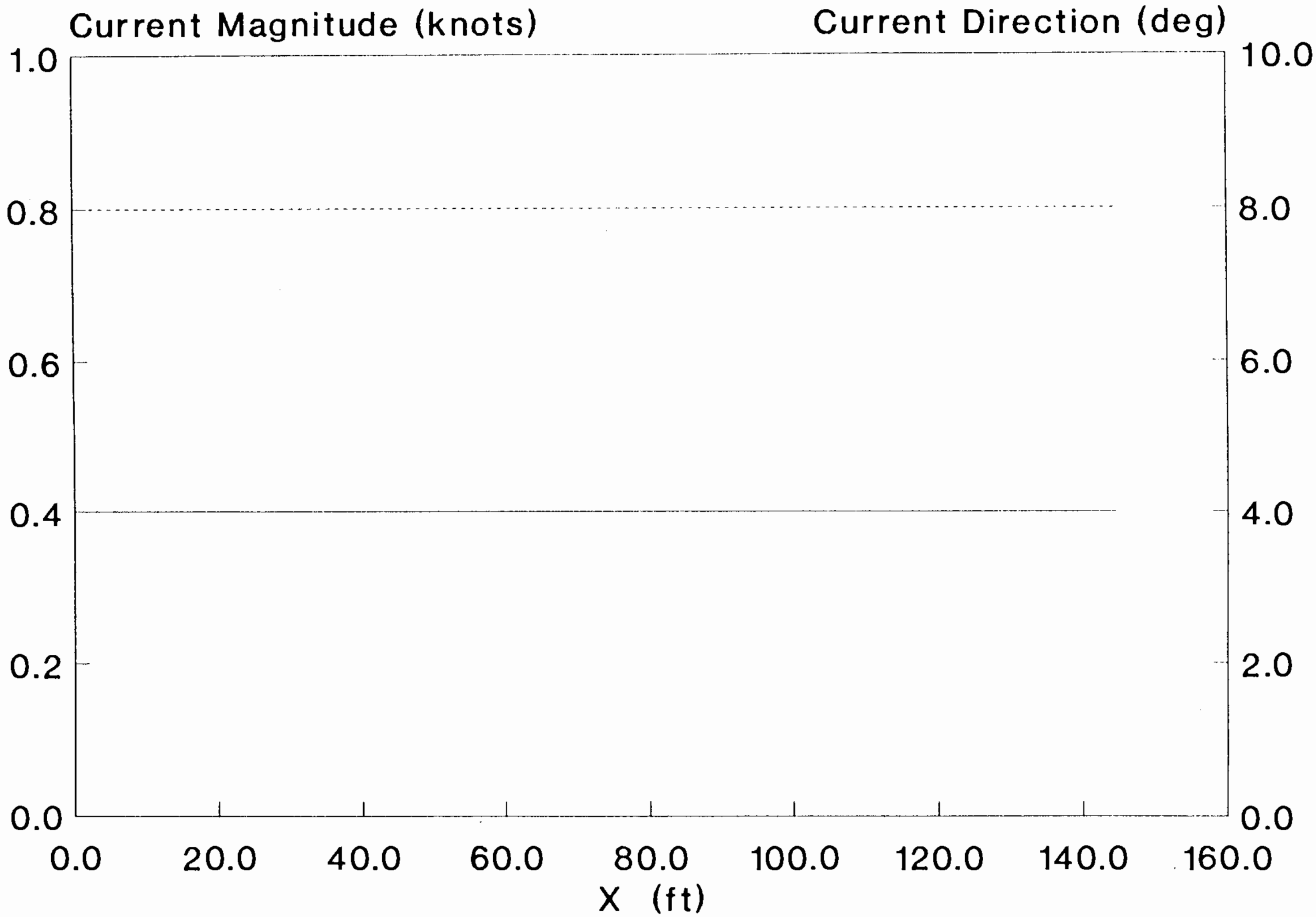

Figure 5.6: Current magnitude (——) and direction (----) for Northeast Petroleum inside flood. Current directions are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	339 °T	
Boom Length	300 ft	
Boom End Location	145 ft	245 ft
Outer, Inner Boom Tensions	103 lbs	100 lbs
Maximum Normal Current	0.4 knots	
Max. Normal Current Location	145 ft	

Table 5.5: Summary of Northeast Petroleum inside flood analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	0.4	8.0
140	0.4	8.0

Table 5.6: Current data used for Northeast Petroleum inside flood.

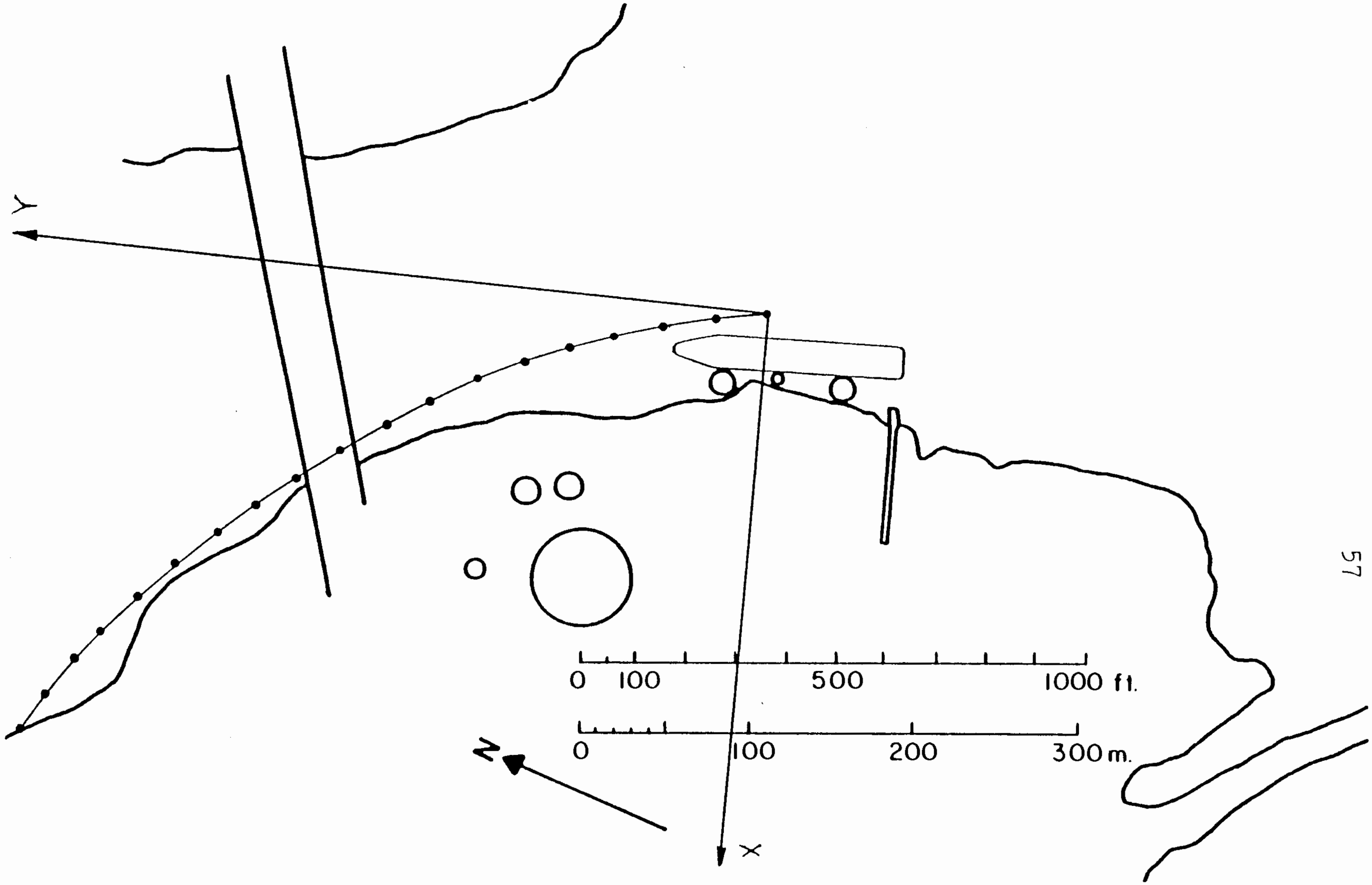

Figure 5.7: Diversion configuration for Northeast Petroleum outside flood. Dots indicate 100' intervals. Outer tension = 3268 lbs. Inner tension = 2803 lbs.

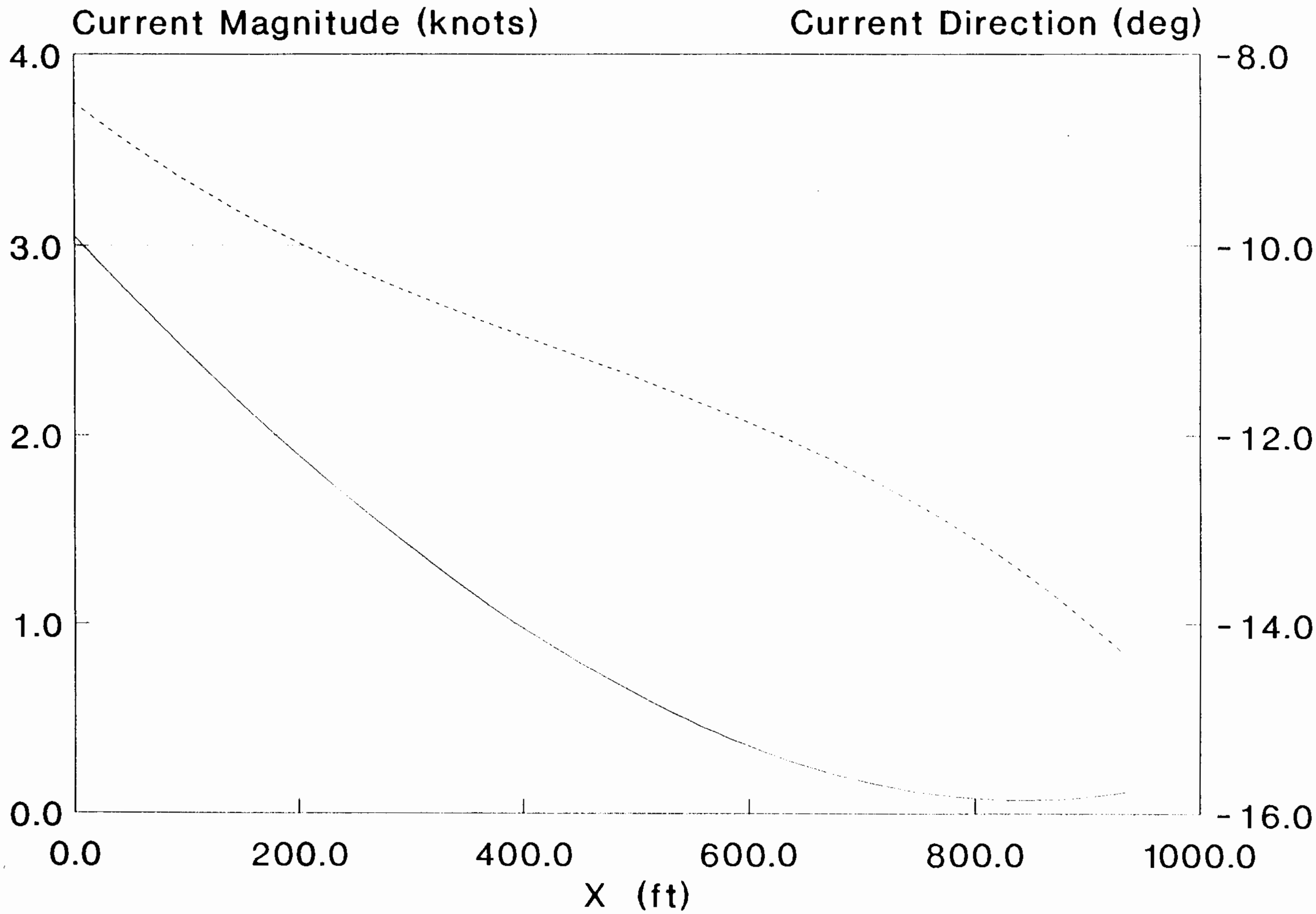

Figure 5.8: Current magnitude (——) and direction (----) for Northeast Petroleum outside flood. Current directions are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	339 °T	
Boom Length	1700 ft	
Boom End Location	935 ft	1371 ft
Outer, Inner Boom Tensions	3268 lbs	2803 lbs
Maximum Normal Current	0.60 knots	
Max. Normal Current Location	276 ft	

Table 5.7: Summary of Northeast Petroleum outside flood analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	3.05	-8.5
125	2.3	-9.5
300	1.4	-10.5
1000	0.2	-15.1

Table 5.8: Current data used for Northeast Petroleum outside flood.

3.2 Mobil Oil Corporation

This facility is the next upriver from Northeast Petroleum (see Figure 1.1), and the outer currents here are somewhat lower, approximately 2 knots. All of the booms for this location show very low tensions. This is because 1) the longer booms follow the current direction very closely, and 2) the short booms experience very low currents.

3.2a Inside Ebb. Figure 5.9 shows this configuration extending from the stern downstream to shore. The boom at the bow is for security against counter-currents and is discussed below. At the outer end, the primary boom is connected to the stern of the ship, and it follows the current very closely to shore. For this reason, it has a very low tension. Also, the currents are not very strong (1.5 knots at the outer end) as can be seen graphically in Figure 5.10. Table 5.9 gives a summary of this analysis, and Table 5.10 provides the current input values.

3.2b Outside Ebb. Figure 5.11 shows the shape of this boom as it extends from the outside of amidships to shore downriver. (The bow security boom is treated below) In general this boom design is very similar to the inside ebb except it is a little longer and, as shown in Figure 5.12, is in slightly stronger currents. The tensions are also a little higher, as stated in Table 5.11. For spills occurring near the stern, it is possible to place the outer anchor at the 200 ft mark reducing the boom length and outer tension somewhat. Current input given in Table 5.12 reflects the faster environment.

<u>3.2c Counter-Ebb Flow.</u> This boom is shown in both Figures 5.9 and 5.11. It is used during the ebb tide during either an inside or an outside spill to keep oil from being carried out of the area by counter-currents. The same design will work for either situation. Figure 5.13 shows the current profile used, while Tables 5.13 and 5.14 show the analysis summary and the current input data, respectively.

<u>3.2d Inside Flood.</u> Figure 5.14 shows this boom design at the bow of the ship, while the current profile is shown in Figure 5.15. This boom is actually not the most important boom in this situation. The counter-flow boom discussed below is at the location where leakage could occur. The currents show a tendency to be directed almost completely counter to the main flood tide direction. The bow boom is here for security and to complete the containment area. Table 5.15 gives the analysis summary, and current input is provided in Table 5.16.

<u>3.2e Inside Flood Counter-Flow.</u> This boom should actually be the main concern in an inside flood spill. Its

configuration is shown in Figure 5.14 at the stern of the ship. Boom tension is very low (see Table 5.17), since the currents in this area are less than 1 knot (see Figure 5.16 and Table 5.18).

3.2f Outside Flood. The outside flood configuration is not possible here. The currents will tend to carry an outside spill away from the side of the ship very quickly. There is no feasible way to configure a boom so as to keep the normal current component less than 0.6 knots.

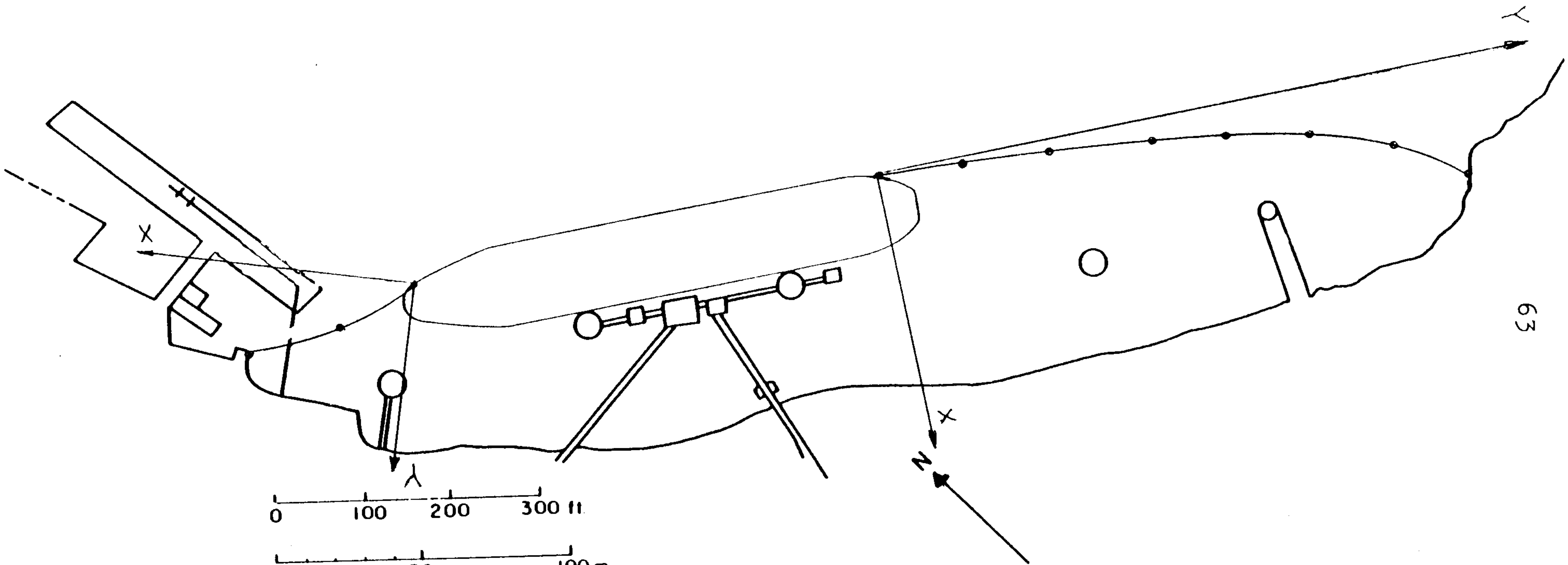

Figure 5.9: Diversion configuration for Mobile Oil inside ebb. Dots indicate 100' intervals. Outer tension = 221 lbs. Inner tension = 104 lbs.

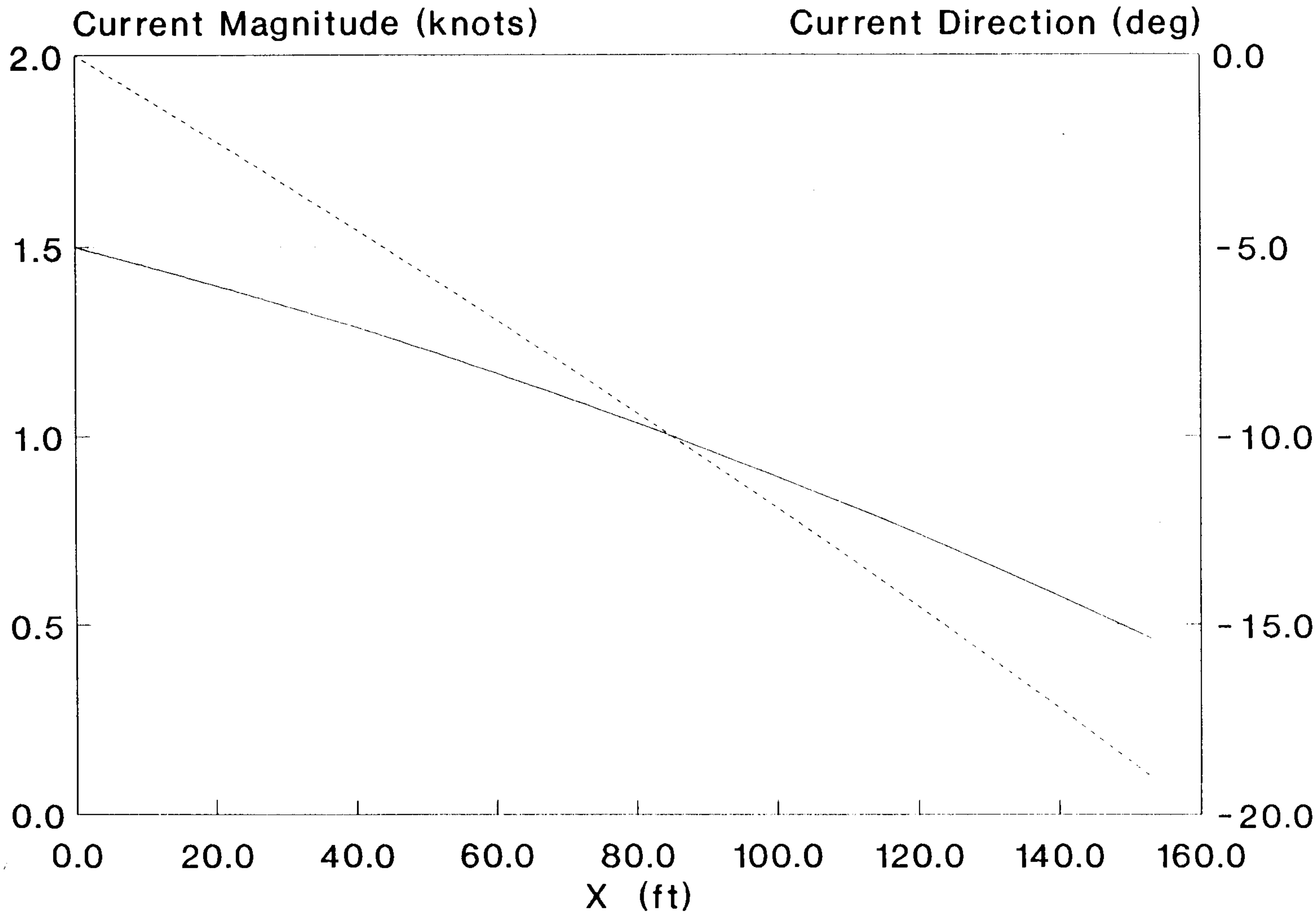

Figure 5.10: Current magnitude (——) and direction (----) for Mobile Oil inside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	125 °T	
Boom Length	700 ft	
Boom End Location	153 ft	651 ft
Outer, Inner Boom Tensions	221 lbs	104 lbs
Maximum Normal Current	0.55 knots	
Max. Normal Current Location	128 ft	

Table 5.9: Summary of Mobile Oil inside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.5	0
85	1.0	-10
160	0.4	-20

Table 5.10: Current data used for Mobile Oil inside ebb.

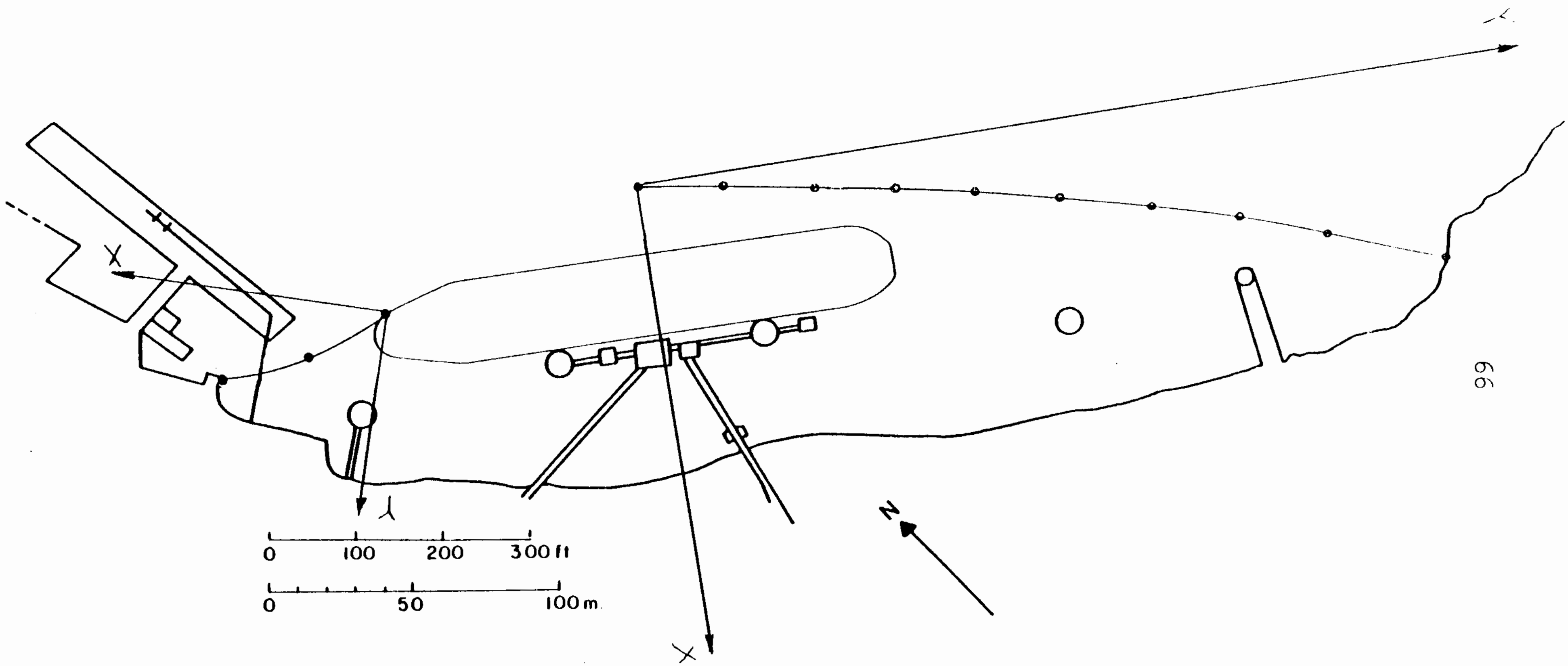

Figure 5.11: Diversion configuration for Mobile Oil outside ebb. Dots indicate 100' intervals. Outer tension = 245 lbs. Inner tension = 118 lbs.

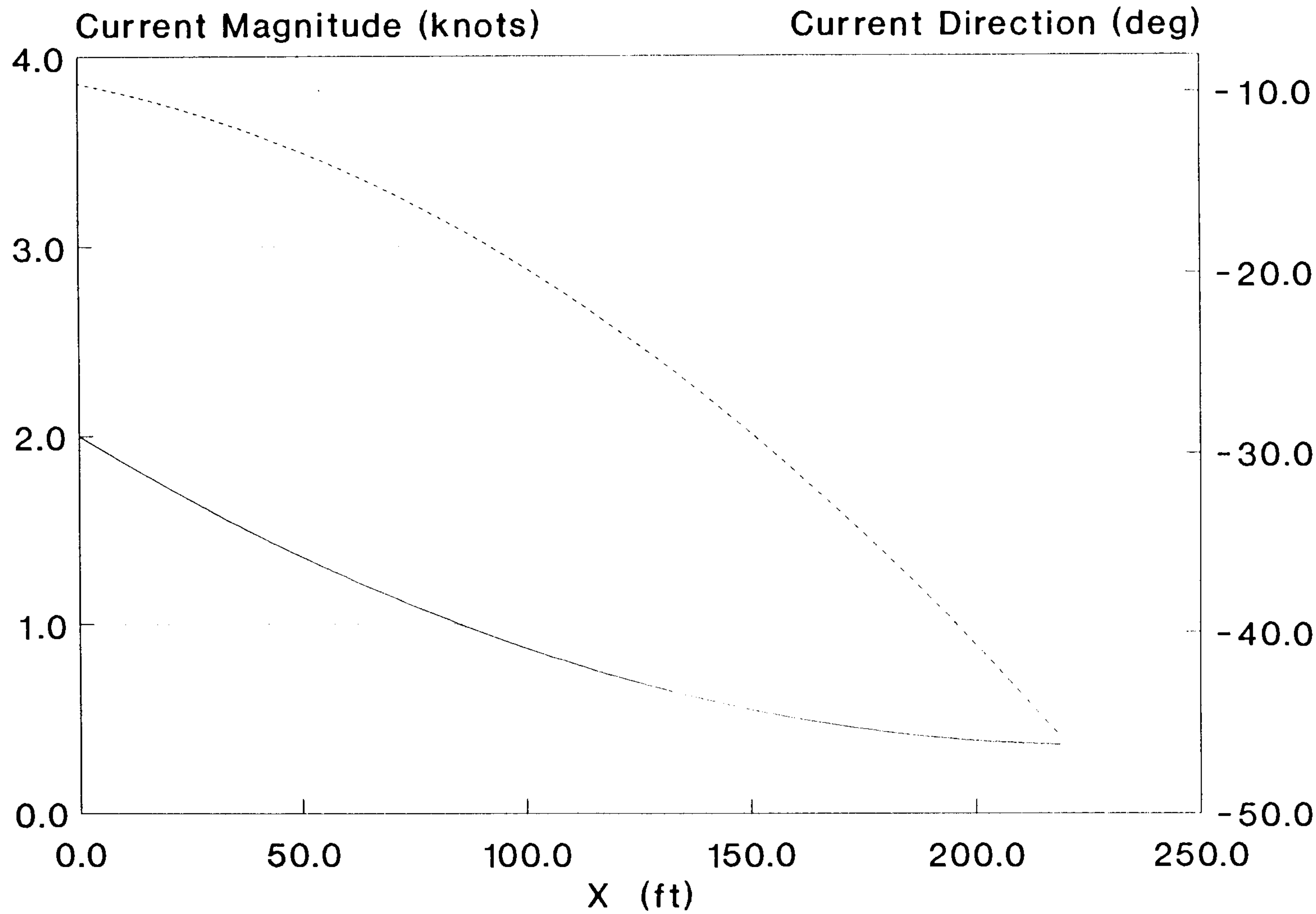

Figure 5.12: Current magnitude (———) and direction (----) for Mobile Oil outside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	125 °T	
Boom Length	900 ft	
Boom End Location	219 ft	870 ft
Outer, Inner Boom Tensions	245 lbs	118 lbs
Maximum Normal Current	0.13 knots	
Max. Normal Current Location	219 ft	

Table 5.11: Summary of Mobile Oil outside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	2.0	-9.5
85	1.0	-17.5
160	0.5	-31.0

Table 5.12: Current data used for Mobile Oil outside ebb.

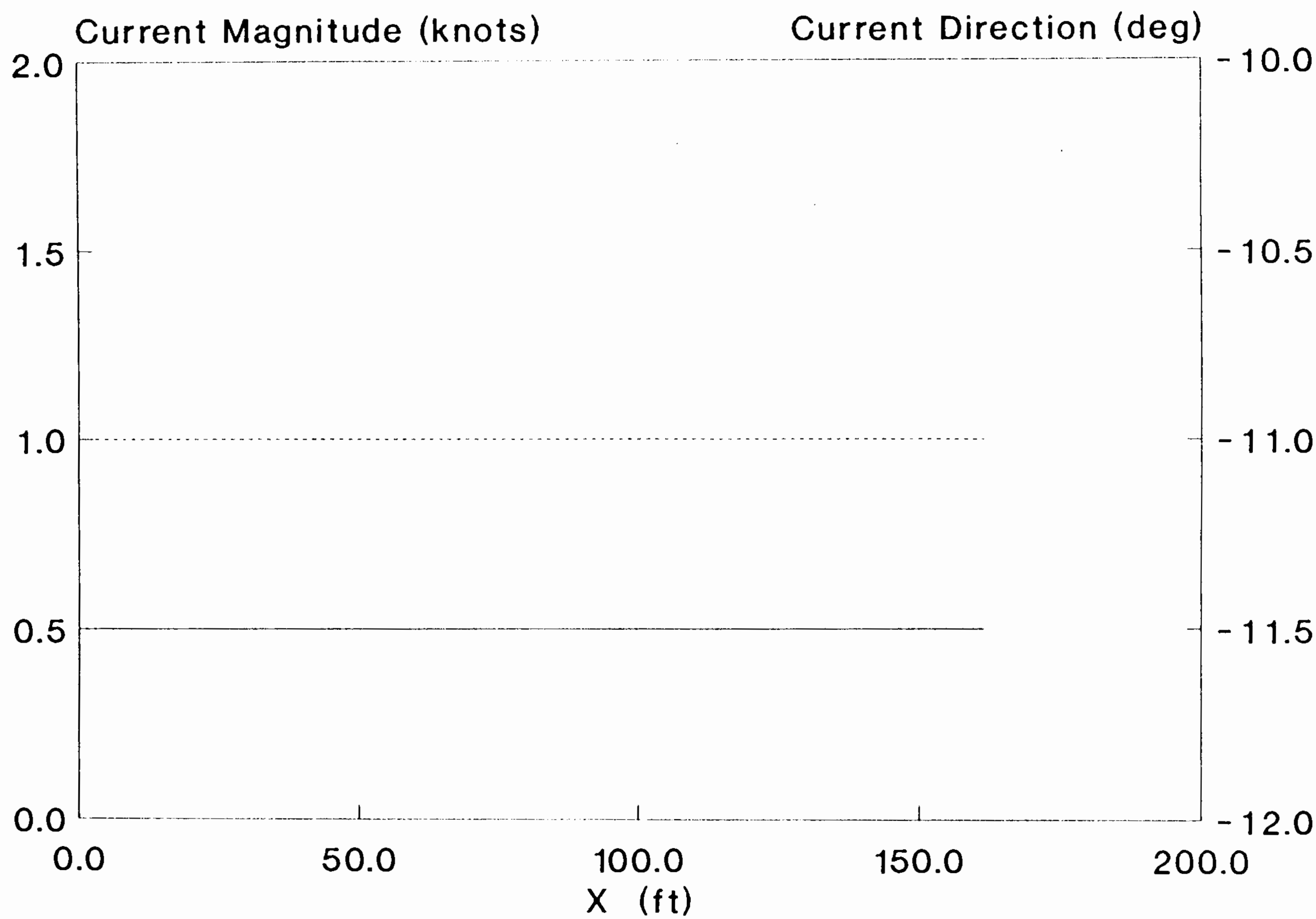

Figure 5.13: Current magnitude (——) and direction (----) for Mobil Oil in/outside ebb counter-flow boom. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	236 °T	
Boom Length	200 ft	
Boom End Location	161 ft	110 ft
Outer, Inner Boom Tensions	205 lbs	202 lbs
Maximum Normal Current	0.48 knots	
Max. Normal Current Location	161 ft	

Table 5.13: Summary of Mobil Oil inside and outside ebb counter-flow analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	0.5	-11
170	0.5	-11

Table 5.14: Current data used for Mobil Oil inside and outside ebb counter-flow boom.

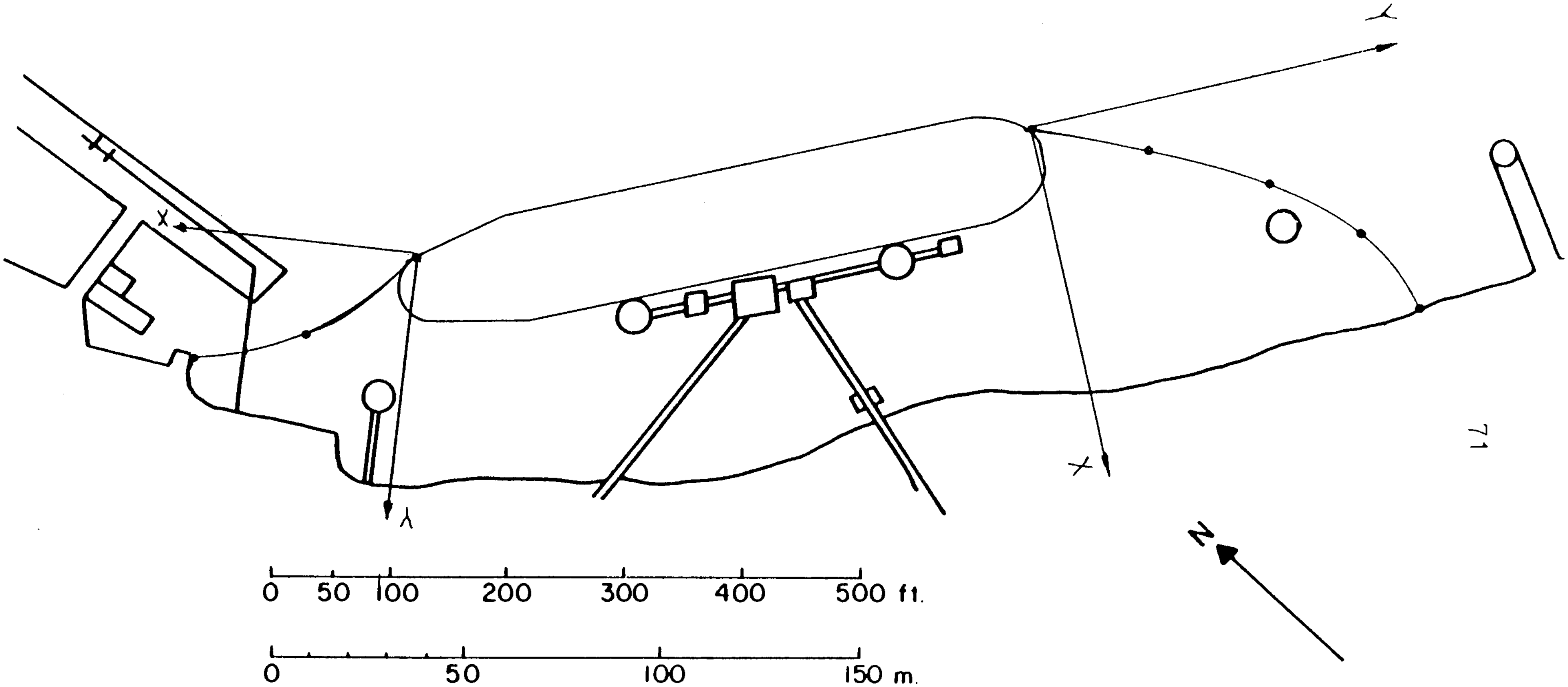

Figure 5.14: Diversion configuration for Mobile Oil inside flood. Dots indicate 100′ intervals. Bow boom outer tension = 126 lbs, inner tension = 126 lbs. Stern boom outer tension = 54 lbs, inner tension = 41 lbs.

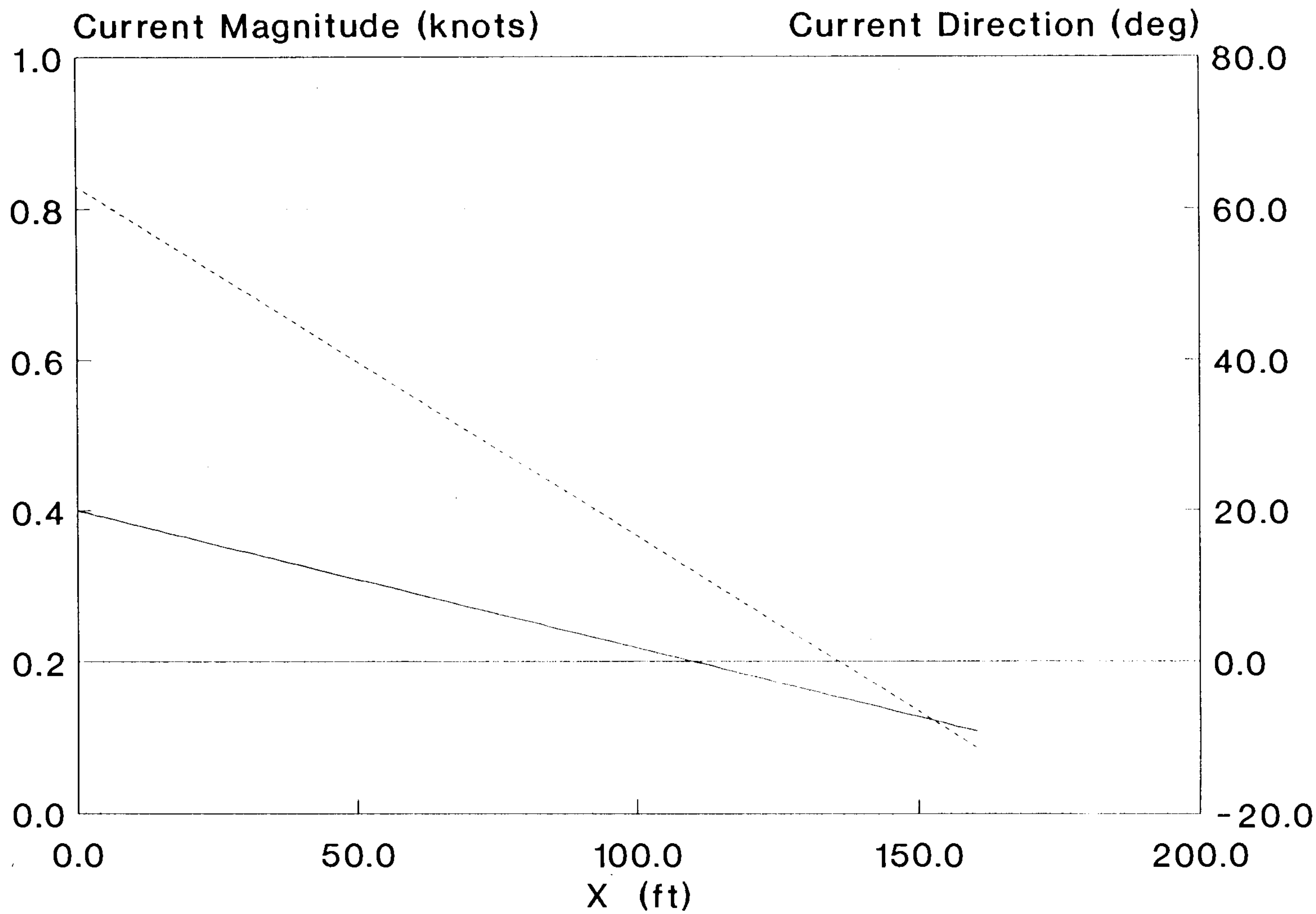

Figure 5.15: Current magnitude (——) and direction (----) for Mobile Oil inside flood. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	236 °T	
Boom Length	200 ft	
Boom End Location	160 ft	110 ft
Outer, Inner Boom Tensions	126 lbs	126 lbs
Maximum Normal Current	0.40 knots	
Max. Normal Current Location	0.0 ft	

Table 5.15: Summary of Mobile Oil inside flood analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	0.4	63
110	0.2	12

Table 5.16: Current data used for Mobile Oil inside flood.

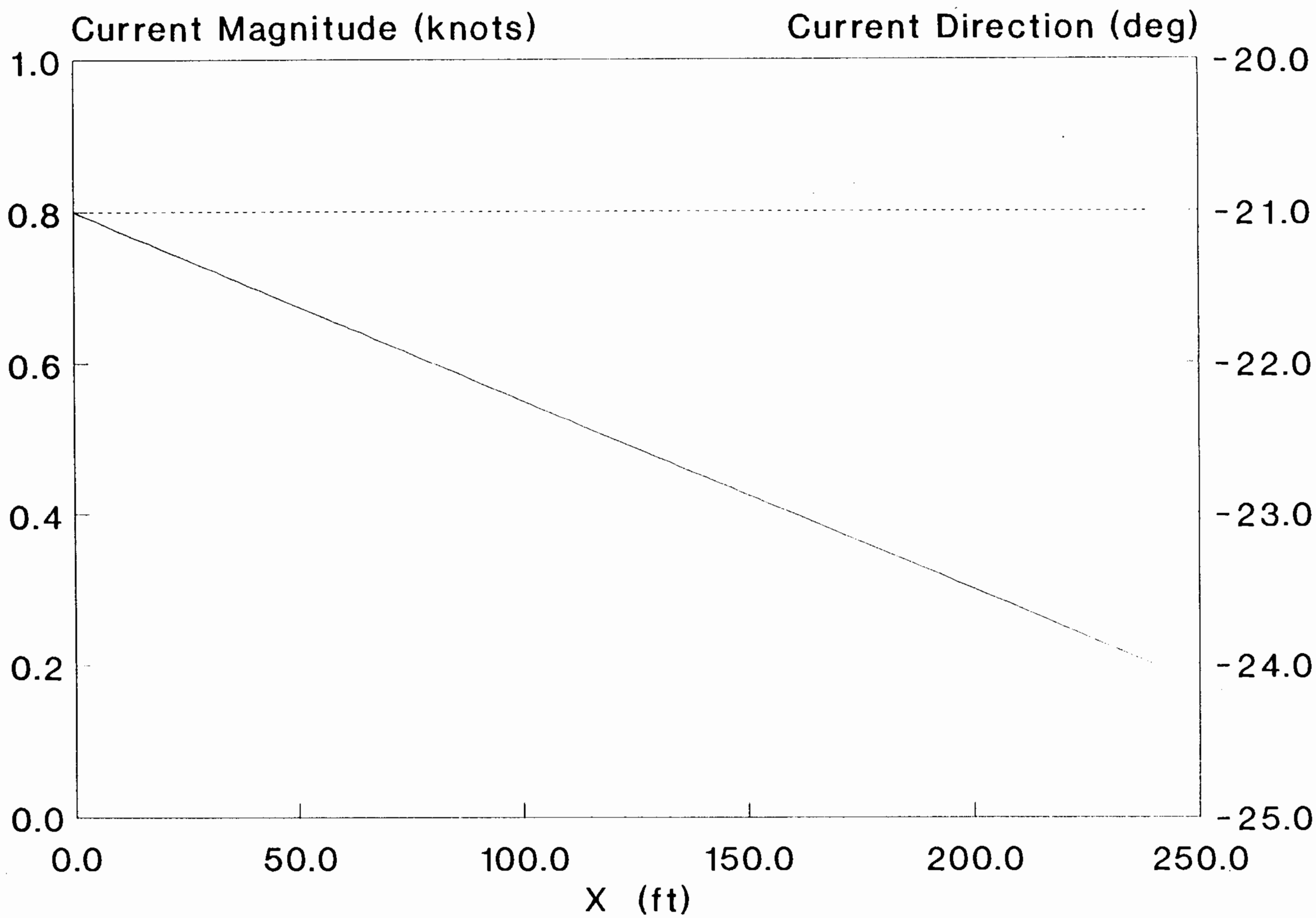

Figure 5.16: Current magnitude (———) and direction (----) for Mobile Oil inside flood counter-flow boom. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	236 °T	
Boom Length	400 ft	
Boom End Location	239 ft	295 ft
Outer, Inner Boom Tensions	54 lbs	41 lbs
Maximum Normal Current	0.24 knots	
Max. Normal Current Location	195 ft	

Table 5.17: Summary of Mobile Oil inside flood counter-flow boom analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	0.8	-21
240	0.2	-21

Table 5.18: Current data used for Mobile Oil inside flood counter-flow boom.

3.3 Public Service

The Sprague/Public Service terminal is located immediately adjacent to Mobil (see Figure 1.1). Since they are so close, the current magnitudes are similar. Also, the outside flood configuration is not possible here for the same reasons as at Mobil; there is no way to configure a boom within the 0.6 knot tolerance.

3.3a Inside Ebb and Flood. The currents inside the ship, contrary to what would be expected, are essentially the same on both the ebb and flood tide. This boom configuration, shown in Figure 5.17, extends from the starboard side stern of the ship to the base of the Mobil dock. This configuration works for both the ebb and flood tides. It is designed for downriver flow near the stern on the ebb, and an approximation to the counter-current on the flood. Table 5.19 shows the specifics of this design; note especially the low (73 lb) tension. Figure 5.18 and Table 5.20 show the currents acting on the stern boom.

Notice that there is an auxiliary boom at the bow end of the dock to contain any oil trying to escape on back eddies. Currents in this area were too low to be recorded accurately, so modeling was impossible. This means, however, that an auxiliary boom should be able to be stretched across this opening with relative ease. The two booms bound a containment area where skimming can occur during the entire tidal cycle.

3.3b Outside Ebb. The outside ebb configuration (Figure 5.19) is very similar to the inside configurations (including the auxiliary boom). The boom is, however, 100 ft longer, and extends part way up the side of the ship. The outer end makes a greater angle with respect to the current, and the shore end is not as close to the Mobil dock. This model has much higher tensions than the inside configuration as can be seen in Table 5.21. These tensions are due to the higher currents experienced a short distance outside of the ship and the steeper initial angle. These currents are shown in Figure 5.20 and Table 5.22.

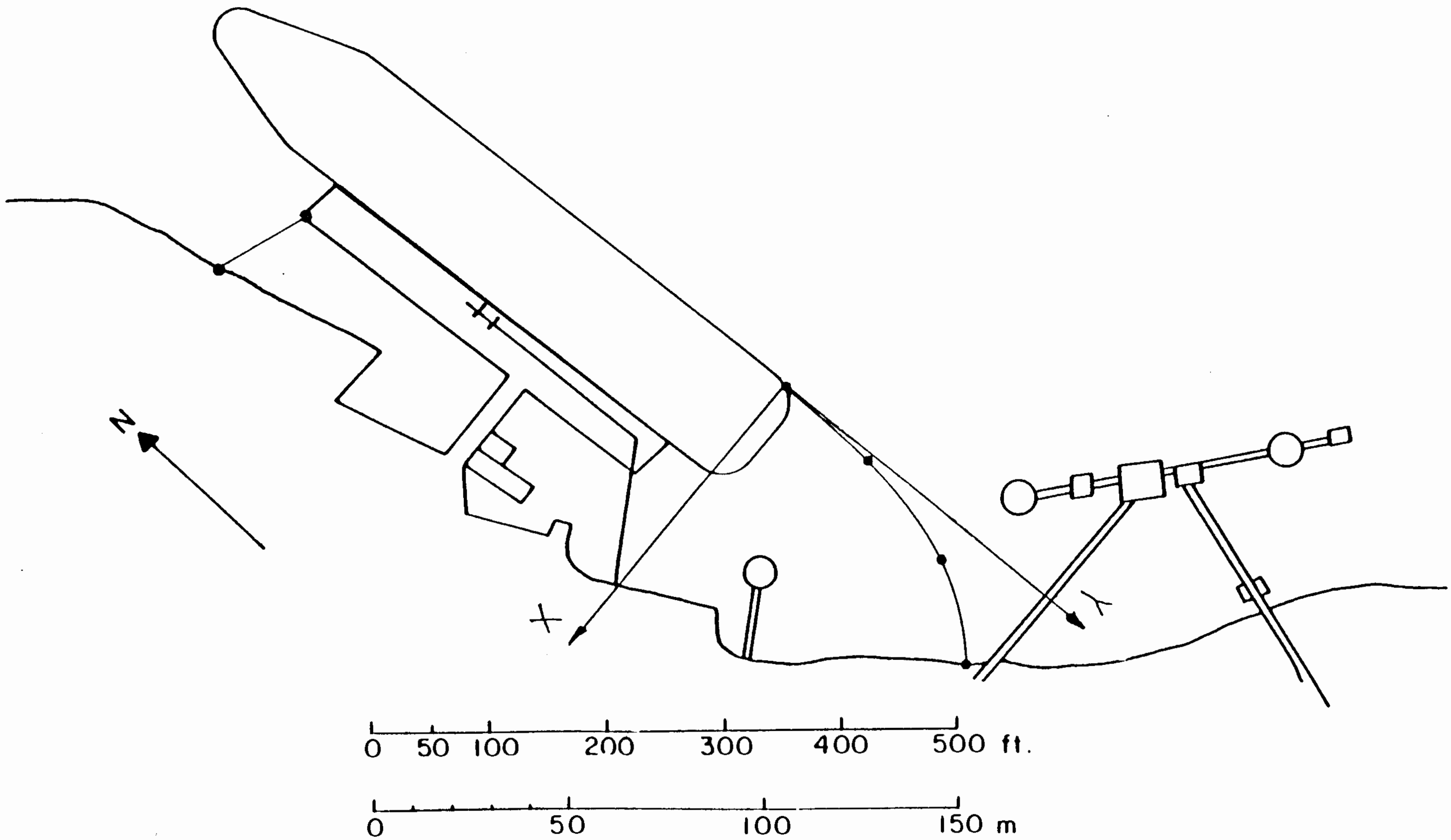

Figure 5.17: Diversion configuration for Public Service inside ebb and flood. Dots indicate 100′ intervals. Outer tension = 73 lbs. Inner tension = 48 lbs.

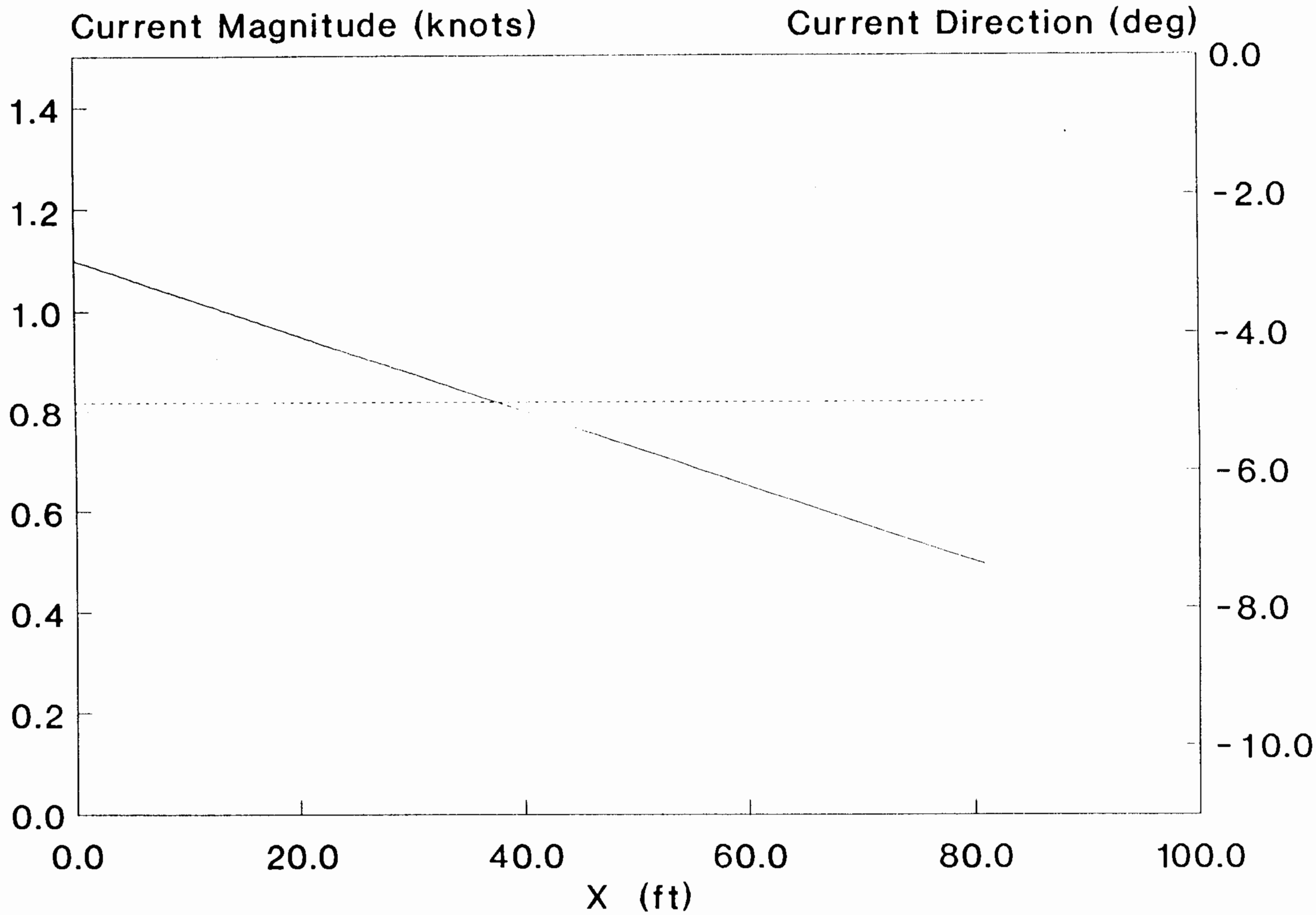

Figure 5.18: Current magnitude (——) and direction (----) for Public Service inside ebb and flood. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	176 °T	
Boom Length	300 ft	
Boom End Location	81 ft	277 ft
Outer, Inner Boom Tensions	73 lbs	48 lbs
Maximum Normal Current	0.51 knots	
Max. Normal Current Location	74 ft	

Table 5.19: Summary of Public Service inside ebb and flood analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.1	-5.0
80	0.5	-5.0

Table 5.20: Current data used for Public Service inside ebb and flood.

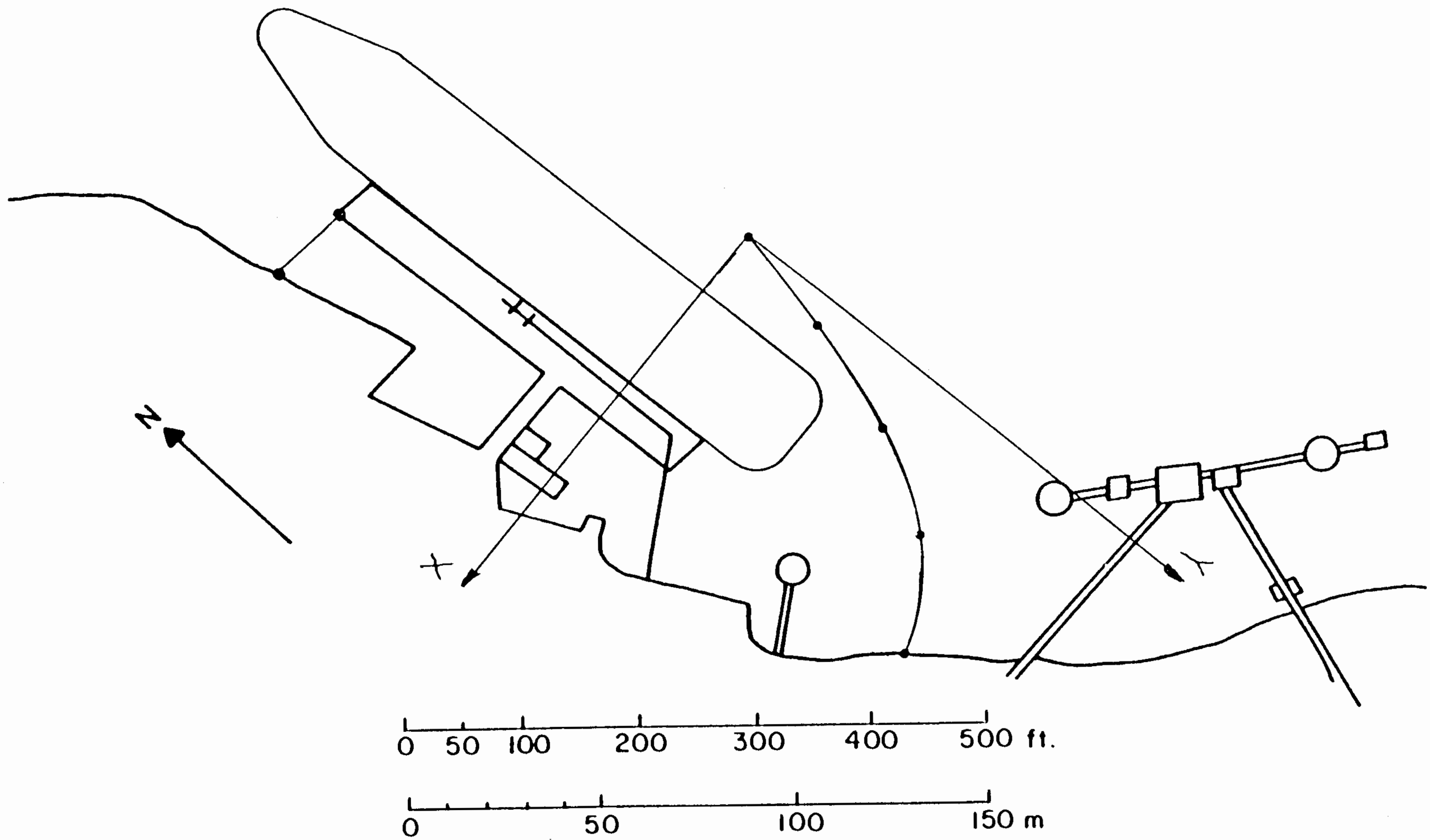

Figure 5.19: Diversion configuration for Public Service outside ebb. Dots indicate 100' intervals. Outer tension = 570 lbs. Inner tension = 521 lbs.

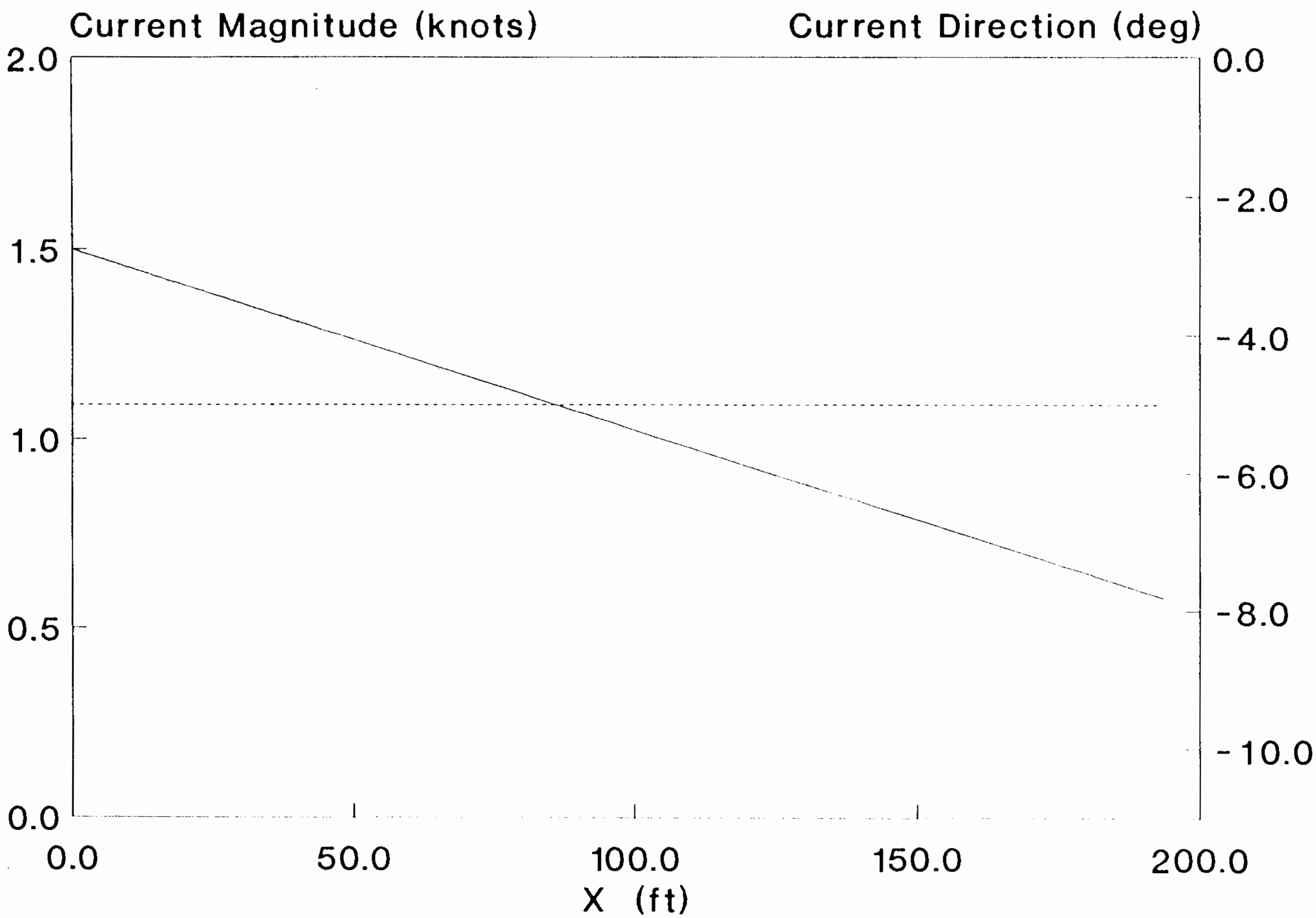

Figure 5.20: Current magnitude (——) and direction (----) for Public Service outside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	176 °T	
Boom Length	400 ft	
Boom End Location	194 ft	333 ft
Outer, Inner Boom Tensions	570 lbs	521 lbs
Maximum Normal Current	0.60 knots	
Max. Normal Current Location	138 ft	

Table 5.21: Summary of Public Service outside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.5	-5.0
210	0.5	-5.0

Table 5.22: Current data used for Public Service outside ebb.

3.4 Fuel Storage Corporation

Fuel Storage Corp. is the fourth petroleum unloading facility upstream from Portsmouth harbor (see Figure 1.1). The modeling for all of these situations is straightforward. The main difficulties this site presents are on the flood tide. The currents are high (up to 2.5 knots), and therefore the mooring loads large. Secondly, the flood tide configurations have a very large containment area, and concentrating the oil in one location for skimming may not be possible. Third, a frontal zone starting inside the flood tide containment areas and extending across the river may cause problems.

3.4a Inside Ebb. This is a very good example of the reason this general model was developed. This configuration (Figure 5.21) is a redesign of the FSC experiment reported in the previous chapter. This design does not have the intermediate anchors, however. This gives a long boom segment, 1300 ft, subject to a varying current distribution. From Table 5.23 it can be seen that the tension drops approximately 20% over the length of the boom. Modeling this with the catenary diversion model could introduce that much error or more due to its constant tension and current assumptions. Figure 5.22 and Table 5.24 give the current data used for this design.

3.4b Outside Ebb. This configuration (Figure 5.23) is similar to the inside design, but it has a longer boom to reach up the side of the ship, and consequently has slightly higher tensions. Table 5.25 shows the summary of this analysis, and Figure 5.24 and Table 5.26 show the currents used.

3.4c Inside and Outside Counter-Flow Boom. This boom is the same for both inside and outside ebb, and is shown in Figures 5.21 and 5.23 at the bow of the ship. While there is little evidence of back eddies inside the ship, it is certainly a possibility. This boom is therefore to prevent any leakage in the event back eddies do exist. A summary is presented in Table 5.27, and currents in Figure 5.25 and Table 5.28.

3.4d Inside Flood. The currents on the flood tide are greater than on the ebb, and longer booms are needed also. These two factors contribute to much higher tensions on the flood tide. The inside configuration is shown in Figure 5.26. The boom must be anchored to the berthing cell because anchoring to the ship does not meet the 0.6 knot criteria. Therefore, a seal between the ship and the berthing cell will be necessary. Relatively little is known about the currents downstream and inside of the dock, so these were estimated as well as possible. Table 5.29 details this analysis, and Figure 5.27 and Table 5.30 show the currents.

3.4e Outside Flood. The 2.5 knot currents outside of the ship and the very long (2600 ft) boom make for extremely high boom tensions and mooring loads. A permanent mooring for the outer end of this boom would be highly advantageous, but may not be feasible for navigational reasons. Figure 5.28 shows the configuration, while Table 5.31 gives the analysis summary. As with the inside design, the currents downstream and closer to shore had to estimated. The data used is presented in Figure 5.29 and Table 5.32.

3.4f Inside and Outside Counter-Flow Boom. These booms are very similar to the ebb tide counter-flow booms. The boom length, tension, endpoints, and currents are the same with respect to their appropriate axes. Only the location and orientation of the axes is different. For clarity, however, a complete set of figures and tables is included below. The configuration is shown in both Figures 5.26 and 5.28, and is summarized in Table 5.33. The currents are shown in Figure 5.30 and Table 5.34.

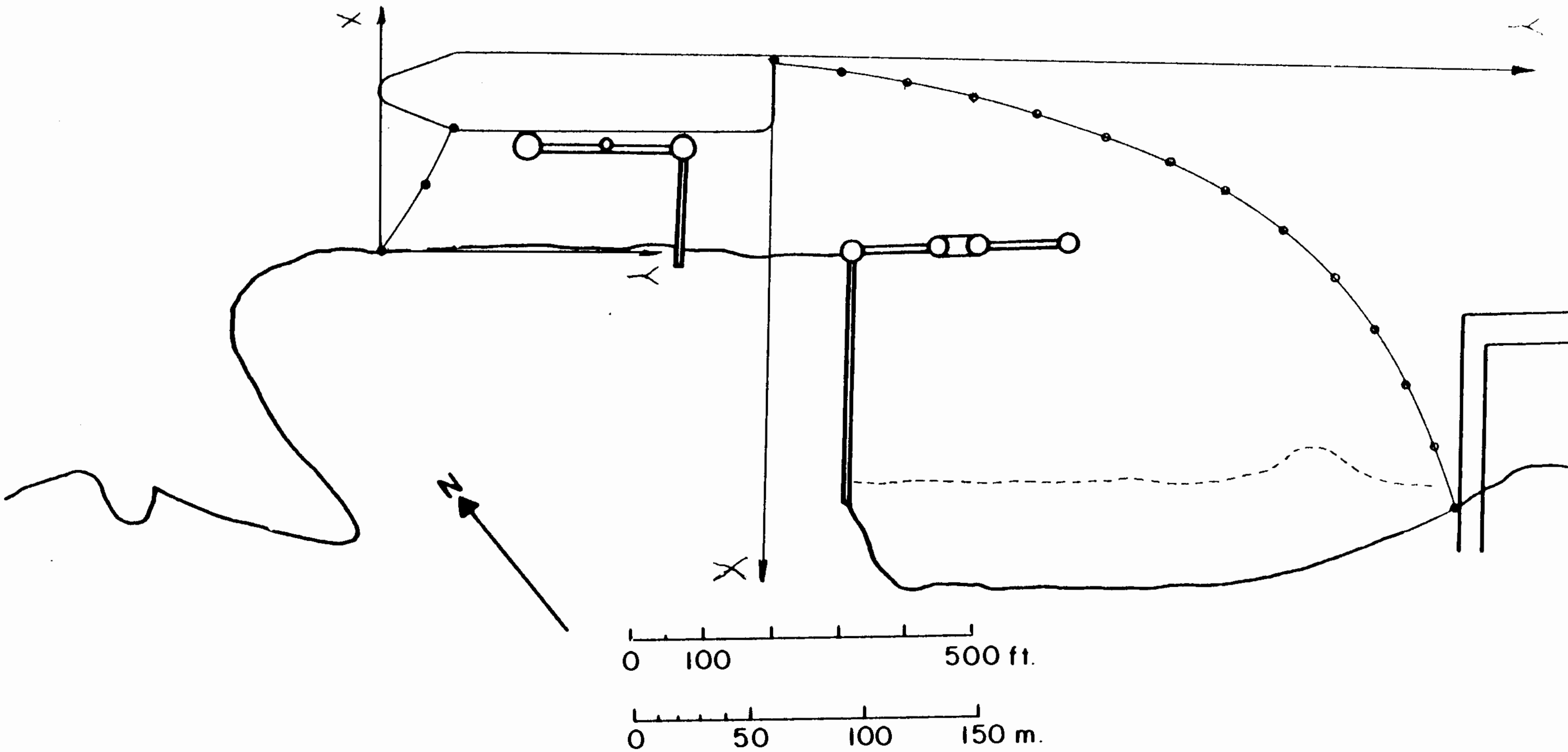

Figure 5.21: Diversion configuration for Fuel Storage Corp. inside ebb. Dots indicate 100′ intervals. Outer tension = 798 lbs. Inner tension = 647 lbs.

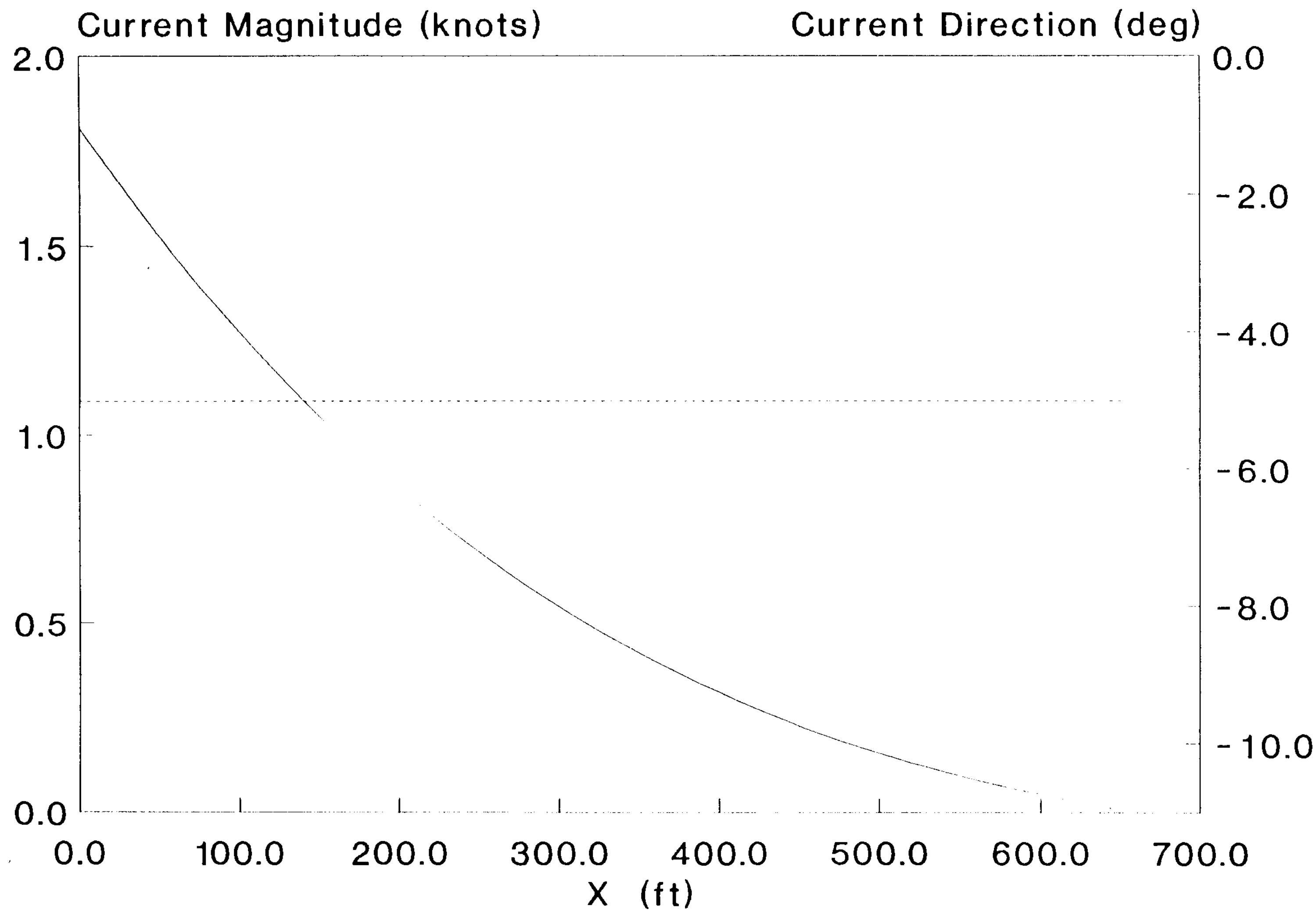

Figure 5.22: Current magnitude (——) and direction (----) for Fuel Storage Corp. inside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	131 °T	
Boom Length	1300 ft	
Boom End Location	652 ft	1041 ft
Outer, Inner Boom Tensions	798 lbs	647 lbs
Maximum Normal Current	0.42 knots	
Max. Normal Current Location	223 ft	

Table 5.23: Summary of Fuel Storage Corp. inside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.81	-5.0
86	1.34	-5.0
350	0.42	-5.0
660	0.00	-5.0

Table 5.24: Current data used for Fuel Storage Corp. inside ebb.

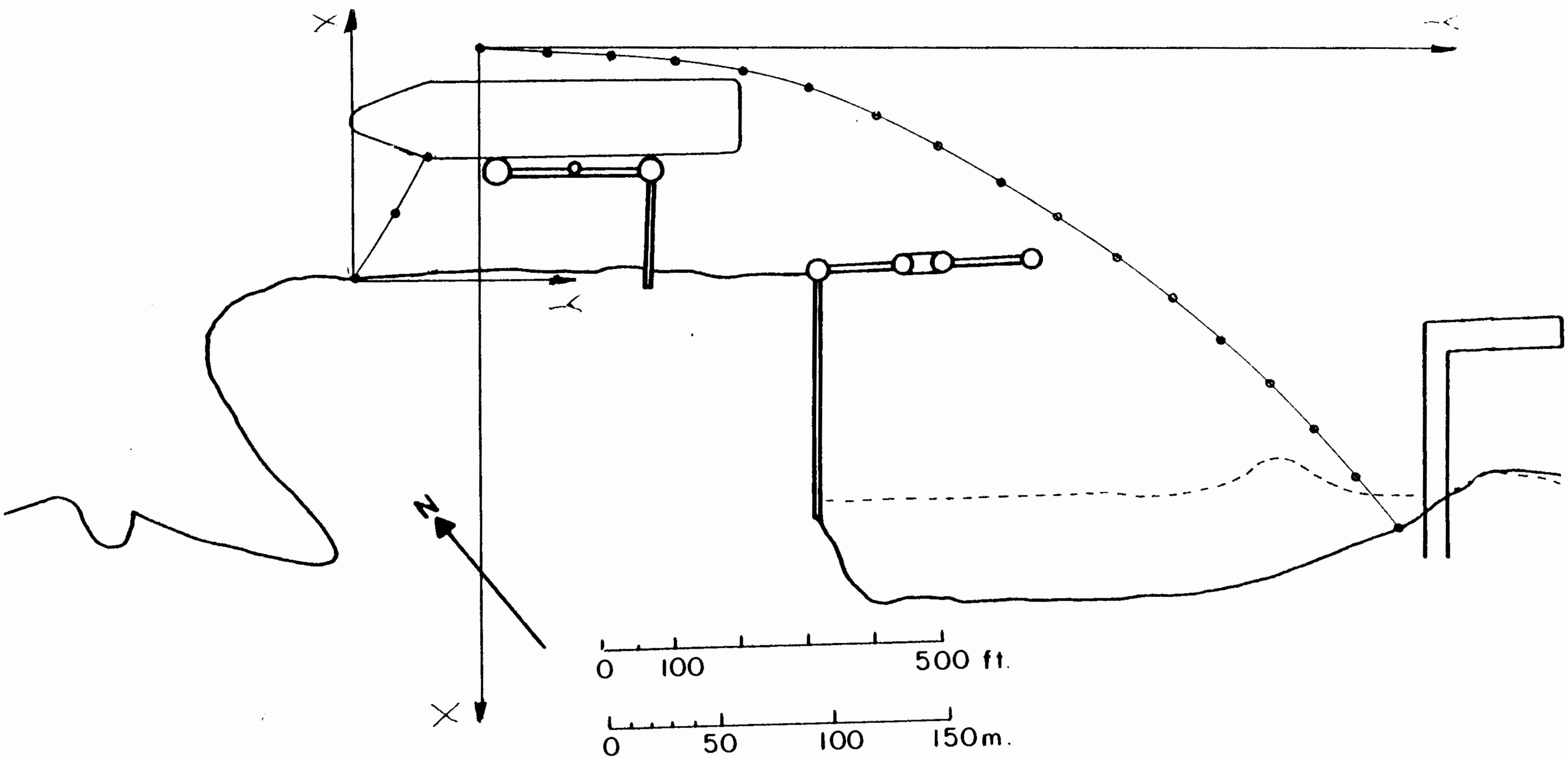

Figure 5.23: Diversion configuration for Fuel Storage Corp. outside ebb. Dots indicate 100' intervals. Outer tension = 846 lbs. Inner tension = 681 lbs.

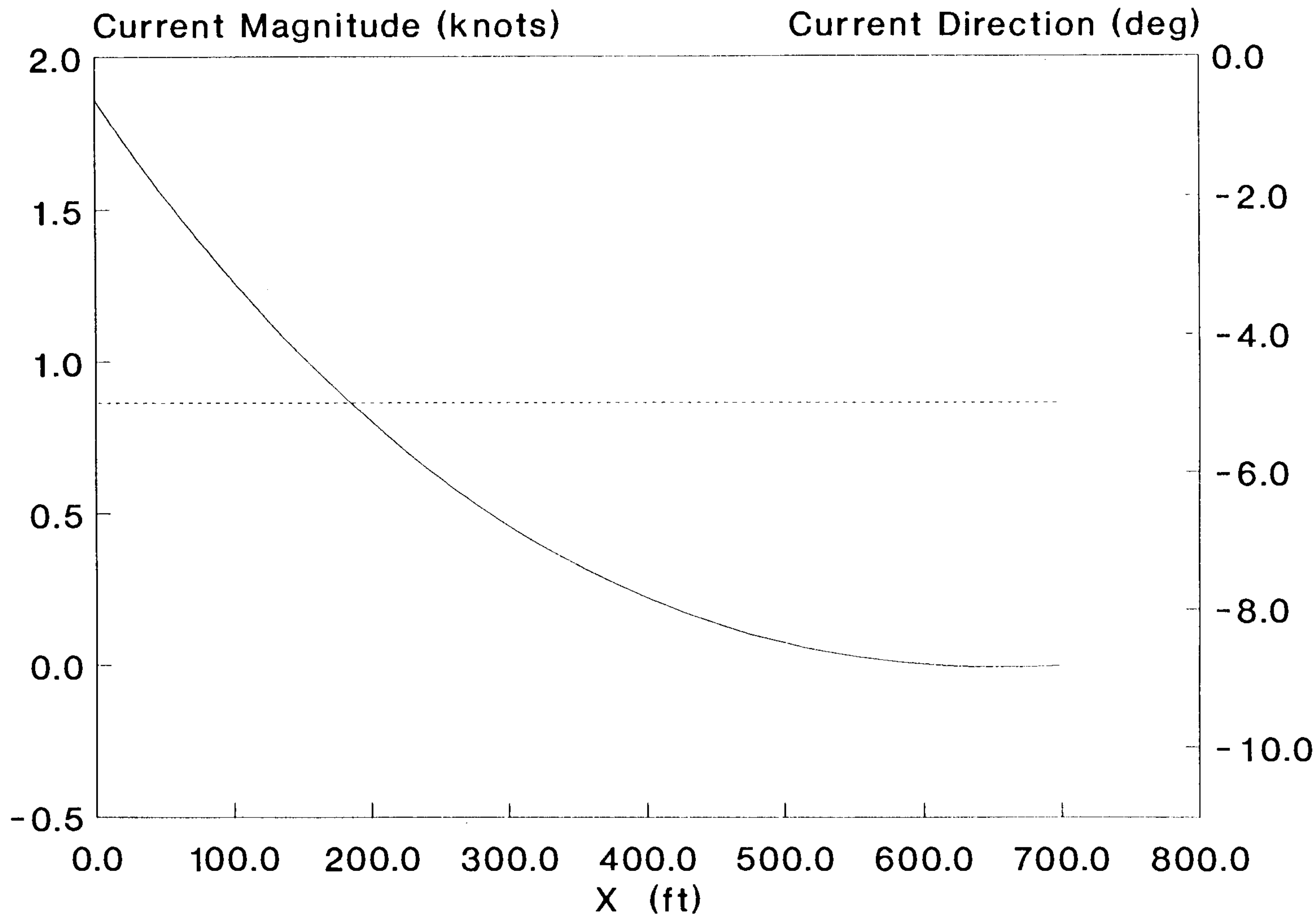

Figure 5.24: Current magnitude (——) and direction (----) for Fuel Storage Corp. outside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	131 °T	
Boom Length	1600 ft	
Boom End Location	698 ft	1400 ft
Outer, Inner Boom Tensions	846 lbs	681 lbs
Maximum Normal Current	0.31 knots	
Max. Normal Current Location	192 ft	

Table 5.25: Summary of Fuel Storage Corp. outside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.86	-5.0
86	1.34	-5.0
400	0.22	-5.0
710	0.00	-5.0

Table 5.26: Current data used for Fuel Storage Corp. outside ebb.

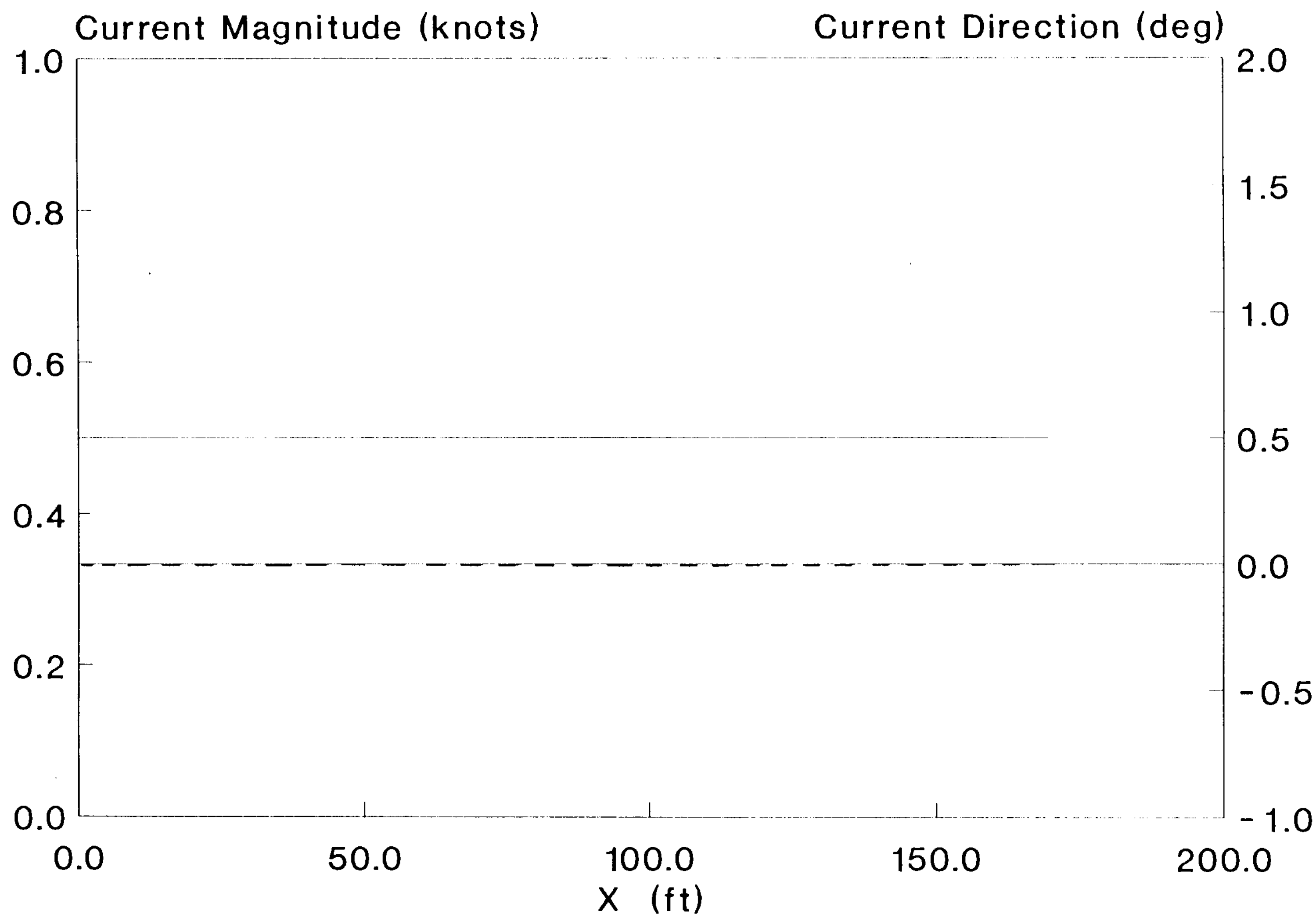

Figure 5.25: Current magnitude (——) and direction (----) for Fuel Storage Corp. in/outside ebb counter-flow boom. Currents are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	131 °T	
Boom Length	200 ft	
Boom End Location	169 ft	94 ft
Outer, Inner Boom Tensions	270 lbs	268 lbs
Maximum Normal Current	0.5 knots	
Max. Normal Current Location	169 ft	

Table 5.27: Summary of Fuel Storage Corp. inside and outside ebb counter-flow analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	0.5	0.0
170	0.5	0.0

Table 5.28: Current data used for Fuel Storage Corp. inside and outside ebb counter-flow boom.

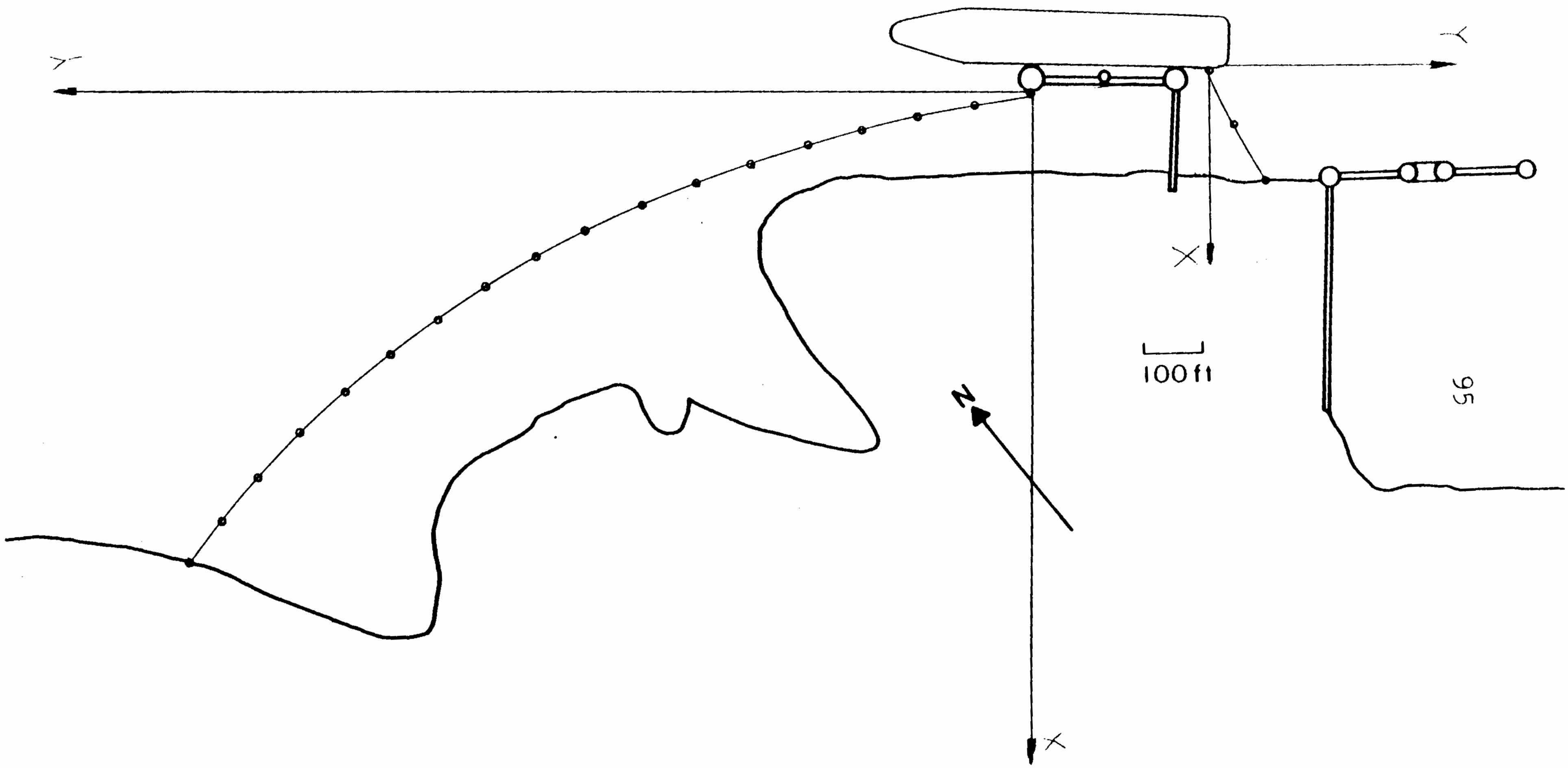

Figure 5.26: Diversion configuration for Fuel Storage Corp. inside flood. Dots indicate 100' intervals. Outer tension = 3750 lbs. Inner tension = 3398 lbs.

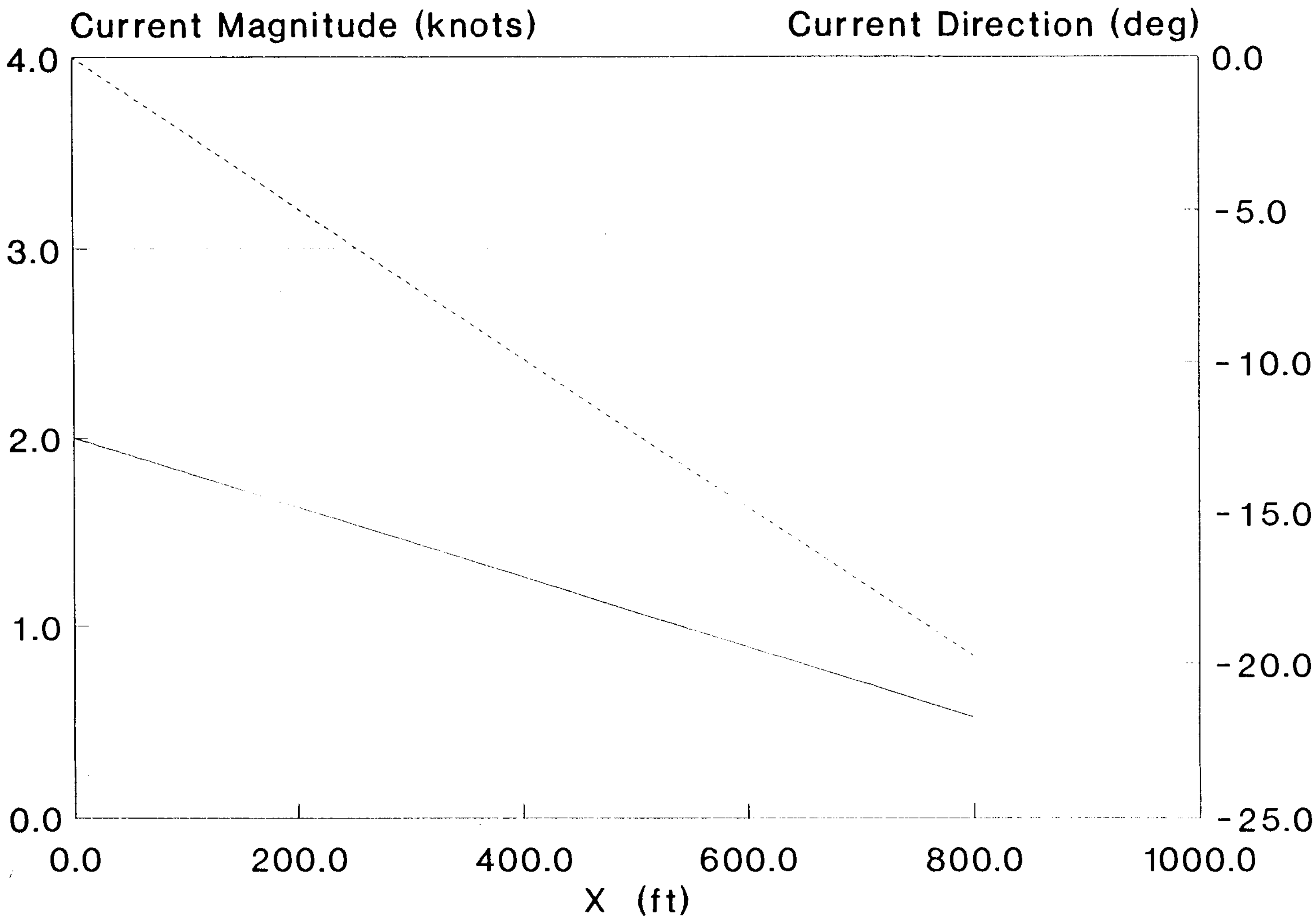

Figure 5.27: Current magnitude (——) and direction (----) for Fuel Storage Corp. inside flood. Current directions are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	311 °T	
Boom Length	1700 ft	
Boom End Location	800 ft	1448 ft
Outer, Inner Boom Tensions	3750 lbs	3398 lbs
Maximum Normal Current	0.58 knots	
Max. Normal Current Location	357 ft	

Table 5.29: Summary of Fuel Storage Corp. inside flood analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	2.0	0.0
810	0.5	-20.0

Table 5.30: Current data used for Fuel Storage Corp. inside flood.

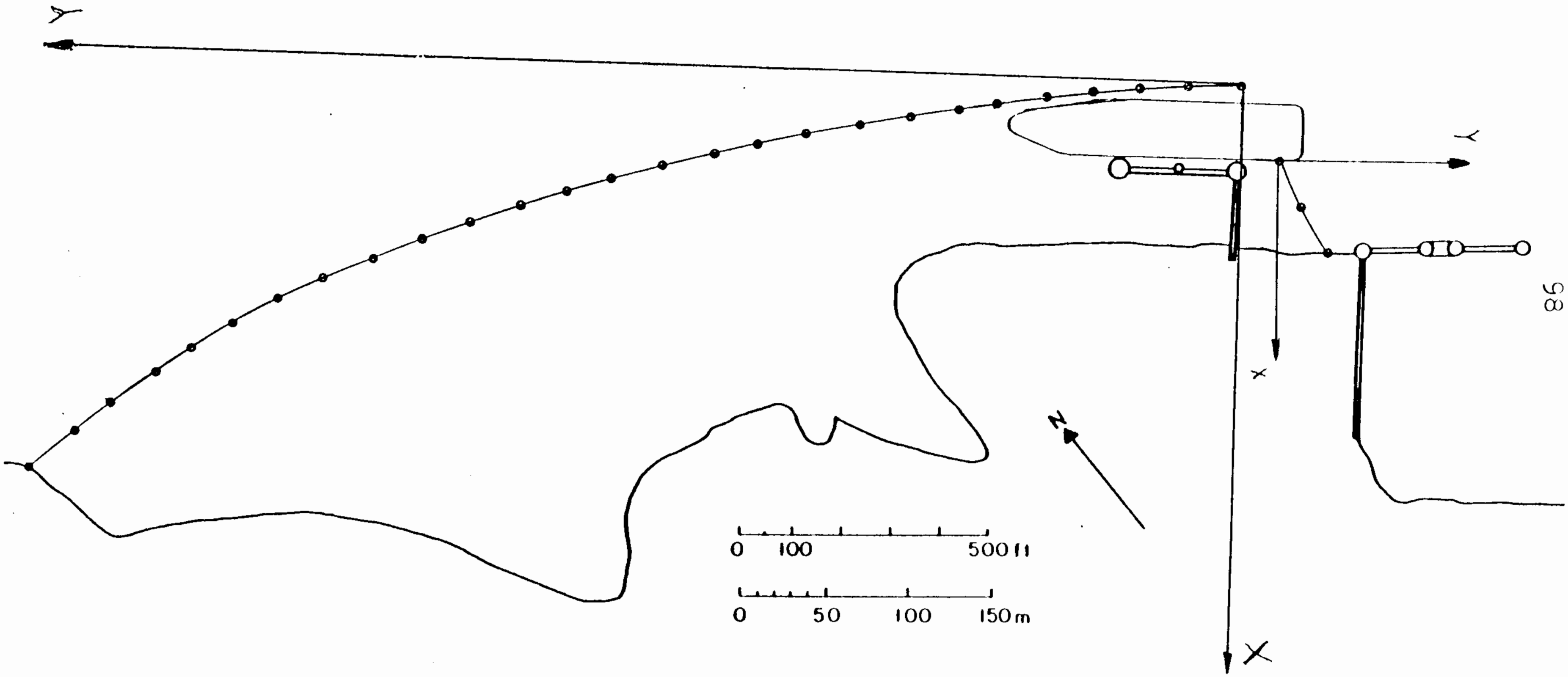

Figure 5.28: Diversion configuration for Fuel Storage Corp. outside flood. Dots indicate 100′ intervals. Outer tension = 4180 lbs. Inner tension = 3252 lbs.

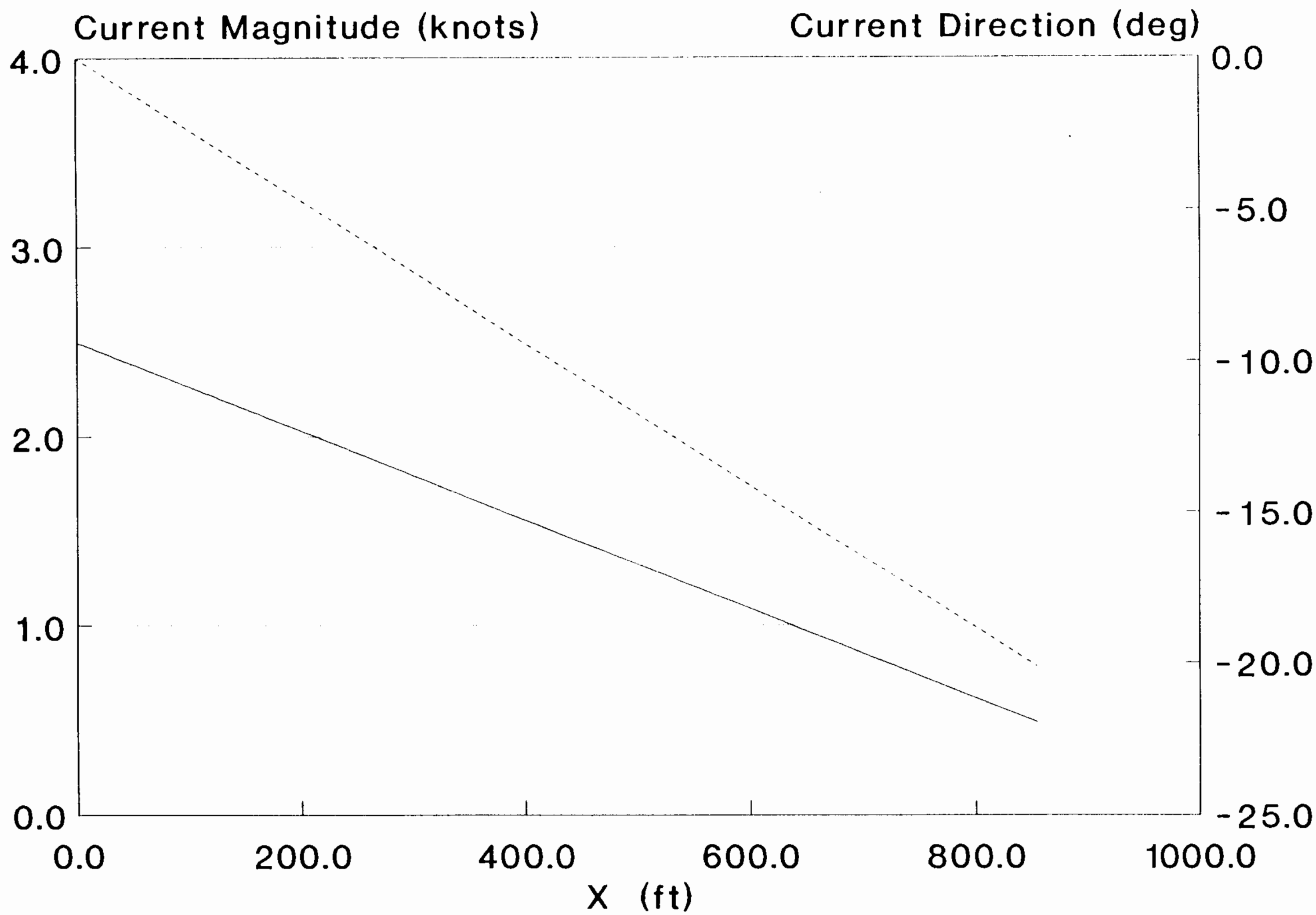

Figure 5.29: Current magnitude (——) and direction (----) for Fuel Storage Corp. outside flood. Current directions are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	311 °T	
Boom Length	2600 ft	
Boom End Location	855 ft	2400 ft
Outer, Inner Boom Tensions	4180 lbs	3252 lbs
Maximum Normal Current	0.47 knots	
Max. Normal Current Location	413 ft	

Table 5.31: Summary of Fuel Storage Corp. outside flood analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	2.5	0.0
850	0.5	-20.0

Table 5.32: Current data used for Fuel Storage Corp. outside flood.

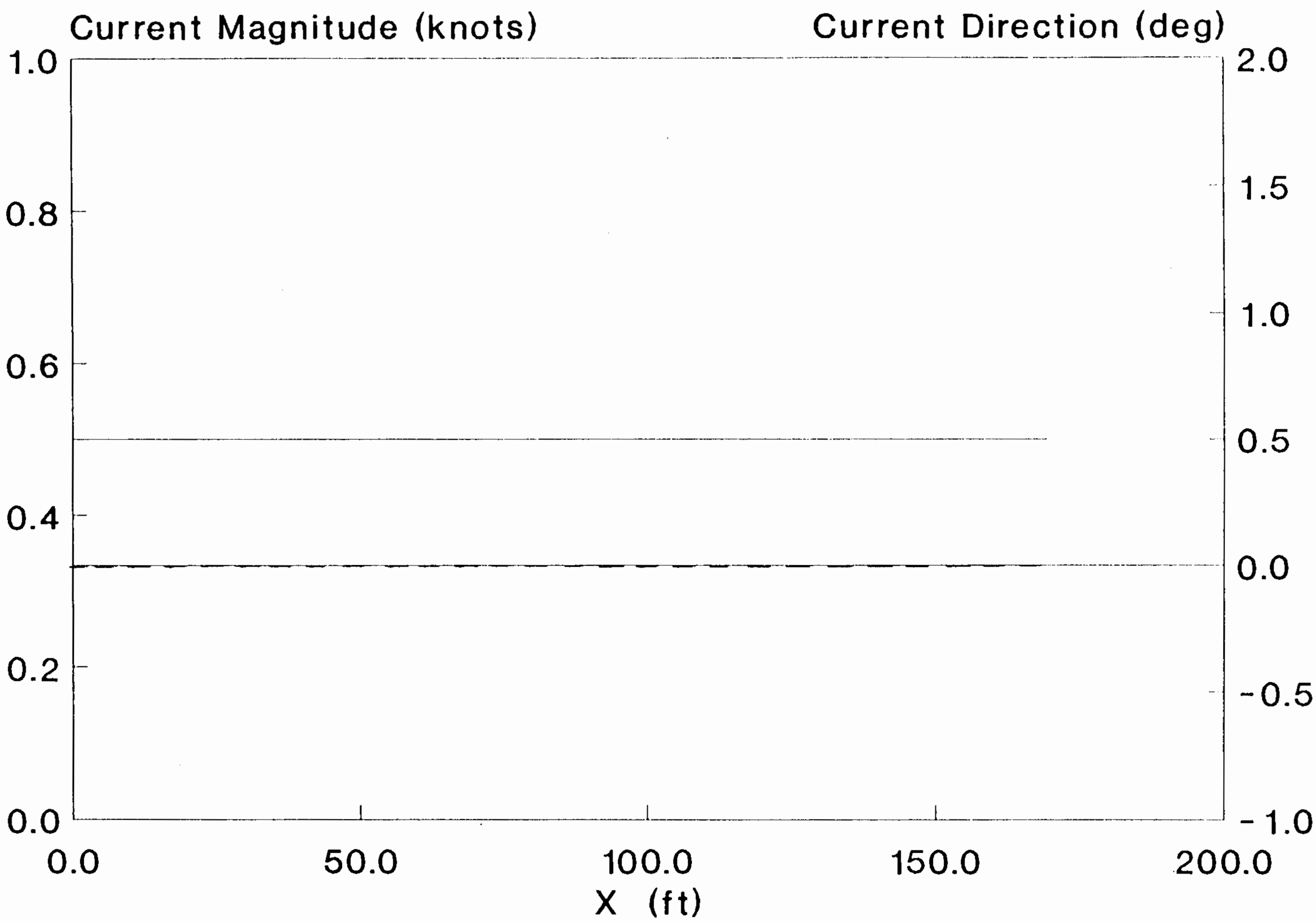

Figure 5.30: Current magnitude (———) and direction for (----) Fuel Storage Corp. in/outside flood counter-flow. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	131 °T	
Boom Length	200 ft	
Boom End Location	169 ft	94 ft
Outer, Inner Boom Tensions	270 lbs	269 lbs
Maximum Normal Current	0.5 knots	
Max. Normal Current Location	169 ft	

Table 5.33: Summary of Fuel Storage Corp. inside and outside flood counter-flow boom analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	0.5	0.0
170	0.5	0.0

Table 5.34: Current data used for Fuel Storage Corp. inside and outside flood counter-flow boom.

3.5 Sprague/ATC

The Sprague/ATC (ATC) site presents some difficulties in boom design and implementation. First, as is usually the case in the Piscataqua, the currents are high outside of the ship. Second, this facility sits on a point of land, so that the shore is falling away from the dock on both the upstream and downstream sides. This requires longer booms to reach the shore, and consequently higher tensions.

3.5a Inside Ebb. This design (Figure 5.31) follows the current very closely in to shore. The normal component of the current, therefore, is small, and so are the tensions. The currents are shown in Figure 5.32; a summary of the analysis is located in Table 5.35, and current input values are given in Table 5.36.

This configuration requires an auxiliary boom to contain oil on back eddies, and this is detailed below. Note: The shore endpoint of this design is about 450 ft downstream from the design proposed in Savage et. al. (1982), but this collection point will still allow easy access for collection equipment.

3.5b Outside Ebb. This design is essentially the same as the inside ebb. It is only 100 ft longer, but starts outside the stern of the ship (see Figure 5.33). It was not necessary to come up the side of the ship with this boom, for the currents (see Figure 5.34) are angled into and along the ship. Any spill would be carried along the side of the ship toward the stern where it would enter the containment area. Tensions, given in Table 5.37, are more than twice as high as the inner design because the boom is angled slightly more with respect to the current. Current input data is provided in Table 5.38. This configuration also needs an auxiliary boom, and this is described next.

3.5c Inside and Outside Counter-Flow Boom. This configuration (shown in Figures 5.31 and 5.33) was unique because part of the boom was in a counter-current and part was in the primary ebb flow. Because of the flow reversal, the analysis was split into two sections, one for each flow direction. First, the counter-flow area was modeled with a short 100 ft boom starting at shore and extending towards the dock. Then a new coordinate system was defined at the endpoint of the first boom. The ending tension and angle from the first section were used as initial conditions for the next section. These two models were adjusted until the outer end of the second boom was in the vicinity of the dock where it could be anchored. Tables 5.39 and 5.41 give the summary of the two designs. Figure 5.35 and Table 5.40 give the currents for the inner section, while Figure 5.36 and Table 5.42 show currents for the outside section. This design is the best estimate which could be made based on limited current information. While it meets the 0.6 knot criteria, it is felt that a more detailed profile of the current between the dock and shore is needed to refine this design.

3.5d Inside Flood. This boom design, shown in Figure 5.37, requires a very long (2500 ft) boom. It is attached to the bow of the ship, and goes around the dock and in toward shore. As mentioned above, the shore is rapidly falling away from the dock here, so the boom has to reach a long way to get to shore. Table 5.43 shows that the outer end tensions are over 2200 lbs. The currents here are between 1 and 2 knots until the boom is around the corner of the point. Table 5.44 and Figure 5.38 show the currents in detail.

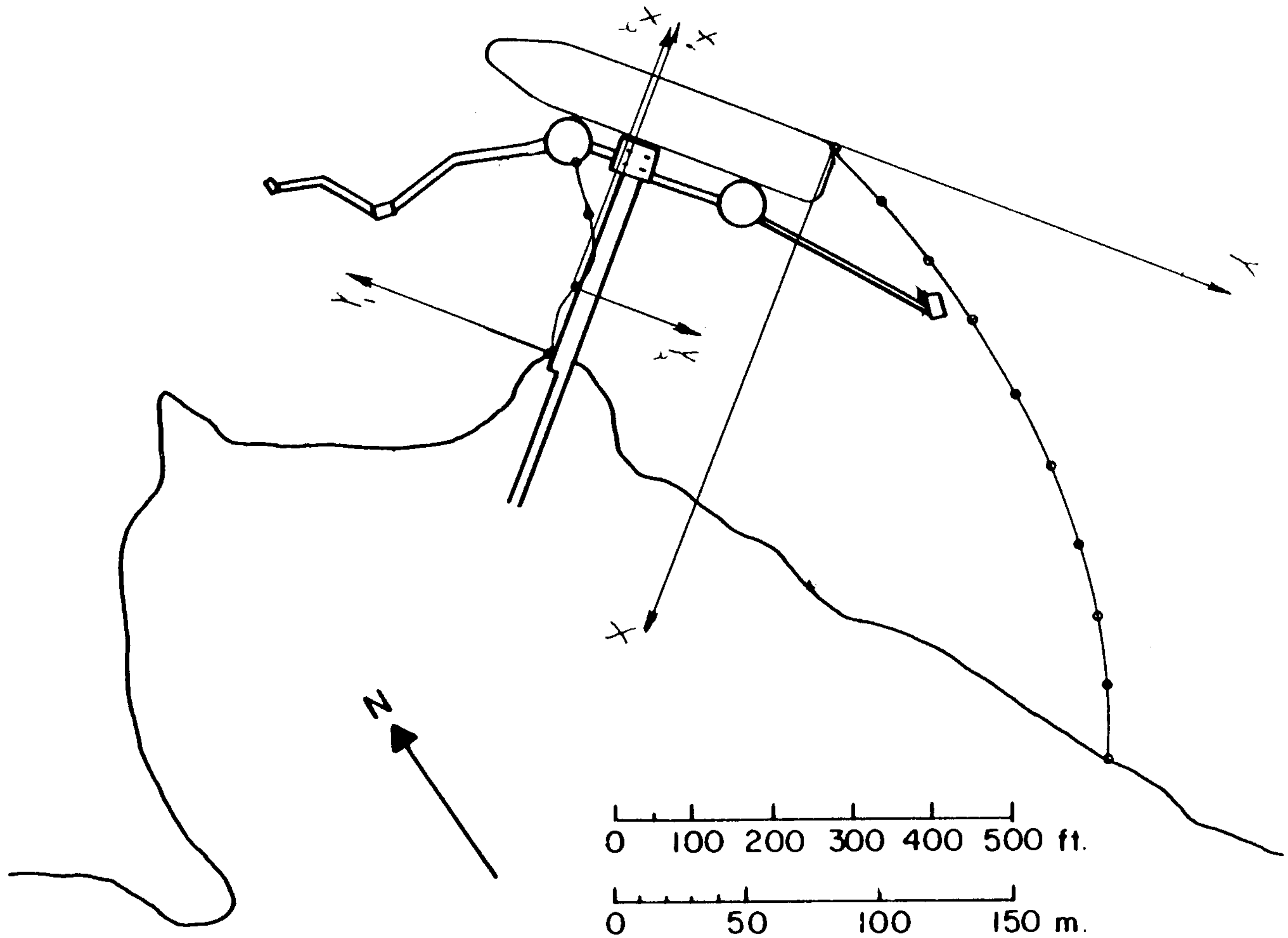

Figure 5.31: Diversion configuration for ATC inside ebb. Dots indicate 100' intervals. Outer tension = 99 lbs. Inner tension = 52 lbs.

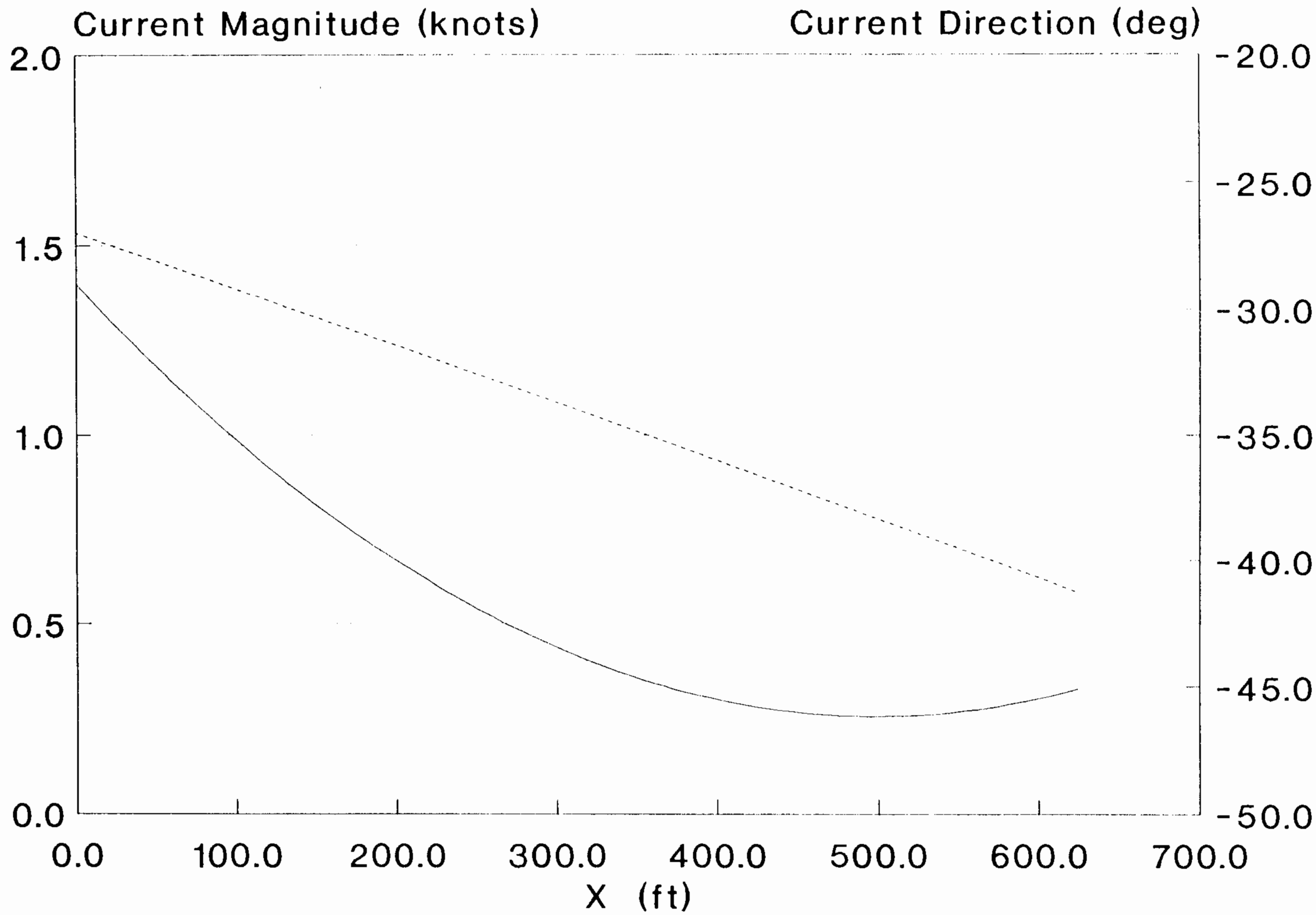

Figure 5.32: Current magnitude (——) and direction (----) for ATC inside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	143 °T	
Boom Length	900 ft	
Boom End Location	624 ft	617 ft
Outer, Inner Boom Tensions	99 lbs	52 lbs
Maximum Normal Current	0.19 knots	
Max. Normal Current Location	624 ft	

Table 5.35: Summary of ATC inside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.4	-27
225	0.6	-32
400	0.3	-36

Table 5.36: Current data used for ATC inside ebb.

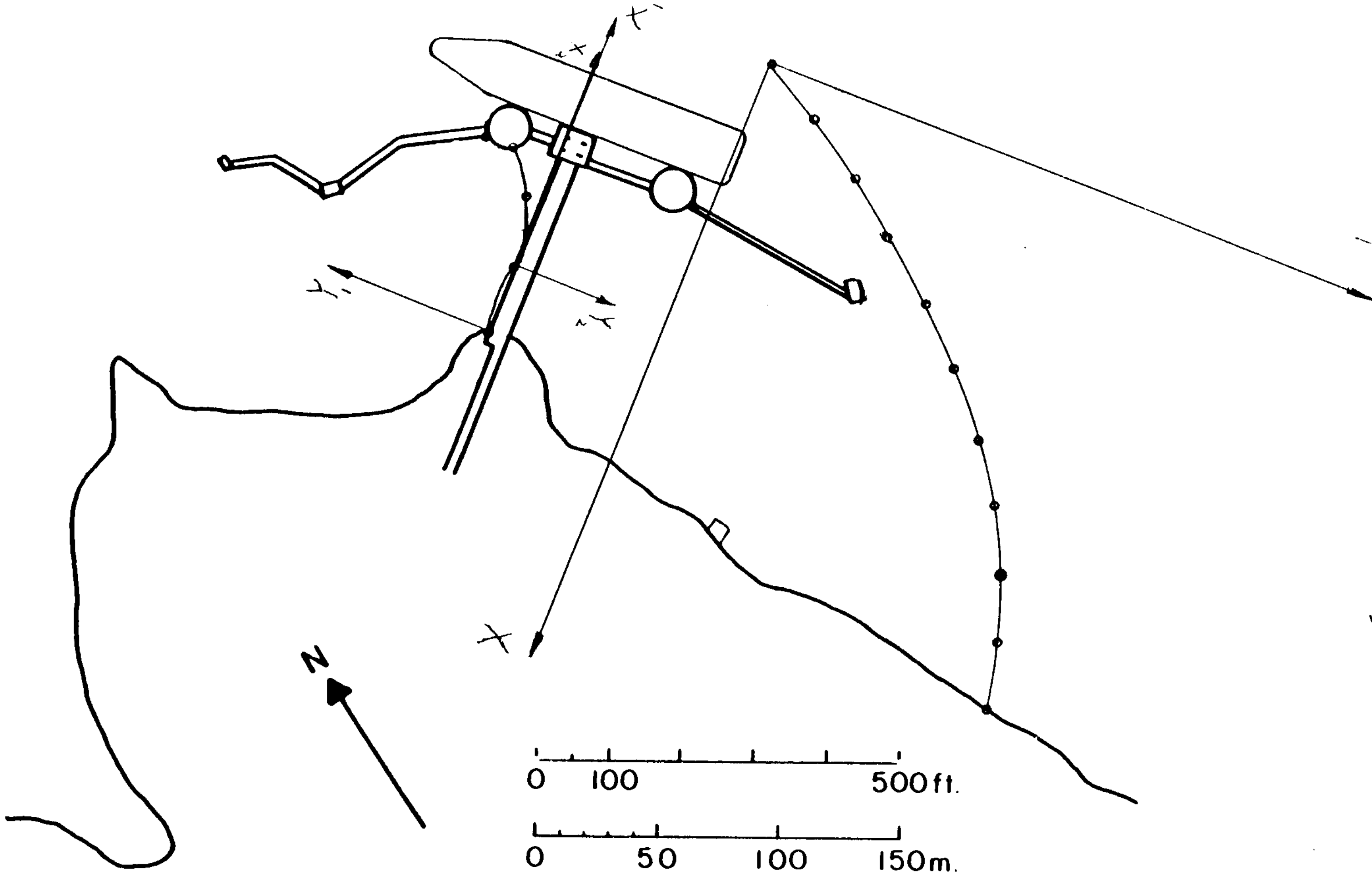

Figure 5.33: Diversion configuration for ATC outside ebb. Dots indicate 100' intervals. Outer tension = 241 lbs. Inner tension = 180 lbs.

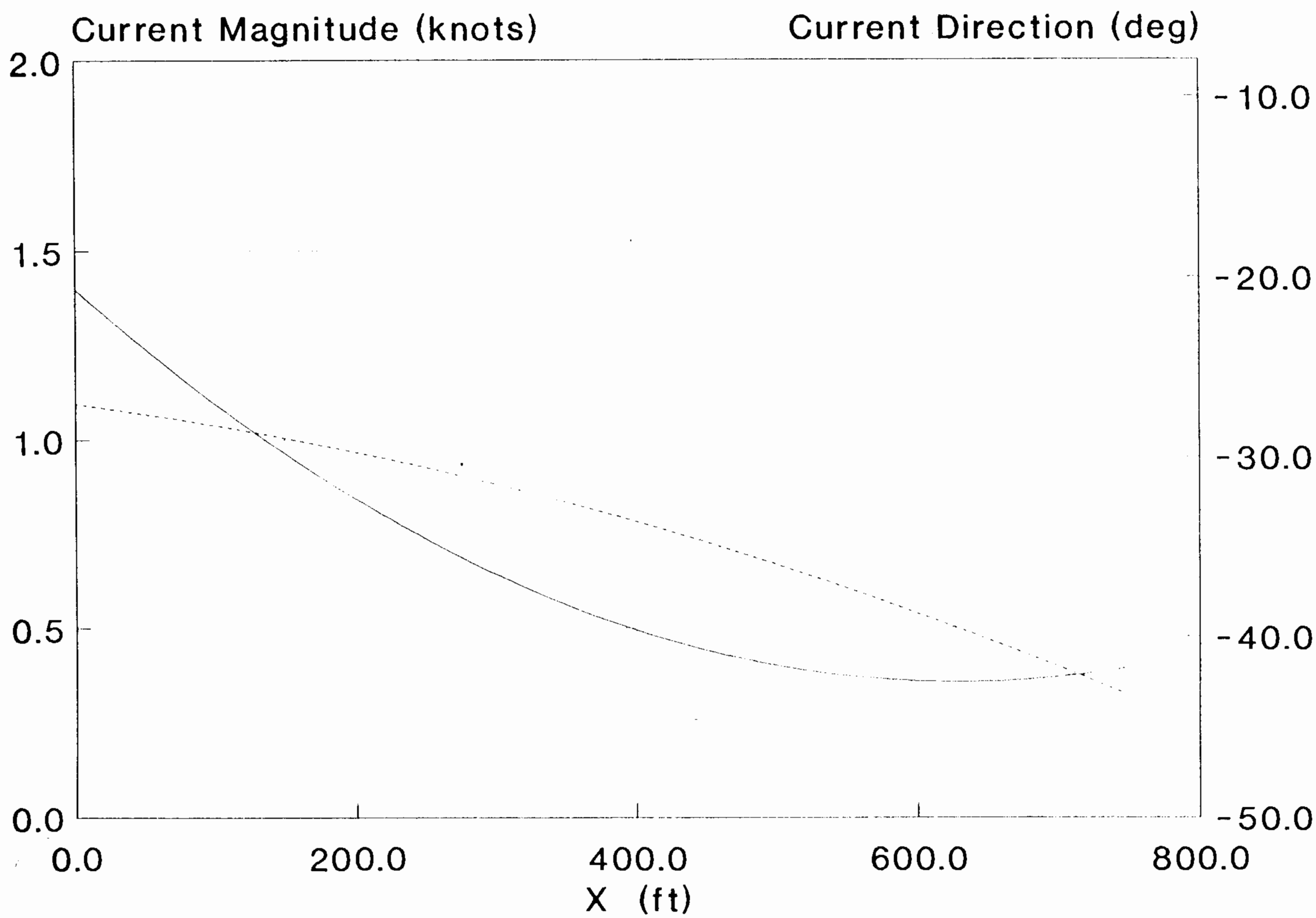

Figure 5.34: Current magnitude (——) and direction (----) for ATC outside ebb. Current directions are measured ccw wrt the y-axis.

Description	Value	
Direction of y-axis	143 °T	
Boom Length	1000 ft	
Boom End Location	747 ft	606 ft
Outer, Inner Boom Tensions	241 lbs	180 lbs
Maximum Normal Current	0.27 knots	
Max. Normal Current Location	747 ft	

Table 5.37: Summary of ATC outside ebb analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y-axis
0	1.4	-27
325	0.6	-32
500	0.4	-36

Table 5.38: Current data used for ATC outside ebb.

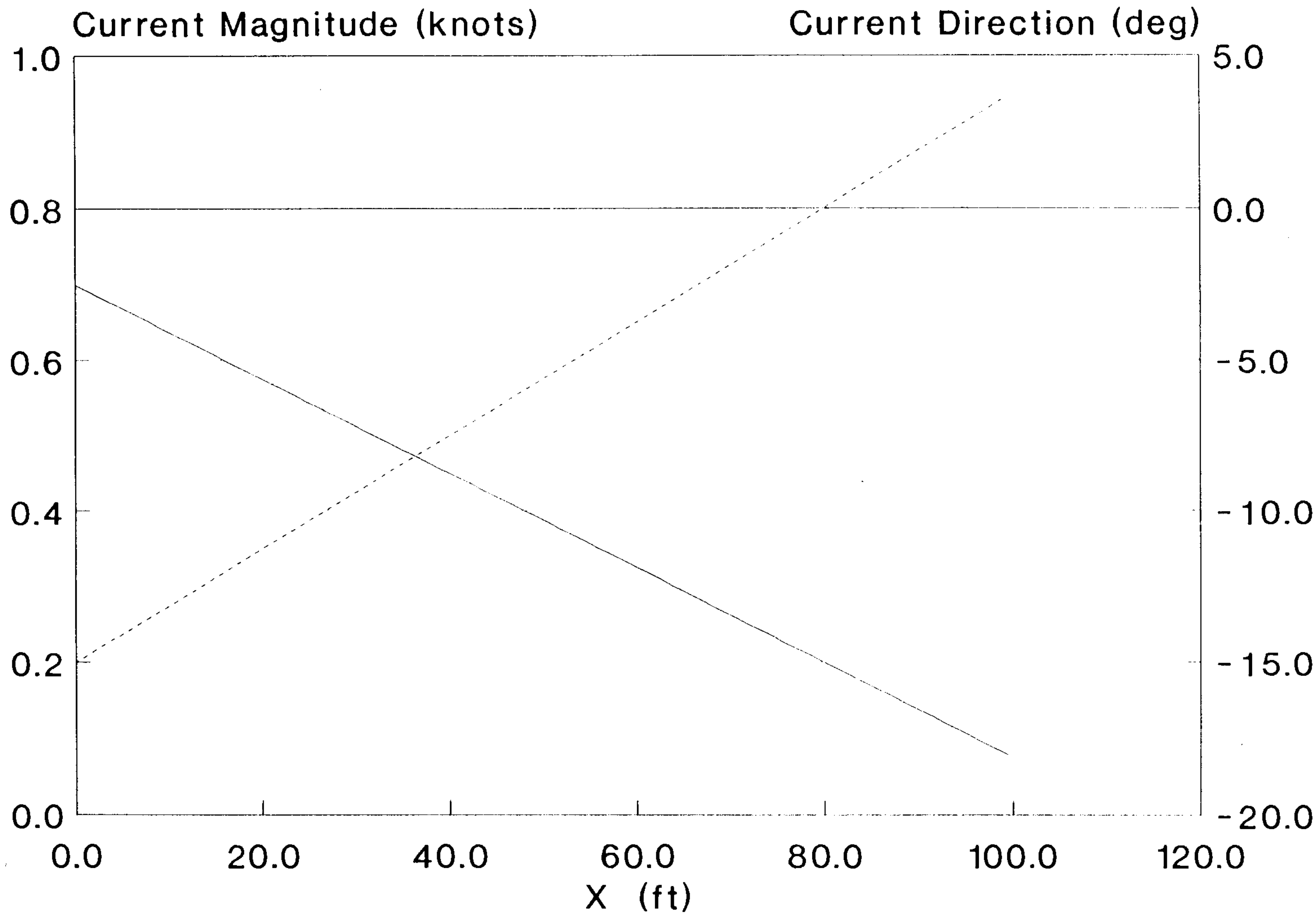

Figure 5.35: Current magnitude (——) and direction (----) for ATC in/outside ebb counter-flow boom section 1. Current directions are measured ccw wrt the y_1-axis.

Description	Value	
Direction of y-axis	323 °T	
Boom Length	100 ft	
Boom End Location	99 ft	3 ft
Outer, Inner Boom Tensions	300 lbs	300 lbs
Maximum Normal Current	0.6 knots	
Max. Normal Current Location	0 ft	

Table 5.39: Summary of ATC inside and outside ebb counter-flow boom section 1 analysis.

X Location	Magnitude	Direction
feet	knots	° ccw wrt y_1-axis
0	0.7	-15
80	0.2	0

Table 5.40: Current data used for ATC inside and outside ebb counter-flow boom section 1.

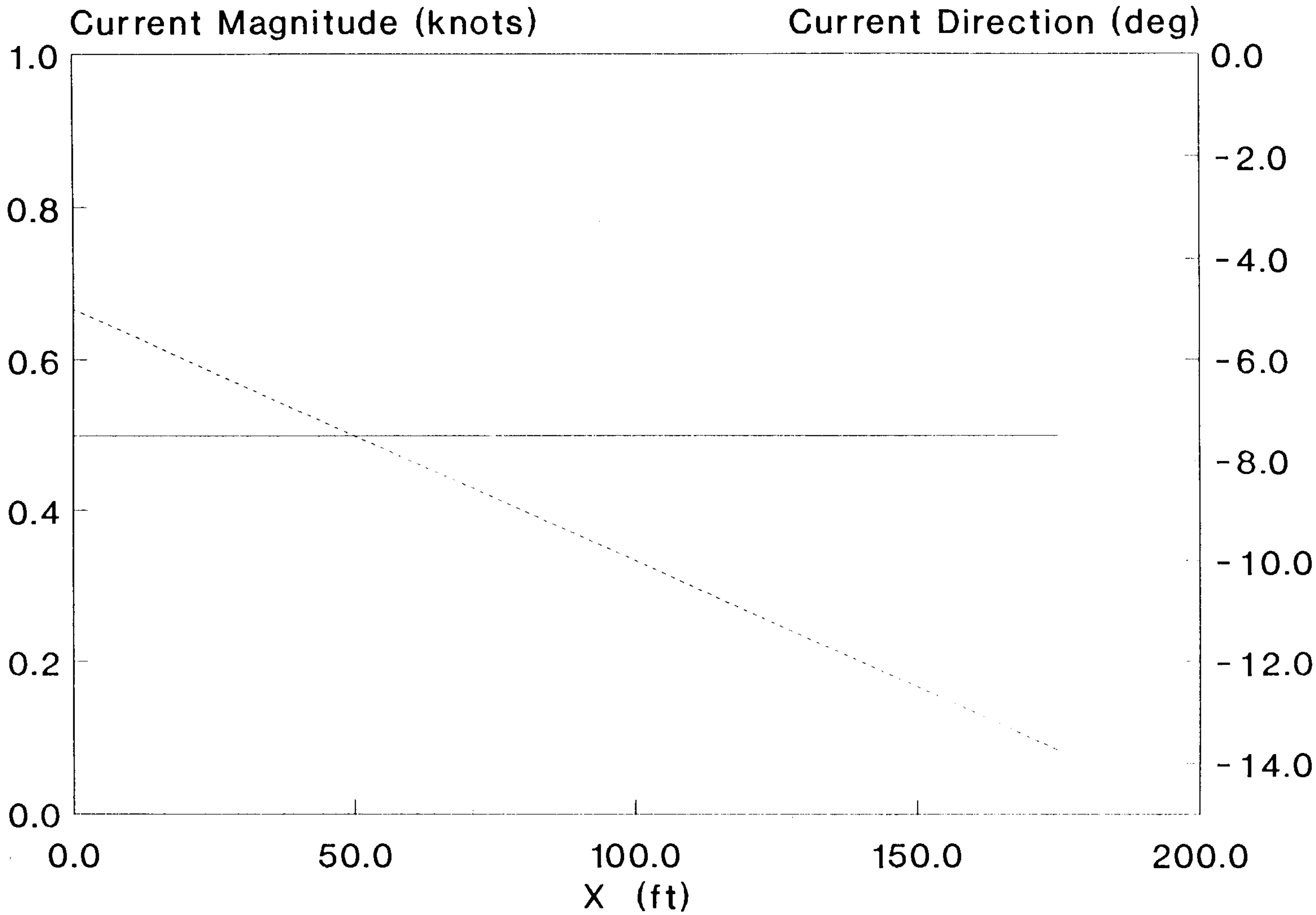

Figure 5.36: Current magnitude (——) and direction (----) for ATC in/outside ebb counter-flow boom section 2. Current directions are measured cw wrt the y_2-axis.

Description	Value	
Direction of y-axis	143 °T	
Boom Length	200 ft	
Boom End Location	175 ft	-80 ft
Outer, Inner Boom Tensions	300 lbs	299 lbs
Maximum Normal Current	0.50 knots	
Max. Normal Current Location	36 ft	

Table 5.41: Summary of ATC inside and outside ebb counter-flow boom section 2 analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y_2-axis
0	0.5	-5
100	0.5	-10

Table 5.42: Current data used for ATC inside and outside ebb counter-flow boom section 2.

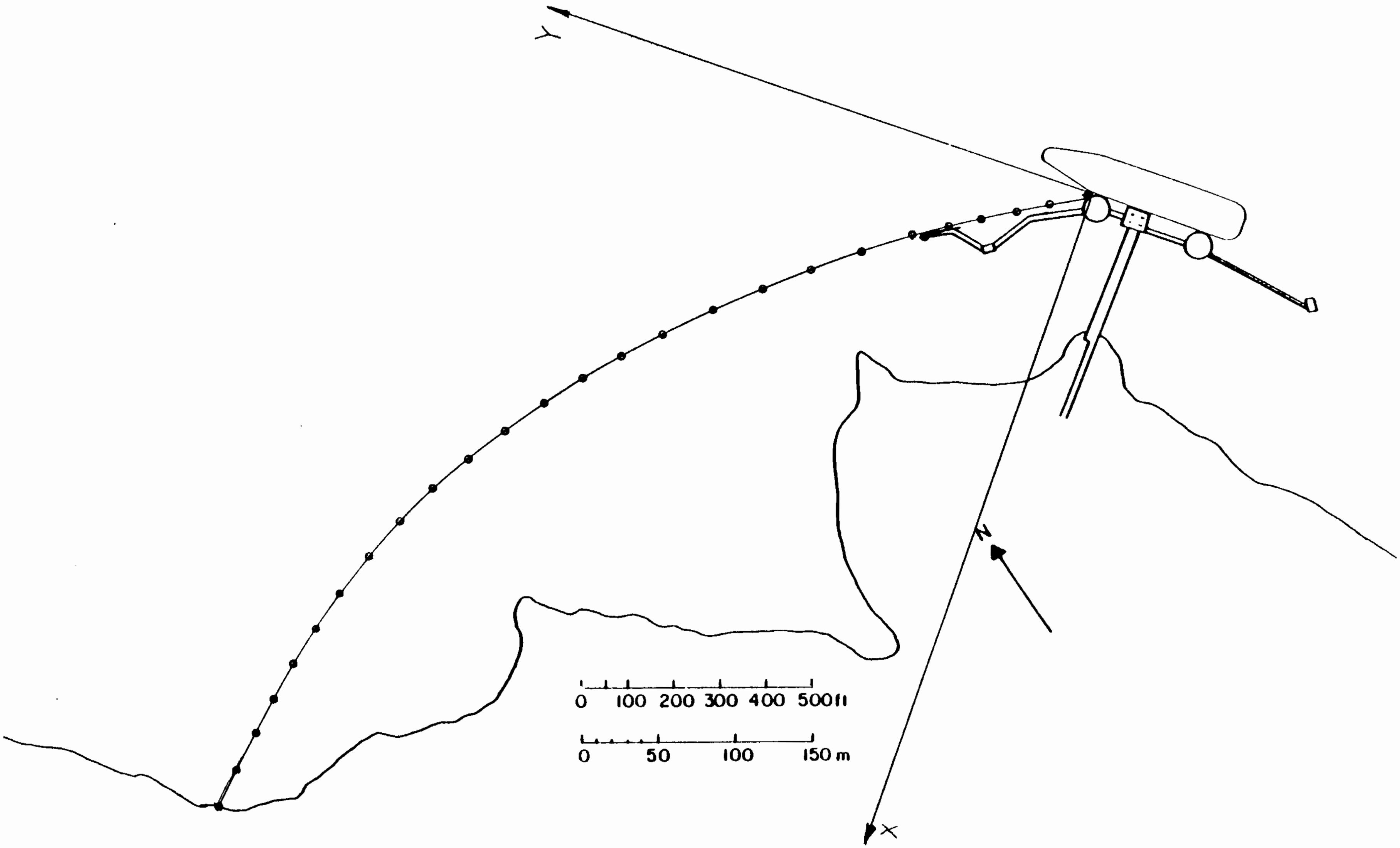

Figure 5.37: Diversion configuration for ATC inside flood. Dots indicate 100′ intervals. Outer tension = 2226 lbs. Inner tension = 1892 lbs.

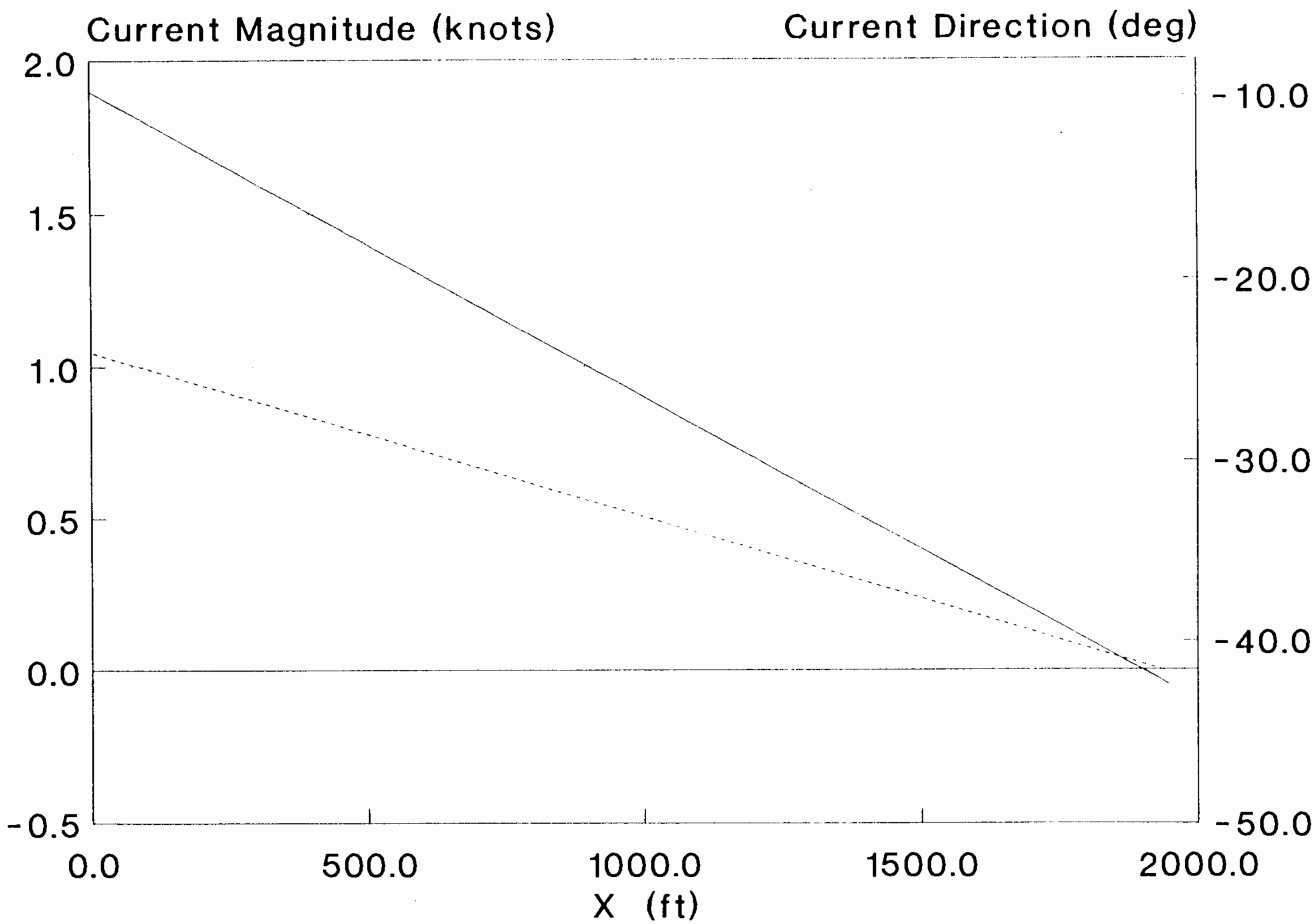

Figure 5.38: Current magnitude (——) and direction (----) for ATC inside flood. Current directions are measured cw wrt the y-axis.

Description	Value	
Direction of y-axis	323 °T	
Boom Length	2500 ft	
Boom End Location	1949 ft	1401 ft
Outer, Inner Boom Tensions	2226 lbs	1892 lbs
Maximum Normal Current	0.43 knots	
Max. Normal Current Location	958 ft	

Table 5.43: Summary of ATC inside flood analysis.

X Location	Magnitude	Direction
feet	knots	° cw wrt y-axis
0	1.90	-24
550	1.35	-29

Table 5.44: Current data used for ATC inside flood.

CHAPTER VI

ANCHORING

1. Terminal Field Work

A series of boom demonstration exercises were conducted at Northeast Petroleum on September 11, 13 and 20, 1990. The objectives were to evaluate deployment methods and to test boom anchoring procedures. Boom setting and recovery were made at slack water using small boats - the DES 19 ft. Pointer, the UNH 25 ft. Adams Point and the UNH 45 ft. Jere Chase.

In one exercise, two 40 lb. Danforths were used which held initially but later dragged before the flood tide had completed. A single 60 lb. Danforth, carefully set, held during an ebb tide deployment. It appeared that the use of Danforths or other lightweight anchors was not reliable due to the difficulty of setting them properly. The bottom was found to be coarse sand in some areas, but is cobble in others. Finding adequate holding ground is, therefore, hit-or-miss.

To obtain a secure attachment point, a screw-in type, permanent system was installed. The anchor consisted of an 8 in. auger head attached to a 6 ft. bar with an eye at the end. The auger was twisted into the bottom sediment by divers, and a chain was run from the eye up to a pickup buoy.

The system was tried during a flood tide set, but pulled out. It is possible that the anchor had been disturbed by a ship which had recently berthed at the terminal. Regardless, the system did not offer any improvement in reliability.

A training exercise was later held by terminal operators and by the U.S. Navy at Fuel Storage Corporation on June 26, 1991. The goal was to set variations of the inside flood and inside ebb configurations provided in Chapter V. UNH personnel were present to advise, but a terminal manager was in charge. The deployments went smoothly except for some minor problems. In particular, on the inside ebb the boom towing boat did not go directly ot the shore attachment point but took a looping course. This created a large bulge which could not be revoved as current speed increased. Previously, on June 21, 1991, UNH personnel successfully set 1000 ft. of boom along the intended condiguration using the DES 36 ft. Admiral Vose. Thus proper setting was demonstrated to be feasible. Since these were all "inside" configurations, the up-current attachment point was at the pier, and consequently no anchoring was required.

2. Anchor Recommendations

One solution to the outside configuration anchoring problem would be to use permanent, buoyed, sinker type moorings. Since the boom loads are up to 2 tons, sinker weights should be at least that amount.

An alternative approach would be to construct a barge capable of storing and deploying oil boom. In an emergency, the barge could be brought alongside the vessel, the boom payed out down-current and the end run into shore. The completed set would appear as in Figure 6.1. The design of a suitable barge was investigated with results reported by Galipeau and McAllister (1991).

In general, it is recommended that all terminals for which outside booming is possible either install permanent moorings or contribute to the construction of an oil boom response barge. The barge system would, of course, also be functional for all inside configurations as well. The use of portable Danforth anchors should be restricted to protective booming of river tributaries where currents are much smaller.

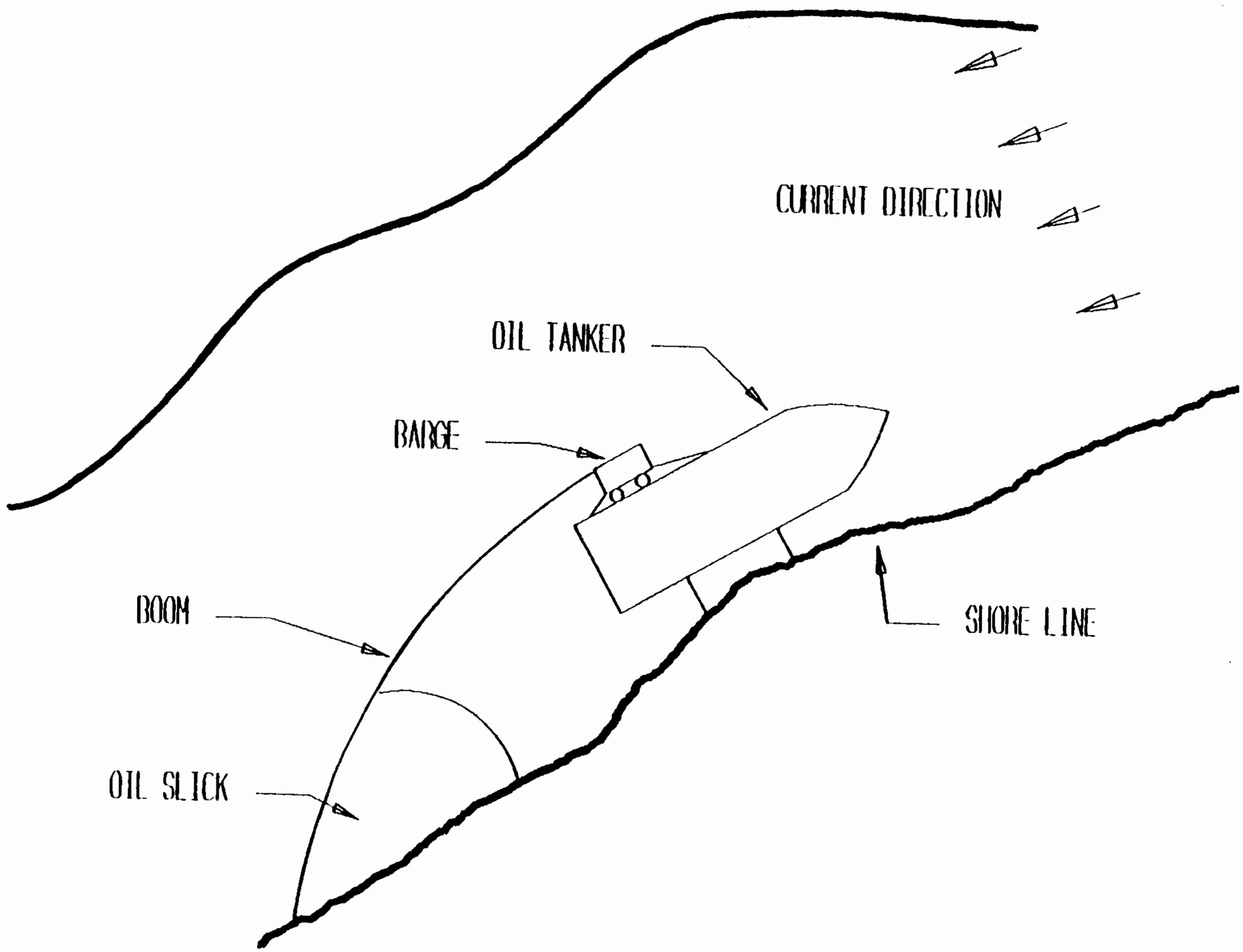

Figure 6.1: Diversion boom deployed from barge.

In these applications, as discussed by Swift et al. (1991), 85 lb. Danforths are normally adequate.

CHAPTER VII

PROTECTIVE BOOMING

1. Squamscott River Wetlands

The NH Department of Fish and Game has designated the tributaries shown in Figure 7.1 as priority resource areas on the basis of their ecological value and vulnerability to oil spill damage. In this report, approaches using oil booms are developed for protecting the Squamscott River Wetlands consisting of the Lamprey and Squamscott Rivers, as well as Lubberland Creek.

2. Methodology

Though currents at the tributary mouths are not as fast as in the Piscataqua, maximum current speeds normally exceed the leakage criterion of 0.6 kts. It is, therefore, not possible to simply deploy a boom across the mouth perpendicular to the flow. The boom must be angled as in the diversion boom concept discussed by Savage et al. (1982), Swift et al. (1990) and Goodwin (1991). To maintain boom

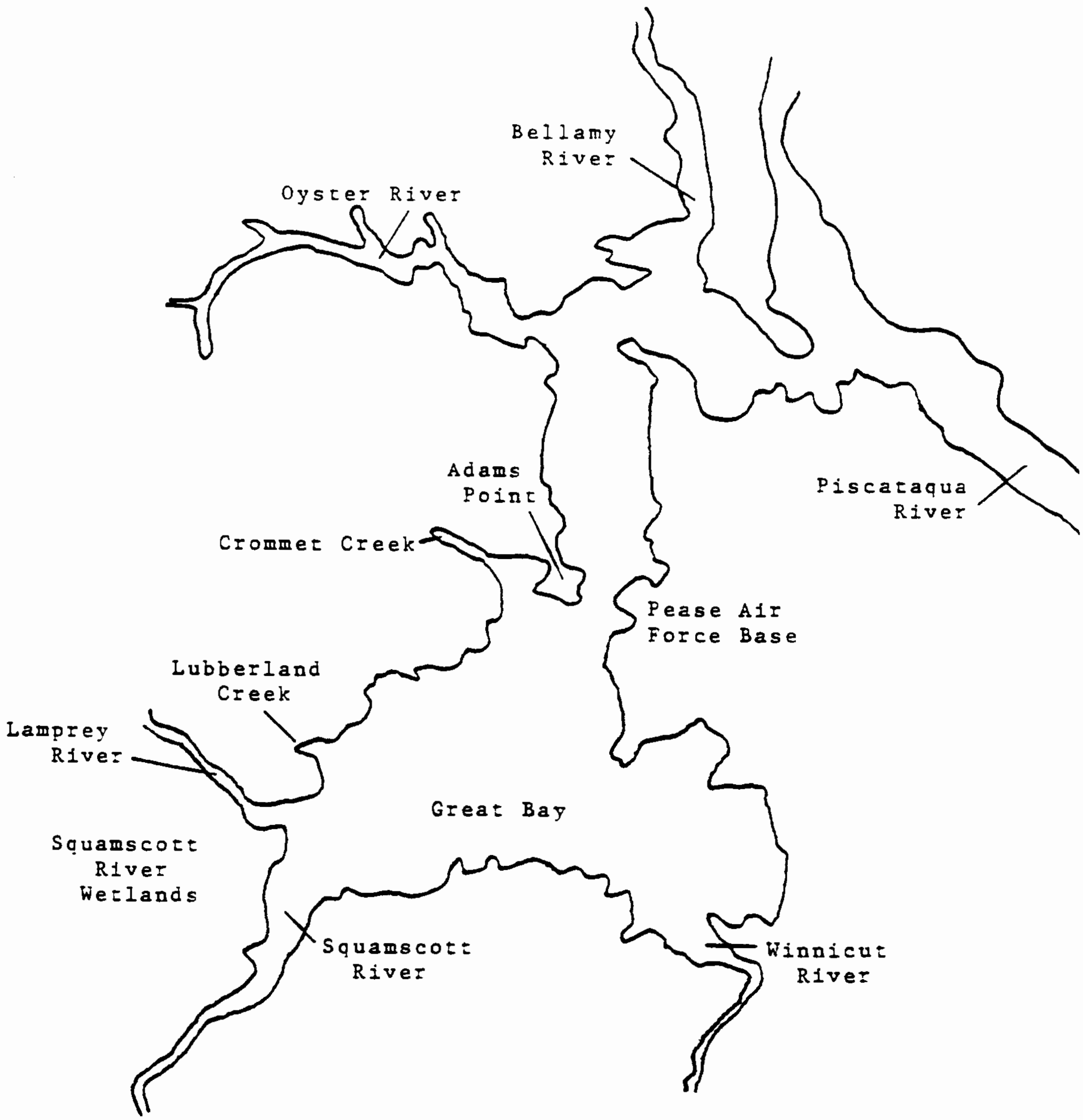

Figure 7.1: Priority tributaries to be protected.

angle and also close the mouth, the protective boom configuration shown in Figure 1.3 can be used.

The protective boom configuration splits the incoming oil flow at the buoy/anchor attachment point. On each side the boom diverts the slick to a shore skimmer/recovery area. Each side individually resembles a diversion boom and can be designed and analyzed using the catenary-based, boom configuration model developed in Chapter II. The critical design criterion is that the boom deflect oil without leaking. This is achieved when the normal (perpendicular) component of current is less than 0.6 kts (see Figure 1.3).

As in the case of diversion boom planning and design, the first step was to obtain the surface currents. A field program was, therefore, completed in which surface currents (due primarily to the tides) were measured and the data processed. Next, protective boom configurations for each tributary mouth were designed and analyzed. A demonstration boom deployment exercise (without oil) was then held at Lubberland Creek. General aspects of boom stability, deployment shape and incident current could be observed.

Field measurements of surface current were made at stations distributed at the mouths of the system tributaries under consideration. Currents at these locations are due principally to the tides with typical speeds about 1 kt or less. Since tides are repeatable, these data sets can be used to infer the maximum flood tide currents to be employed in boom configuration design. Direct measurements were processed to yield current vectors required for boom configuration design and analysis. Maximum currents over the flood phase were interpolated, and adjustments made to correspond to the largest tidal current occurring over the spring-neap cycle. Wind is also an important contributor to oil movement which must be added to the tidal current component. It is known that oil will be driven at 3% of the wind velocity. At each tributary, a worst case direction was identified, and wind statistics were analyzed to determine a suitable design wind speed. The speed selected was such that observed wind components in that direction were less than the selected speed 97% of the time. Oil transport velocities were then calculated as the vector sum of the tidal current plus 3% of the wind velocity.

Using the oil transport vector, a trial protective boom configuration was generated for the tributary mouth. In practice, it is helpful to sketch this on a site map.

critical points are the anchor location and shore tie-off positions. Each side must be angled such that the normal component of current is less than 0.6 kts in order to satisfy the leakage criterion. In planning the trial shape, allowance should be made for some boom sag.

Each side is then analyzed as a separate diversion boom problem using the catenary-based, configuration design software described in Chapter II. This computer program numerically solves the equilibrium and boundary condition equations assuming constant current velocity. The model takes into account the normal component of drag force which is modeled using a drag coefficient approach. This computer program is very easy to use and is sufficiently accurate for the relatively short, moderate velocity configurations used in tributary protective booming.

Since the leakage criterion is the principal design requirement, these computations were done using the design oil transport velocity which includes wind effects. This has the effect, however, of overestimating boom tension. The reason is that the wind driven contribution (3% of the wind velocity) does not penetrate below the surface for the fetch length and duration time scales considered here. The fluid velocity causing hydrodynamic forces on the skirt is essentially the tidal current. Thus each design was re-analyzed using the maximum tidal current as input for the purpose of predicting boom tension. It should be noted that the anchor must sustain the combined tensions of the two sides of the protection configuration.

3. Results

Maximum flood tide currents over the spring-neap cycle are shown in Figure 7.2. Generally, the flow follows the tidal channels with speeds within the range from 1/2 to 1 knot (except for Lubberland Creek). At Lubberland, current entering the inner mouth is only 0.30 kts, while in the outer mouth, speed is negligible.

The design oil transport velocities were calculated using wind directions inward to each individual tributary mouth. For Lubberland, a maximum tidal current of 0.30 kts at 0 deg (True) was added to 3% of the 12 kt wind from the south to give a design oil transport velocity of 0.66 kts at 0 deg (True). For the Lamprey, a maximum tidal current of 0.53 kts at 278 deg (True) was added vectorially to 3% of a 13 kt wind from the east to yield a design oil transport velocity of 0.92

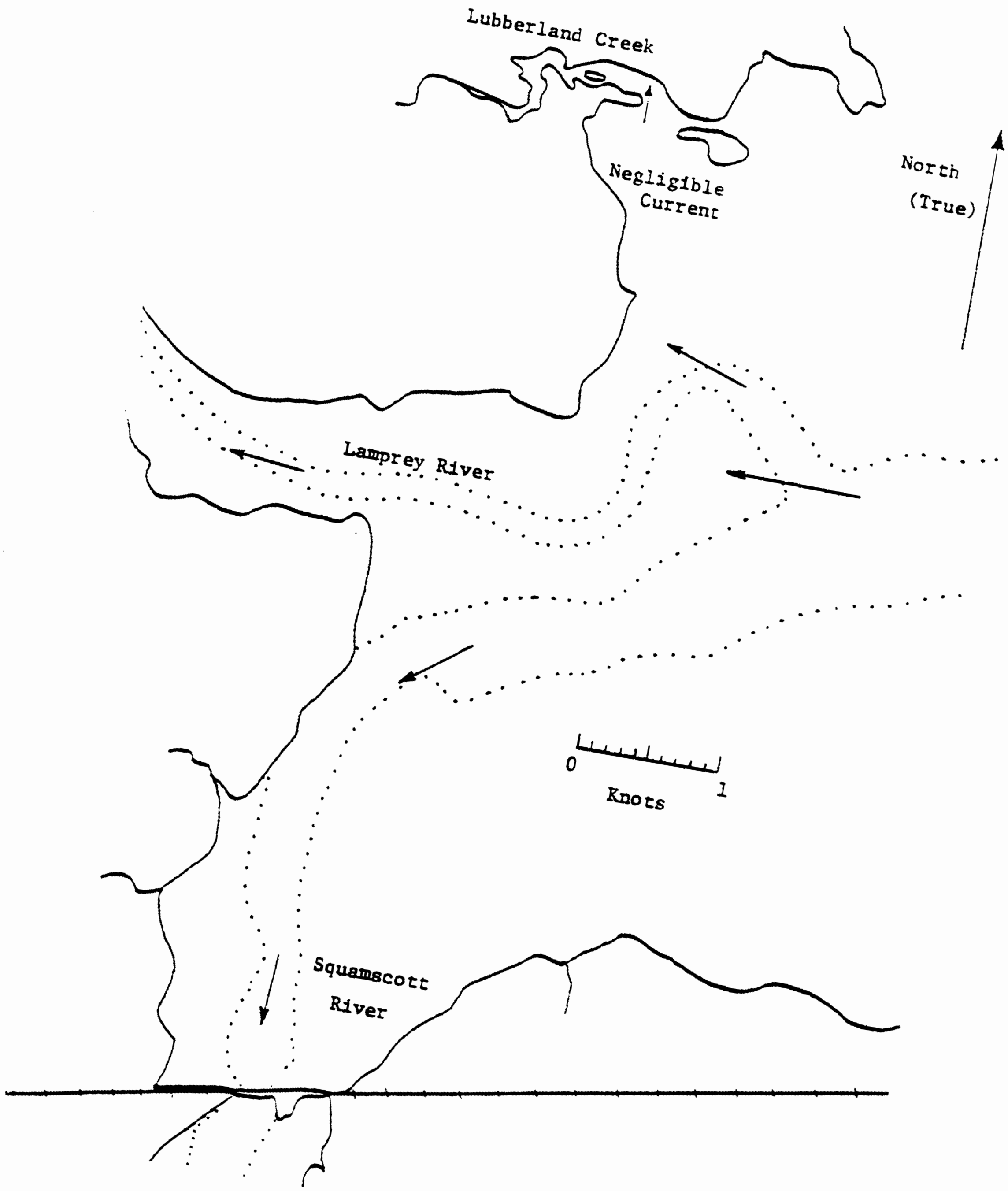

Figure 7.2: Squamscott River wetlands maximum flood tidal currents.

kts at 275 deg (True). For the Squamscott, a maximum tidal current of 0.54 kts at 185 deg (True) was added vectorially to 3% of an 18 kt wind from the north to generate a design oil transport velocity of 1.08 kts at 182 deg (True).

The velocities were used to design the recommended boom configurations shown in Figure 7.3. Each design meets the leakage criterion based on the design oil transport velocity as incident flow. Boom tensions, calculated using the maximum tidal current velocity, are provided in Figure 7.3. Boom lengths, shore attachment points and compass bearings for locating the anchor/buoy positions are also shown in Figure 7.3.

A Lubberland Creek demonstration boom deployment exercise was conducted on July 10, 1991. The boom was secured to a landing pile on the north side of the mouth. The other end was held by a 14 lb Danforth at the Moodys Point shore. Excess boom was taken up by stretching as far as possible along the Moodys Point shoreline. Marsh grass interference prevented the boom from taking a smooth curve. Nevertheless, currents are so weak that the leakage criterion was satisfied everywhere and the Creek was protected. A better shape could be achieved, however, by not using the landing as an

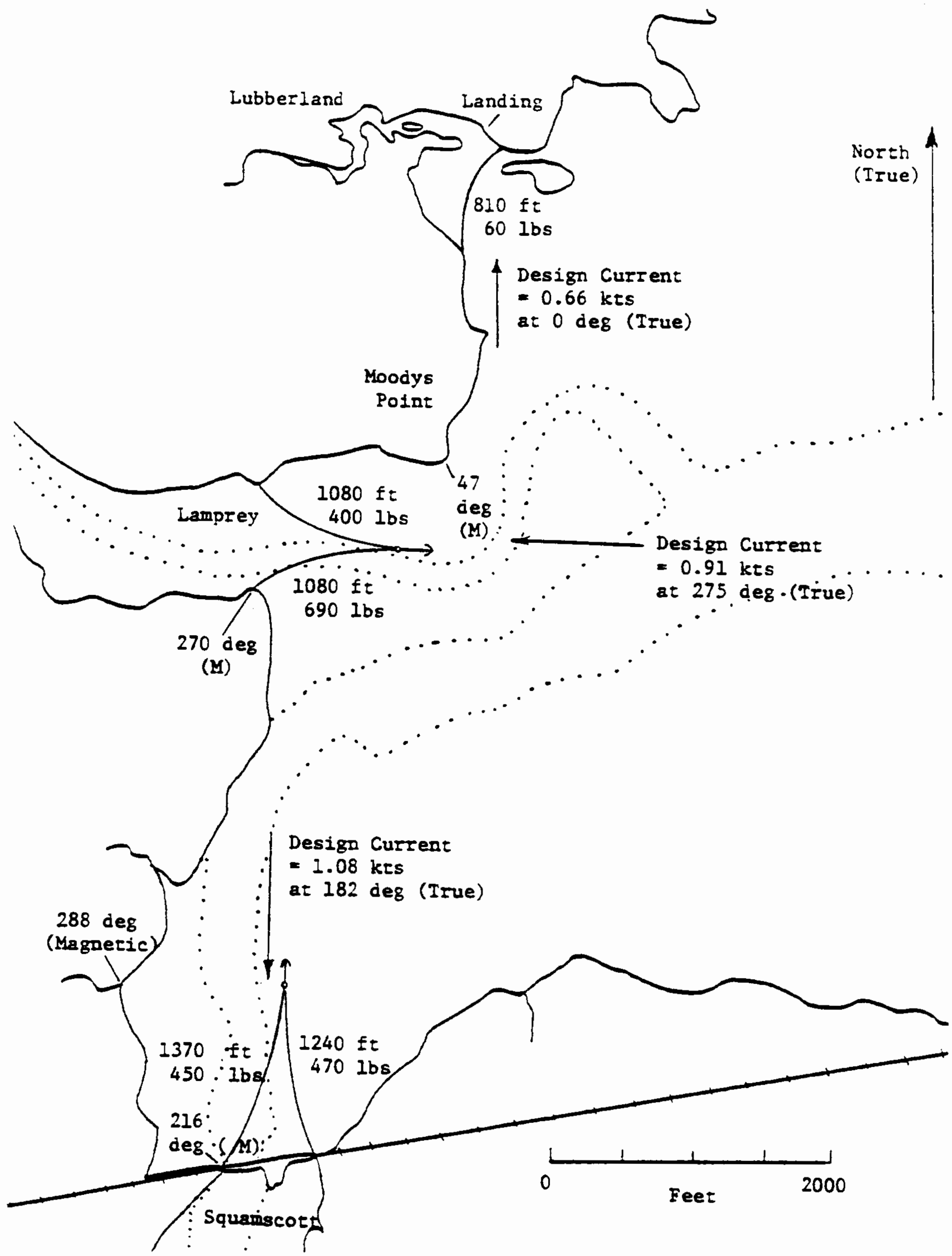

Figure 7.3: Squamscott River wetlands recommended boom configurations.

attachment point (though it is convenient). Instead, that end could be anchored on shore east of the landing with the boom just passing the tip of the island as shown in Figure 7.3. A shore anchor is necessary because there are no nearby trees or rocks to tie around and the ground is marshy.

CHAPTER VIII

OIL SPILL TRAJECTORY MODEL

1. User's Manual

This report describes the operation of a computer model for simulating the trajectory of an oil spill in the Piscataqua River and Great Bay Estuary. The oil spill trajectory program was written for an X Windows system running in a UNIX environment. The program is interactive, allowing the user to graphically display the results of different input parameters.

SYSTEM REQUIREMENTS

To use the oil spill program, your computer system must have the following:

- An IBM PC, PC compatible, or workstation that runs UNIX System V.

- 486 Microprocessor. The program has not been tested on a 386 machine.

- VGA video adapter with at least 16-color and 640X480 resolution.

- Hard drive (At least 1 Mbyte of available memory).

- Double-sided 5¼-inch or 3½-inch disk drive.

- A minimum of 640K of available user memory.

- Math coprocessor recommended.

- X Windows with a standard window manager. The program has been tested on an olwm (OPENLOOK window manager) and mwm (Motif window manager). The program should be compatible with other standard window managers such as the twm (Tab window manager) and uwm (Universal window manager).

INSTALLATION

The program runs best when installed on a hard disk. The following directions are for installation of the program onto the hard drive using UNIX commands. The program can be installed using similar DOS commands under a DOS environment.

1. Log in as a user on the UNIX system.

2. Make a new directory, preferably in the user's home directory.

   mkdir oilspill {RETURN}

3. Move to the new directory oilspill.

   cd oilspill {RETURN}

4. Copy all files from the floppy disk to the oilspill directory on the hard disk.

   tar xvf /dev/"device name" {RETURN}

   Where "device name" is the name of your floppy drive.

5. The program needs to be compiled in the C language. Type:

comp draw_oil {RETURN}

loadoil {RETURN}

ccomp and loadoil are files which perform the operation of compiling and linking the necessary files of the program. The ccomp file compiles all .c files in the current directory by using the "cc -c" command. The loadoil file links all the .o files and names the executable file oil.x by using the "cc -o oil.x file1.o file2.o file3.o ...." command. These commands can be inputed manually if the ccomp and loadoil files are incompatible with your system. Consult your computer's UNIX C language guide if necessary.

RUNNING THE PROGRAM

Once the program has been installed and compiled on the hard drive, you can run the program. At this point we assume you have already entered X Windows. If not, do so now. From a xterm window, enter the directory where the program resides.

cd /"HOME DIRECTORY"/oilspill {RETURN}

You can run the program by typing the following:

```
oil.x      {RETURN}
```

Two windows should appear, a Help Window and a Map Window of the Great Bay.

HELP WINDOW

The Help Window becomes active when the program is started. The Help Window, shown in Figure 8.1, gives common commands which can be used while running the oilspill program.

Clicking the right mouse button while the pointer resides in the Help Window dismisses the window. Pressing H or h while the pointer resides in the Map Window brings up the Help Window. The Help Window can also be iconed for easy access.

MAP WINDOW

The Map Window, shown in Figure 8.2, represents the outline of the Piscataqua River, Little Bay, and Great Bay. The dotted mesh area represents mud flats that flood with the tide. The dotted line that runs down the middle of the River and Bay represents the channel center-line from which the currents are calculated. The zero point of the channel center-line is at the Great Bay end and increases heading

```
While the pointer resides in a Map Window:
 press R, r or right_arrow to pan the map right;
 press L, l or left_arrow to pan the map left;
 press D, d or up_arrow to pan the map down;
 press U, u or down_arrow to pan the map up;
 press I or i to zoom in to the map;
 press O or o to zoom out from the map -
       the zoom focus is the pointer position.
Capital letters perform zoom and pan to a greater
 degree than do small letters or arrows.

While the pointer resides in a Map Window:
 press C or c to copy the map in its un-zoomed,
       un-panned form into a newly created window;
 press N or n to create a new window for a new map;
 press S or s to return the map to its un-zoomed,
       un-panned form and the window to center screen;
 press B or b to send the window below all others;
 press k to kill the window and K to kill all windows -
       the presentation manager program terminates
       when the last Map Window dies;
 press H or h to bring up this Help Window.

Clicking the pointer while it resides in a Map Window
 communicates its position to the map therein and
 initiates possible dialog with that map application.
Clicking the pointer while it sits in the Help Window
 dismisses that window.

Pressing a key unknown to a window or clicking the
 pointer on a static map elicits a beep from
 the program - the Help Window knows no key.

A dynamic map runs only while the pointer resides
 in one of its windows.
```

Figure 8.1: Help window.

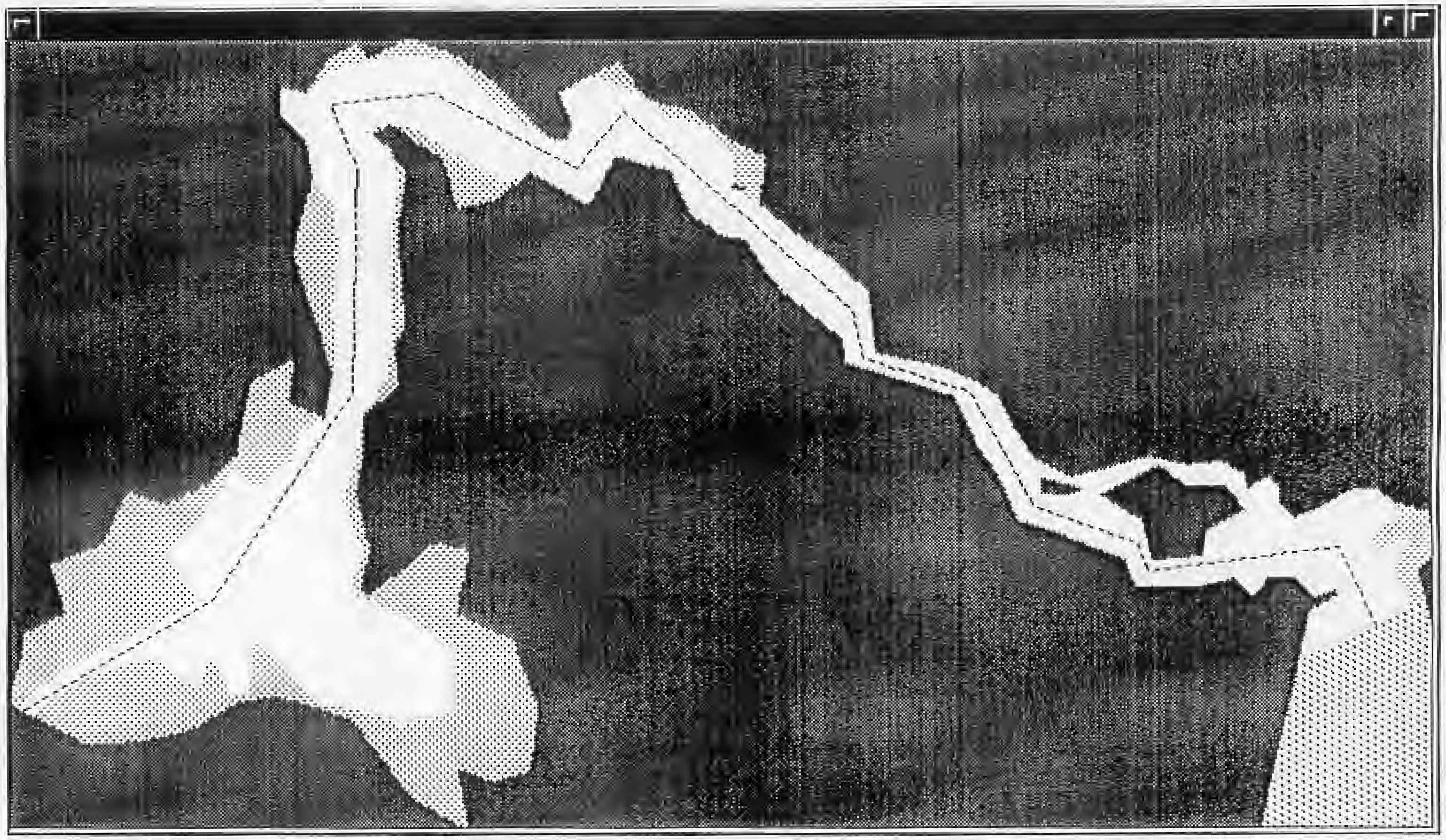

Figure 8.2: Map window.

toward the ocean. The pointer can be moved around the map using the mouse.

SIMULATING AN OIL SPILL

Move the pointer to the location on the map where the oil spill is to occur. Click the left mouse button. This relays the oil spill location to the program. At this point, the xterm window will show location information and ask a series of questions which will determine the size of the spill, wind speed, time, and tide status.

The xterm screen should display a similar message:

```
u = 10781, v = 8453
s = 15.88 kilometers, mean current 0.148 knots.
low-tide at 241, high tide at 626 minutes.
point number>>
```

The u and v terms represent the x and y coordinates of the chosen oil spill location. The s term is the distance along the channel center-line from the zero starting point. The mean current is for the chosen point in knots.

The tide cycle is represented on a scale of 770 minutes. The program sets the low-tide and high-tide automatically. With this information, the actual tide at time of the spill can be chosen.

Point Number

The first question asked is the point number. This represents the number of oil points to be released. A value of 1 will produce a single oil drop on the screen. A value of 100 will produce one hundred oil drops. The size of the oil points is determined by dividing the amount of oil spilled (in gallons) by the point number.

Volume and Thickness

The next question is on the amount of oil spilled.

volume (gallons), initial thickness>

Input the amount of oil spilled in gallons. If an initial thickness of the oil is desired, input the measurement in millimeters. The following shows a spill of 100000 gallons with an initial thickness of 2 mm.

volume (gallons), initial thickness> 100000 2

The program will come back with a similar message:

Region radius is 109.77 meters, marker radius is 35 meters.

The region radius is the total size of the oil spill. The marker radius is the size of the individual points of oil as specified by the point number.

By typing "p", the default will be invoked. The default for this step is 10,000 gallons and 1 mm.

Wind Speed and Direction

Next the program asks for the wind speed and wind direction:

wind speed (knots), wind direction (degrees)>>

The wind speed is inputed as knots. The wind direction is based on an X-Y coordinates, with east in the positive x direction and north in the positive y direction. The wind directions are "direction from". The following would give a wind of 4 knots from the north.

wind speed (knots), wind direction (degrees)>> 4 -90

The default "p" is 0 knots and -45 degrees.

Start Time and Time Step

The start time and time step deal with the tidal cycle. The following question is prompted:

start time, time step (minutes)>>

The current tide at time of the spill can be specified by choosing the appropriate start time. For example, lets say that the oil spill occurs exactly at high tide and we wish to calculate the spread every ten minutes. Looking back at the introductory location information:

```
u = 10781, v = 8453
s = 15.88 kilometers, mean current 0.148 knots.
low-tide at 241, high tide at 626 minutes.
point number>>
```

The high tide begins at 626, so the response to the question would be:

```
start time, time step (minutes)>> 626 10
```

If the spill occurred 30 minutes after low-tide and we wish to plot the spread every five minutes, the response would be:

```
start time, time step (minutes)>> 271 5
```

The default "p" is 0 start time, and 10 for the time step.

Local Time

The local time of the oil spill is specified during this step.

```
local start time (hh:mm:ss)  (24 hours)>>
```

The local start time is the time that the spill occurred in 24 hour time system (military time).

The default "p" is 00:00:00.

Injection Period and Time Step

This step allows for the user to specify how long it took for the oil to spill into the water.

injection period (minutes), injection time steps>>

The injection period is the time that it took for the oil to enter the water. This value should be in minutes.

The injection time steps indicate how many times the oil is to be released into the water. This must be a whole number and should be at least one less than the point number.

For example, assume that the oil is to be released over two hours at six different times. The point number is twenty. The information would be input as follows:

injection period (minutes), injection time steps>> 120 6

The default "p" is 0 minutes for the injection period, and 0 for the time steps.

Time Interval

The program will then come back with a similar message:

```
There are n points in the region.
The tide is ebbing.
Time interval between display frames in seconds (0
     is static)>>
```

This last question deals with how fast the display will change with each new calculation. A value of 0 will stop the screen after the oil is released. A value of one will produce the quickest response in the display. If for example you wish to have the screen change every ten seconds so you can analyze each screen, then the input would be:

Time interval between display frames in seconds (0 is static)>> 10

Tracking The Oil Spill

At this point, the program will release the oil and track its progress through the bay and river. The pointer must be located in the Map window for the program to run. The program can be paused at any time by moving the pointer out of the Map Window.

The xterm window will then begin printing the information on the amount of oil that is free, stuck, or departed for each time step. The following is an example:

```
00:10:00 - 100.00% free, 0.00% stuck, 0.00% departed
00:20:00 - 100.00% free, 0.00% stuck, 0.00% departed
00:30:00 - 100.00% free, 0.00% stuck, 0.00% departed
00:40:00 - 100.00% free, 0.00% stuck, 0.00% departed
00:50:00 - 100.00% free, 0.00% stuck, 0.00% departed
01:00:00 - 100.00% free, 0.00% stuck, 0.00% departed
Injection completed
01:10:00 - 100.00% free, 0.00% stuck, 0.00% departed
01:20:00 - 100.00% free, 0.00% stuck, 0.00% departed
01:30:00 -  97.96% free, 2.04% stuck, 0.00% departed
01:40:00 -  95.92% free, 4.08% stuck, 0.00% departed
01:50:00 -  91.84% free, 8.16% stuck, 0.00% departed
```

```
02:00:00 -  90.82% free, 9.18% stuck, 0.00% departed
02:10:00 -  85.71% free, 14.28% stuck, 0.00% departed
```

The percent free means the oil is still caught in the current. If the oil makes contact with the shore line, it then becomes stuck. The percent departed is the portion of oil that has floated out of the river and is heading toward the ocean and beaches.

When the program is completed, the following message will appear:

```
Less than 1% of the oil remains free.
```

A sample oil spill may look like so:

```
u = 10958, v = 8188
s = 16.19 kilometers, mean current 0.133 knots.
low-tide at 239, high tide at 624 minutes.
point number>> 10
volume (gallons), initial thickness> 10000 1
Region radius is 109.77 meters, marker radius is 35
     meters.
wind speed (knots), wind direction (degrees)>> 5 85
start time, time step (minutes)>> 239 30
local start time (hh:mm:ss) (24 hours)>> 12:40:00
injection period (minutes), injection time steps>>
     p
There are 10 points in the region.
The tide is flowing.
Time interval between display frames in seconds (0
     is static)>> 1
12:50:00  -  100.00%  free,     0.00%  stuck,  0.00%
     departed
13:20:00  -  100.00%  free,     0.00%  stuck,  0.00%
     departed
13:50:00  -  100.00%  free,     0.00%  stuck,  0.00%
     departed
```

```
14:20:00 -   90.00% free,   10.00% stuck,  0.00%
     departed
14:50:00 -   90.00% free,   10.00% stuck,  0.00%
     departed
15:20:00 -   20.00% free,   80.00% stuck,  0.00%
     departed
15:50:00 -   10.00% free,   90.00% stuck,  0.00%
     departed
16:20:00 -   10.00% free,   90.00% stuck,  0.00%
     departed
15:50:00 -    0.00% free,  100.00% stuck,  0.00%
     departed
Less than 1% of the oil remains free.
```

At this time another point may be chosen for an oil spill by moving the pointer to the location on the Map Window and clicking the mouse button.

PROGRAM FILES

The oil spill program consists of the following components:

File	Description
ccomp	Compiles the C programs
loadoil	Links the C programs into an executable file named oil.x
great_bay	Data file for the geometry of the Piscataqua River and Great Bay.
map_windows.c	Main program. This file is the window and program manager.
map_move.c	Utility program for the Map Window. Allows for panning, zooming, and resizing of the window.

map_struct.c	Communication utility in Map Windows.
draw_oil.c	Requests the initial oil parameters from the user and then tracks the oil slick through the bay.
ledger.c	Generates a grid for the bay and determines current direction.
surface_f.c	Generates the current velocity at each node for the grid generated in ledger.c. This program takes into account the tide cycle.
chain.c	Breaks the shoreline boundary into chains and keeps account of their order.
intersect.c	Determines where oil will stick on the shoreline by calculating the intersection of the oil slick with the boundary chain.
heap_sort.c	Utility program which does a heap sort on the chains.
bay_bounds.c	Reads in the Great Bay data file.
poll.c	Polling program. Allows for pause between displays by setting an alarm clock.
rk4.c	Solution of differential equations for velocities with a Runge-Kutta routine.
urand.c	Uniform random number generator. Used to randomly place oil injections into a given area.
event_names.h	Diagnostic program that goes with the Map Window.
help_text.h	Help Window file.

stipples.h	Data file of available stipples for background characters.
icon.h	Produces the icon figure.

2. Current Generation

The primary process controlling the movement of oil in the estuary is tidal currents. The strength and speed of the changing currents causes the oil to spread throughout the estuary quickly. The current cycle is based on 770 minutes, and can change in both magnitude and direction on a minute-by-minute basis. It is therefore important to provide a method for determining the current velocity and direction at any given time step.

The tidal currents in the Great Bay and Piscataqua River were estimated by using the data taken by Swift and Brown (1981) for stations C104, C119, C124, and C131. Equation 8.1 was derived from the data for these stations.

$$U_s(s_{u,d},t) = m_i + A_i \sin(w(t - T_i)) \qquad (8.1)$$

m_i = mean station current

A_i = 1/2 the current range between high and low tide

w = (2 * PI)/T

T = 770 minutes

t = time

T_i = time delay with respect to a current station.

Equation 8.1 estimates the current at any point along the center-line axis. Axial currents off the center-line axis are linearly interpolated by using Equation 8.2 and 8.3.

$$U_L = U_s(s,t)(1 - (\frac{n}{w})^2) \tag{8.2}$$

$$U_s(s,t) = \frac{(s-s_u)U_s(s_d,t) + (s_d-s)U_s(s_u,t)}{s_d - s_u} \tag{8.3}$$

s = axial coordinate of nodal point

$s_{u,d}$ = axial coordinate of next upstream, downstream station

n = transverse distance

w = effective width scale for parabolic solution

The current direction was assumed to be parallel to the channel center-line axis at the center-line axis and parallel to the shoreline at the shoreline. A linear interpolation was used for the current direction between the center-line axis and shoreline.

3. Oil Slick Trajectory Algorithm

The oil-spill model predicts the advection of an oil spill of finite duration from a point source. The advection $\vec{U}_T$ is governed by Equation 8.4

$$\vec{U}_T = \vec{U}_L + 0.035\ \vec{U}_w \qquad (8.4)$$

where $\vec{U}_L$ is the tidal current as predicted by Equation 8.2, and $\vec{U}_w$ is the user-specified wind velocity.

The advection of the oil slick is modeled using Equation 8.4. A percentage of the wind velocity is added to the tidal surface current to obtain the total current in the estuary.

The theoretical justification of this approach lies in the balance between the surface shear stresses of the air and fluid sides of the air-sea interface. Surface shear from the air layer is a product of the density of the air, ρ_a, the square of the wind velocity vector measured at 10 meters above the water surface, $\vec{W}$, and a coefficient of friction between the air and water, C_{fa}. Surface shear from the fluid layer has the form

$$\vec{\tau}_{sw} = \frac{1}{2} C_{fw} \cdot \rho_w |\Delta\vec{U}_T|\Delta\vec{U}_T \qquad (8.5)$$

where C_{fw} is the coefficient of friction between the water and air, ρ_w is the density of water, and ΔU_T when added to the depth averaged tidal velocity vector, yields the surface velocity vector. Equating these shear stresses gives

$$\frac{\Delta\vec{U}_T}{U_w} = \left(\frac{C_{fa}}{C_{fw}}\right)^{1/2} \cdot \left(\frac{\rho_a}{\rho_w}\right)^{1/2} \qquad (8.6)$$

Because the friction factors in both air and water depend upon the hydrodynamic surface roughness, it can be assumed they are equal, so the effect of wind reduces to

$$\Delta\vec{U}_T = 0.035\ \vec{U}_w \qquad (8.7)$$

Hence the advection, $\vec{U}_T$, is the tidal current, $\vec{U}_L$, plus the wind-driven circulation, $\Delta\vec{U}_w$, resulting in the basic governing equation. The advantage of this approach is that it is simple to implement and can be coupled with the depth-averaged velocities calculated by some other means.

4. Sample Runs

Several simulated oil spills were tested using the oil trajectory program. The following are the results of four test spills at the fuel storage terminal in Newington. The spills were simulated at low and high tide, and with and without a nine knot wind from the SE. The oil was injected over a period of eighteen minutes with ten points.

Test 1 (Low tide, no wind)

```
low-tide at 243, high tide at 628 minutes.
point number>> 10
volume (gallons), initial thickness> 100000 1
Region radius is 347.12 meters, marker radius is 110
     meters.
wind speed (knots), wind direction (degrees)>> 0 0
start time, time step (minutes)>> 243
local start time (hh:mm:ss) (24 hours)>> p
injection period (minutes), injection time steps>> 18 9
There are 1 points in the region.
The tide is flowing.
Time interval between display frames in seconds (0 is
     static)>> 1
00:18:00 - 80.00% free, 20.00% stuck, 0.00% departed
Injection completed
02:18:00 - 63.64% free, 36.36% stuck, 0.00% departed
06:18:00 - 27.72% free, 72.73% stuck, 0.00% departed
10:18:00 -  9.09% free, 90.91% stuck, 0.00% departed
14:18:00 -  9.09% free, 90.91% stuck, 0.00% departed
```

Figures 8.3 through 8.7 show the oil spill trajectory for 00:18, 02:18, 06:18, 10:18, and 14:18 hours after the oil spill respectfully.

Test 2 (High tide, no wind)

```
low-tide at 243, high tide at 628 minutes.
point number>> 10
```

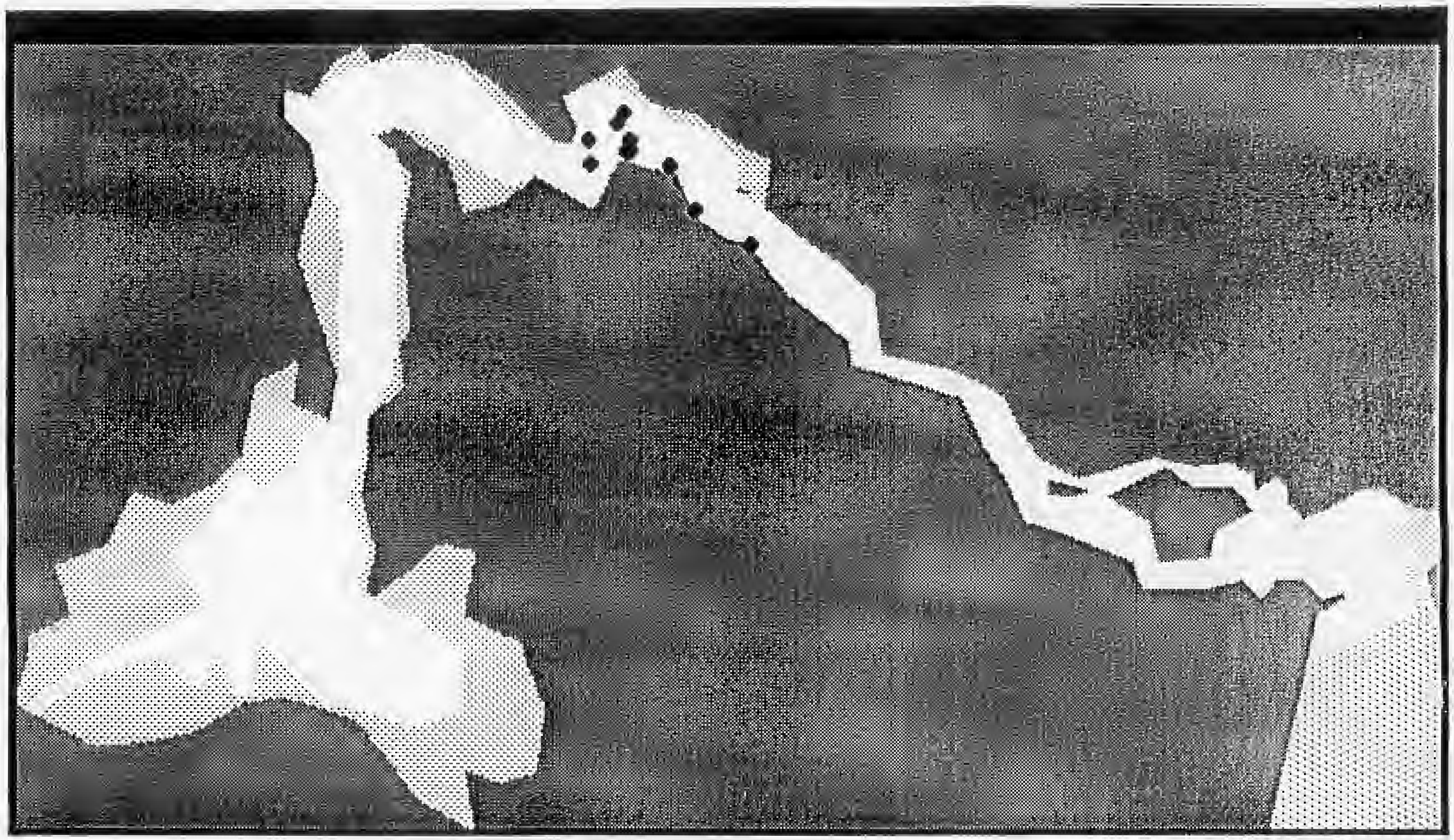

Figure 8.3: Test 1 at 00:18 hours.

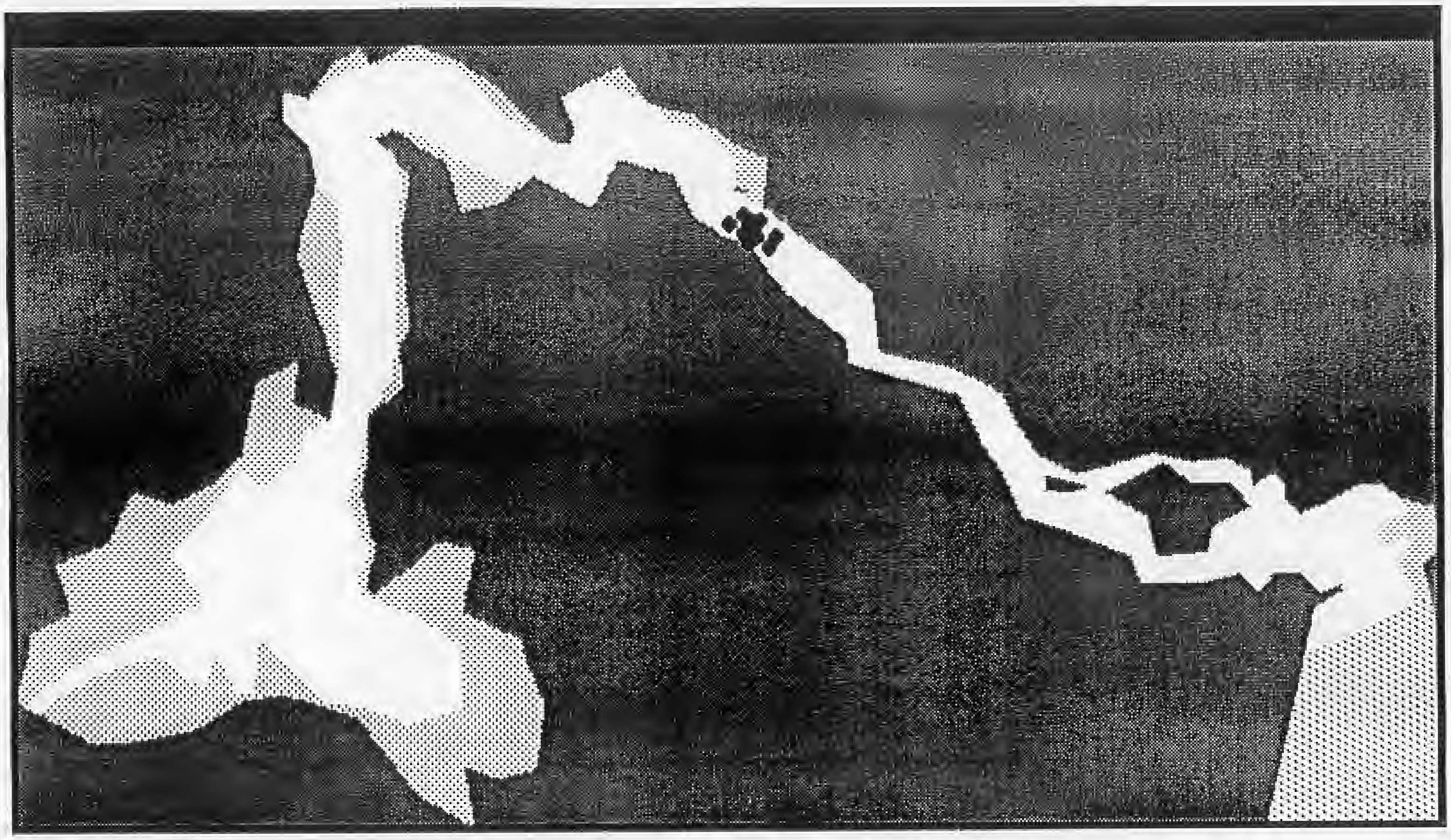

Figure 8.4: Test 1 at 02:18 hours.

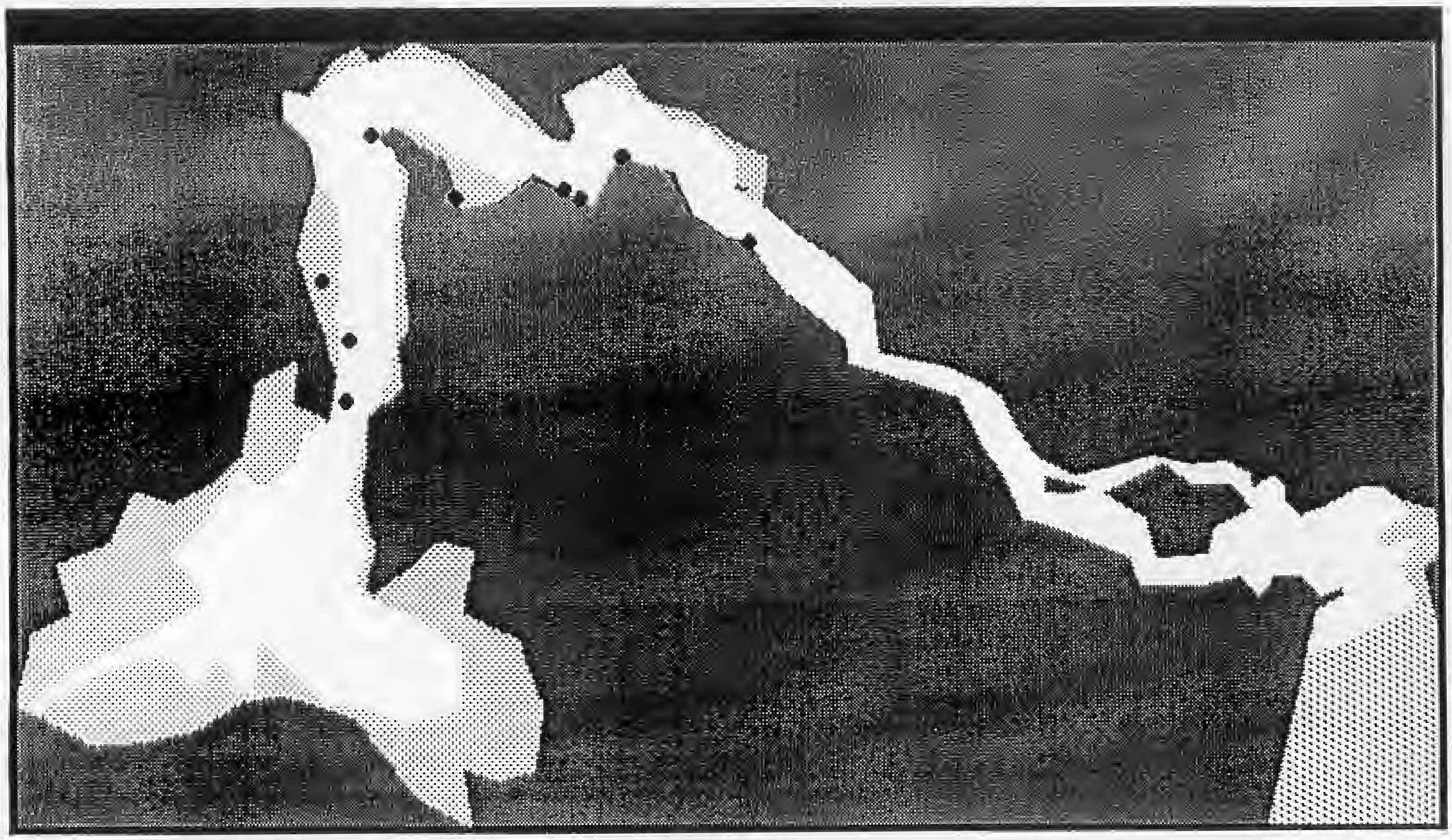

Figure 8.5: Test 1 at 06:18 hours.

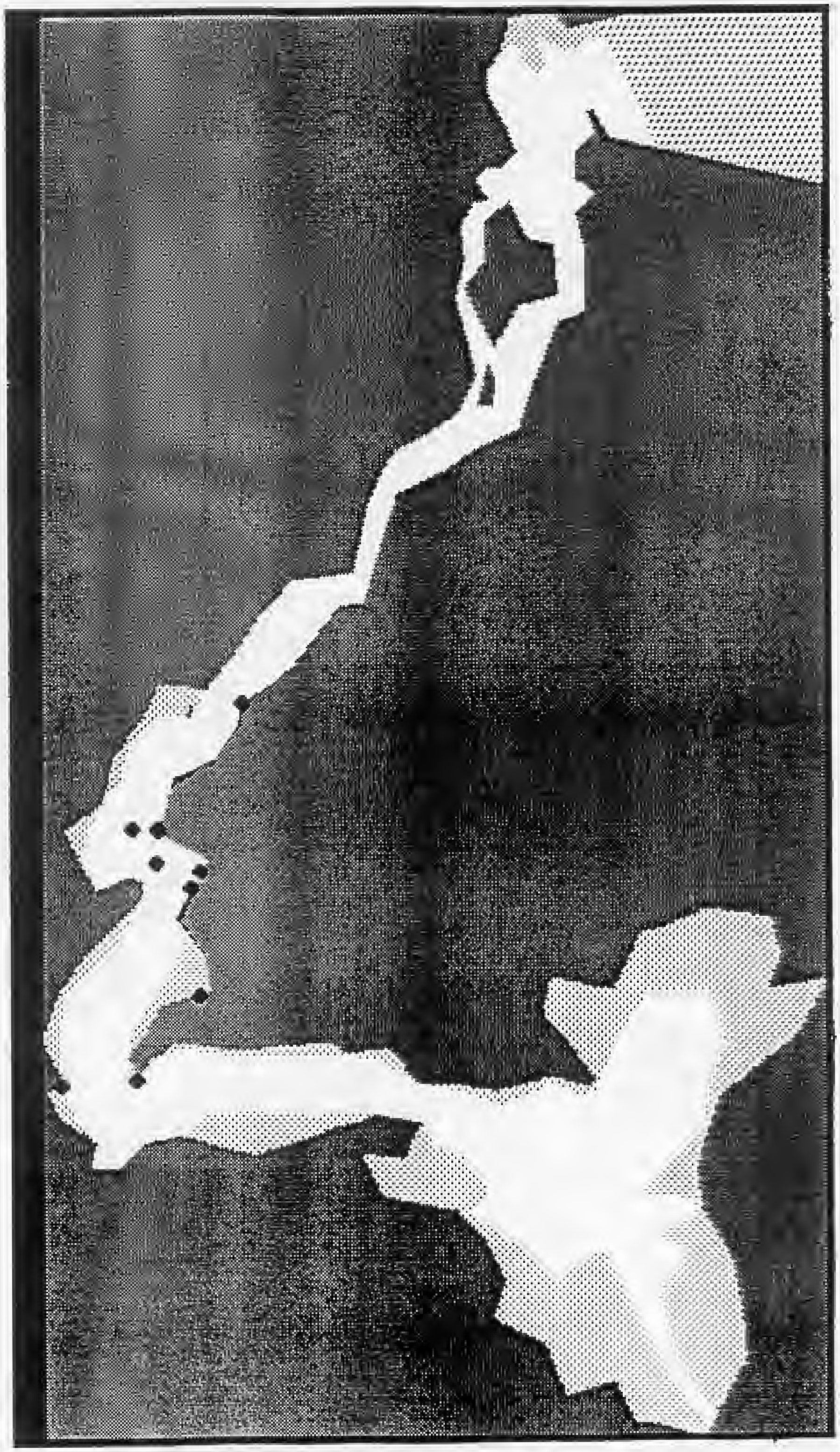

Figure 8.6: Test 1 at 10:18 hours.

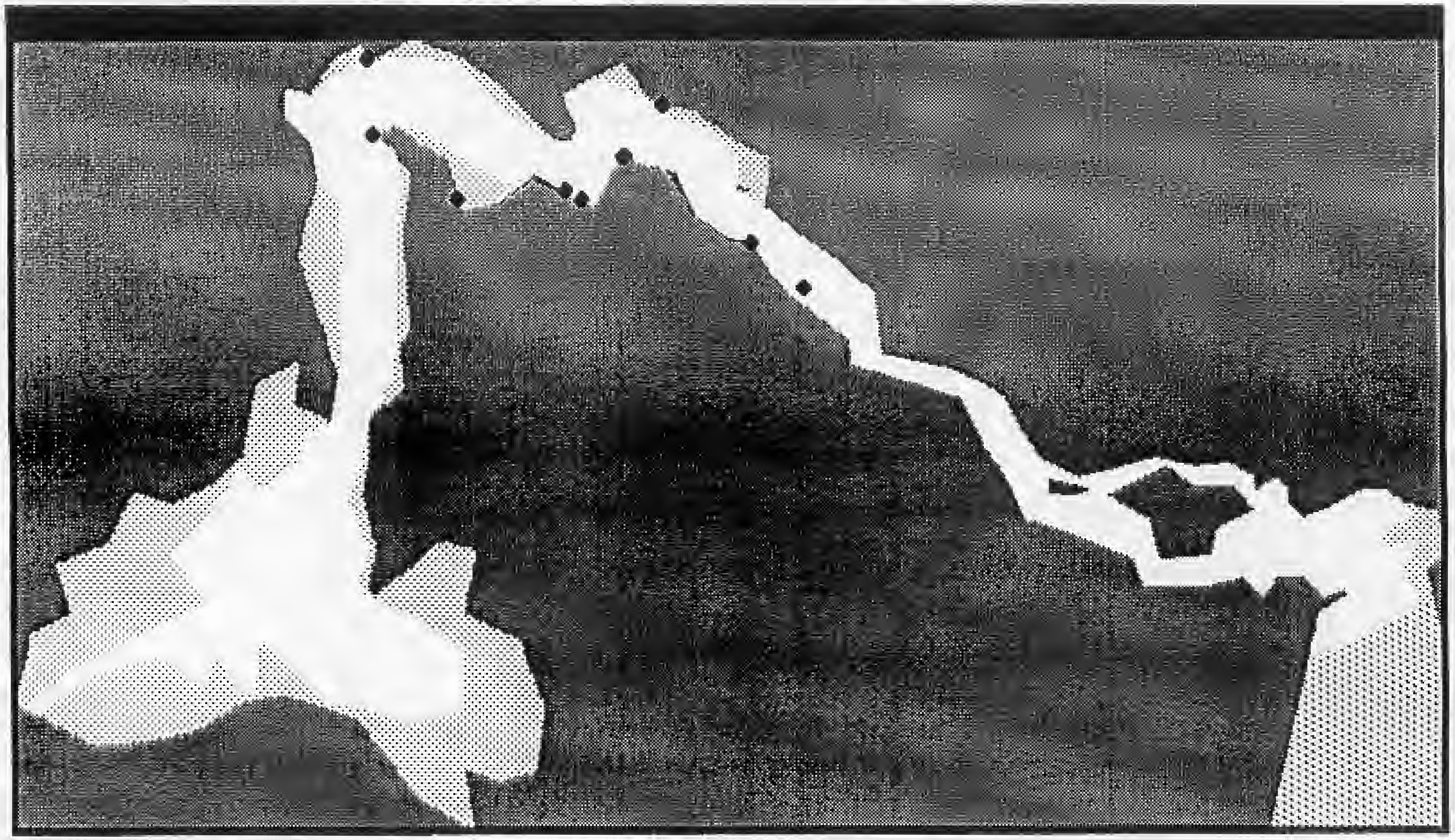

Figure 8.7: Test 1 at 14:18 hours.

```
volume (gallons), initial thickness> 100000 1
Region radius is 347.12 meters, marker radius is 110
     meters.
wind speed (knots), wind direction (degrees)>> 0 0
start time, time step (minutes)>> 628
local start time (hh:mm:ss) (24 hours)>> p
injection period (minutes), injection time steps>> 18 9
There are 1 points in the region.
The tide is ebbing.
Time interval between display frames in seconds (0 is
     static)>> 1
00:18:00 - 80.00% free, 20.00% stuck, 0.00% departed
Injection completed
02:18:00 - 40.00% free, 60.00% stuck, 0.00% departed
06:18:00 - 20:00% free, 70.00% stuck, 10.00% departed
10:18:00 - 10.00% free, 70.00% stuck, 20.00% departed
```

Figures 8.8 thru 8.11 show the oil spill trajectory for 00:18, 02:18, 06:18, and 10:18 hours after the oil spill respectfully.

Test 3 (Low tide, 9 Knot wind from SE)

```
low-tide at 243, high tide at 628 minutes.
point number>> 10
volume (gallons), initial thickness> 100000 1
Region radius is 347.12 meters, marker radius is 110
     meters.
wind speed (knots), wind direction (degrees)>> 9 135
start time, time step (minutes)>> 243
local start time (hh:mm:ss) (24 hours)>> p
injection period (minutes), injection time steps>> 18 9
There are 1 points in the region.
The tide is flowing.
Time interval between display frames in seconds (0 is
     static>> 1
00:18:00 - 90.00% free, 10.00% stuck, 0.00% departed
Injection completed
02:18:00 - 72.73% free, 27.72% stuck, 0.00% departed
05:28:00 -  0.00% free, 100.00% stuck, 0.00% departed
```

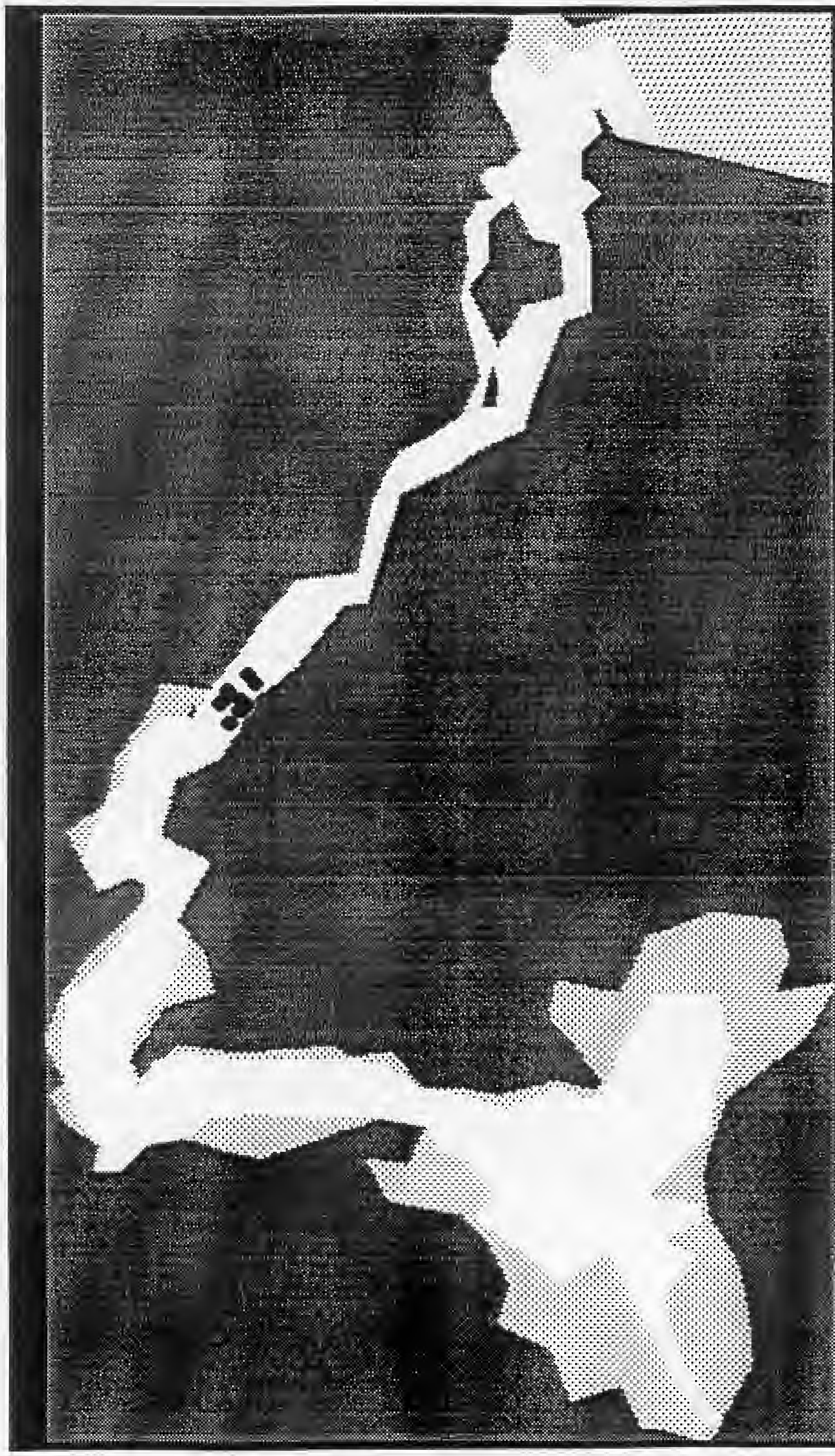

Figure 8.8: Test 2 at 00:18 hours.

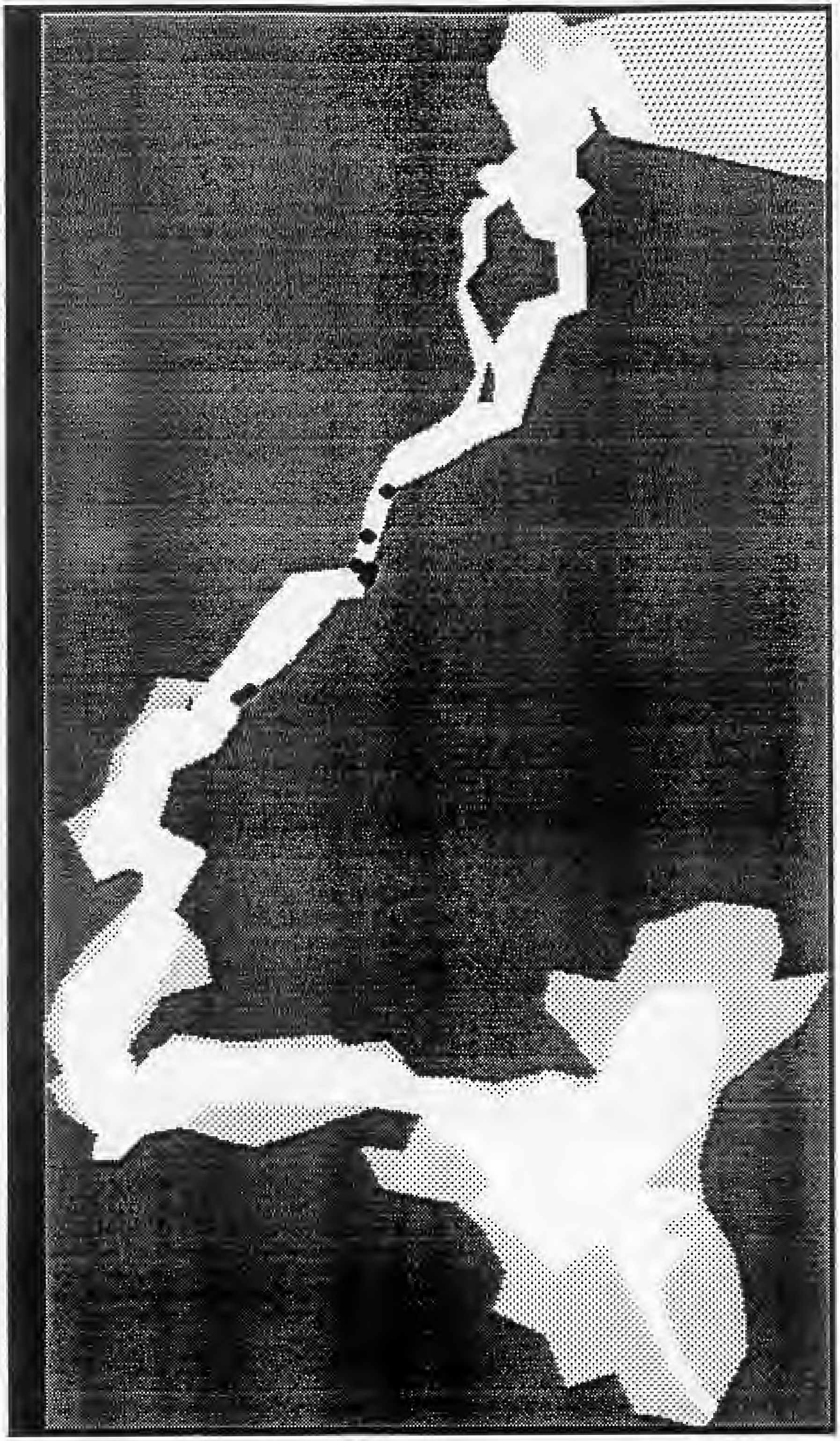

Figure 8.9: Test 2 at 02:18 hours.

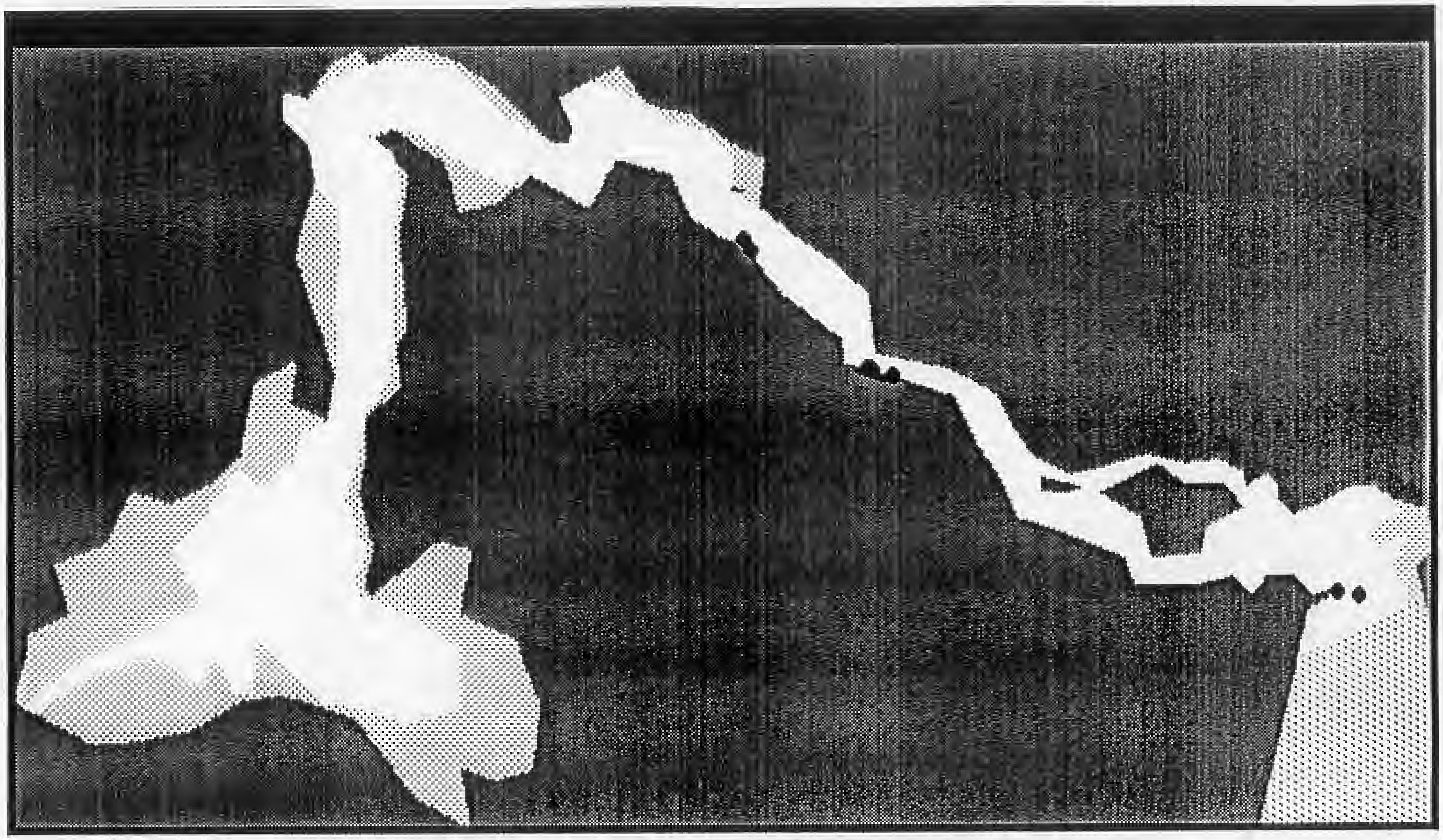

Figure 8.10: Test 2 at 06:18 hours.

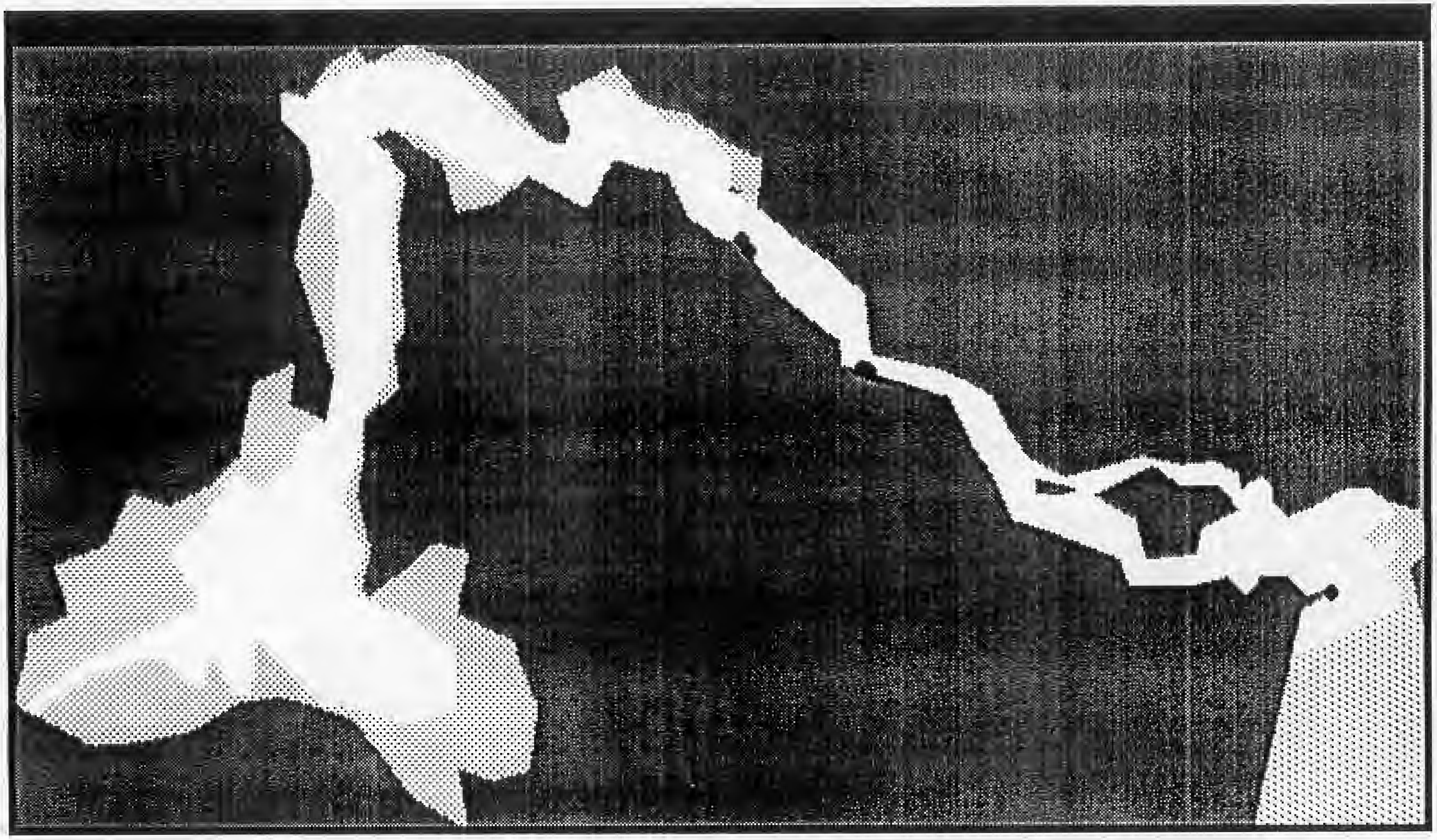

Figure 8.11: Test 2 at 10:18 hours.

Figures 8.12 thru 8.14 show the oil spill trajectory for 00:18, 02:18, and 05:28 hours after the oil spill respectfully.

Test 4 (High tide, 9 Knot wind from SE)

```
low-tide at 243, high tide at 628 minutes.
point number>> 10
volume (gallons), initial thickness> 100000 1
Region radius is 347.12 meters, marker radius is 110
     meters.
wind speed (knots), wind direction (degrees)>> 9 135
start time, time step (minutes)>> 628
local start time (hh:mm:ss) (24 hours)>> p
injection period (minutes), injection time steps>> 18 9
There are 1 points in the region.
The tide is ebbing.
Time interval between display frames in seconds (0 is
     static)>> 1
00:18:00 - 90.00% free,  10.00% stuck, 0.00% departed
Injection completed
02:18:00 - 45.45% free,  54,54% stuck, 0.00% departed
03:18:00 -  0.00% free, 100.00% stuck, 0.00% departed
```

Figures 8.15 thru 8.17 show the oil spill trajectory for 00:18, 02:18, and 03:18 hours after the oil spill respectfully.

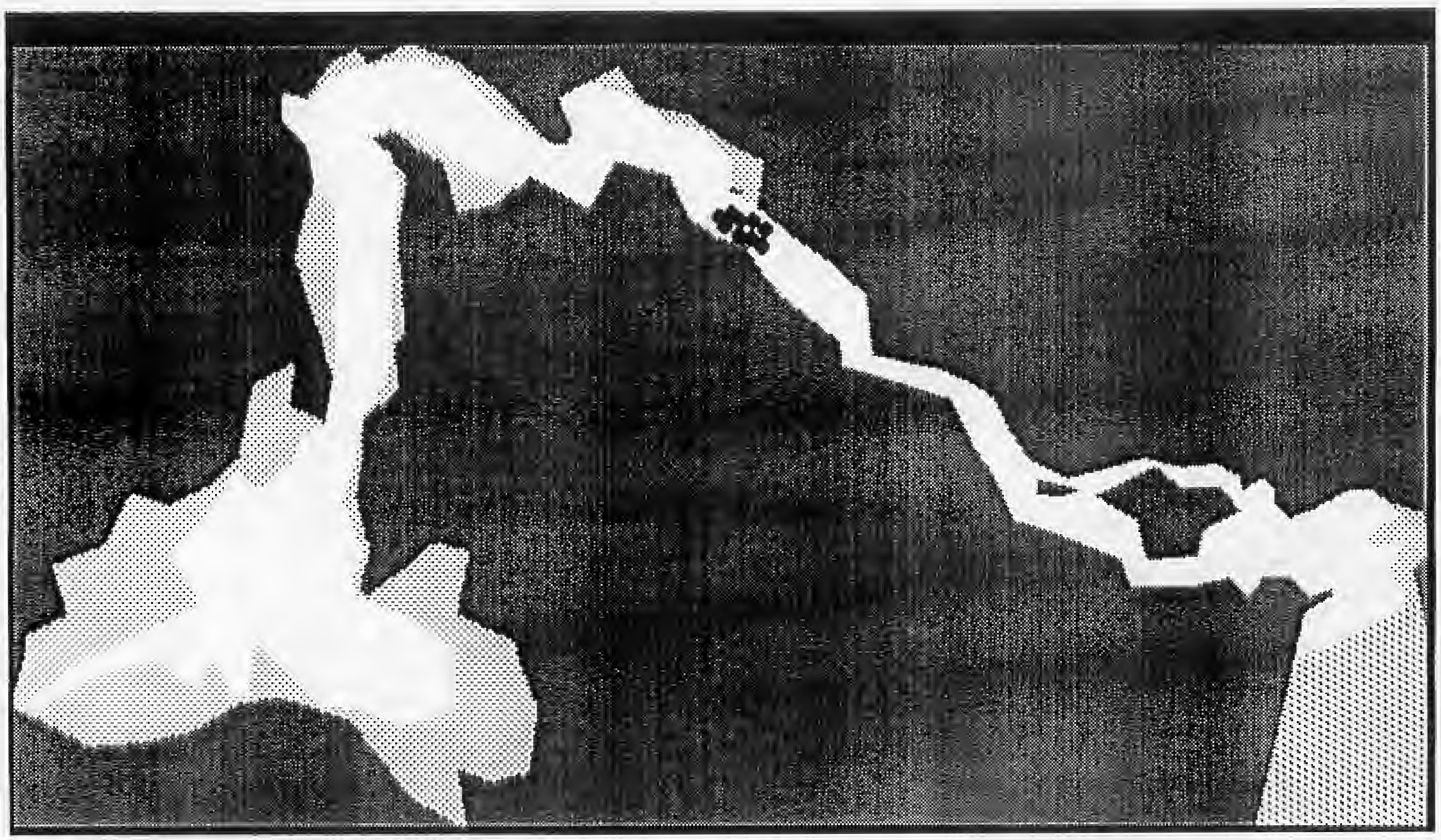

Figure 8:12: Test 3 at 00:18 hours.

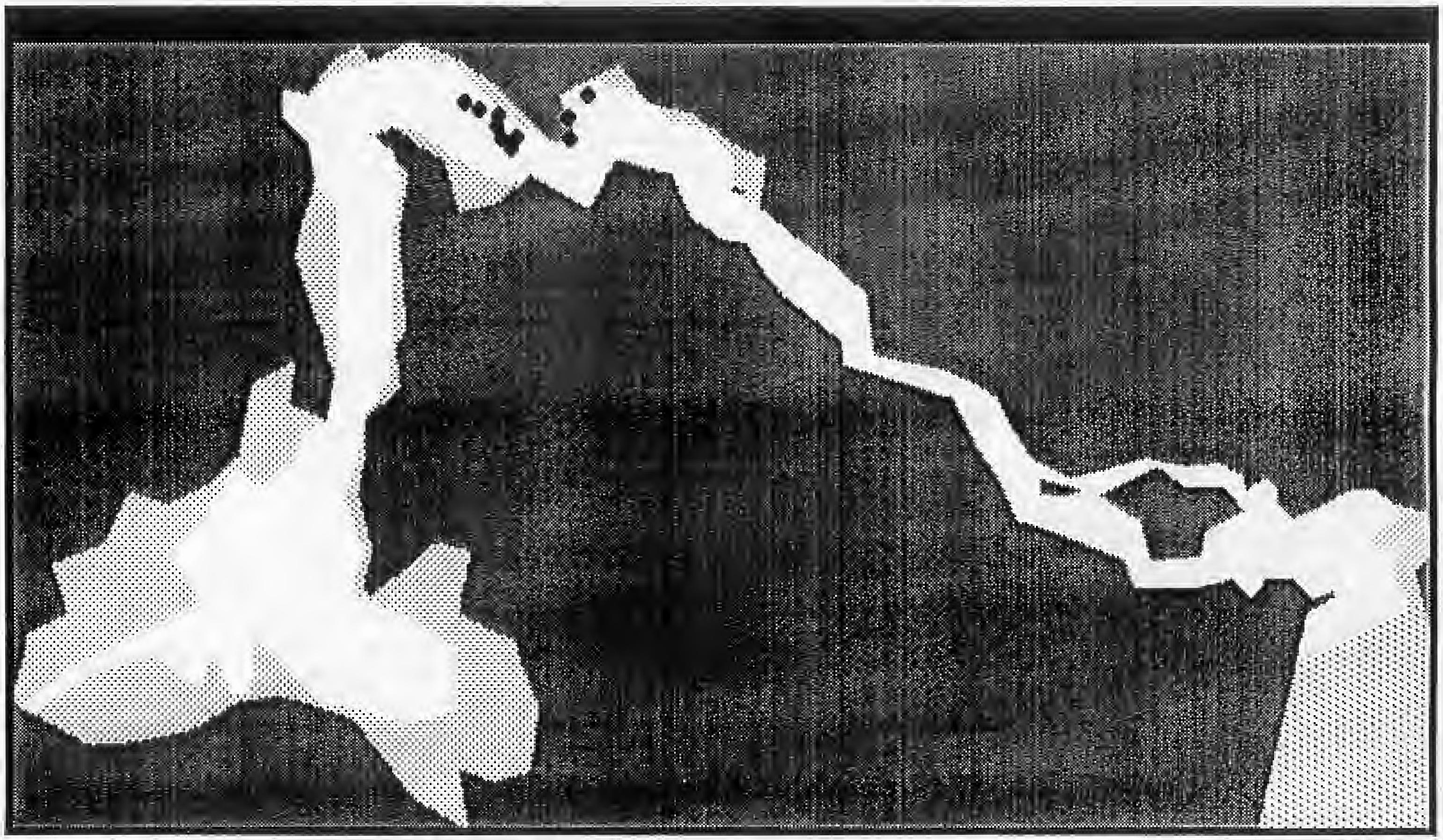

Figure 8.13: Test 3 at 02:18 hours.

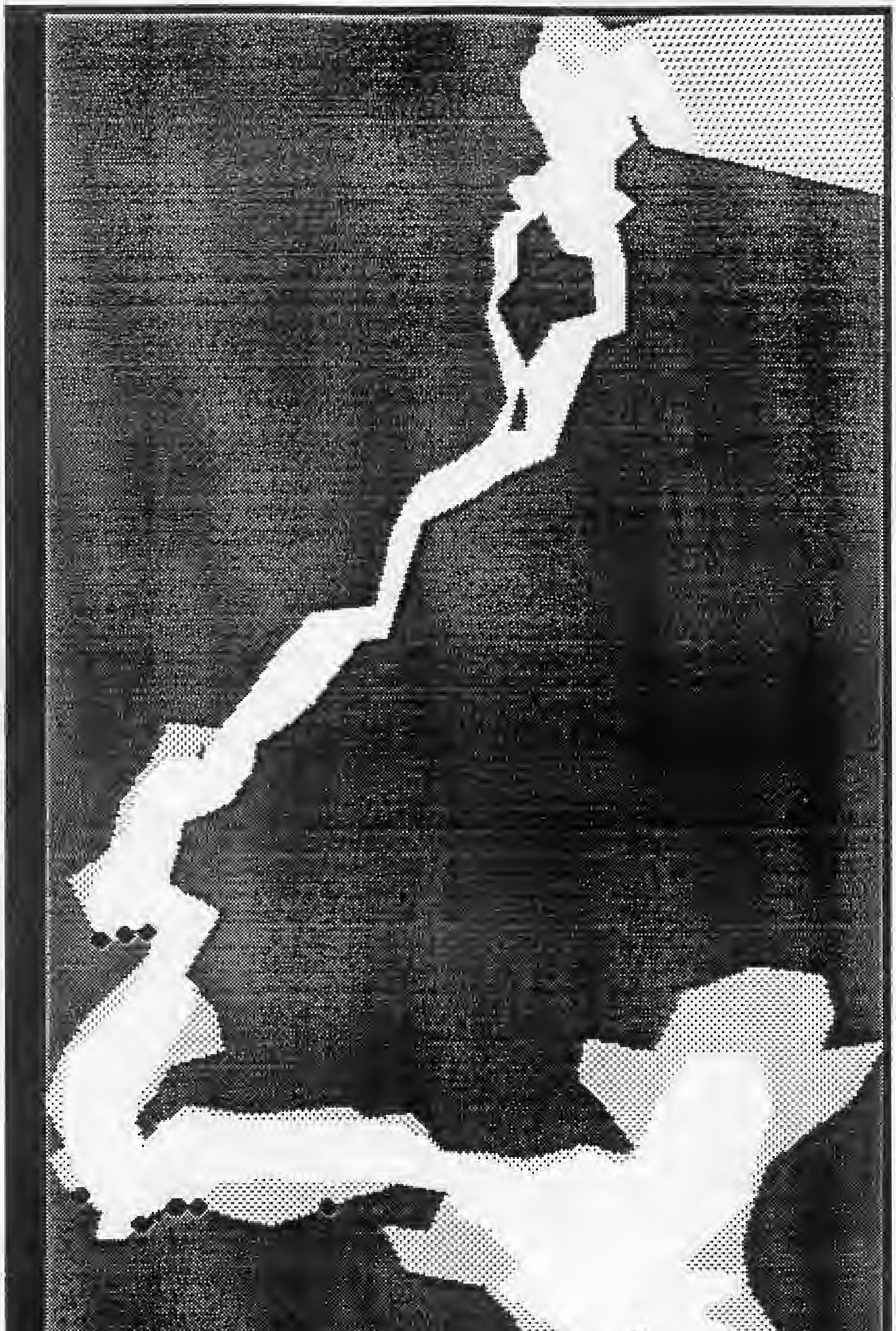

Figure 8.14: Test 3 at 05:18 hours.

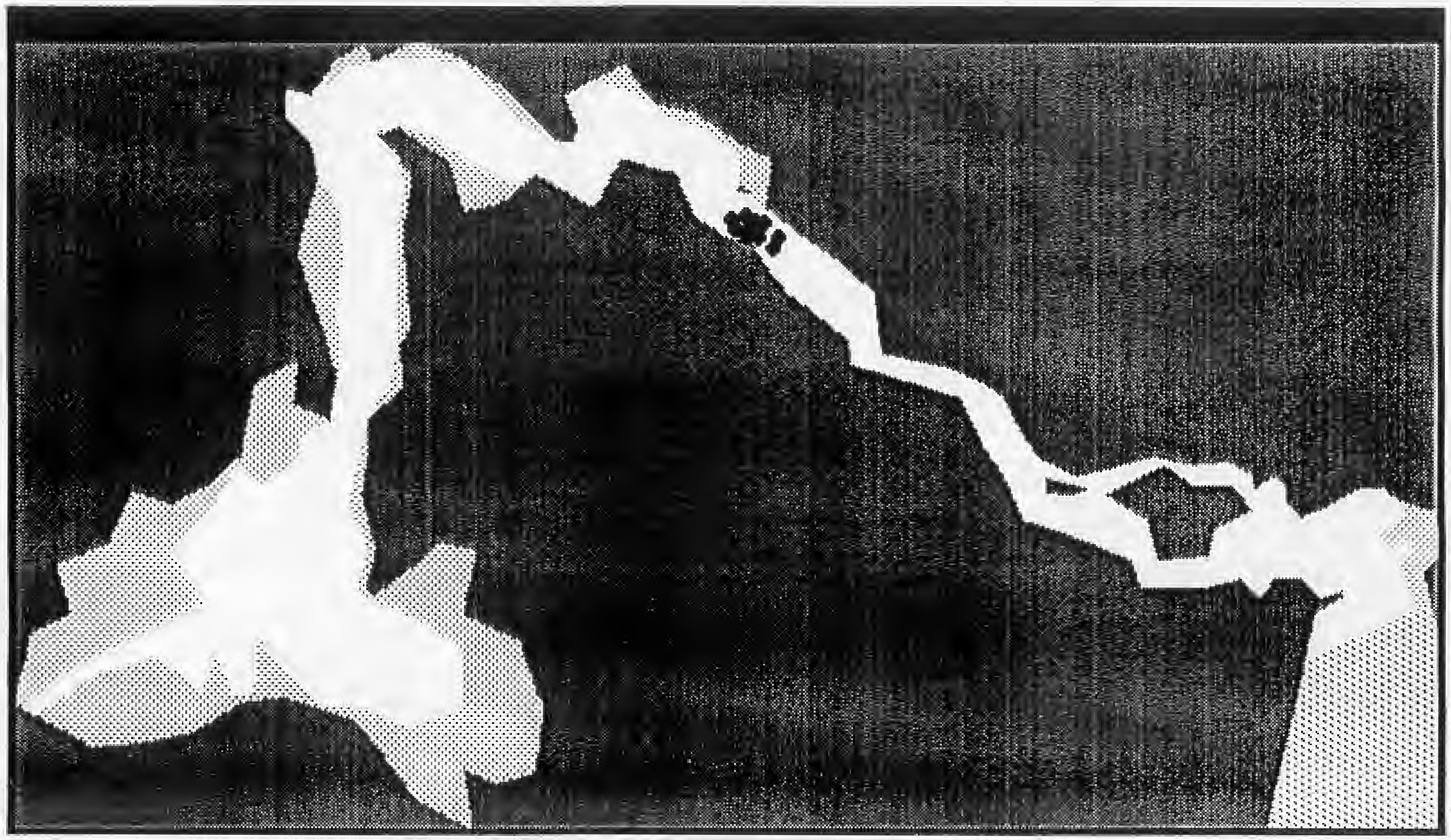

Figure 8.15: Test 4 at 00:18 hours.

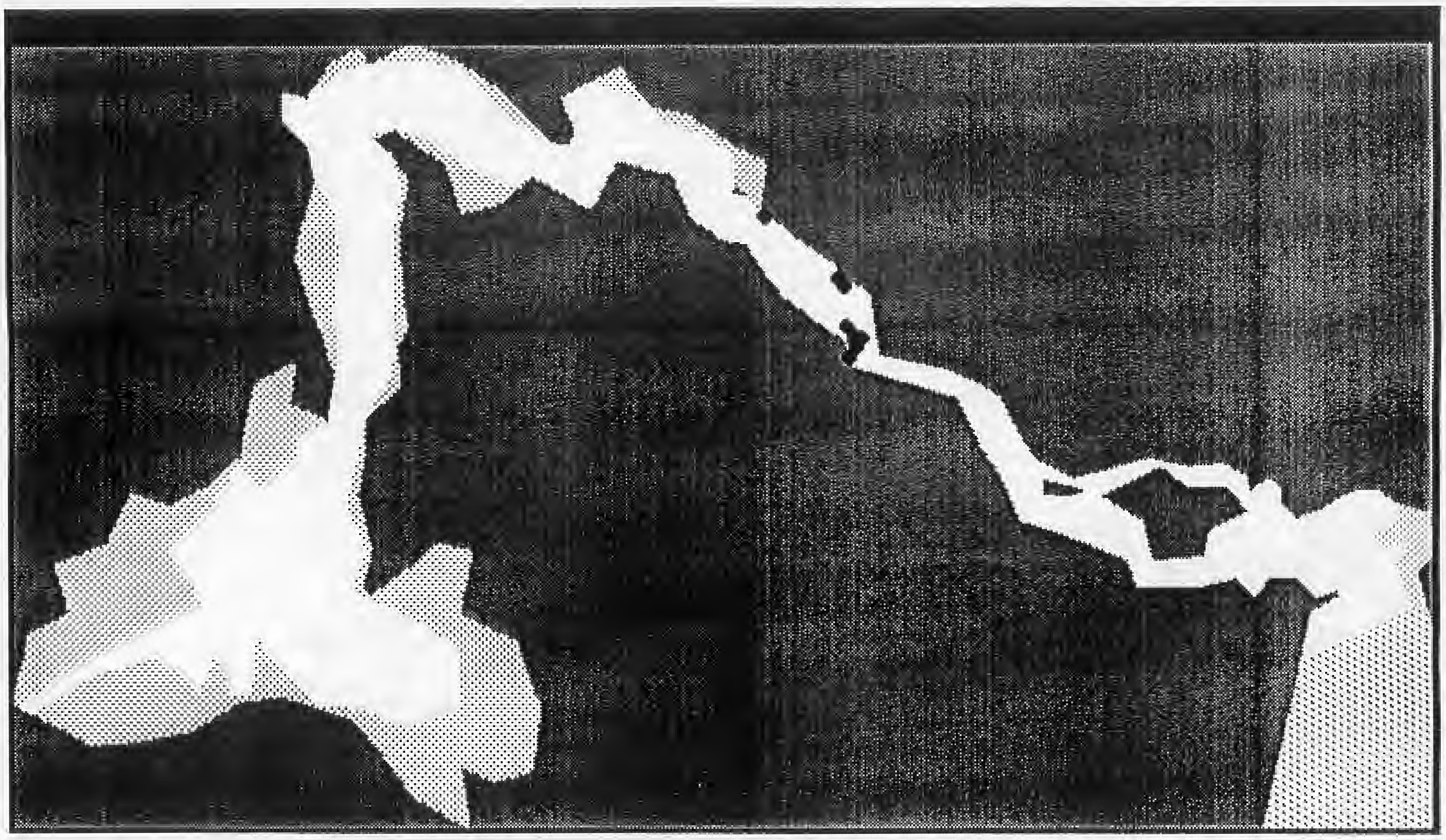

Figure 8.16: Test 4 at 02:18 hours.

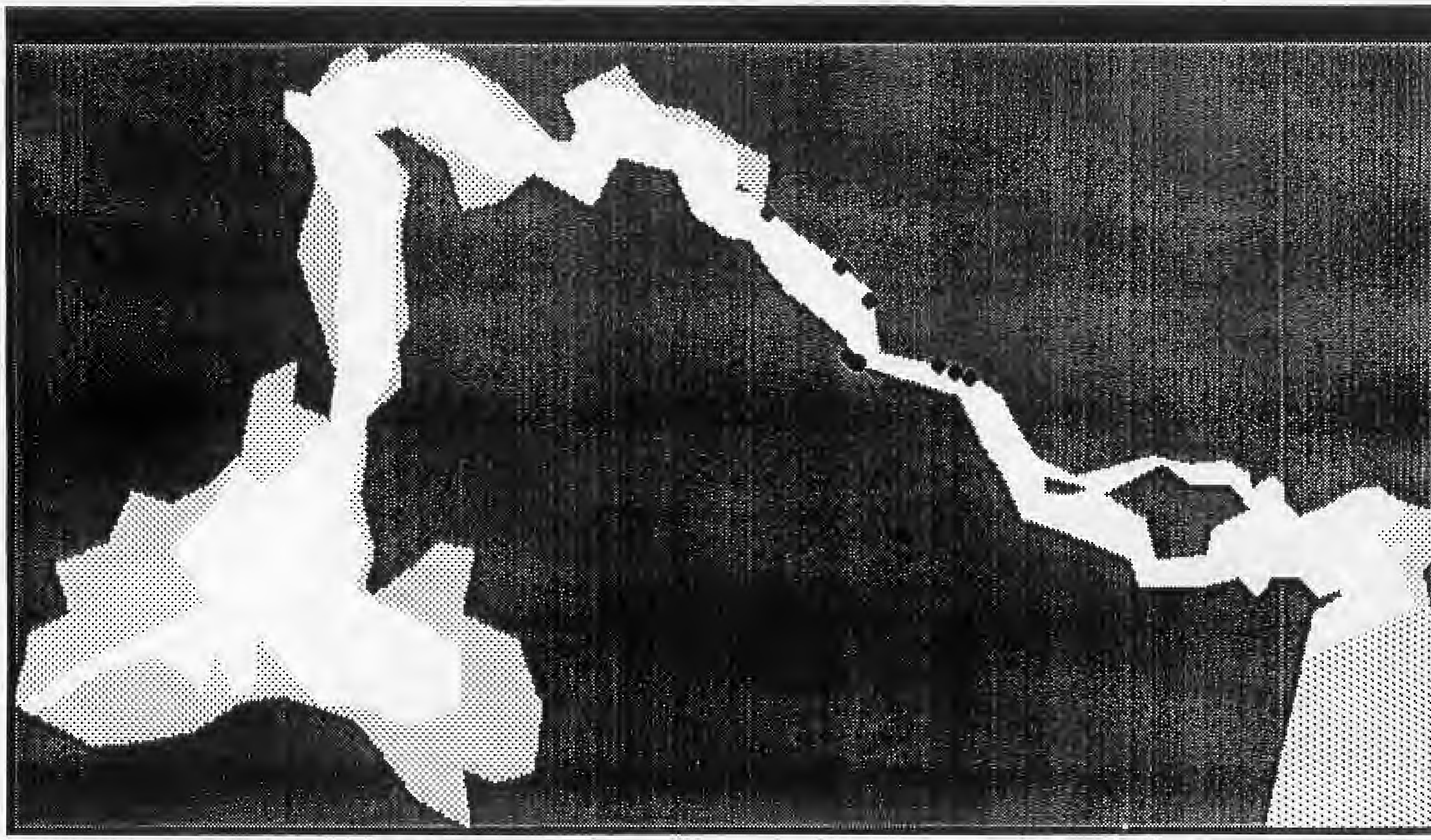

Figure 8.17: Test 4 at 03:18 hours.

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