MODELING OF PROPOSED LAMPRICIDE APPLICATIONS TO THE BOQUET RIVER, LAKE CHAMPLAIN

prepared for

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July 1988

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INTRODUCTION

This report provides technical assistance to the New York State Department of Environmental Conservation (NYDEC) in projecting the transport of lampricides applied to the Boquet River. The information will be used by NYDEC to evaluate impacts on water supplies and on sensitive ecological areas and to design procedures for monitoring and mitigating impacts associated with the proposed lamprey control program.

Mathematical models are used to project the spatial and temporal histories of lampricide plumes resulting from specified treatment conditions (defined by applied concentration, duration, location, streamflow, wind regime, and season). The sizes and locations of the lampricide plumes are projected down to 50 and 20 ppb concentration levels. This report focuses on proposed TFM and Bayer-73 treatments for the Boquet River. The technical approach and projections for five other treatment sites are described in a previous report prepared for the NYDEC (Laible and Walker, 1987). The reader is referred to Sections 1-11 of the previous report for a detailed description of the methodology applied below to evaluate the proposed Boquet River treatments.

WIND-DRIVEN CURRENT MODEL

Local wind-driven currents in the Boquet River region of Lake Champlain (Figure 1) have been simulated using the finite element model employed at five other proposed treatment sites (Laible and Walker, 1987). In brief, the model is based upon the three-dimensional equations of continuity and momentum and simulates steady current fields due to surface wind loading. This model is particularly important for simulating currents in shallow regions at the mouth of the river and along the shoreline. The finite element mesh consists of 224 nodes and 395 elements, as shown in Figure 2.

In shallow regions (up to 25 meters), actual lake depths have used in the model. In deeper waters, a maximum depth of 25 meters has been used, to approximate the location of the thermocline. In shallow regions, the bottom roughness has been set to a value consistent with moderate weed growth, while in stratified regions the roughness has been set to a value consistent with the interface shear between epilimnetic and metalimnetic waters.

The model has been run for the eight wind load directions: N, NE, E, SE, S, SW, W and NW. Predicted current velocities and flux values for NW, N, and NE wind loadings are shown in Figures 3-5, respectively. Flow directions shown in these figures would be reversed for winds from the SE, S, and SW, respectively. All of the simulations have been done with a surface stress corresponding to an 8.7 mph wind. Results can be rescaled to estimate flow fields for other wind speeds, roughly in proportion to the square of the speed. The velocities are vertically averaged over the surface-layer depth. The true vertical distribution of velocity is not constant, but can be estimated from the model output.

By vertically integrating the variable flow field over the depth and keeping track of the negative and positive velocities, exchange terms and net flow terms are obtained. These values are rechecked for hydrodynamic balance and subsequently used in the mass transport model.

Flow fields in the vicinity of the mouth of the Boquet are shown in Figures 3-5 to be primarily along shore and in the general direction of the N-S component of the wind. Maximum vertically integrated velocities in the very near shore region are 3-4 cm/sec and fairly constant over the depth, but decreasing towards the bottom where frictional effects retard the flow. Just outside of the shallows, the flow is still along shore but the variation of flow over the depth is more pronounced, with surface flows significantly greater than the bottom flows. Reverse currents exist primarily in east/west directions, particularly for winds with strong east/west components. This flow structure will promote exchange between the shallow regions and the open portion of the lake, as well as move constituents in the north/south directions. Gyre effects are present in the flow fields and will also promote transport out into the main lake.

DYE STUDY RESULTS

Dye study data and proposed treatment conditions for the Boquet River are summarized in Table 1. Two dye studies have been conducted by the NYDEC to support projections of lampricide transport at this site (Meyers, 1986,1987). Wind speed data from Burlington Airport during these study periods are displayed in Figure 6. The June 1986 dye release (Meyers,1986) was conducted during a period of strong (~15 mph), northerly winds and when river temperatures were slightly above lake surface temperatures. Under these conditions, the dye plume was observed to mix vertically and travel south from the river mouth. The September 1987 release (Meyers, 1987) was conducted during a period of weak (~ 5 mph) northwesterly winds and when river temperatures were below lake surface temperatures. Under these conditions, vertical mixing was slight and the dye plume traveled along the bottom of the shallow river delta, with maximum concentrations observed in a general direction ESE of the river mouth, towards deep offshore regions.

It is apparent that plume behavior was controlled by different mechanisms during the study periods. The June 1986 plume was dominated by surface currents in the vicinity of the river mouth, as driven by local wind conditions. The September 1987 plume was dominated by density currents, which caused the river inflow to travel along the bottom towards deeper, cooler regions of the lake. The latter mechanism tends to minimize transport in shallow, shoreline waters. For this reason, projections of lampricide transport based upon the wind-driven current models likely over-estimate the extent of along-shore transport under fall treatment conditions. Given the proposed fall treatment schedule, it is likely that the September dye study more accurately reflects the transport of TFM applied to the Boquet River during the Fall.

Although density currents are likely to be important for the fall Boquet River TFM treatment, it is still important to consider wind-driven transport in the mixed layer for the following reasons:

(1) Wind speeds during the September 1987 dye study were light. It is likely that mixing of the river inflow with the warmer lake surface waters in the shallow delta would be greater under normal or high wind conditions. This would bring more of the applied TFM into regions dominated by local wind-driven currents.

(2) Density currents would be less important for the proposed Bayer-73 treatments. Bayer-73 would be applied directly to the river delta, whereas TFM would be mixed with cooler river waters before entering the lake. While a portion of the applied Bayer-73 would be carried to deeper lake regions as the cool river flows over treated delta areas, Bayer-73 would be released into the surface layer and subsequently transported by wind-driven currents in treated areas which are not in the path of the cool river inflow.

Model projections of transport in the surface layer are supplemented with empirical projections based upon direct rescaling of dye data, using methodology described previously (Laible and Walker,1987). Potential impacts of lake seiche activity on lampricide transport at this site are also discussed.

TRANSPORT MODELING OF DYE PLUMES

As shown in Figure 7, transport calculations are performed on a grid of square cells, each 400-meters on a side. The model region (Figure 1) extends from Cannon Point on the South to Ligonier Point on the North. Figure 7 displays mean cell depths, as derived from the NOAA navigation chart for this region of Lake Champlain. Depths in this figure are truncated at 25 meters, although shallower mixed-layer depths are used in the simulations discussed below.

Dye study observations and simulations for the June 2, 1986 study are displayed in Figure 8. Dye concentrations have been rescaled to an applied concentration of 1000 ppb. Contour lines show the spatial extents of 10- and 100-fold dilution of the concentration applied to the river. On the left, observed maximum dye concentrations are displayed for surface and subsurface measurements. Although the model predicts average dye concentration in each cell as a function of time, the observed dilution contours are based upon the cell-maximum dye concentration. The latter avoids difficulties associated with spatial weighting of observations and provides a conservative basis for comparison with model simulations. Model predictions for observed wind conditions at Burlington Airport (Direction=N, Mean Speed = 14.5 mph, Load Factor = 3.2) are shown on the right side of Figure 8. Simulations have been performed for maximum plume depths of 5 and 10 meters, respectively.

As discussed in the previous report (Laible and Walker,1987), the wind-driven models assume the river inflow is well-mixed into the surface layer of the lake. The models tend to under-predict observed maximum dye concentrations in the immediate vicinity of the river mouth, where well-mixed conditions have not yet been achieved. At greater distances and times from the river mouth, the plume (assuming weak density currents) mixes vertically and horizontally and model projections on a 400-meter grid scale become more realistic. As shown in Figure 8, model projections for a 100-fold dilution of the applied river concentration compare favorably with the observed maximum extent of the 100x dye plume. Consistent with simulations performed at other sites (Laible and Walker,1987), a maximum plume depth of 5 meters is used below to develop projections of lampricide transport in the absence of significant density currents.

Dye observations and simulations for the September 22, 1987 study are displayed in Figure 9. The observed plume traveled out into the lake along the bottom of the shallow river delta. The dye was not tracked beyond the edge of the delta (roughly 3,300 feet from the river mouth), where the depths increase rapidly from less than 12 feet to more than 200 feet. After spilling over the delta, it is likely that the dye continued to track along the lake bottom until it reached the thermocline region at approximately 100 feet, where it began to spread laterally and vertically. Because the river temperature (53-59 deg F) exceeded that of the hypolimnion (< 52 deg F), it is unlikely that the inflow penetrated below the thermocline.

Some dilution of the plume occurred as it traveled across the delta. Based upon maximum dye observations at the edge of the delta, the river inflow was diluted by at least 4-fold before it encountered the edge of the delta. Accompanied by this dilution would be an increase in plume temperature and corresponding decrease in thermal stability. Based upon a 4-fold dilution of dye at the edge of the delta, the difference between the lake and plume temperatures decreased from approximately 9 deg-F at the river inflow to 2.3 deg-F at the edge of the delta. Further decreases would be expected as the dye traveled further out into deeper regions of the lake and became increasingly unstable. With increasing dilution, it is possible that the dye plume dissipated into the offshore epilimnion before reaching the thermocline. In offshore waters, entrainment and transport in north/south currents attributed to lake seiche activity (see **INFLUENCES OF LAKE SEICHE**) are likely.

As shown in Figure 9, simulations of the September 1987 dye plume using the wind-driven model show the plume moving south in response to the ambient wind condition (Northwest, Mean Speed = 5.6 mph, Load Factor = .45). This behavior is qualitatively and quantitatively different from that observed. It is likely that density currents dominated over wind-induced mixing and transport under these conditions of cool river inflows and light winds. When density currents are dominant, simulation of plume dynamics is infeasible using one-layer models of the type employed here. Because of the impacts of density currents encouraging plume movement towards deep, offshore regions, model projections presented below likely over-estimate the extent of lampricide transport in shallow shoreline areas north and south of the river mouth.

EMPIRICAL PROJECTIONS OF TFM PLUME

As described previously (Laible and Walker, 1987), dye study data can be manipulated to provide empirical projections of the TFM plume as a function of time and distance from the river inflow. This is performed by rescaling the observed dye concentrations based upon the ratio of TFM load under proposed study conditions to dye load under dye study conditions (Table 1). To a first approximation, maximum concentrations decay approximately exponentially as a function of time and distance from the inflow point. Although projections account approximately for differences in streamflow, treatment duration, and applied concentration, they apply only for ambient wind and temperature conditions present during the dye study.

Empirical projections of the TFM plume based upon the June 2, 1986 dye study are shown in Figure 10. For this relatively high-wind condition, the projections indicate durations of approximately 17 and 20 hours (from start of TFM loading to lake) to reach maximum TFM concentrations of 50 and 20 ppb, respectively. The maximum 50 and 20 ppb TFM concentration contours would extend (to the south) for approximately 3.3 and 4 kilometers, respectively, or just above the village of Essex (5 kilometers). These projections apply directly to the strong northerly winds which were present during the June 1986 study.

Based upon model sensitivity analyses conducted for this and other sites (see **PLUME DURATION**), projections of the maximum spatial extent of the plume are governed primarily by lake topography and wind directions and are insensitive to wind speed. Conversely, plume durations are strongly dependent upon wind speed. Thus, for average or low northerly winds, longer durations and similar transport distances would be expected, assuming that density currents are unimportant.

Corresponding plots of September 1987 dye data are shown in Figure 11. Dye observations ceased as the trailing edge of the river dye plume entered the lake (after a 12-hour loading period). Dye movement along the bottom of the river delta was primarily towards deep offshore waters; it was not tracked beyond the edge of the delta, however. For these reasons, empirical projections of plume behavior out into the deeper offshore regions are not possible with these data. Movement in a north/south direction along the shoreline was tracked, however, and indicates much lower transport distances (< 1.5 km), as compared with results of the June 1986 study (~3.2 km, Figure 10).

SIMULATIONS OF TFM TREATMENTS

Simulations of TFM transport under the proposed treatment conditions (streamflow = 150 cfs, concentration = 4.2 ppm, duration = 12 hours) are shown in the following Figures:

12	Maximum TFM Conc. vs. Wind Direction
13	Maximum TFM Conc. - Composite
14	Maximum TFM Conc. - Contour Map

As shown in Figures 12, simulations have been performed separately for each of eight wind directions until the TFM concentration in each model cell drops below 10 ppb (vs. criteria of 20 and 50 ppb). These simulations have been performed for a standard wind load factor of 1.0, which corresponds to an average wind speed of 8.7 mph. As shown below, simulations of the maximum spatial extent of the plume are insensitive to wind speed.

Results for each of the eight wind directions have been overlayed to develop composite projections of maximum concentrations which are independent of wind direction and speed (Figure 13). The actual plume would fill different regions of these contours, depending upon the particular wind conditions which are present during the treatment period. The composite projections have been subsequently overlayed on lake depth charts to facilitate interpretation (Figure 14).

As shown in Figure 12, model simulations indicate longest transport distances for northerly and northwesterly winds. The composite 20 ppb contour extends from a point just north of Essex (3.9 km south of the river mouth) to just north of Jones Point (2.3 km). As discussed above, shorter along-shore transport distances would be expected under fall treatment conditions when density currents are important.

As described previously (Laible and Walker, 1987), these simulations of the proposed treatment conditions can be rescaled to project maximum concentration contours under conditions of different streamflow and/or applied concentration, based upon the ratio of TFM loading. For example, if the treatment were to occur at a streamflow of 300 cfs (instead of 150 cfs) and same applied concentration (4.2 ppm), the 10 ppb contours in Figures 12-14 would represent the 20 ppb contours for the higher-flow treatment condition.

SIMULATIONS OF BAYER-73 TREATMENTS

Simulations of BAYER-73 transport under the proposed treatment conditions (application area = 250 acres, applied dose 100 lbs/acre, 5% active ingredient, 6-hour release period) are shown in the following Figures:

As discussed above, wind-driven currents are likely to be more important than density currents in driving the transport of Bayer-73 because the material is applied directly to shallow near-shore waters. The projected Bayer-73 contours generally fall within those projected for the TFM treatment. This primarily reflects the lower dose of active ingredient for Bayer-73 (1250 lbs vs. 1698 lbs, Table 1).

PLUME DURATIONS

Plume duration can be defined as the time required for lampricide concentrations to drop below 20 or 50 ppb throughout the lake region. Important factors influencing plume duration for a given treatment program include lampricide decay, wind speed, and wind direction.

The simulations discussed above assume that lampricides behave conservatively in the lake environment; i.e. that dilution is the only mechanism responsible for decreases in concentration following treatment. TFM and Bayer-73 are subject to a number of physical, chemical, and biological processes which cause removal from the water column. Sediment adsorption and photolysis are considered to be important decay mechanisms; half-lives in the range of 2.5-10 days have been reported (NRCC,1985; Ho and Gloss, 1987). Sensitivity analyses for other treatment sites (Laible and Walker, 1987) indicate that consideration of lampricide decay would generally have little effect on maximum plume areas but may have substantial effects on plume duration.

Figure 18 displays time series of simulated TFM and Bayer-73 concentrations (maximum values for all grid cells and wind directions) for lampricide decay rates of 0.0, .07, and .23 days^{-1}, which correspond to half-lives of infinity, 10, and 3 days, respectively. Predicted TFM plume durations (based upon a maximum concentration of 20 ppb) are 90, 78, and 66 hours, respectively. Predicted Bayer-73 plume durations are 67, 62, and 52 hours, respectively. Shorter durations for the latter reflect the lower applied dose.

Figure 19 shows the sensitivities of TFM plume duration and size to wind load for a decay rate of 0.0 day^{-1}. Simulated current speeds are proportional to the wind load factor, which, in turn, varies approximately as the square of the wind speed. A wind load factor of 1.0 corresponds to an average wind speed of 8.7 mph. Consistent with results obtained at other treatment sites, the size of the plume is insensitive to wind load and is governed primarily by topography and wind direction. The duration of the plume, however, is dependent upon wind load. As shown in Figure 19, the time to reach TFM concentrations below 20 ppb varies from 50 hours for a wind load factor of 2.0 to 150 hours for a load factor of .5.

Based upon data from Burlington Airport for May to September 1986 (Laible and Walker, 1987, Figure 2), the 3-day moving-average load factor varies from .5 to 4 and averages 1.59. The airport data are based upon three-hour observations and under-estimate actual wind loads because the energy associated with high-frequency variations in speed are not reflected. On the other hand, wind load statistics in this region of the lake may differ from those at Burlington Airport. Continuous wind measurements at nearby Willsboro indicated an average speed of 5.7 mph and average load factor of 1.24 (Laible and Walker, 1988) for the period from August 22 to September 4, 1987. Over the same period, average values at Burlington Airport were 8.6 mph and 1.29, respectively. Thus, despite lower average wind speeds at the site, the 3-hour Burlington Airport wind record can be used to approximate load factors in this lake region.

Sensitivity of TFM plume duration to wind direction is illustrated in Figure 20. These simulations are for a wind load factor of 1.0 and TFM decay rate of 0.0 day^{-1}. Longest plume durations are predicted for winds from the NW or SE. As shown in Figure 20, these wind directions also generate the greatest along-shore transport distances.

INFLUENCES OF LAKE SEICHE

Current fields used to generate the above projections of lampricide transport are driven by local wind conditions and topography. These mechanisms are expected to be dominant in shallow shoreline regions when the river inflow is neutrally buoyant. Under fall treatment conditions, because of the influence of density currents, the lampricide would be transported more efficiently to deeper, offshore regions. Lake seiche activity is an important mechanism to consider in evaluating the transport materials in offshore waters.

The wind driven currents simulated by the one-layer hydrodynamic model provide details of the currents that exist in the shallow shoreline regions, but without the impacts of currents attributed to internal wave motions of the lake. These waves, referred to as seiches, can generate significant currents in the main lake and possibly in regions just outside the shallow areas. In order to evaluate this type of activity, a two-layered model of Lake Champlain has been developed (Laible, 1988). This model idealizes the lake as a long narrow body of water. The predominant motion of the internal wave is a rocking motion of the thermocline about a node which appears to be located near Burlington, probably close to Schyler Island. The motion is a standing wave that pumps fluid predominantly in the north-south orientation of the lake. The model predicts the vertically and laterally integrated velocity at any east-west transect across Lake Champlain attributed to the north-south wind stress. The model has been calibrated to a limited data set from another study on Lake Champlain (Laible,1988).

The basis of the model is the generalized wave equation form of the governing equations of momentum and continuity for a two-layered, thermally stratified body of water (Laible,1988). This condition is typical of the lake during late summer and early fall when a distinct thermocline has developed. Separate equations are developed for the upper layer (epilimnion) and lower layer (hypolimnion). According to the wave equation form, changes in the elevations of the lake surface and interface (at the thermocline) are computed, followed by computation of the corresponding flow in each of the two layers.

The finite element method is used to solve the governing differential equations. The model can be described as an "X-Z model" with the "X" axis along the longitudinal axis of the lake and "Z" being the vertical direction. The lake is discretized by 20 node points and 19 finite elements as shown in Figure 21. At each node, the cross-sectional area above and below the equilibrium position of the thermocline (assumed to average 20 meters) are entered as input data. The coordinates of the nodes, density difference (approximately 1 kg/m^3), gravity, shear-stress coefficients, and the wind-load time series are also read into the program. For the purposes of this study, the model has been run from an initially static condition using 4 different wind load records (July 1986, August 1986, September 1986 and August 1987). Each of the wind stress records has been derived from Burlington airport weather data and adjusted to lake sites based on wind records obtained in other studies at various locations (Laible and Walker 1987-1988). Each simulation period consists of approximately one month of data with a time step of one hour. At each time step, the N-S wind stress is changed in accordance with the aforementioned wind records.

Figure 22 illustrates the time series of N/S wind stress, thermocline motion, and average velocities in the epilimnion during August 1987 at model node 9, which is at the latitude of the Boquet River. Positive wind stresses or velocities are towards the North and positive thermocline displacements are towards the lake surface. It is apparent that the thermocline generally rises at node 9 when the wind load is from the South and that the thermocline is depressed when the wind load is from the North. This is consistent with a uninodal rocking of the lake thermocline about a location just above Burlington. Peak excursions of the thermocline appear to occur about 12-20 hours after peaks of strong wind events.

Peak positive velocities generally follow peak positive wind stresses, and vice versa for negative velocities and stresses. However, when the wind is from a particular direction for several days (e.g., Days 12-16) the flows can reverse. Fluid accumulated in the epilimnion in the north end of the lake has a tendency to return south when the southerly winds diminish (Days 13-16). The peak fluid velocity for this particular wind data set is approximately 7 cm/sec. Simulations of longer wind series (Figure 23) indicate an average amplitude of approximately 4 cm/sec for velocities generated by seiche activity in this region of the lake.

The above predictions of flow velocity attributed to seiche activity are horizontally and vertically averaged within the epilimnion at a given latitude. The two-dimensional, one-layer model used previously for quantifying wind-driven currents can also be used to estimate the distribution of seiche-generated flow velocities within the epilimnion at a given latitude. This is done by imposing a constant south-to-north throughflow (e.g., 4 cm/sec) at the northern boundary of the model. A hydrodynamically balanced flow is imposed on the southern boundary to preserve continuity. The model subsequently computes the currents at the remaining nodes and in transverse directions at the northern and southern boundaries. Figure 24 illustrates the resulting flow field. Directions would be reversed for a north-to-south throughflow. Flows are restricted primarily to the center of the lake, where bottom frictional effects are much smaller than those in the shallow areas.

This analysis suggests that currents generated by the general lake motion (seiche), tend to concentrate in deep, offshore waters and have little influence in shallow shoreline areas, where currents driven by local wind action (Figures 3-5) are dominant. A comprehensive model which considers both local wind-driven currents and seiche activity simultaneously has not yet been developed. Additional transport model simulations of Boquet River TFM treatments using flow fields representative of seiche activity (e.g., Figure 24) give plume sizes and durations which are much smaller than those derived from the wind-driven model (Figure 12-14). Consideration of seiche activity in addition to local wind-driven currents would likely reduce the projected plume sizes and durations under conditions when inflow density currents are negligible.

When inflow density currents are important, however, as expected for fall TFM treatments, seiche-driven currents would be important to consider in predicting the transport and dispersion of lampricide in deep offshore waters. Approximate perspectives on the spatial scales of seiche-driven transport can be developed by considering the path of a particle released into an oscillating (sinusoidal) flow field with an amplitude (4 cm/sec) and period (3.5 days) typical of seiche-driven currents in the Boquet River region of Lake Champlain (Figures 22-23). Results are displayed in Figure 25. Ignoring local wind-driven currents, a particle or substance traveling with the average velocity of the epilimnetic seiche would have a maximum excursion of 2 to 4 kilometers north or south from the point of entry, depending upon the time of release in relation to the phase of the seiche. Maximum excursions to the North (4 kilometers) result when the release coincides with the start of the northward flow (Phase = A in Figure 25). Conversely, maximum excursions to the South (4 kilometers) result when the release coincides with the start of the southward flow (Phase = C in Figure 25). Other release times would tend to give maximum excursions in the range of 2 to 4 kilometers.

Figure 26 shows the projected paths of particles released into the surface seiche and traveling with the average velocity predicted at one-hour intervals by the wave model described above. Particles are released at the start of each of monthly simulation period. The Y-axis shows the location of the particle north(+) or south(-) of the release point, assuming that it travels according to the average velocity predicted by the wave model during each hourly time step. Maximum excursions of 2 to 5 kilometers are predicted by this approach. These excursions would refer to the center of mass of the lampricide plume; the 50 and 20 ppb contours may extend beyond the center of mass because of dispersion processes. Excursions in offshore waters are similar in magnitude to maximum shoreline transport distances for the 20 ppb TFM plume projected by the wind-driven current model (Figure 14).

Whether or not these maximum excursions would be reached before dispersal of the lampricide plume (as defined based upon 50 or 20 ppb criteria) would depend upon the magnitudes of longitudinal, lateral, and vertical dispersion processes which would cause dilution of the plume in deep offshore regions as it moves with seiche-driven and wind-driven currents. Dispersion of the lampricide plume would be promoted by entrainment into currents, by shearing effects attributed to vertical and horizontal variations current velocities, and by wind-induced turbulence (Fischer et al., 1979). Data are not available for quantifying these processes in the lake region of concern. This underscores the importance of lake and intake monitoring following lampricide applications.

CONCLUSIONS

The above calculations provide approximate perspectives on lampricide plume sizes and durations for a range of treatment and environmental conditions anticipated for lampricide applications to the Boquet River. Because it is impossible to predict the particular set of environmental conditions (streamflow, wind speed, wind direction) present during the treatments, it is impossible to predict actual plume sizes and durations beforehand. Model results have been expressed so that they can be interpreted and rescaled to reflect environmental conditions present during treatment.

Given the proposed fall treatment schedule and probable importance of density currents, it is likely that the wind-driven current models employed in this report over-estimate the extent of lampricide transport in shallow shoreline areas and under-estimate transport in deep offshore waters. More comprehensive models of lampricide transport under fall treatment conditions would consider the impacts of inflow density currents, seiche-driven currents, and local wind-driven currents in a full three-dimensional framework. A much more comprehensive data base on hydrodynamic aspects of Lake Champlain would be require to support development of such a model and application to the Boquet River or other proposed treatment sites. Despite their limitations, predictions of the wind-driven current models are adequate and conservative for evaluating potential lampricide transport to shoreline water-use points.

Along with projections based directly upon dye study results, model results can be used to evaluate treatment impacts and to design monitoring programs for tracking plume behavior following lampricide application. Because of the likely importance of density currents, water intakes extending into deep offshore regions should be given special consideration for monitoring, in addition to those located in shallow shoreline regions. Monitoring programs should also include vertical profile sampling at offshore locations to track lampricide transport and dispersal following application periods. Given the probable importance of seiche-driven currents in transporting lampricides in offshore waters, monitoring of regional water intakes (e.g., Essex) should extend over at least one full period of the seiche following application (typically, 3-4 days). Monitoring of thermocline movements (e.g., Figure 22) would provide a basis for tracking seiche activity during treatment periods and, to some extent, anticipating the directions (north or south) of seiche-related currents in the region to assist in plume tracking.

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TABLES

Table 1
Boquet River Dye Study and Treatment Conditions

Dye Study Conditions....		SPRING	FALL
Start Date		6/2/86	9/22/87
Start Time	hours	5.4	6.0
River Temperature	deg-F	54-60	53-59
Lake Surface Temperature	deg-F	53-59	65-66
Lake Hypolimnion Temp.	deg-F	-	< 52
Thermocline Level	feet	-	100
Resultant Wind		N	NW
Mean Speed	mph	14.5	5.6
Wind Load Factor		3.19	0.45
Mean Flow	cfs	415	220
Applied Dye Conc.	ppb	2.85	8.20
Duration	hrs	12	12
Total Dye Dose	lbs	3.19	4.86
TFM Treatment Conditions...			
Flow	cfs	150	
Applied Conc	ppm	4.2	
Treatment Duration	hrs	12	
Total TFM Dose	lbs	1698	
BAYER 73 Treatment Conditions...			
Application Area	acres	250	
Total Dose	lbs/acre	100	
Active Fraction		0.05	
Duration of Release	hrs	6	
Total Dose of Active Ingred.	lbs	1250	

FIGURES

Figure 1
Boquet River - Model Region
Map Scale = 1:88816, 1 Inch = 1.4 miles = 2.3 kilometers

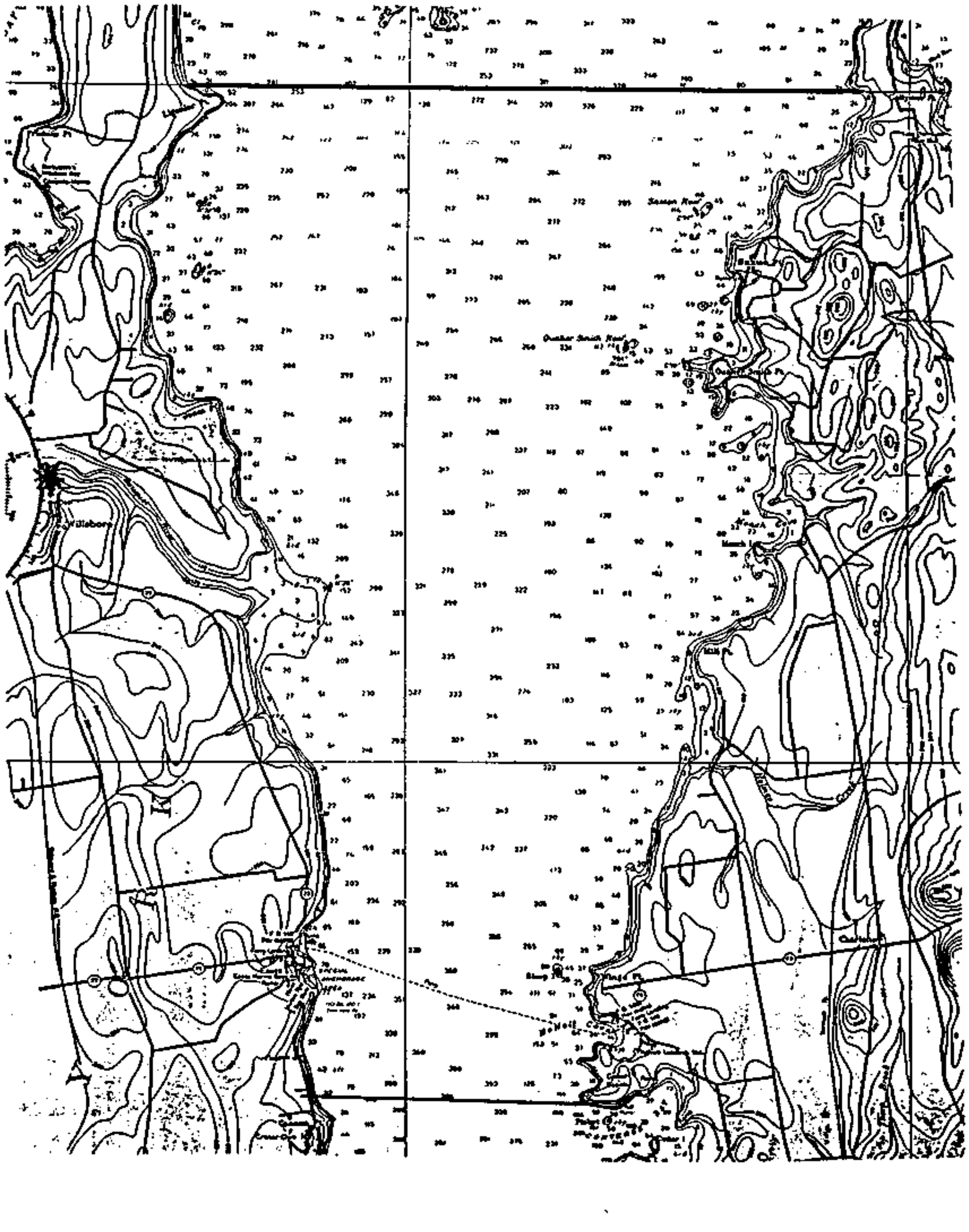

Figure 2
Boquet River - Finite Element Mesh

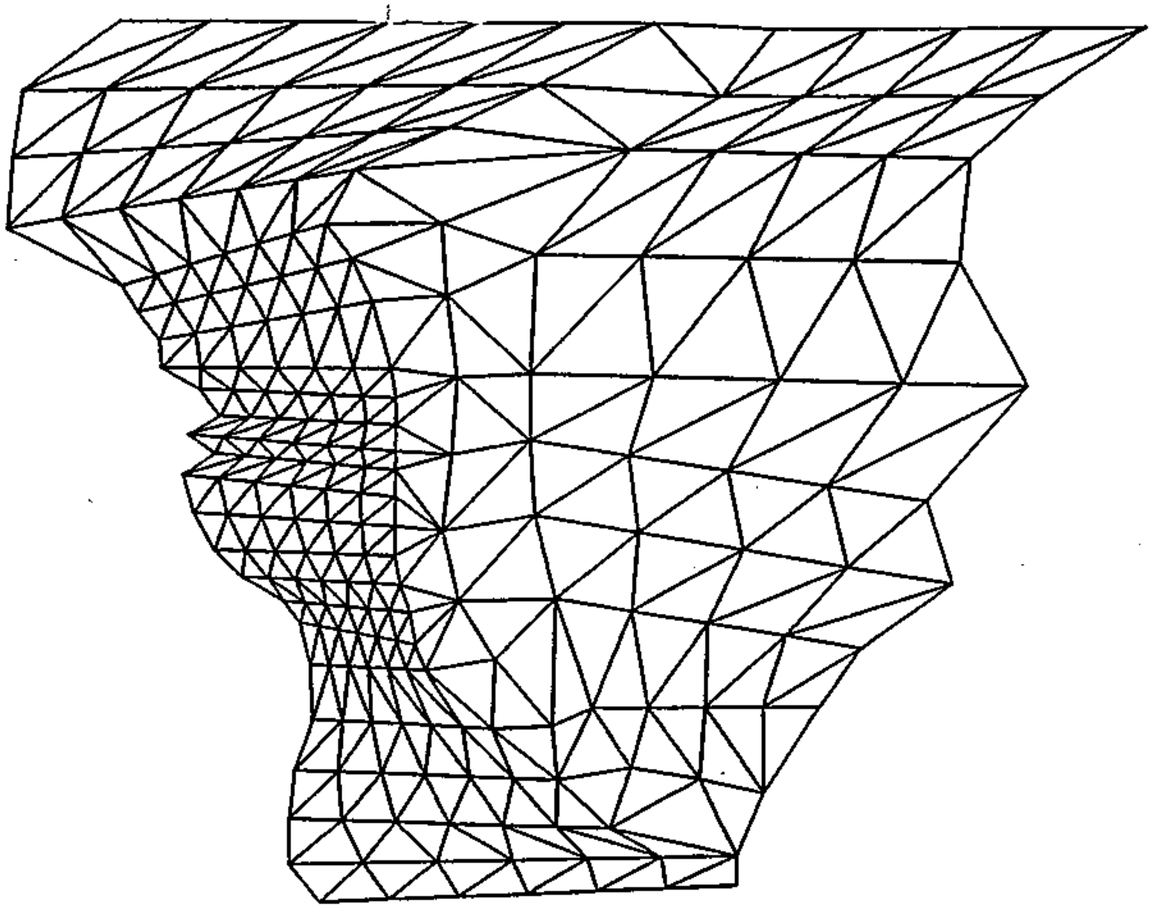

Figure 3
Boquet River - Vertically Averaged Circulation Patterns - Northwest Wind
(Directions Reversed for Southeast Wind)

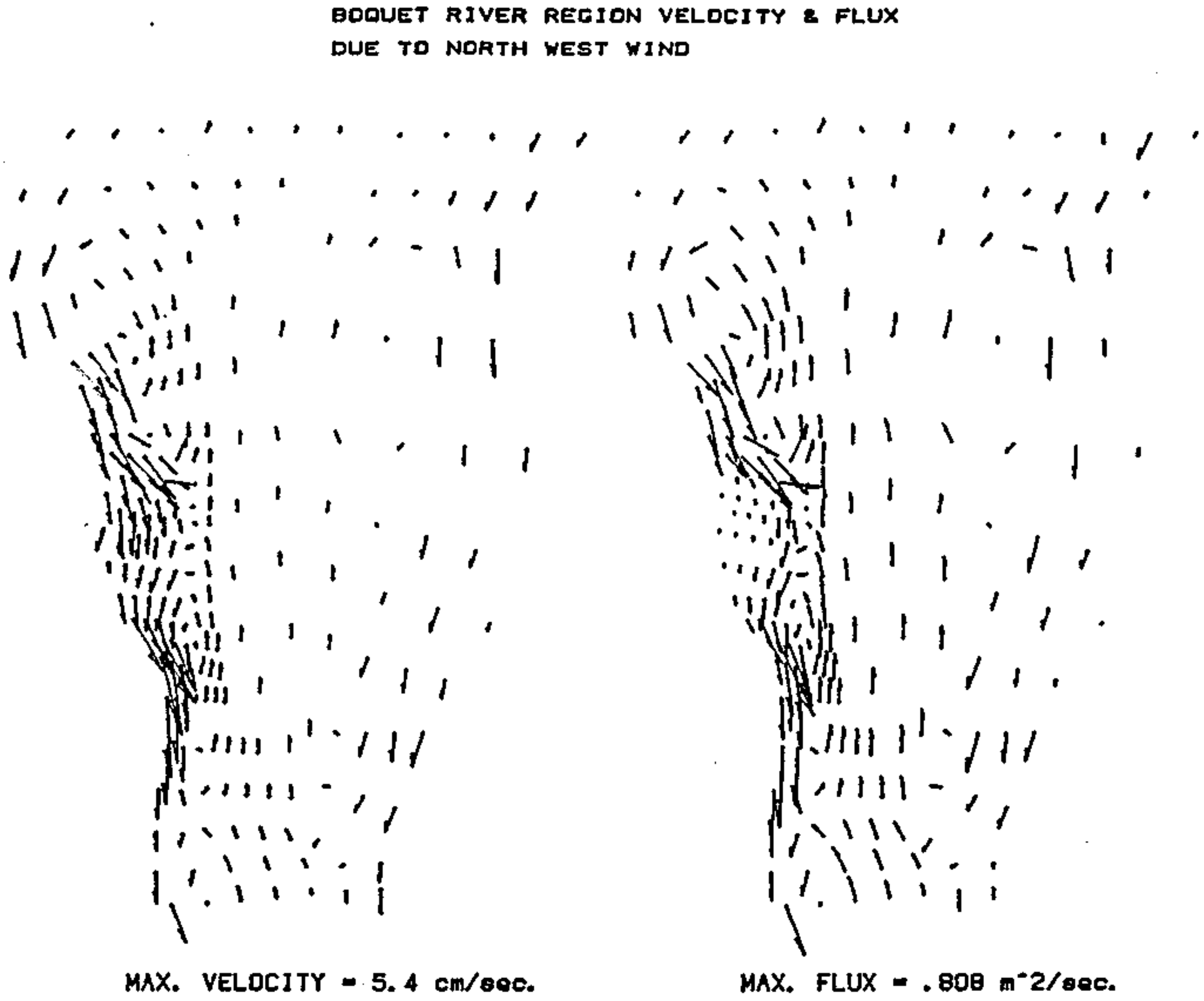

Figure 4
Boquet River - Vertically Averaged Circulation Patterns - North Wind
(Directions Reversed for South Wind)

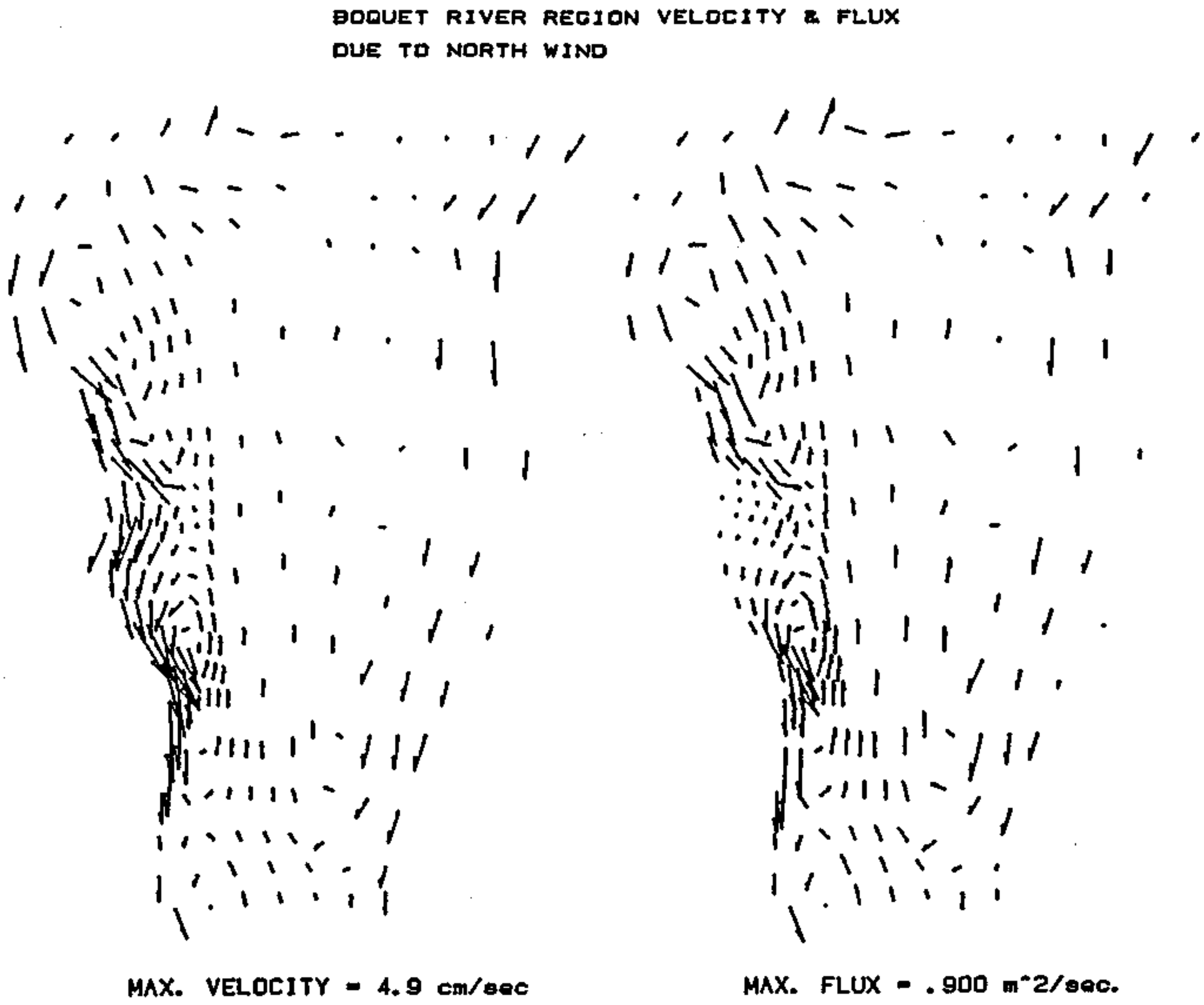

Figure 5
Boquet River - Vertically Averaged Circulation Patterns - Northeast Wind
(Directions Reversed for Southwest Wind)

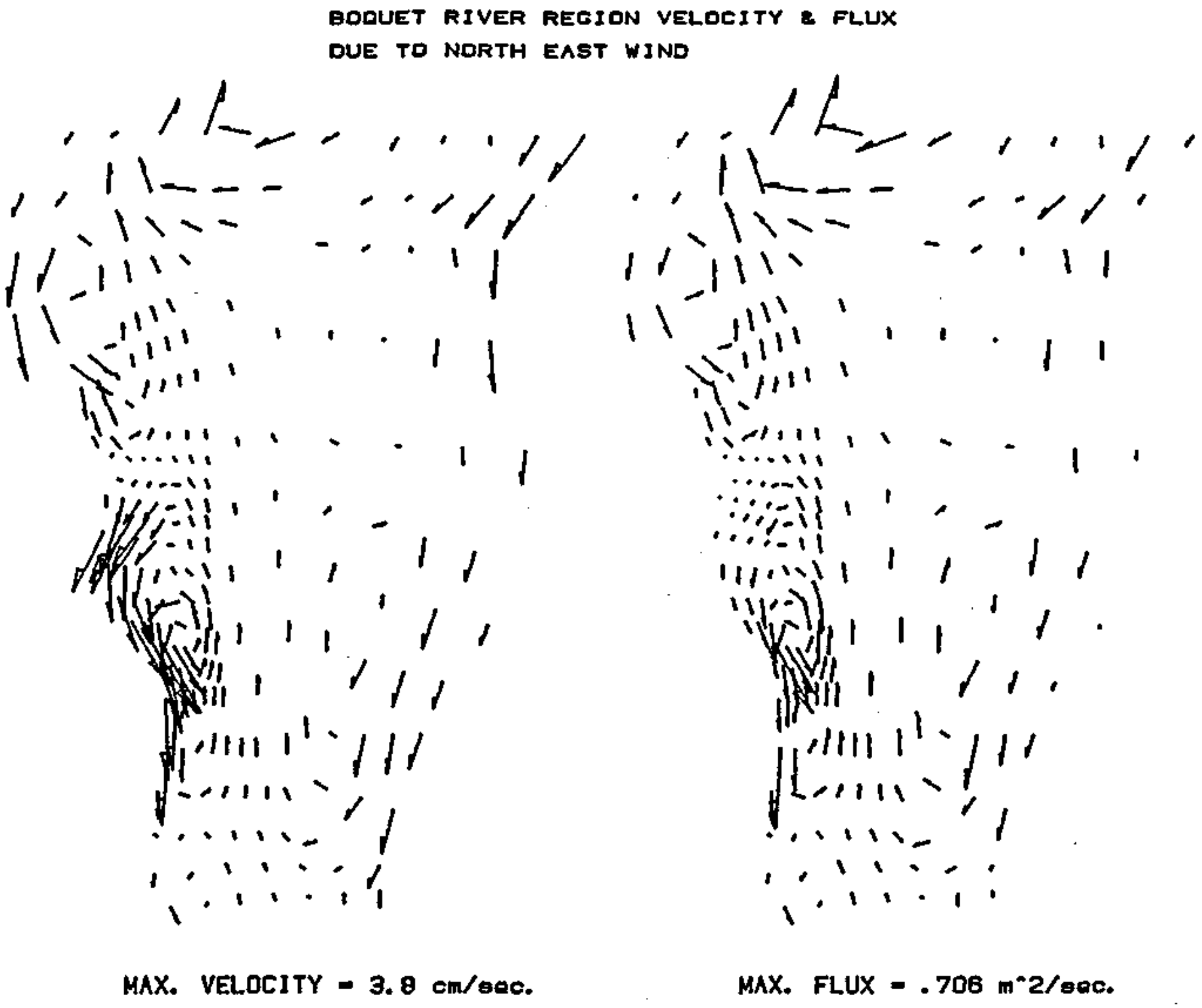

Figure 6
Wind Velocities at Burlington Airport During Dye Study Periods

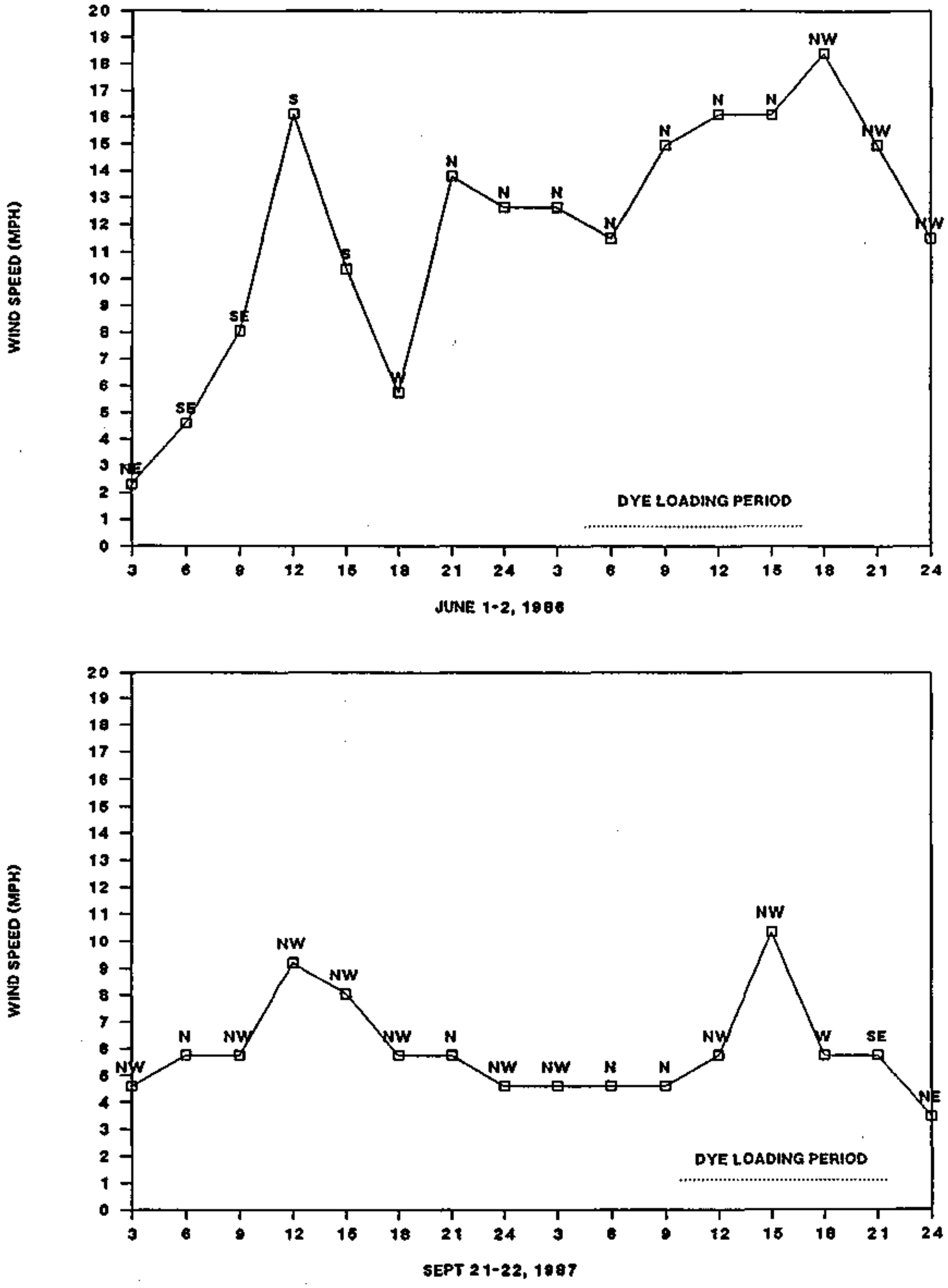

Figure 7
Boquet River - Transport Model Grid
Cell Depths (Meters) at Minimum Lake Elevation (92.9 ft, msl)
Depths Truncated at Maximum Value of 25 meters
xxx = Land Mass, Cell Dimension = 400 meters = 1312 feet

```
     1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
  +------------------------------------------------------------------------+
 2|xxx 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 24 23 12  7|
 3|xxxxxx 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 21 21 15  6|
 4|xxx  7 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 22 18 12  7xxx|
 5|xxx 15 11 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 13 15xxxxxxxxx|
 6|  9 15 24 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 12  9xxxxxxxxx|
 7|  7 15 18 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 12xxxxxxxxxxxx|
 8|  6 12 18 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 19 12xxxxxxxxxxxx|
 9|  6 13 18 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 21  7xxxxxxxxxxxx|
10|  6 13 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 15 12  7xxxxxxxxxxxx|
11|xxx 12 21 25 25 25 25 25 25 25 25 25 25 25 25 25 25 18  9xxxxxxxxxxxxxxx|
12|xxx  6 12 25 25 25 25 25 25 25 25 25 25 25 25 25 25 22  6xxx  3xxxxxxxxx|
13|xxxxxxxxx 15 25 25 25 25 25 25 25 25 25 25 25 25 25 24  9  6  4  0xxxxxx|
14|xxxxxxxxx  9 24 25 25 25 25 25 25 25 25 25 25 25 25 24 13 17  6  1xxxxxx|
15|xxxxxxxxx  9 15 25 25 25 25 25 25 25 25 25 24 25 25 25 24 12  9  0xxxxxx|
16|xxxxxxxxxxxx  8 19 25 25 25 25 25 25 25 25 25 25 25 24 24 15 11  1xxxxxx|
17|xxxxxxxxxxxx  1 15 25 25 25 25 25 25 25 25 25 25 25 24 23 18  6xxxxxxxxx|
18|xxxxxxxxxxxx  1  3 25 25 25 25 25 25 25 25 25 25 25 25 23 15  7xxxxxxxxx|
19|xxxxxxxxxxxx  1  1 25 25 25 25 25 25 25 25 25 25 25 21 18 15  7xxxxxxxxx|
20|xxxxxxxxxxxx  1  2 21 25 25 25 25 25 25 25 25 25 25 18 18  4xxxxxxxxxxxx|
21|xxxxxxxxxxxx  4  4 25 25 25 25 25 25 25 25 25 25 25 18  3xxxxxxxxxxxxxxx|
22|xxxxxxxxxxxx  6  9 15 25 25 25 25 25 25 25 25 25 17 15  3xxxxxxxxxxxxxxx|
23|xxxxxxxxxxxxxxx 12 21 25 25 25 25 25 25 25 25 25 18 12  4xxxxxxxxxxxxxxx|
24|xxxxxxxxxxxxxxx  6 18 25 25 25 25 25 25 25 25 25 15  7  4xxxxxxxxxxxxxxx|
25|xxxxxxxxxxxxxxxxxx  9 25 25 25 25 25 25 25 25 21 13  7xxxxxxxxxxxxxxxxxx|
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27|xxxxxxxxxxxxxxxxxx  6 25 25 25 25 25 25 25 24 15  7xxxxxxxxxxxxxxxxxxxxx|
28|xxxxxxxxxxxxxxxxxx  9 25 25 25 25 25 25 25 25 15  7xxxxxxxxxxxxxxxxxxxxx|
29|xxxxxxxxxxxxxxxxxx 12 25 25 25 25 25 25 25 25 19  3xxxxxxxxxxxxxxxxxxxxx|
30|xxxxxxxxxxxxxxxxxx 15 25 25 25 25 25 25 25 21 16xxxxxxxxxxxxxxxxxxxxxxxx|
31|xxxxxxxxxxxxxxxxxx 21 25 25 25 25 25 25 25 15  9xxxxxxxxxxxxxxxxxxxxxxxx|
32|xxxxxxxxxxxxxxxxxx 21 25 25 25 25 25 25 25  7xxxxxxxxxxxxxxxxxxxxxxxxxxx|
33|xxxxxxxxxxxxxxxxxx 25 25 25 25 25 25 25 25 18xxxxxxxxxxxxxxxxxxxxxxxxxxx|
34|xxxxxxxxxxxxxxxxxx 24 25 25 25 25 25 25 25 15  7xxxxxxxxxxxxxxxxxxxxxxxx|
35|xxxxxxxxxxxxxxxxxx 13 25 25 25 25 25 25 25 18xxxxxxxxxxxxxxxxxxxxxxxxxxx|
36|xxxxxxxxxxxxxxxxxx  9 25 25 25 25 25 25 25 25xxxxxxxxxxxxxxxxxxxxxxxxxxx|
  +------------------------------------------------------------------------+
```
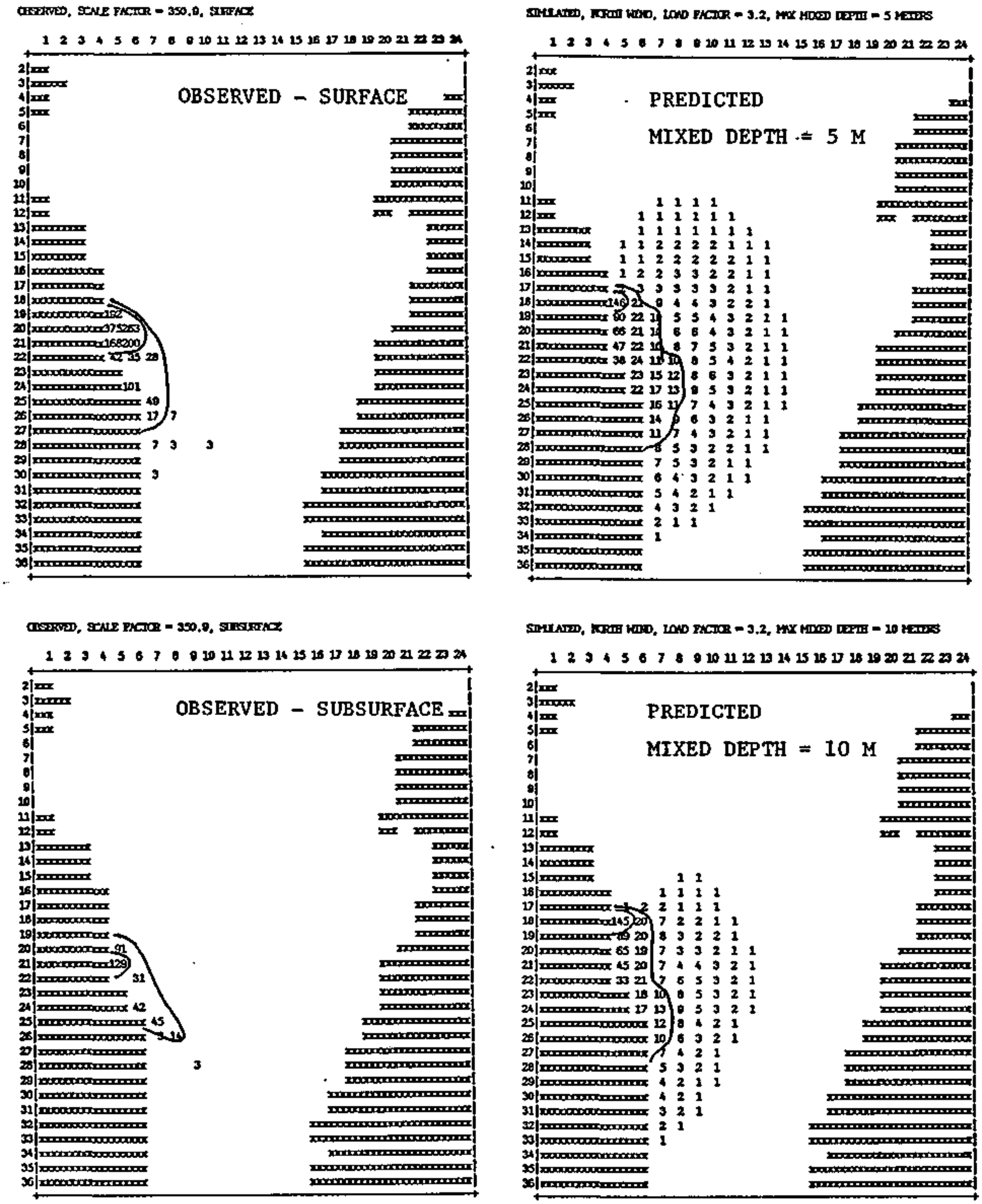

Figure 8

Boquet River - Observed and Predicted Maximum Dye Concentrations
June 2, 1986 Dye Study

Dye Concentrations Rescaled to Applied Conc. of 1000 ppb
Contours = 10- and 100-Fold Dilution


OBSERVED, SCALE FACTOR = 350.9, SURFACE

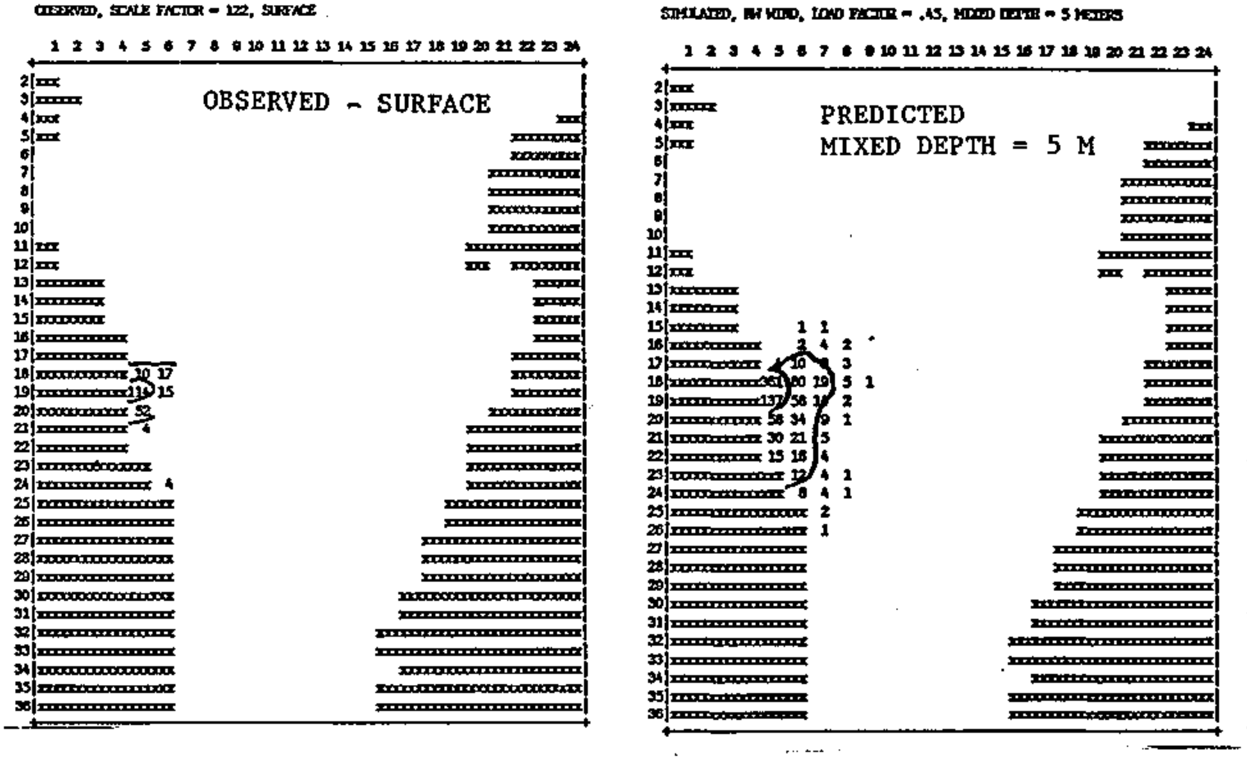
SIMULATED, NORTH WIND, LOAD FACTOR = 3.2, MAX MIXED DEPTH = 5 METERS

OBSERVED, SCALE FACTOR = 350.9, SUBSURFACE

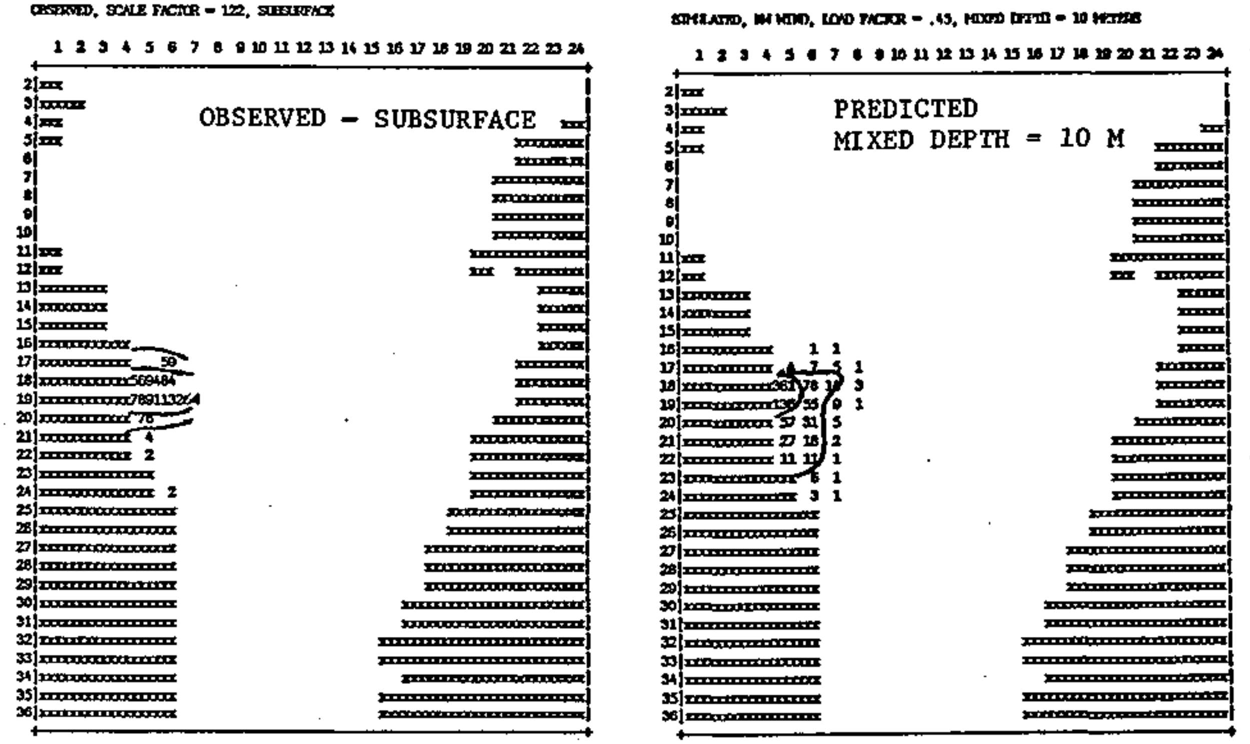
SIMULATED, NORTH WIND, LOAD FACTOR = 3.2, MAX MIXED DEPTH = 10 METERS

Figure 9
Boquet River - Observed and Predicted Maximum Dye Concentrations
September 22, 1987 Dye Study

Dye Concentrations Rescaled to Applied Conc. of 1000 ppb
Contours = 10- and 100-Fold Dilution


OBSERVED, SCALE FACTOR = 122, SURFACE

SIMULATED, NW WIND, LOAD FACTOR = .45, MIXED DEPTH = 5 METERS


OBSERVED, SCALE FACTOR = 122, SUBSURFACE

SIMULATED, NW WIND, LOAD FACTOR = .45, MIXED DEPTH = 10 METERS

Figure 10
Empirical Projection of TFM Plume Based Upon June 2, 1986 Dye Study

TFM CONC = Measured Dye Conc. x TFM Load / Dye Load
LOAD = Streamflow x Applied Conc. x Treatment Duration

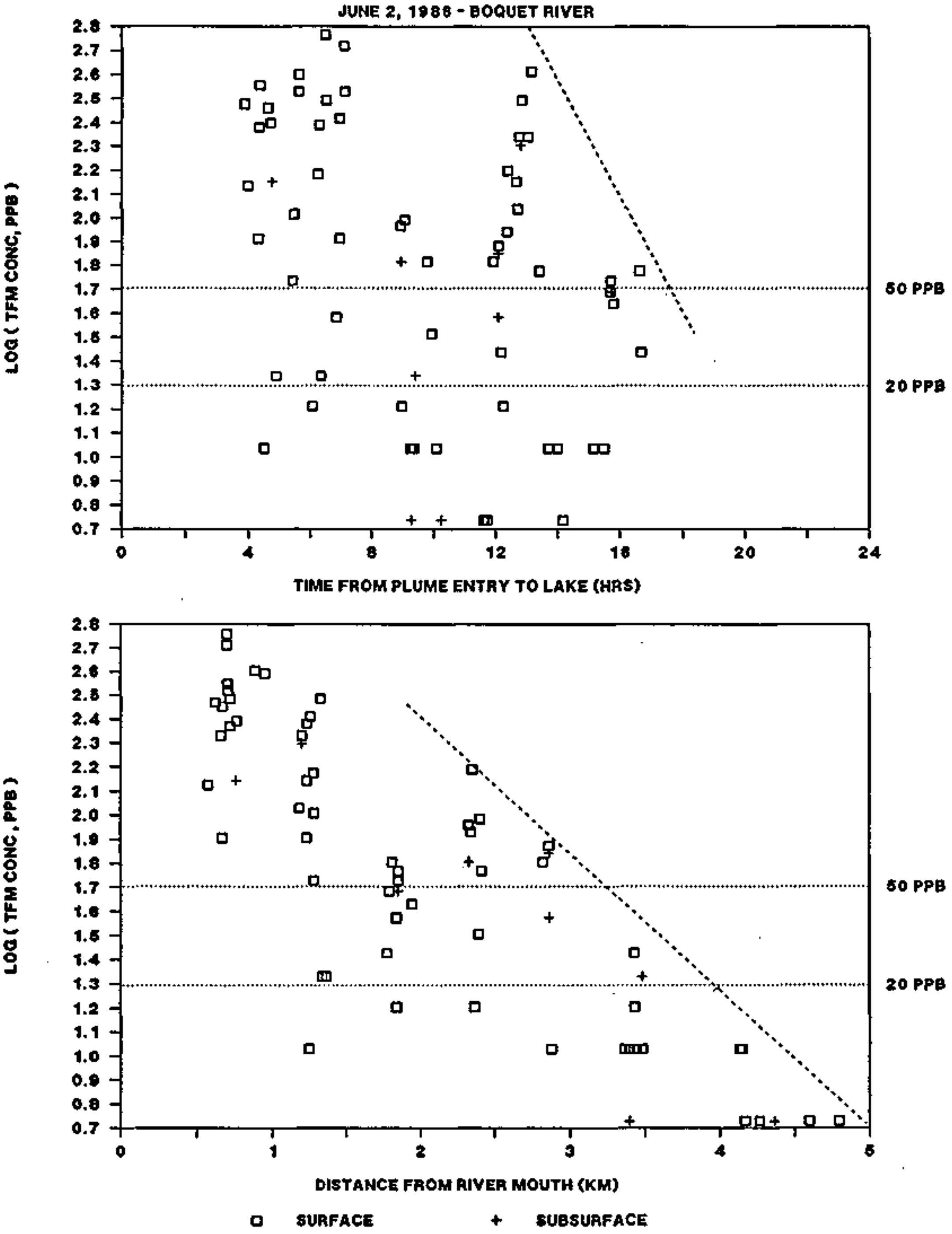


Figure 11
Empirical Projection of TFM Plume Based Upon September 22, 1987 Dye Study

TFM CONC = Measured Dye Conc. x TFM Load / Dye Load
LOAD = Streamflow x Applied Conc. x Treatment Duration

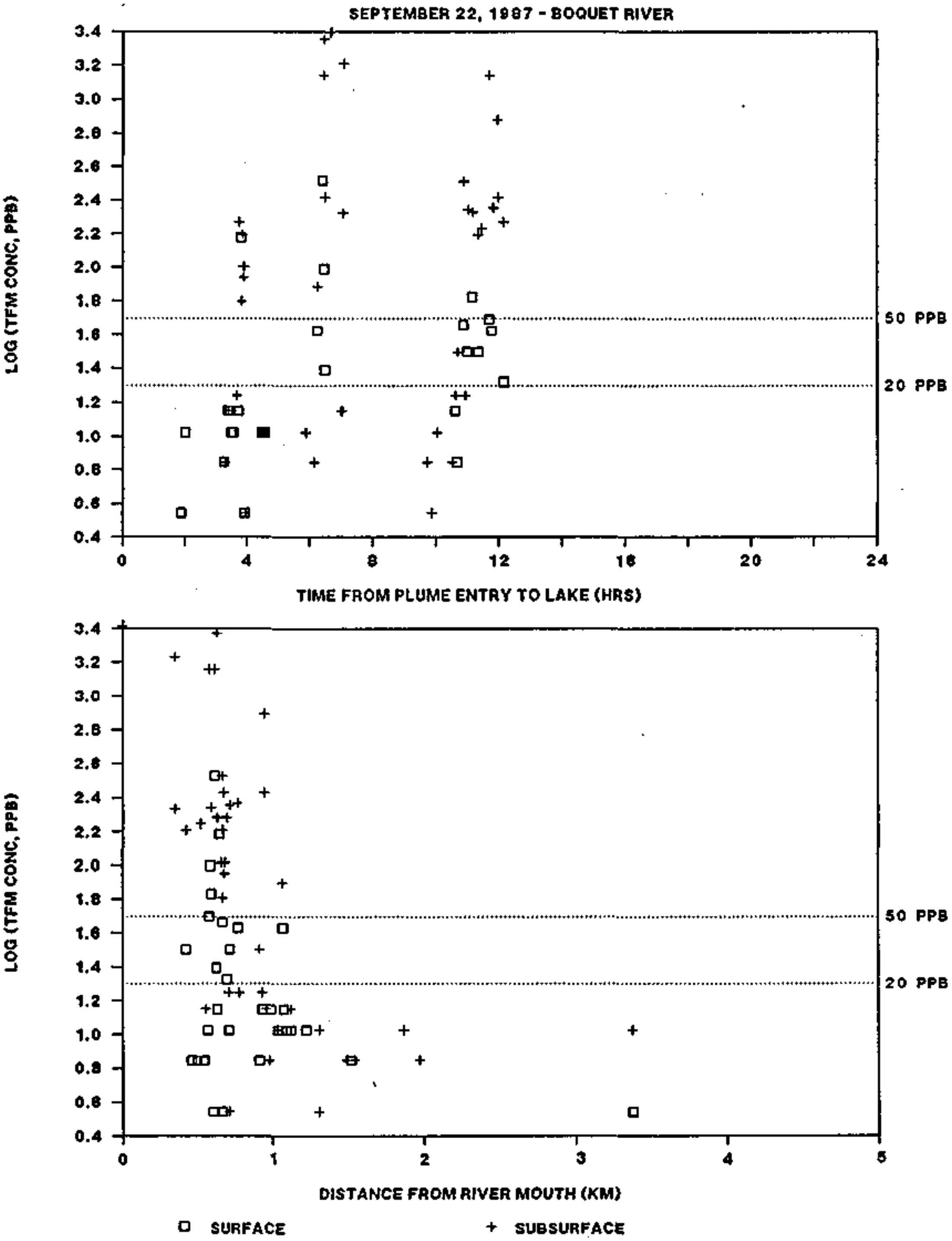


Figure 12
Boquet River - Maximum TFM Concentrations vs. Wind Direction

Maximum Mixed Layer Depth = 5 meters
Streamflow = 150 cfs, Applied Conc. = 4.2 ppm, Duration = 12 hrs
Digits = Maximum Concentration (ppb / 5)
Contours = 10, 20, 50 ppb

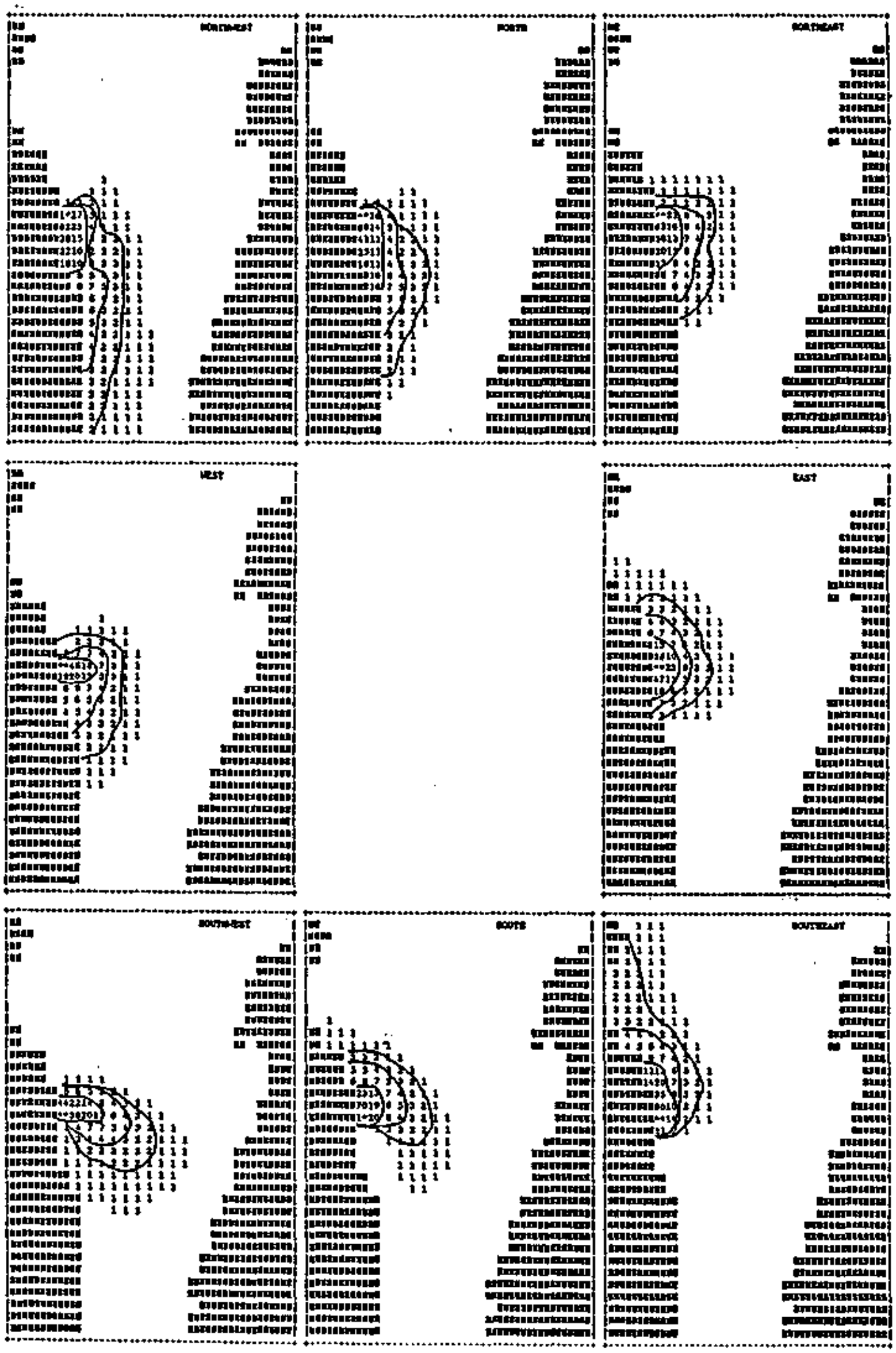


Figure 13

Boquet River - Composite Maximum TFM Concentrations

Composite Projections for Eight Wind Directions
Maximum Mixed Layer Depth = 5 meters
Streamflow = 150 cfs, Applied Conc. = 4.2 ppm, Duration = 12 hrs
Digits = Maximum Concentration (ppb / 5)
Contours = 10, 20, 50 ppb

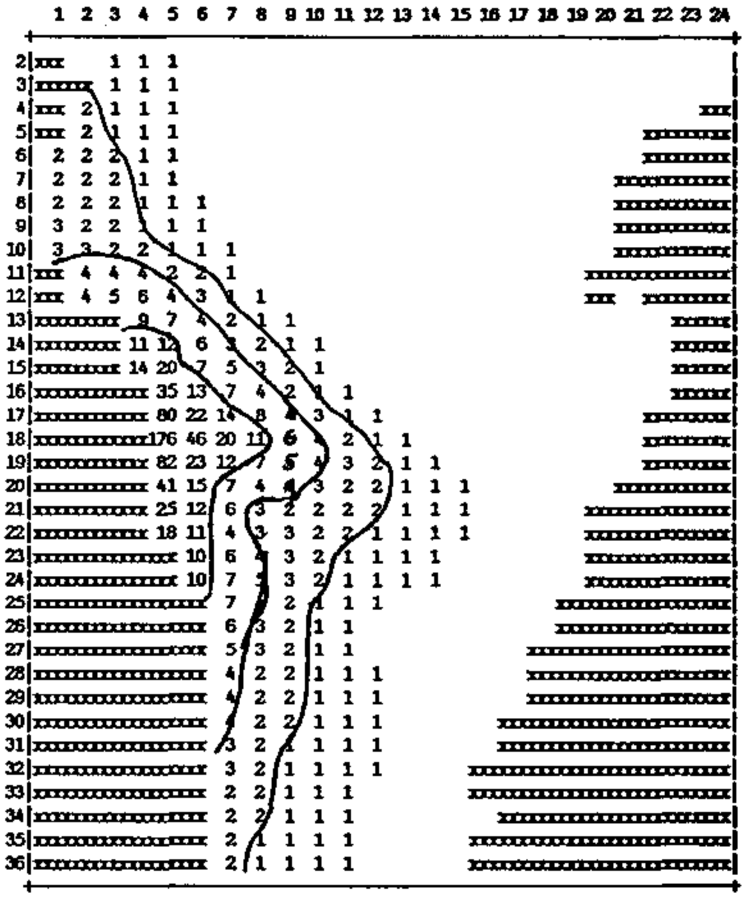


Figure 14
Boquet River - Maximum TFM Concentration Contours

Composite Projections for Eight Wind Directions
Streamflow = 150 cfs, Applied Conc. = 4.2 ppm, Duration = 12 hrs
Maximum Mixed Layer Depth = 5 meters
Map Scale = 1:88816, 1 Inch = 1.4 miles = 2.3 kilometers

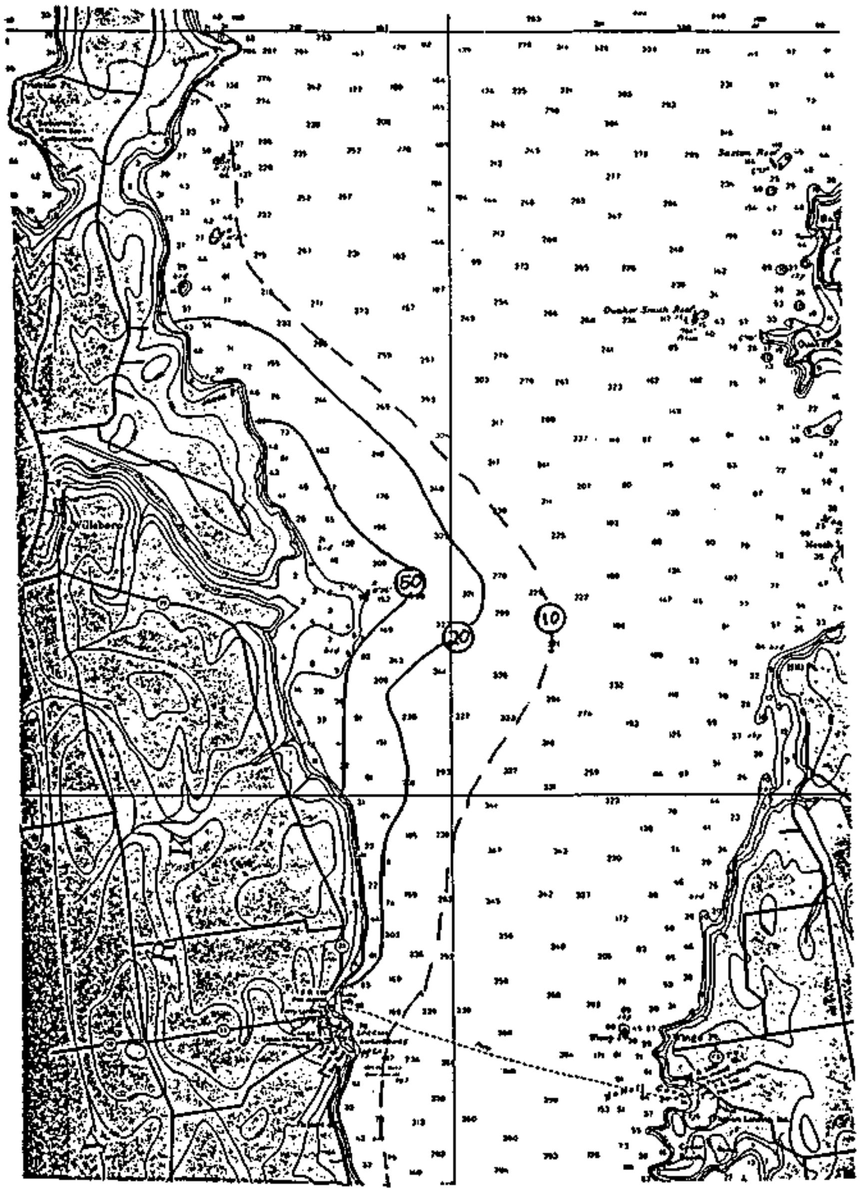


Figure 15
Boquet River - Maximum Bayer-73 Concentrations vs. Wind Direction

Maximum Mixed Layer Depth = 5 meters
Applic. Area = 250 acres, Dose = 100 lbs/acre (5% Active Ingredient)
Digits = Maximum Concentration (ppb / 5)
Contours = 10, 20, 50 ppb

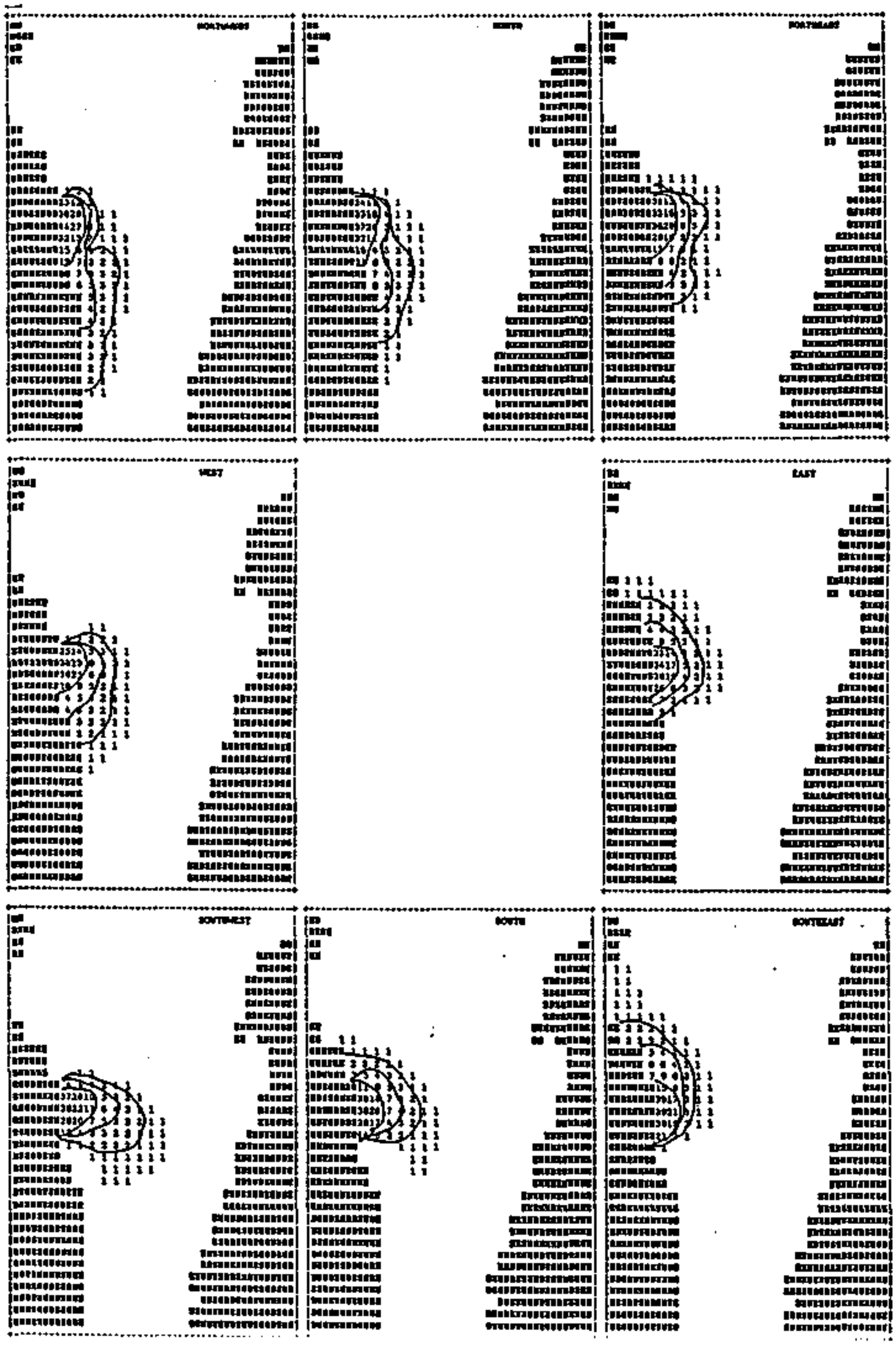


Figure 16
Boquet River - Composite Maximum Bayer-73 Concentrations

Composite Projections for Eight Wind Directions
Maximum Mixed Layer Depth = 5 meters
Applic. Area = 250 acres, Dose = 100 lbs/acre (5% Active Ingredient)
Digits = Maximum Concentration (ppb / 5)
Contours = 10, 20, 50 ppb

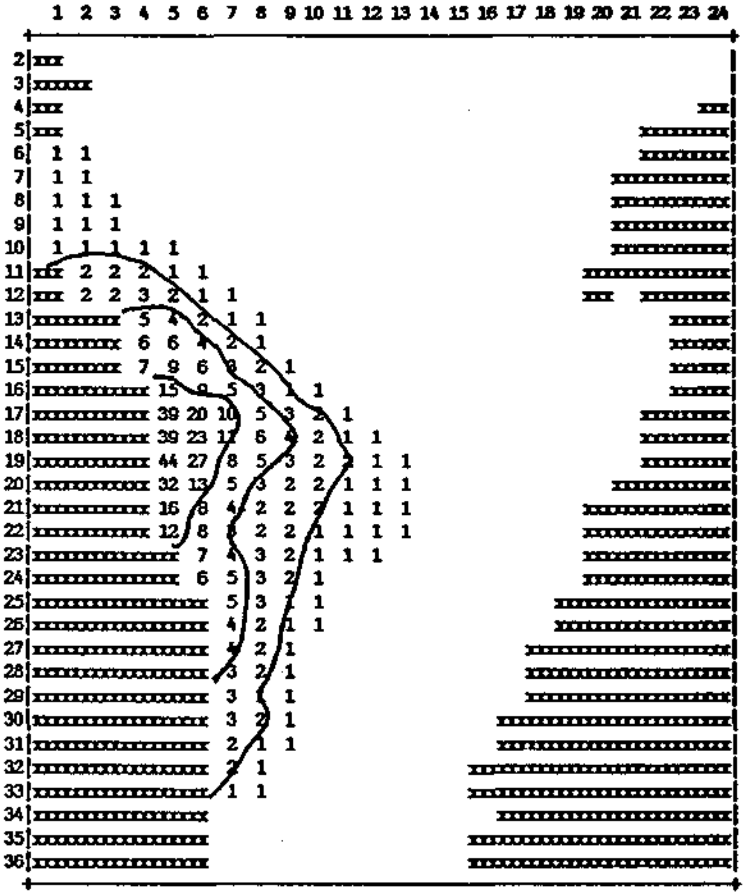


Figure 17
Boquet River - Maximum Bayer-73 Concentration Contours

Composite Projections for Eight Wind Directions
Applic. Area = 250 acres, Dose = 100 lbs/acre (5% Active Ingredient)
Maximum Mixed Layer Depth = 5 meters
Map Scale = 1:88816, 1 Inch = 1.4 miles = 2.3 kilometers

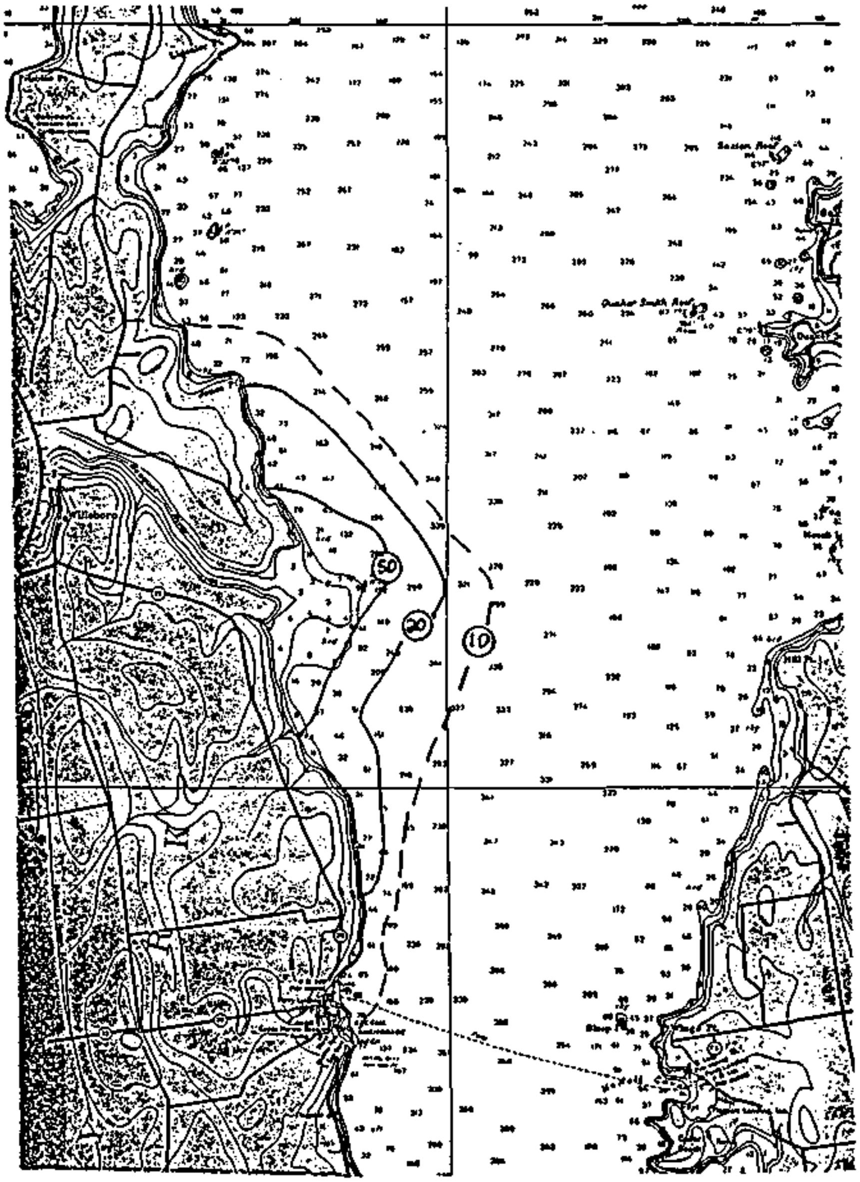


Figure 18
Simulated Maximum Concentrations vs. Time
Boquet River TFM and Bayer-73 Applications

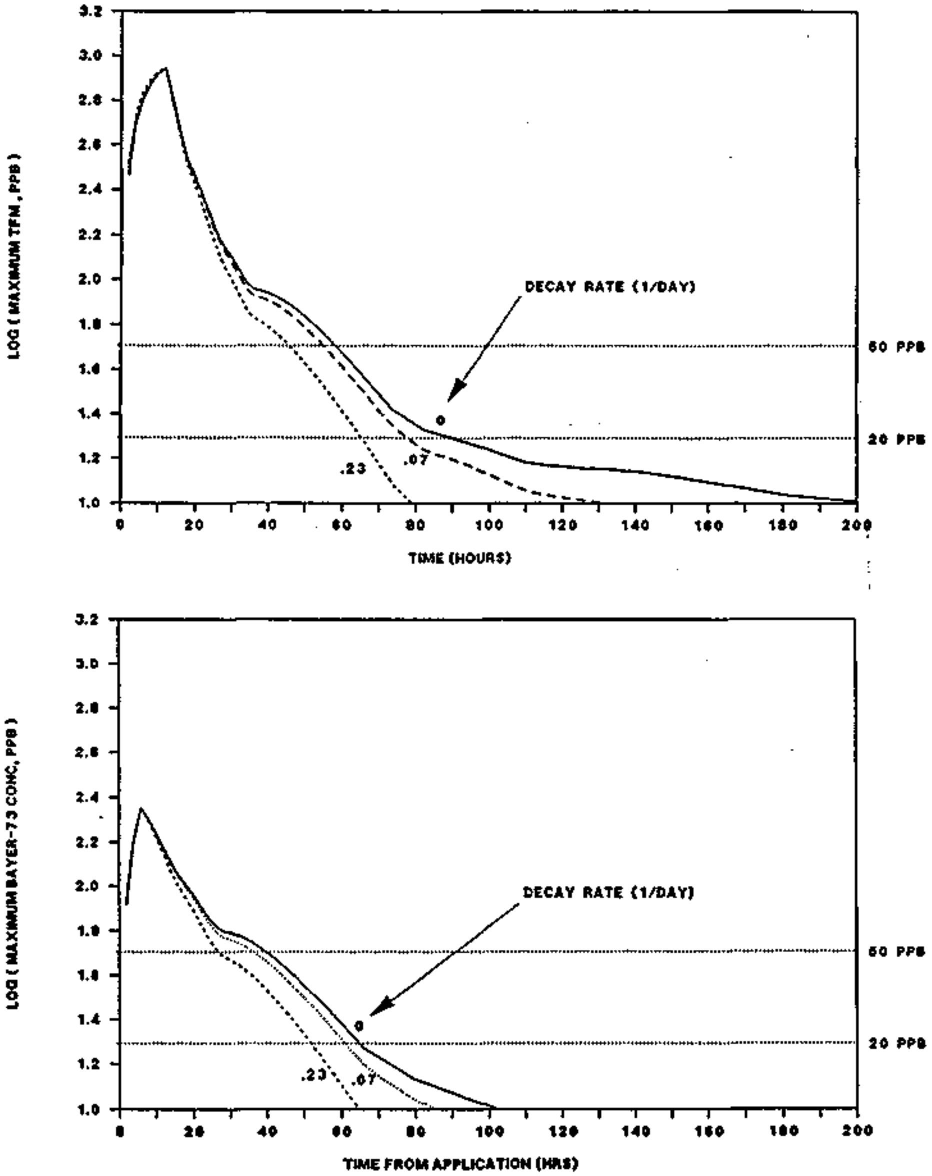
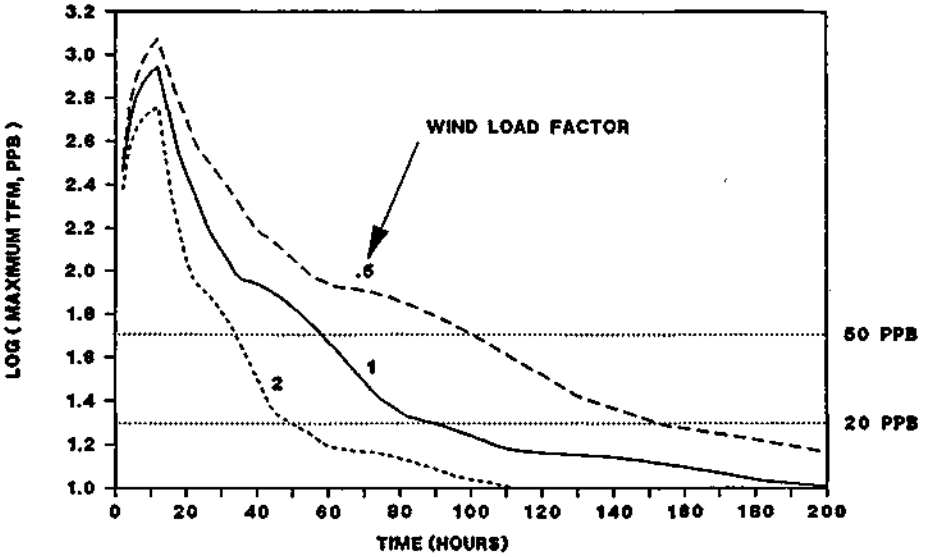


Figure 19
Sensitivity of TFM Plume Duration and Size to Wind Load Factor
Boquet River TFM Treatment
Composite Projections for Eight Wind Directions



Digits = Maximum Concentration (ppb / 5)
Contours = 10, 20, 50 ppb

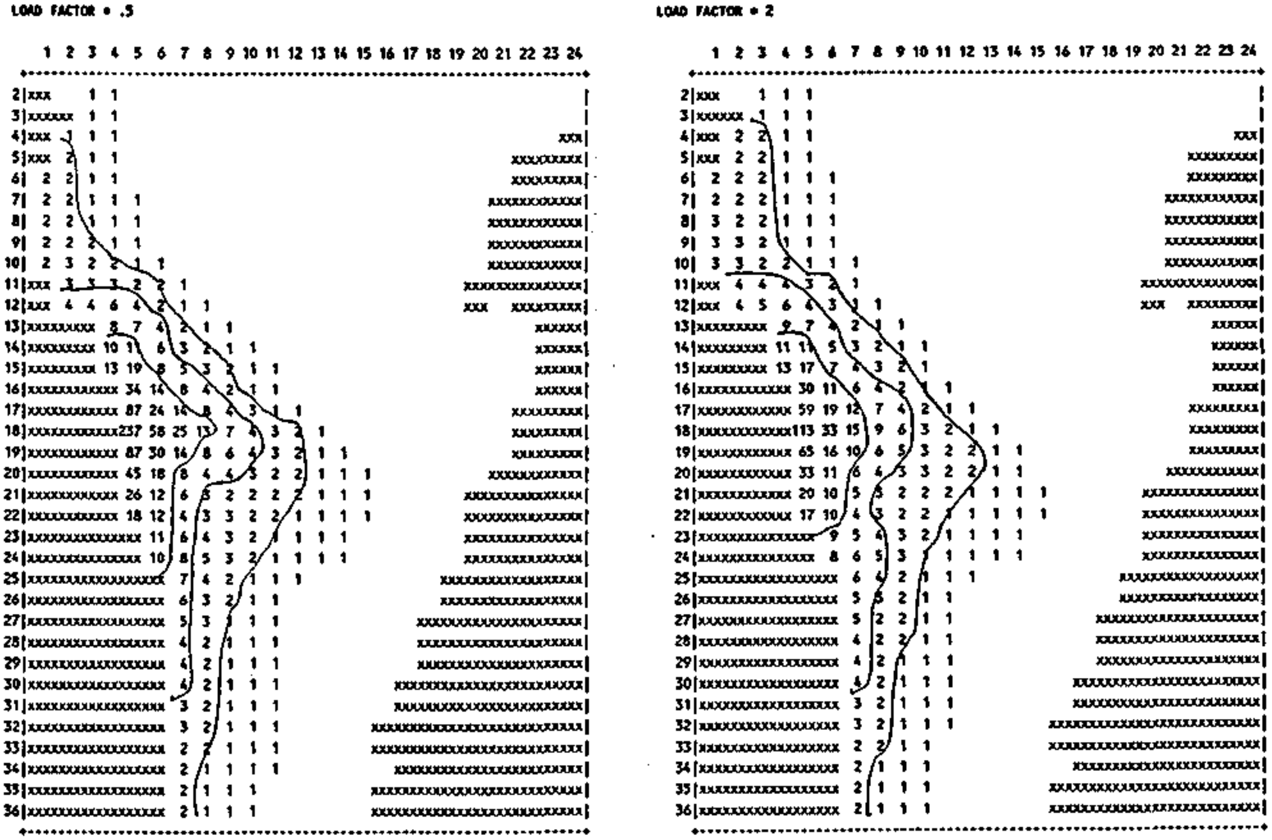


Figure 20
Sensitivity of TFM Plume Duration to Wind Direction
Boquet River TFM Treatment

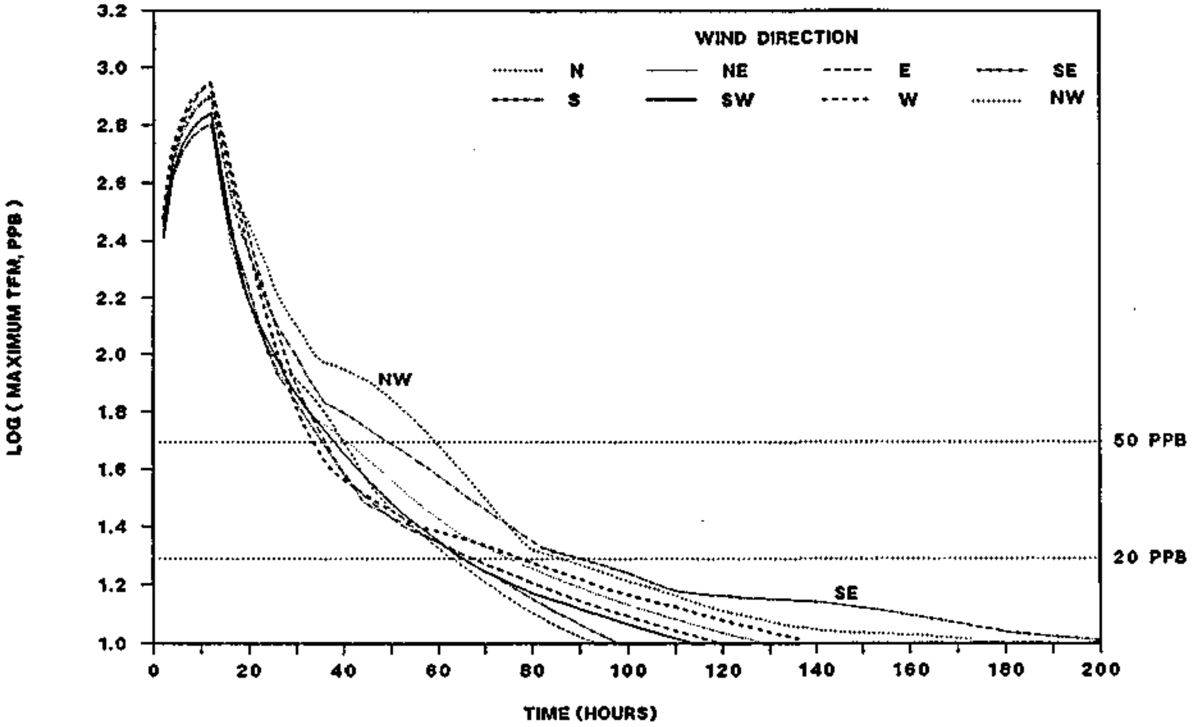


Figure 21
Two-Layer Model Nodes

LAKE CHAMPLAIN & Finite Element Nodes

Grand Isle = 17   Burlington Bay = 11   Kingsland Bay = 5

Talweg Length = 73.6 km

Figure 22
Two-Layer Model Responses at Boquet River
August 1987 Wind Load

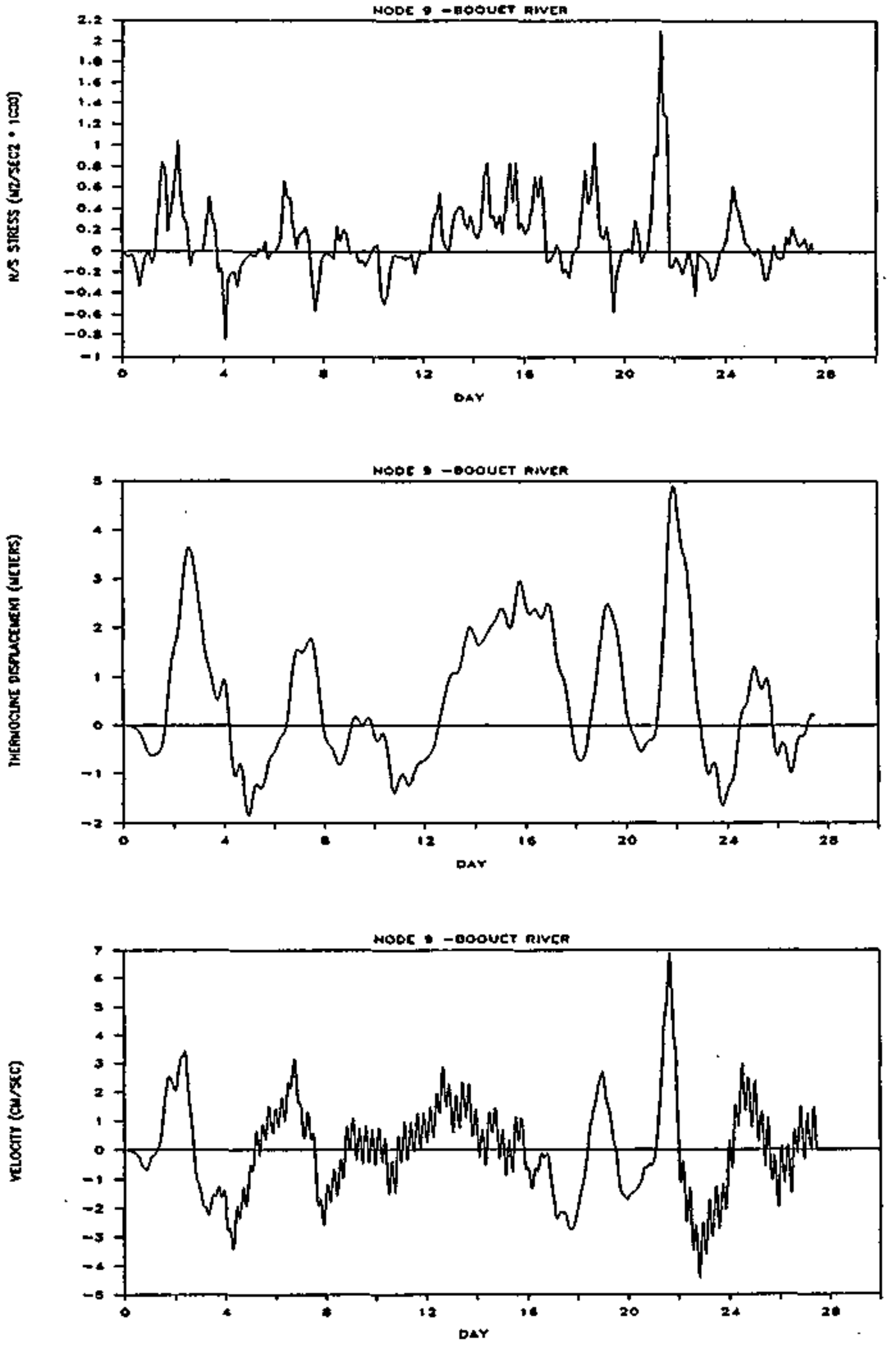


Figure 23
Two-Layer Model Responses at Boquet River
July -September 1986 Wind Load

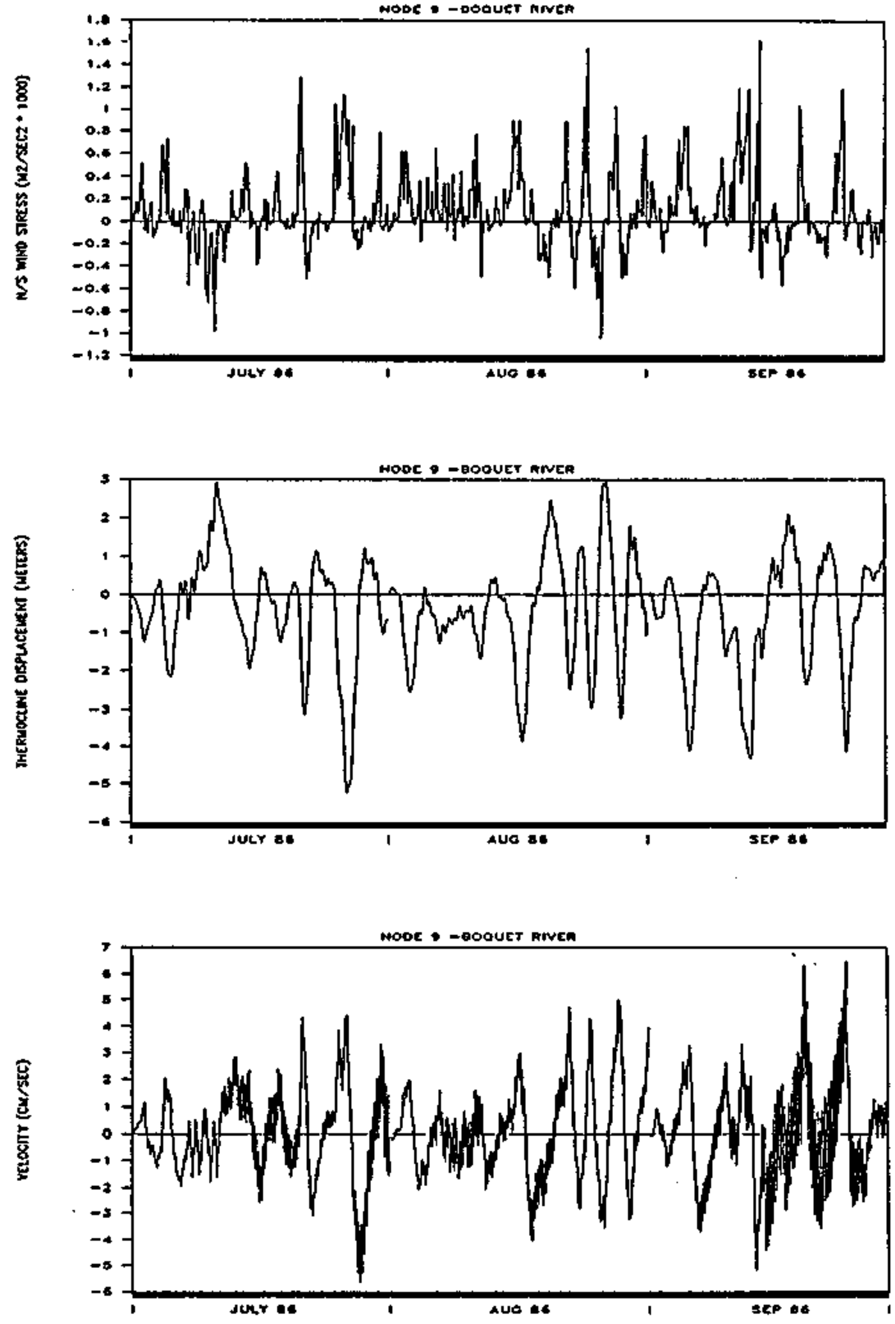


Figure 24
Flow Velocities for Northern Through-flow

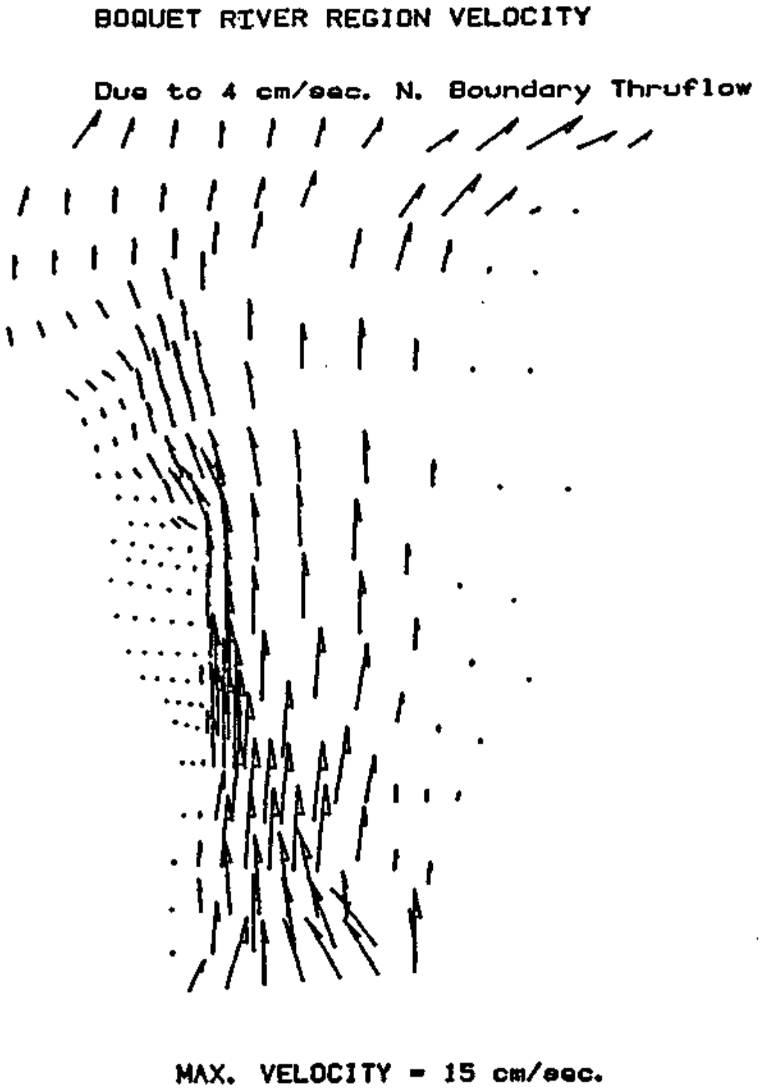


Figure 25
Particle Trajectories Based upon Sinusoidal Model of Seiche

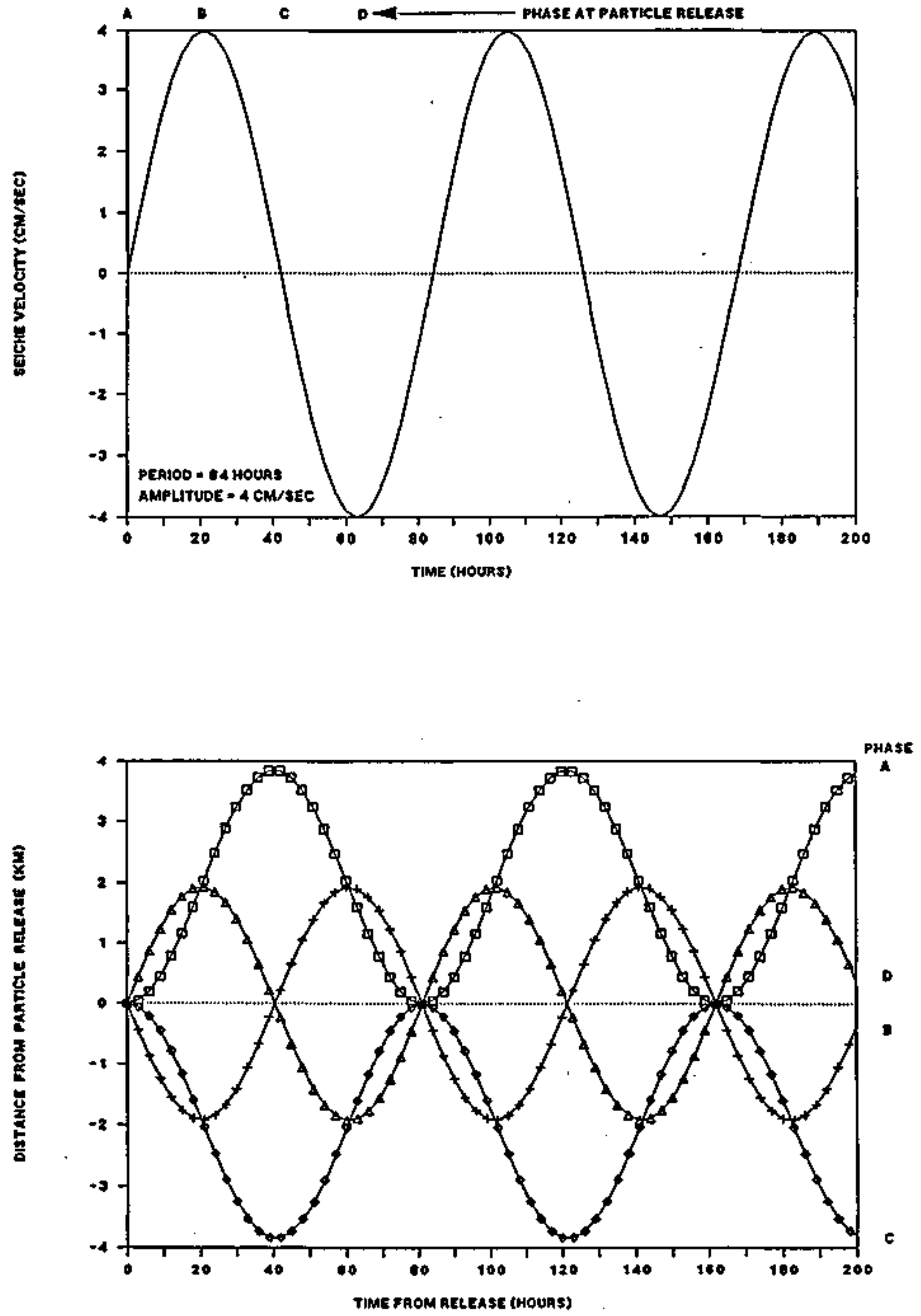


Figure 26
Particle Trajectories Based upon Predicted Velocity Time Series