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RESEARCH REPORT H-74-2

PROBLEM DEFINITION AND MODELING TECHNIQUES FOR THE STUDY OF KANEOHE BAY, OAHU, HAWAII

by

William H. McAnally, Jr., John D. Lunz, Donald C. Raney,
Robert Y. Hudson, Joseph V. Letter, Jr.

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P. O. Box 631, Vicksburg, Miss. 39180

December 1974

Final Report

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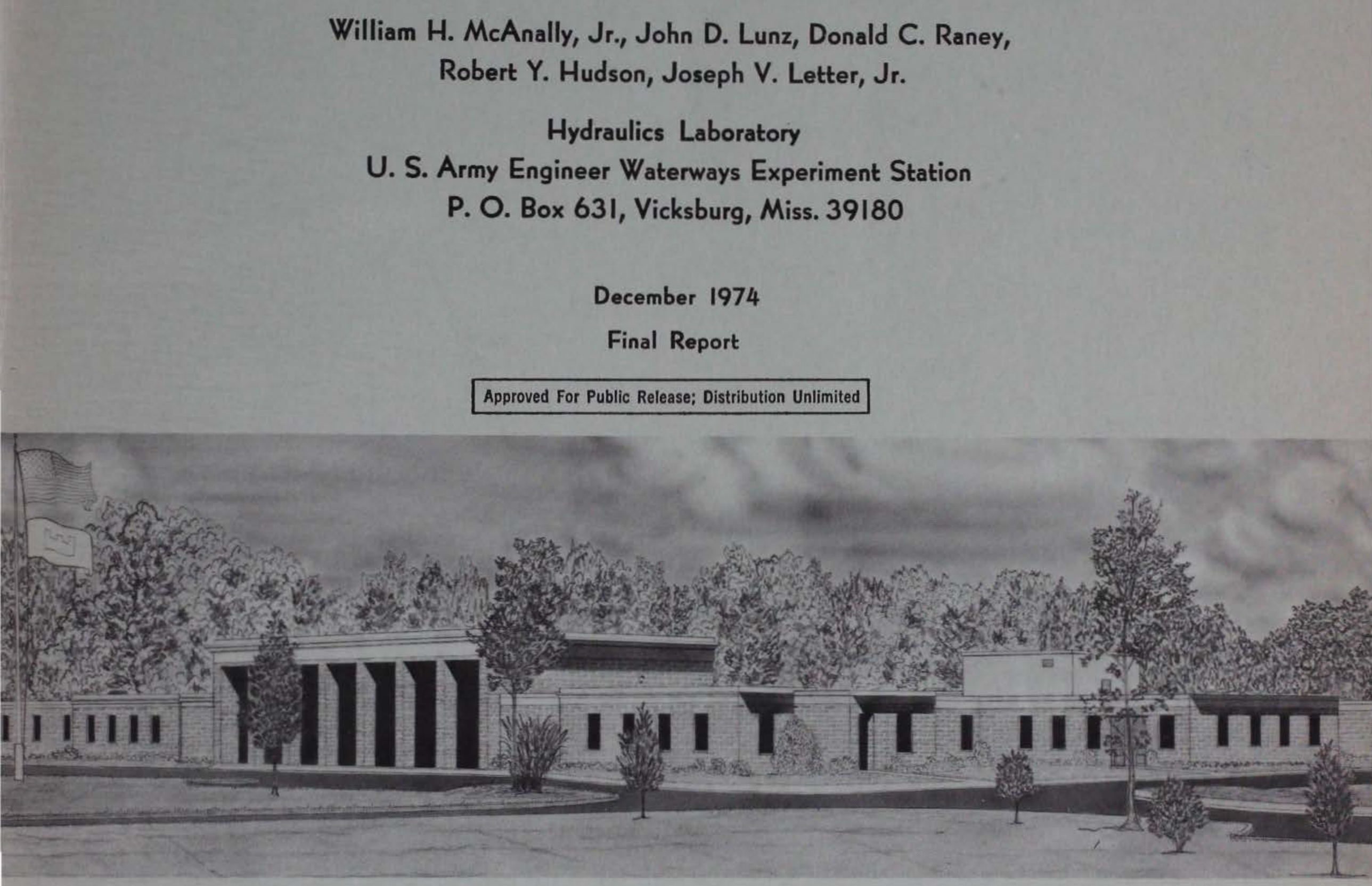

Prepared for U. S. Army Engineer Division, Pacific Ocean
Honolulu, Hawaii

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A study was conducted to define the problems of Kaneohe Bay, Oahu, Hawaii, that require further investigation commensurate with the ongoing urban study and to determine appropriate solution techniques for use in the investigations. It was concluded that a prototype data collection program and a numerical hydrodynamic model are minimum requirements for the study of the bay, and that for a detailed, quantitative evaluation of potential alterations, a physical
(Continued)

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hydraulic model also is required. Length scales of 1:40 vertically and 1:200 horizontally for a fixed-bed physical model are recommended. A prototype data acquisition program for problem identification and verification of both the numerical model and the physical model is described.

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PREFACE

The study reported herein was requested by the U. S. Army Engineer Division, Pacific Ocean (POD), in a letter to the U. S. Army Engineer Waterways Experiment Station (WES), dated 12 September 1973. The study was conducted during the period 1 December 1973 to 31 March 1974.

This report was prepared by WES personnel under the direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, Dr. R. W. Whalin, Chief of the Wave Dynamics Division, Mr. R. A. Sager, Chief of the Estuaries Division, and Mr. G. M. Fisackerly, Chief of the Harbor Entrance Branch. The interdisciplinary project team was formed under the direction of Dr. Whalin, and its activities were coordinated by Mr. Fisackerly. This report was prepared by Mr. W. H. McAnally, Jr., Research Engineer, Estuaries Division, Mr. J. D. Lunz, Marine Biologist, Environmental Effects Laboratory, Dr. D. C. Raney, Research Engineer, Wave Dynamics Division, Mr. R. Y. Hudson, Consultant, Wave Dynamics Division, and Mr. J. V. Letter, Jr., Engineer, Estuaries Division. Mr. H. L. Butler, Wave Dynamics Division, assisted in the development of the numerical model.

Director of the WES during the conduct of the study was COL G. H. Hilt. Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U. S. statute)	1.609344	kilometers
square feet	0.09290304	square meters
square miles	2.5899881	square kilometers
cubic feet	0.02831685	cubic meters
gallons	3.785412	cubic decimeters
feet per second	0.3048	meters per second
miles per hour	1.609344	kilometers per hour
cubic feet per second	0.02831685	cubic meters per second

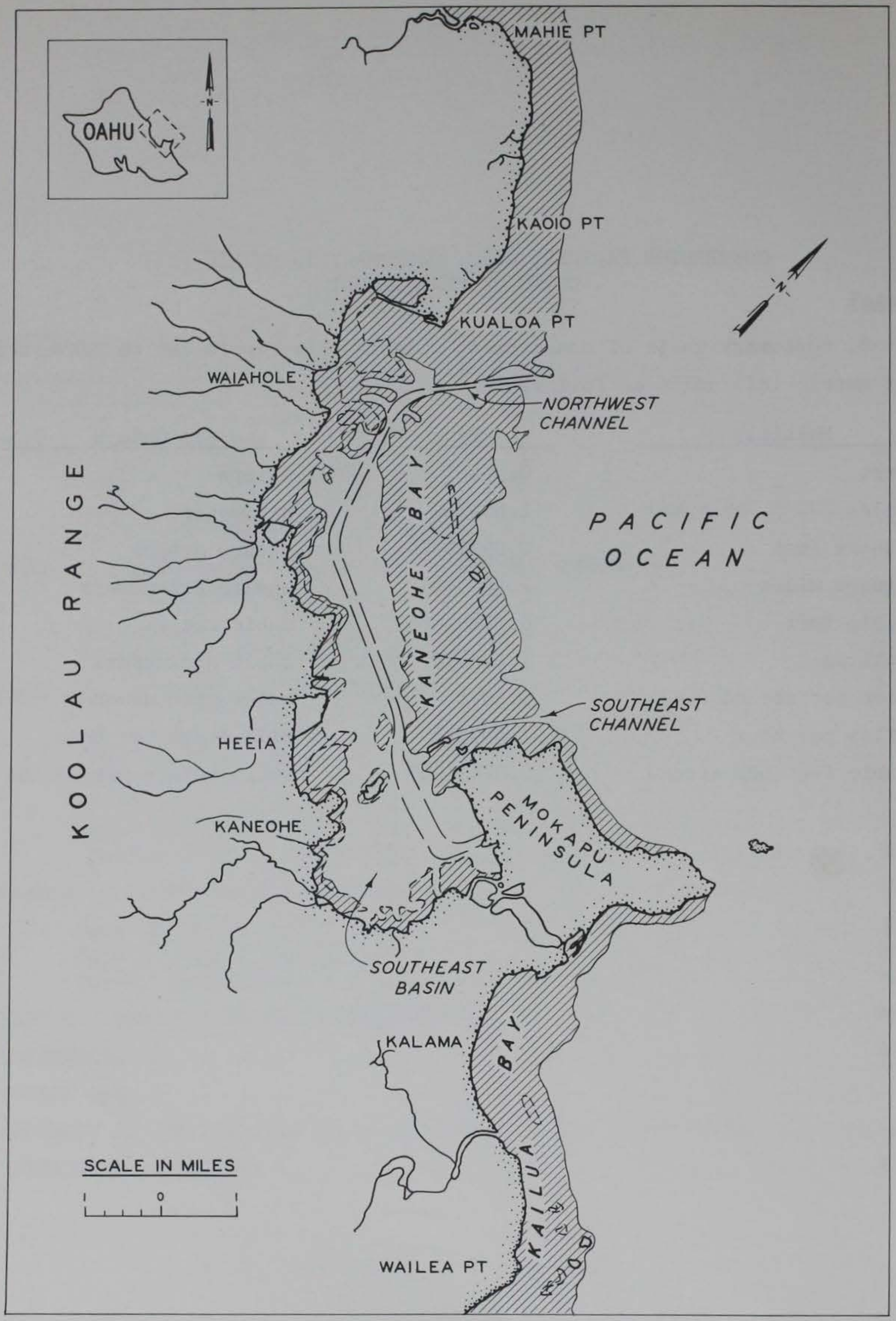

Figure 1. Site map

PROBLEM DEFINITION AND MODELING TECHNIQUES FOR THE STUDY OF KANEOHE BAY, OAHU, HAWAII

PART I: INTRODUCTION

Purpose of Investigation

1. The findings of a 4-month investigation into the need for a model study of the Kaneohe Bay area, Oahu, Hawaii, are described herein. The investigation was conducted in response to a request by the U. S. Army Engineer Division, Pacific Ocean (POD), that the U. S. Army Engineer Waterways Experiment Station (WES) perform the following:

   a. Review information on Kaneohe Bay provided by the POD.

   b. Define the problems that require additional investigation commensurate with the urban study of Kaneohe Bay.

   c. Determine the necessity of a model study for investigation of these problems.

   d. If a model study is recommended, specify the prototype data requirements.

   e. Prepare a report on the study findings.

2. This report does not present an exhaustive analysis of Kaneohe Bay and its problems but rather describes the phenomena that are pertinent to model studies of the problems encountered in the bay.

Description of Kaneohe Bay

3. Kaneohe Bay is on the northeast coast of Oahu, Hawaii (Figure 1). It is the largest estuary in the Hawaiian Islands and has a surface area of about 18 square miles.* The bay is about 7.5 miles long with its axis oriented roughly parallel to the coastline.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is given on page 3.

4. The bathymetry of Kaneohe Bay is characterized by a shallow coral reef separating the bay from the ocean and a fringe reef that separates the southeast basin from the rest of the bay. The barrier reef is cut by a 30-ft-deep navigation channel at the northwest end and an 8-ft-deep channel at the southeast end. Water depths vary from less than 1 ft on the reef to about 50 ft in the lagoon.

5. Kaneohe Bay experiences diurnal to semidiurnal tides with a mean range of about 2 ft and a maximum range of 3.7 ft. According to a survey reported in 1968, the phase lag between the times of high water averaged about 15 min from one end of the bay to the other.[1] Tidal currents were generally less than 0.5 fps and exhibited a pronounced stratification with some current reversals between the surface and bottom layers.

6. Primary current-producing forces, other than the tides, include waves, wind, ocean currents, and, under some conditions, density gradients.

7. Wave-induced currents include: (a) mass transport of wind-generated ocean waves, (b) currents entering the bay caused by the breaking of ocean waves on the reefs and other shallow-water portions of the bay, (c) littoral currents inside the bay and along the coastline caused by waves breaking along the beach, (d) seiche-type oscillations of the water masses in the bay, and (e) tsunamis.

8. A permanent ocean flow around the island affects currents within the bay. This flow usually has a northwesterly set and a speed ranging from about 0.2 to 2 fps at Kaneohe Bay.[2] This permanent flow, which is the result of wind-induced ocean currents, is modified by tidal flow to and from the bay, the tidal currents around the island, and littoral currents.

9. In addition to oceanic currents due to wind, setup and currents within the bay can be induced by local winds. The trade winds are from a northeasterly direction with speeds ranging from 10 to 30 mph, averaging about 14 mph. Winter storms produce gusty winds, often with speeds up to 50 mph in the bay area.

10. Density differences due to salinity and temperature affect

the hydrodynamic response of the bay by both stratification and the currents that they induce. Density stratification combined with the bathymetry results in layered flows with differing circulation patterns. Following heavy rainfall runoff, a considerable portion of the bay may be covered with a layer of extremely low-salinity water, particularly in the southeast basin. High salinity gradients also can occur in the lower reaches of the streams that flow into the bay, with vertical salinity variations of from 10 to 30 percent occurring.

11. Because of flow stratification, the transport and dispersion of pollutants can be profoundly affected by the depths at which they are concentrated. Discharges that form surface plumes, such as sewer outfalls or streamflows, may experience residence times radically different from those of pollutants that do not. Overall circulation is such that pollutants in the center portion of the bay tend to be transported northward and flushed through the northwest channel while those in the southeast basin are retained due to the lack of a significant net circulation.

12. Rainfall surface runoff into the bay is carried by twelve streams, of which Waikane stream at the northwest end of the bay and Kamooalii stream at the southeast end have the greatest potential flood flow.[1] The average monthly runoff rate varies between 40 and 150 cfs,[1] but U. S. Geological Survey streamflow estimates for several streams show a combined flow of approximately 28,000 cfs following the storm of May 1965.[3]

13. Sediments in Kaneohe Bay consist of alluvial sediments, organic materials, and coral reef debris. The silt and clay size fractions of the alluvial sediment discharge are deposited principally in the deepwater portions of the bay, since the currents appear to be too small to transport a significant amount of suspended sediment outside the bay.[4,5]

14. Two basic current patterns occur consistently.[1] A large portion of the flood tide enters the bay over the central reef and turns principally to the northwest. The bottom currents diverge just east of Waiahole and flow in opposite directions along the axis of the bay. In the northwest channel, the current below 23 ft is generally ebbing during

both incoming and outgoing tides. The surface currents diverge at the intersection of the southeast channel and the interior channel, flowing toward the northwest and into the southeast basin. Flood currents enter the southeast basin on both sides of Mokuoloe Island, setting up a large surface eddy moving counterclockwise.

15. During ebb flow the currents across the reef still tend to be inward due to wind and breaking waves, and the flow in the northwest channel is strongly ebbing at all depths. The eddy in the southeast basin is much less pronounced, and flow direction reverses with depth.

Biological Components of the Bay

16. Kaneohe Bay has been called the most thoroughly studied coral reef system in the world.[6] Detailed descriptions of the biota of the bay are available in a number of comprehensive general reports and papers. This report discusses the biological components of Kaneohe Bay at the population (group of species) and community (group of populations) levels, and for the most part considers effects of environmental conditions at these levels.

17. A coral reef is a magnificent and complex community of marine organisms which are able collectively through the formation of limy ($CaCO_3$) skeletons to construct, modify, or maintain a shore environment. Even under the most ideal circumstances, the reef system is in a very dynamic state. The reef-building animals, i.e., the corals themselves and their close relatives the millepores, and the encrusting lime-producing algae must overcome the destructive forces of the waves, the sponges, echinoderms (starfishes and sea urchins), certain mollusks, algae, and fish which erode and feed upon the live coral. The crevices and irregular surfaces of the coral reef provide shelter and protection for various crabs, small crustaceans (shrimplike animals), cephalopods (octopi), and occasionally a spiny lobster.

18. A diversity of marine plants and animals exists on the lagoon floor--some corals, red and green algae, mollusks, protozoa

(foraminifera), sea cucumbers, and various burrowing worms. The water of the lagoon and over the fringing and barrier reefs contains numerous types of phytoplankton (plant plankton) and zooplankton (animal plankton, which are very weak swimmers and are largely at the mercy of the water currents). Also included among the plankton are the eggs and larvae of certain fishes and crabs, the comb jellies or ctenophores, the jellyfish, and an important constituent of plankton community, the arrow-worms, which are chaetognaths.

19. The fishes of the bay are numerous and are discussed in detail in Reference 6. Several reef fishes can be found in the bay, most of which use the coral as a source of food and/or protection near a source of food (sometimes plankton). Other open water fishes present include the important nehu or bait anchovy, which is commercially netted by the skipjack tuna fishermen. Important sport fish are present, along with barracuda and various species of sharks.

PART II: PROBLEMS OF THE BAY AND POTENTIAL METHODS OF IMPROVEMENT

The Problems

Overall view of causes

20. The problems currently encountered in Kaneohe Bay have been caused by the activities of man combined with the naturally poor circulation of the bay. The impact of a rapid urbanization trend has been tremendous, especially in those areas of the bay where circulation is sluggish and turnover rates of the water are slow. The simplistic solution would be the removal of man from the area, with remedies taken to return the countryside surrounding the bay to its preurbanized condition. However, since the state of the bay is not the only concern, the simplistic solution is not realistic, and the problem of removing or greatly minimizing the perturbations that man has effected in the system still exists. Solution of this problem requires:

a. Identification of all primary perturbations that directly affect the bay ecosystem.

b. Identification of the subeffects induced by the primary perturbations.

c. An understanding of the interactions and/or relationships between these subeffects and the primary perturbations.

d. Development of the technical capability to (1) eliminate the primary perturbations and/or (2) alter the interactions or relationships between the primary perturbations and the subeffects so as to eliminate the subeffects.

21. Maragos[7] states that the major factors affecting the nature of the lagoon are sedimentation, dredging, freshwater flooding, and nutrient input due to the presence of sewage and that these influences are not independent of each other, thereby implying additive or synergistic effects. Other authors agree that either one or all of these perturbations are detrimentally altering the bay ecosystem. The single point of disagreement lies in the source of phosphate enrichment. The consensus of studies suggests that phosphate enrichment is the result of sewage input while nitrogen enrichment is due to land runoff.

Primary perturbations

22. Sewage. At the present time there exist three discrete sewage inputs in Kaneohe Bay. The Kaneohe municipal sewage treatment plant discharges an average of 2.1 mgd* of secondary treated sewage. The Kaneohe Marine Corps Air Station discharges an average of 0.8 mgd of primary treated sewage into the bay, and there is an input of 0.02 mgd of raw sewage from the Hawaii Institute of Marine Biology on Coconut Island. The effects of sewage input are increased concentrations of nutrients (nitrogen, phosphorus, and carbon forms) along with inputs of poorly defined, potentially toxic, or biostimulatory chemical compounds. A subeffect of the sewage input is an increase in phytoplankton productivity. This productivity increase, which can be called eutrophication, indirectly affects: (a) populations of zooplankton, (b) the deposition of organic materials on the bay floor, (c) the light transparency of the water, and sometimes (d) the dissolved oxygen (DO) concentrations of the water. Decreased light intensities, lowered DO, and changes in zooplankton populations in turn affect forms of estuarine life in the bay which require them, e.g., corals require zooplankton as food. The botanical nature of many of the reef-forming organisms and the microscopic plants called zooxanthellae, which are symbionts in the coral, are dependent upon light for continued existence. If the coral die, reef fish which live among the coral and depend upon it for food and protection leave the area or are destroyed by predation. Larger carnivorous fish species, which feed upon the reef fish and attract sports fishermen, would no longer be attracted to the area.

23. Recently, considerable attention has been given to the effects of chlorine and chlorine compounds upon aquatic organisms.[8] The general increase in the quantity of chlorinated sewage effluent entering the hydrosphere has stimulated studies on its potential acute and chronic toxicity. A major fish kill which occurred on the James River of Virginia in 1972 was attributed to chlorine from a sewage treatment plant

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

discharging into the river. The chemistry of chlorine is very complex and its study is made difficult by the instability of chlorine compounds. An appraisal of its toxicity is made more difficult because the toxicity of free chlorine and its complexes differs in fresh and estuarine/marine environments. The principal complexes formed are chloramines, which result from the reaction between chlorine and ammonia. Unfortunately, ammonia is ubiquitous in areas fed by sewage effluent and characterized by high organic loadings.

24. Other potentially toxic substances often associated with sewage include metals, pesticides, petroleum hydrocarbons, and complex organics, such as chelating agents (Table 1).

25. Finally, the increase in nutrients from sewage and other sources effects an increase in the productivity of some undesirable benthic algae species, e.g., Dictyosphaeria cavernosa, a green alga which grows in a flat mat, covers and kills a coral growth, and then erodes the dead coral with acidic secretions.

26. Sedimentation. The second primary perturbation in Kaneohe Bay is sedimentation, which is primarily due to the increase in sediment entering the bay with fresh water from the streams. The excessive sediment flow results from upstream land-use practices and adjacent reclamation projects. The decrease in natural vegetative cover caused by these practices results in greater erosion, faster runoff, and increased amounts of soil washing into the streams. These eroded materials are carried downstream, especially during the periods following high precipitation and runoff. The waters and silt entering the bay also carry with them chemicals associated with the multiple utilization of land. Among these, the most important are agricultural chemical fertilizers and pesticides. The silt, upon entering the bay, diffuses according to its density, local current and turbulent conditions, and salinity. Effects of salinity on the dispersion of suspended material are twofold: on one hand, the relative densities of bay water and suspended material interact physically to determine settling rates; on the other hand, reactions between the silt particles and aqueous medium affect settling velocities through flocculation and precipitation. While the silt is in suspension,

it creates turbidity, which attenuates light and thereby decreases the depth of penetration and the intensity of light energy. This results in obvious aesthetic effects. The water is no longer clear and sparkling, and no longer can the bottom be seen. The water now takes on the reddish-brown color consistent with the soil character of the adjacent land. Naturally, plant organisms which are dependent upon light energy for growth and reproduction cannot thrive under such conditions. If these conditions persist, the food chain will be affected by the loss of primary producers.

27. Another direct effect of siltation develops as suspended material settles to the bottom. Bottom organisms become smothered or may be forced to expend energy to keep their feeding apparatus cleared of the clogging material. Organisms, including corals, various types of algae, etc., which require substrate of a particular character but are not compatible with the silt-laden bottom habitat will not recolonize the area. As a result, the area will be taken over by sponges, anemones, bryozoans, and tunicates, which do not have aesthetic appeal and do not serve as habitat for as diverse a biota as do the corals.

28. Due to its chemical oxygen demand, siltation also effects a decrease in oxygen levels in the water. The decrease in oxygen, which can be sudden, can kill benthic (bottom), planktonic, and nektonic (free-swimming) organisms.

29. Dredging. The effects of dredging in Kaneohe Bay are not discussed as frequently as the effects of the other three primary perturbations. It seems obvious that mechanical destruction of the lagoon or reef bottom causes an immediate severe localized impact within the dredged area. Ordinary dredging methods also cause turbidity, which has the effects indicated above.[5] Maragos[7] has observed that recovery of corals on reefs dredged below 9 m has not occurred at all, and these dredged areas are being covered with sediments. At the present time, no dredging activities, maintenance or otherwise, are being conducted in Kaneohe Bay. It is of interest to note the significant outflow of water from the bay via the dredged 30-ft-deep shipping channel during ebb tide. The question might be asked as to the effects which this

artificial channel or path of least resistance has upon the flushing characteristics of the southern sector.

30. Freshwater flooding. The fourth primary perturbation to be discussed is the discharge of fresh water into the bay. Increased freshwater input into the system is the result of differential land use, removal of natural vegetation cover, and construction of impermeable surfaces, such as the roofs of homes and commercial buildings, roads, and paved parking areas. As a result of these urban alterations, rain, instead of being retained by vegetation and allowed to slowly percolate through porous lava and gradually enter the bay, is now channelized into streams or into storm sewer systems and then into the bay. The introduction of some fresh water into Kaneohe Bay is not an unnatural phenomenon; indeed, it is one of the properties that define the system as an estuary. Changes taking place in the bay that can be detrimental to the ecosystem are dependent upon both the quantity of the fresh water introduced and the rate of its introduction. A large volume of fresh water flowing into the bay over a short period of time decreases the salinity of the bay where the fresh and saline waters mix. Where thorough mixing does not take place due to a lack of adequate mixing forces and the differing densities of fresh and saline waters, a layer of low-salinity water covers the more saline water and forms a halocline. The halocline inhibits normal exchanges which take place between the atmosphere and water column, the most important of which is diffusion of oxygen. Continuous use of oxygen through biological and chemical processes in the waters below creates a DO deficit which can become so severe as to kill all forms of life near or on the bottom. Reference 3 provides a very detailed observation of a coral reef kill that occurred in Kaneohe Bay as a result of extremely high precipitation in May 1965. Among the observations are reports of a plankton bloom which occurred in the surface water due to its enrichment with runoff nutrients and the odor of sulfide (H_2S), no doubt generated by anaerobic conditions that developed in the bay as a result of the mechanisms described above.

Other variables

31. Two of the primary perturbations, freshwater runoff and

sedimentation, are natural to the estuary, the differences under natural and perturbed conditions being those of degree. Other primary perturbations, i.e. dredging and sewage input, are unnatural to the ecosystem, and their influences upon the estuary are more difficult to evaluate.

32. Certain variables may be considered as basic in character because they function as the roots from which most of the undesirable changes occurring in the ecosystem are derived. These variables include salinity, DO, turbidity, concentrations of substances classed as micronutrients, which include metals and vitamins, substrate character, and wave and current energy.

33. Establishing standards and predicting ecosystem effects of changes in the basic variables are difficult due to our ignorance of natural ecosystem interactions. Detailed biological and chemical studies of Kaneohe Bay would require extremely large sums of money but might produce new information to aid in a better understanding of the problems; however, such studies would not solve the bay's problems. In the absence of standards, the extremes within which some basic variables should be maintained can only be approximated. The following paragraphs describe effects of variable changes.

34. DO. No general statement can be made giving the minimum DO concentration required to support aquatic life because an organism's oxygen requirement varies with the species, age, prior acclimatization, temperature, concentration of other substances in the water, and several other factors.[9]

35. The lethal effect of low concentrations of DO appears to be increased by the presence of toxic substances, such as excessive dissolved carbon dioxide, ammonia, cyanides, zinc, lead, copper, and cresols. With so many factors influencing the effect of oxygen deficiency, it is difficult to estimate minimum safe concentrations at which fish will be unharmed under natural conditions.

36. The basic characteristic of the DO variable is demonstrated by the inverse relationship between oxygen demand and DO. As the biological and chemical oxygen demands increase, the DO decreases. The formation of hydrogen sulfide, a highly toxic substance and aesthetic

nuisance, requires reducing conditions associated with an anoxic environment.

37. Salinity. Dissolved solids may influence the toxicity of heavy metals and organic compounds to fish and other aquatic life primarily because of the antagonistic effect of hardness metals (calcium and magnesium). Chromates, copper, cyanides, detergents, phenolic compounds, zinc, and several other substances are generally more toxic in distilled water than in hard water of high dissolved solids.[9]

38. This point may be academic in considering the Kaneohe ecosystem, especially with reference to the sessile coral reef organisms which are not noted for their euryhaline character, but it serves to point out the complexity of chemical reactions and biological consequences which exist in natural systems.

39. Turbidity. Turbidity, which is attributed to dissolved, suspended, and colloidal matter, diminishes light penetration. Turbidity may be caused by microorganisms, organic detritus, silica, and other mineral substances including zinc, iron, and manganese compounds, clay, silt, sawdust fibers, and other materials present as a result of the natural processes of erosion or the addition of domestic or industrial wastes.

40. Discussion. The basic variables which seem to be of special significance in the Kaneohe Bay ecosystem can be tabulated, indicating, qualitatively at least, magnitudes of desirable and undesirable extremes:

Variable	Desirable	Undesirable
Salinity	34 ppt ± 4 ppt	Fresh water
DO	Saturation	<4 mg/ℓ
Turbidity	Transparency	High turbidity
Nutrients: N, P, and C forms	NA	Concentrations leading to eutrophication
Micronutrients: metals, vitamins	NA	Concentrations leading to toxicity (acute and chronic)
Substrate character	Small deposits of soft sediments	Heavy deposits of soft sediments
Wave and current energy	Ample circulation to flush the bay and transport biota	Stagnation

41. Figures 2-5 show some possible interactions between the primary perturbations to the Kaneohe Bay system and some of the subeffects. The figures are qualitative, representing possible, not inevitable, effects. The following symbols are used to describe perturbation effects:

a. (-) Decrease - e.g., decrease in light intensity as a function of turbidity or a decrease in the living coral population caused by a decrease in food supply (zooplankton).

b. (+) Increase - e.g., increase in biological oxygen demand (BOD) caused by the decomposition of an algal population resulting from eutrophication.

c. (Δ) Delta or change - e.g., a change in phytoplankton (species composition) relative to the input of a nutrient form (NH_3, NO_3, NO_2, etc.) which some phytoplankton species can use more effectively than others.

42. It should be pointed out that the figures are by necessity oversimplified in that they attempt to isolate the perturbations. In the natural system, it is impossible to separate the freshwater inflow which comes with overland precipitation from sedimentation carried by the freshwater inflow. In addition, there are likely additive or synergistic effects which are not indicated, e.g., the combined effects of pollutants with lowered salinity.

Potential Methods of Improvement

43. Potential alterations to the bay system designed to alleviate the problems described above can be divided into two classes, those that remove or reduce the primary perturbation and those that modify the response of the bay and eliminate the subeffects. To the first class belong such alterations as improved land management, sedimentation basins in the streams, and sewage treatment or exportation. Measures to improve circulation and flushing belong to the second class.

44. The most effective solution to the problems of Kaneohe Bay is removal of the unnatural primary perturbations and minimization of the natural perturbations through upland land use and water resource management. Other solutions indicated here are compromises which will have

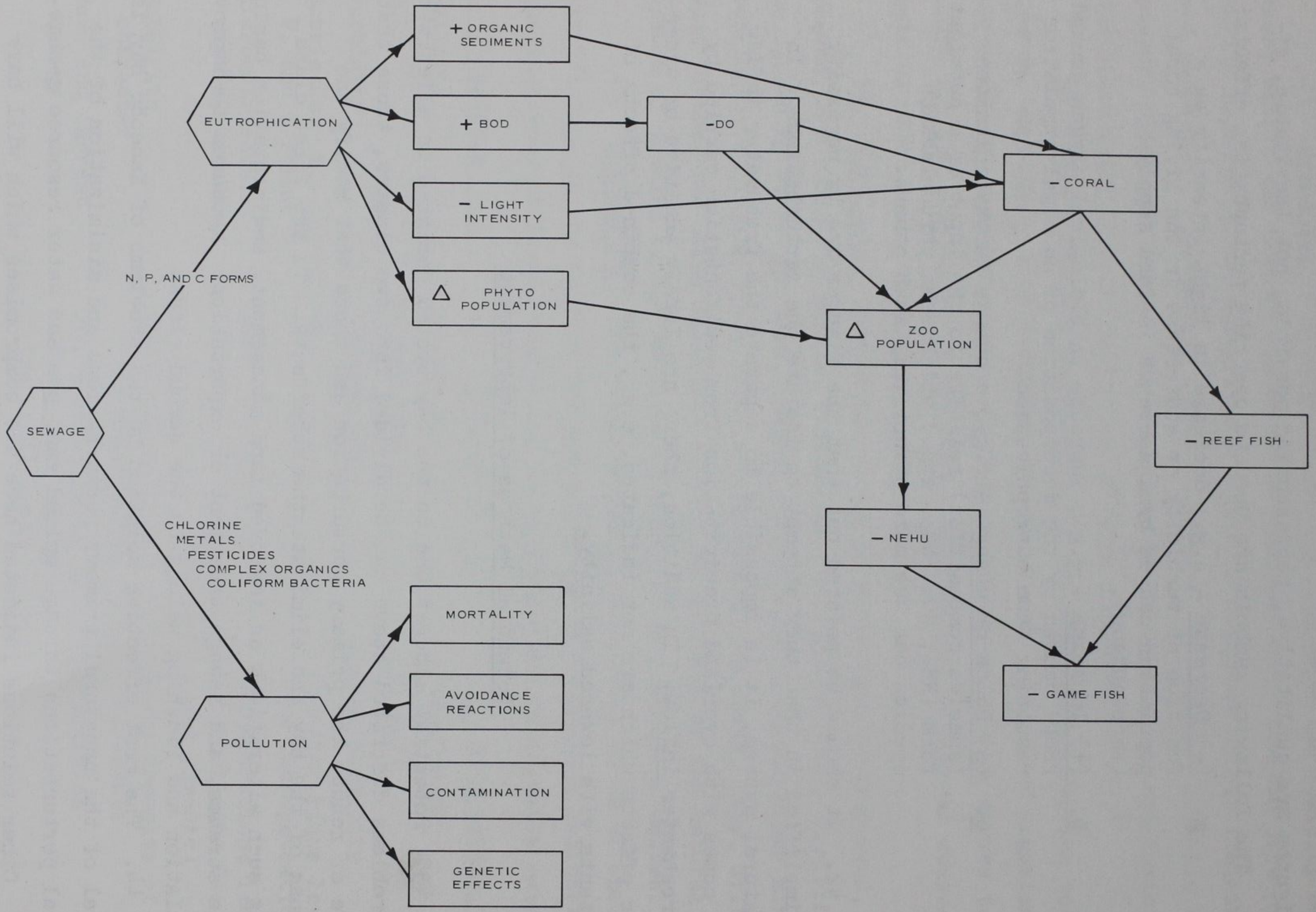

Figure 2. Kaneohe Bay sewage effects

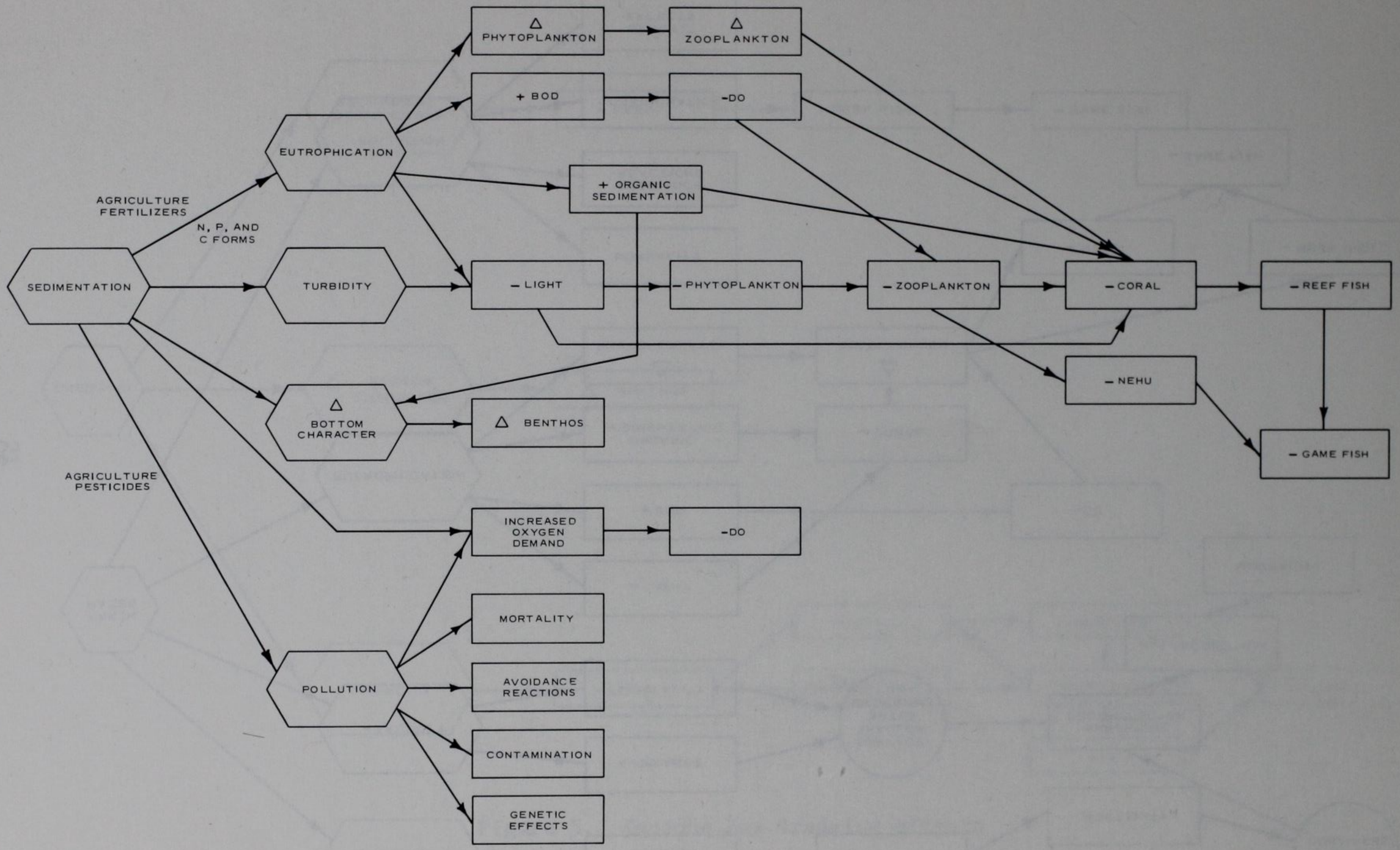

Figure 3. Kaneohe Bay sedimentation effects

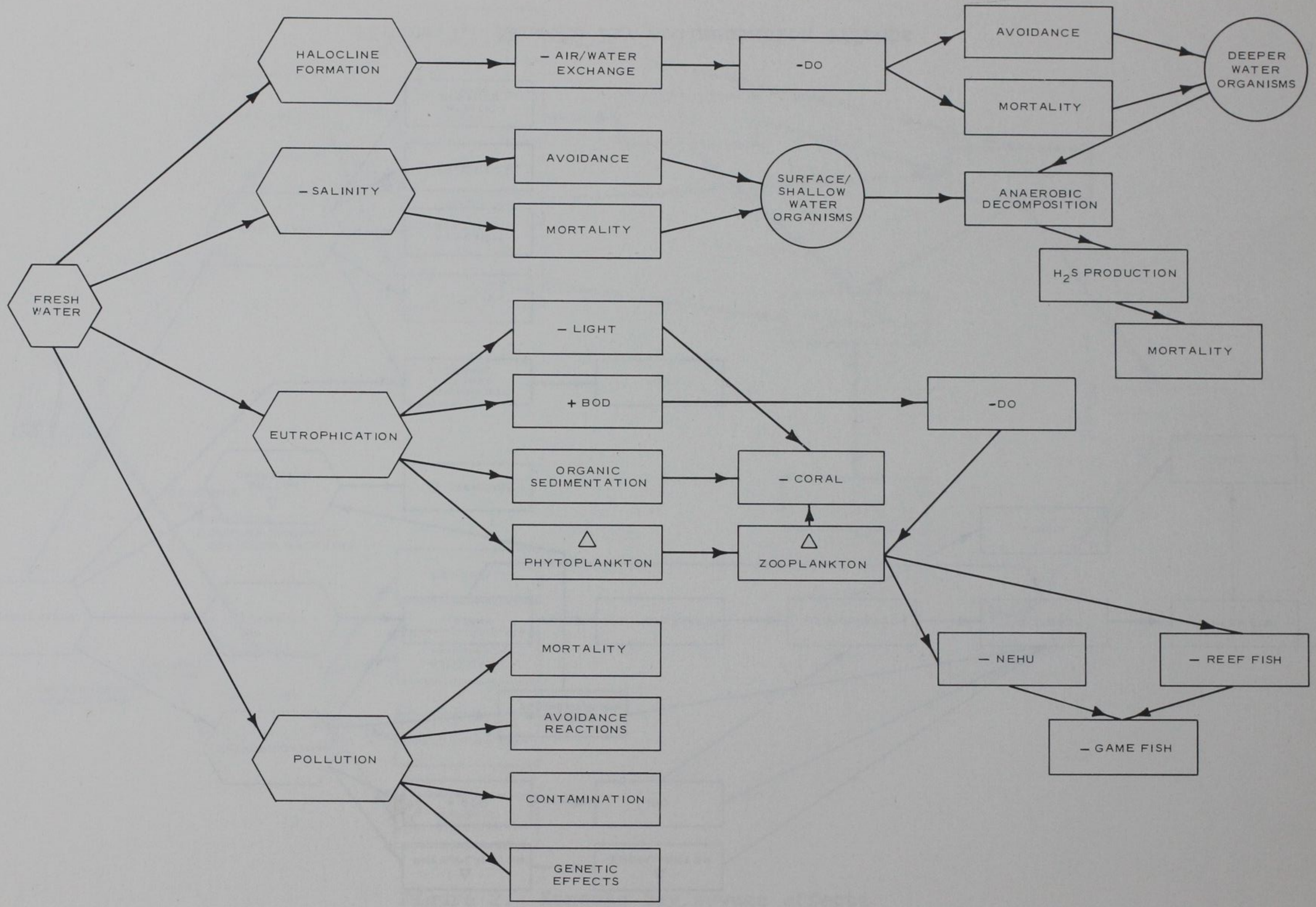

Figure 4. Kaneohe Bay freshwater runoff effects

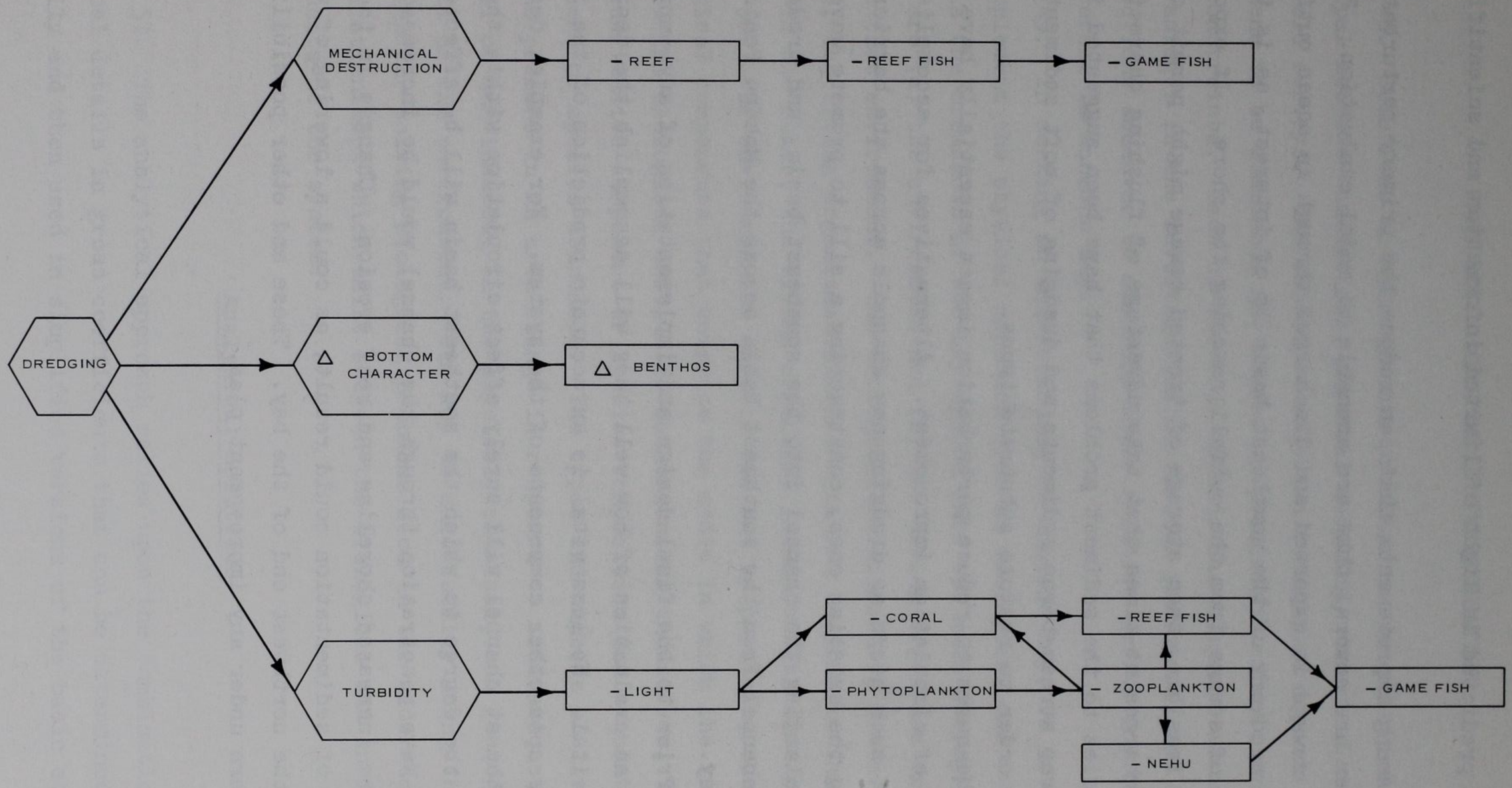

Figure 5. Kaneohe Bay dredging effects

the effects predicted in light of limited information and scientific intuition.

45. Among improvements that can reduce the primary perturbations to the system are several that are amenable to model evaluation. For example, if sewage is exported and discharged through an ocean outfall, the rate of recovery of the southeast basin is of interest, as is the possibility of sewage from the outfall reaching the shore. If exportation is not feasible, then storage of treated sewage might permit controlled discharges at times that take advantage of flushing characteristics. Remedies to the sediment problems that have been suggested include basins to trap stream-borne sediments and dredging of soft sediment deposits in order to restore substrate types.

46. Measures to reduce perturbation impact essentially have the common goal of circulation improvement. Alternatives for accomplishing this include such steps as dredging new channels across the barrier reef or deepening the existing ones, constructing a sill to promote wave breaking, enlarging the channel into the southeast basin, and dredging a connecting channel from the southeast basin across the Mokapu Peninsula to Kailua Bay.

47. Prior to the final design and implementation of any improvement plans, an evaluation of how well they will accomplish the desired effects is vital. No less vital is an accurate prediction of the impact of the plans upon other components of the system. For example, deepening the southeast channel will surely affect circulation within the main lagoon, but the degree to which the southeast basin will be affected is uncertain. Wave penetration through the channel would be increased and could lead to increased shoreline and reef erosion. Changes in the rate and pattern of sedimentation could result, as could a lowering of water quality in the northwest end of the bay. These and other possibilities are of concern under any improvement plan.

PART III: METHODS OF INVESTIGATION

48. Solutions to hydrodynamic problems can be obtained by four principal methods--analytical, physical modeling, numerical modeling, and field surveys. The choice of solution techniques depends upon the phenomena to be examined, the degree of precision desired, and time and cost constraints. Each of the four methods has inherent advantages and disadvantages in the investigation of various phenomena, and the following sections endeavor to describe their relative merits for the phenomena of interest in Kaneohe Bay.

49. In seeking an understanding of Kaneohe Bay, it is convenient to supplement the physical approach with an ecological one. The first task is the breakdown of the bay system into two main ecological units, which are (a) the environment and (b) the living organisms existing within that environment. The ecological relationships are of two types. In one, the living organisms interact with and respond to their environment; in the other, the living organisms interact with each other.

50. The environmental unit is defined by physical, chemical, and geological components that comprise the media in which the life forms exist. The biological unit, i.e. the organisms themselves, is defined by a qualitative component or species composition and a quantitative component or species abundance. The types and numbers of living organisms present in an area change in response to alterations, either natural or man-induced, in the physical, chemical, and geological components of the environment. The key to successfully using the modeler's approach for solving biological problems lies in the understanding of the relationships which exist between the biological and environmental components of the system.

Analytical Solutions

51. The analytical approach relies upon the combination of unknown physical details in gross coefficients that can be determined experimentally and then used in simplified versions of the basic equations.

Where applicable, the method has the advantages of speed and simplicity.

52. As the complexity of a system increases, the usefulness of the analytical method diminishes; therefore, an analytical description of Kaneohe Bay and its behavior is unsuitable. However, it can be used advantageously in the initial designs of an ocean outfall, sedimentation basins, and a channel across Mokapu Peninsula.

Physical Modeling

53. A physical hydraulic model of Kaneohe Bay can reproduce tides and other long waves, short-period windwaves, freshwater inflows, pollutant discharges, and three-dimensional variations in currents, salinity, density, and pollutant concentrations. Mass transport by breaking waves can be modeled as can net transports due to wind-induced currents. Present model practice does not include simulation of setup and vertical current structure due to wind.

54. Applicability of model laws and choice of model scales are dependent on the phenomena of interest. Conflicts of modeling requirements usually force the modeler to neglect some phenomena in the interest of more accurate reproduction of the dominant forces. Available data on the hydrodynamics of Kaneohe Bay indicate that the effects of the tides, waves, wind, and density gradients tend to be of roughly the same order of magnitude. If this is the case, none of these mechanisms can be justifiably neglected in a hydrodynamic analysis of the bay. Accurate reproduction of all these phenomena will place severe and possibly conflicting constraints on modeling of the bay.

55. The large size of the area to be modeled will make it necessary to choose differing scales for horizontal and vertical dimensions of the model, thus distorting it. Distortion is a common and acceptable practice in physical modeling, but it will create some difficulties in the study of Kaneohe Bay. One difficulty is that similarity will not be achieved for the phenomena of refraction and diffraction of waves with periods and water depths such that the velocity of propagation is a function of wave period and water depth. Another is that reflection of

wave energy from bottom slopes and coastal structures with sloping sides will be increased because of steeper slopes in models with distorted scales.

56. Modeling of phenomena that are dominated by gravity and inertial forces will require that Froudian similarity be obtained, i.e., the Froude number must be equal in model and prototype. This may be expressed as

$$F_p = F_m \tag{1}$$

or

$$\left(\frac{u}{gd}\right)_p = \left(\frac{u}{gd}\right)_m \tag{2}$$

where

F = Froude number

p = subscript denoting a prototype quantity

m = subscript denoting a model quantity

u = a characteristic velocity

g = the acceleration of gravity

d = a characteristic depth

Satisfaction of Equation 2 results in the following scale relationships where L is a horizontal dimension, Y is a vertical dimension, and the subscript r denotes a model to prototype ratio of the subscripted parameter.

$$\text{Velocity} \quad u_r = Y_r^{1/2} \tag{3a}$$

$$\text{Time} \quad t_r = L_r Y_r^{-1/2} \tag{3b}$$

$$\text{Discharge} \quad Q_r = L_r Y_r^{3/2} \tag{3c}$$

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Similarity of short-period wave refraction can be achieved if the time scale is adjusted such that for the short-period waves

$$\left(\frac{d}{\lambda}\right)_m = \left(\frac{d}{\lambda}\right)_p \tag{4}$$

where λ is the wave length. For this, the time scale must be

$$t_r = Y_r^{1/2} \tag{5}$$

The use of this time scale for the short-period waves has the effect of increasing wave lengths, compared with lengths determined by Equation 3b. This in turn results in a discharge scale for the mass transport of short-period waves that break on the reef and other shallows along the bay entrance in variance with that of the tidal discharges into and out of the bay and the storm runoff and sewage discharge into the bay. Some techniques for overcoming this conflict are discussed in the section on integrated methodologies.

Choice of model scales

57. The vertical length scale ratio must satisfy two basic requirements. First, the water depths and wave heights must be of sufficient magnitude to prevent capillary effects from seriously affecting the results; second, turbulent flow must be maintained throughout most of the tidal cycle to keep the proper relationship between the magnitudes of viscous and gravitational forces. Prevention of laminar flow requires that the Reynolds number be greater than about 1500. In order to maintain high Reynolds numbers over a large portion of the tidal cycle, a vertical scale of 1:40 has been found to be the minimum acceptable for a model of Kaneohe Bay.

58. With a vertical length scale chosen, the distortion ratio Y_r/L_r fixes the horizontal length scale. Accepted practice for model studies of sedimentation, pollutant flushing, and short-period waves suggests that a distortion no larger than five be used. For the vertical scale of 1:40, a distortion of five yields a horizontal scale of

1:200. These scales combined with Equation 3 yield the following set of scales for the physical model.

Vertical length	Y_r = 1:40
Horizontal length	L_r = 1:200
Velocity	u_r = 1:6.325
Time	t_r = 1:31.623
Discharge	Q_r = 1:50,600
Surface area	SA_r = 1:40,000
Cross-sectional area	CA_r = 1:8000
Length of lunar day	= 0.786 hr
	= 47.13 min

Model verification

59. Careful verification will be necessary to adequately reproduce the hydrodynamic response of the bay system and the environmental conditions of interest. This verification will require the prototype data described in Part IV. Model roughness, ocean currents, and tides will be adjusted to faithfully reproduce the behavior of the bay as determined in prototype surveys. Wave energy and direction also will be adjusted to compensate for the effects of distortion upon wave reflection, refraction, and diffraction.

Model limits and equipment

60. A study of the problems and possible solutions described in Part I will require that the modeled area include all of Kaneohe Bay, the lower reaches of the major streams that flow into it, Kailua Bay, a portion of the ocean necessary to study the motion of the sewage plume from an ocean outfall and to permit proper wave approach, and a length of coastline on both sides of the area of interest sufficient to permit generation of littoral currents. The approximate model limits are shown in Figure 6.

61. For scales of 1:40 and 1:200 given previously and model limits shown in Figure 6, the model will cover about 70,000 sq ft and have a maximum tidal prism of about 5000 cu ft.

62. Required model appurtenances will include the following:

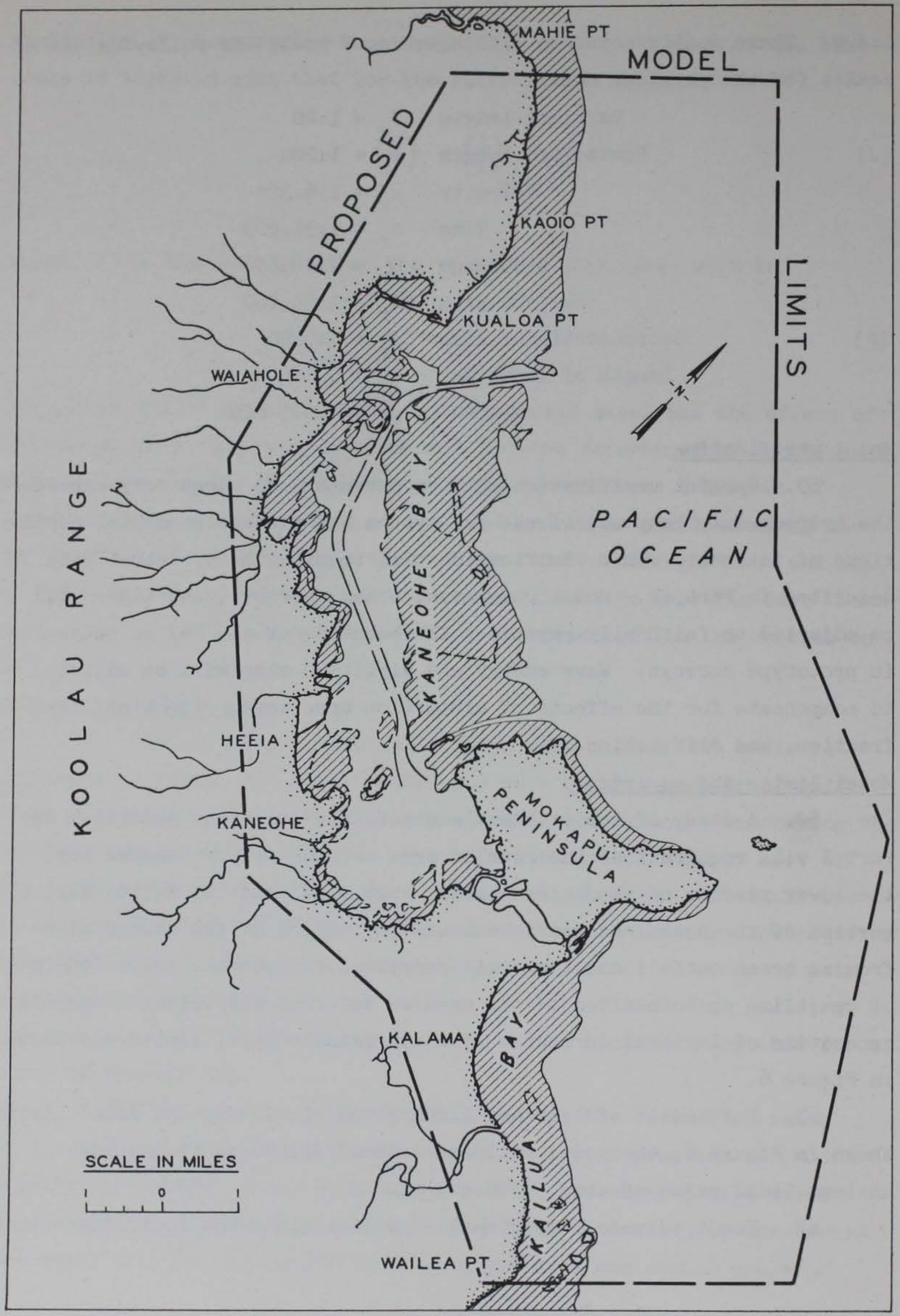

Figure 6. Proposed model limits

a. Saltwater sump to supply the tidal prism.

b. A chambered headbay complex.

c. Automatic tide generation and control system.

d. Variable flow controllers for streamflows.

e. A segmented wave machine.

f. Pollutant discharge simulation equipment.

g. Automatic model data acquisition system.

Numerical Modeling

63. Numerical modeling involves the solution of the simplified equations of motion by numerical procedures, usually with the aid of a high-speed digital computer. A complete mathematical description of the hydrodynamic flow in an estuary would require that the velocity u and density ρ be completely specified for every point in the estuary at all times.

$$u = u\ (x, y, z, t)$$

$$\rho = \rho\ (x, y, z, t)$$

where

x = longitudinal coordinate measured along the estuary axis

y = transverse coordinate

z = vertical coordinate

t = time

If both u and ρ are known, either by solution of the hydrodynamic equations subject to appropriate boundary conditions or from prototype data, and if a turbulent mixing coefficient $E_{ij}\ (x,y,z,t)$ relating mass transfer to concentration gradient also is specified, it may be possible to write a general program to determine the complete hydrodynamic response to the forcing phenomena and the movement and spreading of a dissolved substance. Unfortunately, even with modern computers such a numerical project is overly ambitious and prototype data in

sufficient detail are generally not available. Not only is the flow three-dimensional, but the boundary conditions and perhaps the turbulent mixing coefficient vary with time as the estuary fills and empties. Because of these difficulties, researchers have devised a variety of estuarine models of various degrees of simplification. In general, the simpler the model, the less reliable and less adaptable it is to changing conditions.

64. The pollutant transport program for tidal waters developed by Fischer[10] appears to be more sophisticated in several respects than other models available. A slightly modified version of this program has been tentatively selected for use in the Kaneohe Bay numerical modeling efforts. The numerical program consists of two parts, a two-dimensional hydrodynamic program and a two-dimensional pollutant transport program. The only parameter for the hydrodynamic portion of the program which must be measured in the field (or obtained from published records), other than geometric and bathymetric data, is the tidal fluctuation of the water surface elevation at the ocean entrance to the bay. Results of the hydrodynamic program are obtained independent of the results of the transport portion of the program and (if desired) stored on magnetic tape for use in the pollutant transport program. The pollutant transport portion of the program requires an input for the eddy diffusivity coefficient. This information must be obtained from prototype data or estimated, based on previous experience with similar systems.

The hydrodynamic program

65. The hydrodynamic equations in two dimensions can be obtained by averaging the Navier-Stokes equations and the equation of continuity over the vertical dimension to yield[11]

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV + g \frac{\partial h}{\partial x} + g \frac{U\sqrt{U^2 + V^2}}{C^2 h} = \frac{T^x}{\rho h} \qquad (6a)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU + g \frac{\partial h}{\partial y} + g \frac{V\sqrt{U^2 + V^2}}{C^2 h} = \frac{T^y}{\rho h} \qquad (6b)$$

$$\frac{\partial h}{\partial t} + \frac{\partial (hV)}{\partial x} + \frac{\partial (hV)}{\partial y} = 0 \qquad (6c)$$

in which

U = depth-averaged velocity in the x direction

f = Coriolis parameter

V = depth-averaged velocity in the y direction

g = acceleration of gravity

h = depth of flow

C = Chezy friction factor

ρ = density of water

T^x = shear stress due to wind in x direction

T^y = shear stress due to wind in y direction

66. These equations are solved by Leendertse's implicit-explicit multioperation method,[11] which has been extended to include the wind stress terms and a provision for a boundary where discharge, rather than elevation, is specified. This can be used to simulate a river discharging into a bay. An example of the results of a trial run of the model is given in Appendix A.

The transport program

67. Two basic processes involved in the movement of a dissolved substance in estuaries are convection and diffusion. Convection is the movement of a dissolved substance in a flow at the same velocity as the local velocity of the fluid. Diffusion accounts for the difference in motion between the fluid and the substance. If there were no diffusion, then the path line of the substance would be the same as the path line of the fluid. Because of diffusion the path lines of molecules of the dissolved substance depend on both the hydrodynamic flow pattern of the fluid and the magnitude of the turbulent mixing coefficient. The diffusion coefficient describes the local mixing of the dissolved substance between or along streamlines.

68. All simplified models involve some averaging process, either over time, flow cross section, or both. Two terms result, which are a net convection term and a term called the eddy diffusivity, which lumps together the remaining effects of averaging. A value for the eddy

diffusivity is normally chosen such that the model reproduces as well as possible any available prototype data. Those models which specify more detail of the convective motion require less manipulation of the eddy diffusivity coefficient to reproduce prototype conditions because less averaging of convection is included in the eddy diffusivity coefficient.

69. The physical transport process is modeled directly by the digital computer program, simulating the convection along lines of flow and the diffusion between adjacent streamlines. The numerical model is used in a manner similar to that of a hydraulic model, but the numerical model has an advantage--the rate of transverse mixing due to eddy viscosity often can be more readily matched to what is observed in the prototype.

70. The two-dimensional pollutant transport program uses the same two-dimensional grid already established for the hydrodynamic program, for which velocities have been computed. The concept is to follow the motion of marker particles and superimpose on their motion a diffusion at some specified rate. The rate and frequency of the diffusion step are the primary parameters to be selected in matching prototype data.

71. The transport program uses the velocity output for the entire tidal cycle from the hydrodynamic program to determine the concentration of a dissolved substance at each grid point in the two-dimensional field. This is accomplished by introducing a pollutant at a desired location and moving it through various segments of the tidal cycle to determine subsequent concentrations at each point of the computational grid. In the absence of diffusion, the point at which a molecule of dissolved substance ends any phase of its motion coincides with the homologous position of a water molecule from the hydrodynamic portion of the model. Diffusion is simulated by using an average of concentrations at surrounding points rather than using only that concentration at the convective location of the point. A greater rate of diffusion can be simulated by averaging the concentrations over a larger number of points; a lesser rate can be obtained by taking a smaller grid size and averaging between neighboring points. This is the weakest part of the program, since eddy

diffusivity coefficient information for estuaries is not readily available.

Major assumptions and
limitations of the model

72. The most important approximations used in the model are those of constant density and of two-dimensionality in plan. Vertical variations of both velocity and concentration are averaged over depth to produce a two-dimensional vector field of velocity and a two-dimensional scalar field of concentration. This means that the model is more appropriate for the well mixed, constant density case than for the case in which vertical density gradients inhibit vertical mixing. The model does have a pseudo three-dimensional effect since variation in depth of the estuary is considered. As has already been indicated, truly three-dimensional, variable density models and computers large enough and fast enough on which to run them are not available.

73. Because of computer time requirements, short-period wave effects cannot be easily represented in the hydrodynamic model. Therefore, the model cannot be readily used to determine the effects of short-period waves unless this information can be obtained from other means and superimposed in some manner upon the basic program output. Only tidal currents and wind-driven currents are easily simulated.

74. In real bays the direction of the velocity vector often changes with depth, and the velocities obtained from this model represent a depth averaging in both magnitude and direction. This skew in direction with depth of the velocity vector produces more transverse mixing than would otherwise be present. This complicates the problem of determining the appropriate eddy diffusivity coefficient since in most field experiments the investigator tends to sample mainly near the surface of the flow. The appropriate choice for the eddy diffusivity coefficient is the most critical aspect of the problem.

75. As a result of the averaging of the equation over the depth, the wind stress is applied as a body force per unit depth on the fluid rather than as a stress on the surface. This results in faster acceleration in shallow areas and tends to establish currents flowing in the

wind direction in the shallows and returning in deep areas. This is a simplification of the actual three-dimensional flow, in which a surface current can be formed with a return current underneath. For smaller bays, however, the results obtained are probably a suitable approximation for predicting pollutant transport. The primary effect of the subsurface return flows established in the real bay is modification of the eddy diffusivity coefficient.

Verification of the numerical model

76. The two-dimensional hydrodynamic program described is a recent development not yet fully verified by field experiments. The method shows agreement with tidal measurements in Tokyo Bay and the North Sea[11] and with tidal elevations and velocities in Jamaica Bay, New York.[12] Some verification work on the hydrodynamic and transport portions of the model has also been reported.[10] Although the initial application of the model to Kaneohe Bay (see Appendix A) yields realistic results, verification of the model will require reliable prototype data.

Prototype Surveys

77. The collection of prototype data can serve as an independent solution technique and as input to the other approaches. By itself, field information shows the system under a certain set of circumstances and defines the magnitude of the problems encountered. It is difficult, however, to isolate the effects of the various forcing phenomena and system perturbations. As a basis for model verification, prototype data are indispensable. For either use the data required are very similar. Part IV describes the data that will be required for either a physical or numerical model of Kaneohe Bay.

Ecological Analyses

78. The most promising sources of input for determining what is required in order to produce a certain environment, i.e., a certain group of organisms, are (a) a procedure known as "principal component

factor analysis with varimax rotation"[6] and (b) a trophic level ecosystem model developed for plankton community analysis.[13] In the first approach, patterns called "factors" are mathematically defined to be underlying similarities in the distribution of the variable (or organism); that is, an organism may show a tendency to be associated with a factor or not to be associated with a factor. Other information associated with the procedure is the degree of relationship or lack of relationship between the pattern and the variable.

79. The trophic level ecosystem model[13] deals with the relationship between the limiting substrate concentration* in the environment and the rate of substrate utilization by the dependent population. The model is valuable to comparative ecosystem studies and applied problems in resource management. It can be employed to answer questions concerning the effects of substrate concentrations upon planktonic interrelationships. Of specific importance to the recovery of Kaneohe Bay, the trophic level ecosystem model might be used to predict changes in planktonic populations related to changes in substrate levels which have been effected by removing sewage, altering land runoff, etc.

Integrated Solution Methods

80. For a complex estuary system it is virtually impossible to investigate all phenomena of interest with a single model, whether it be physical, analytical, numerical, or analog. To obtain maximum benefit from a model investigation, integration of two or more models may be required. Each model has certain strengths and limitations such that a given phenomenon may best be investigated by one particular model;

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* The term "limiting substrate concentration" refers to the quantity of a required substrate available to the organism. According to Leibig's "Law of the Minimum," a living organism is limited in growth and development by the parameter in its environment that is shortest in supply relative to its needs; high concentrations of other nutrients cannot stimulate growth if one is deficient. The "substrate" typically is taken to mean nutrient but could also include light intensity, bacterial population, etc.

however, for many phenomena the contributions from the various models are complementary and reinforcing.

81. For Kaneohe Bay, a program involving the combined efforts of a physical model and a numerical model plus contributions from other methods appears necessary for maximum benefit to be derived. Some of the areas in which a numerical model can make contributions are:

a. In determining average tidal currents.

b. In determining average wind-driven currents.

c. In determining mass transports between various segments of the bay.

d. In calculating the tidal prism and flushing characteristics of the bay and of the southeast basin.

e. In conducting pollutant and/or freshwater dispersion studies.

f. In investigating methods for increasing circulation in the bay or in the southeast basin.

82. A physical model can provide detailed information on stratification and current patterns that are depth dependent. It can be used to study sedimentation and shoreline erosion and short-period wave effects; it can also be used in determining boundary conditions for use in a numerical model.

83. The problems involved in wave refraction in a distorted physical model were discussed earlier in this report. Several means of overcoming these difficulties may be considered. If the ocean waves approaching the bay break across the reef before extensive refraction occurs, no remedial action is required. If this is not the case, the additional wave tests can be conducted using the time scale indicated by Equation 5 to develop short-period wave directions, heights, and periods that are necessary to generate the currents measured by prototype surveys. Regardless of which approach is ultimately taken, this problem can be overcome and will comprise a portion of the model verification effort.

PART IV: PROTOTYPE DATA REQUIREMENTS

Data for Model Verification

84. High quality prototype data are required for verification of numerical and physical models. Each parameter to be predicted by the model should be measured in order to calibrate the model and verify the model results. In a physical model the verification process consists of changes in roughness, wave characteristics, and other variable factors to achieve accurate reproduction of prototype phenomena. In a numerical model the process consists of changes in boundary conditions and coefficients. The predictive capability of either model is only as good as the prototype data used for calibration.

85. Hydrodynamic data should be accurately located geographically and with respect to time. An additional requirement for Kaneohe Bay is that the tidal, current, wave, wind, and salinity data be synoptic. This is dictated by the relative equality of the effects of these phenomena in the bay.

Hydrodynamic verification

86. Because of the low flow velocities within the bay, the prolonged data collection periods, and the prevailing wave environment, it will be necessary to take measurements from rigid, permanently installed stations. These permanent stations can be piles or towers fixed to the bottom. Sampled data will be transmitted to a shore-based control station, where they will be recorded. Locations of the proposed data stations are shown in Figure 7 and described in Table 2. Some locations, such as navigation channel center lines, cannot receive permanent stations; therefore, some supplemental data will be required on an intermittent basis.

87. Data from remote stations will be conditioned and telemetered to the control station. Tentative sampling rates for the data collection are shown in Table 3.

88. Tidal elevations. Tidal elevations will be recorded by flotation tide gages with stilling tubes to damp out short-period waves;

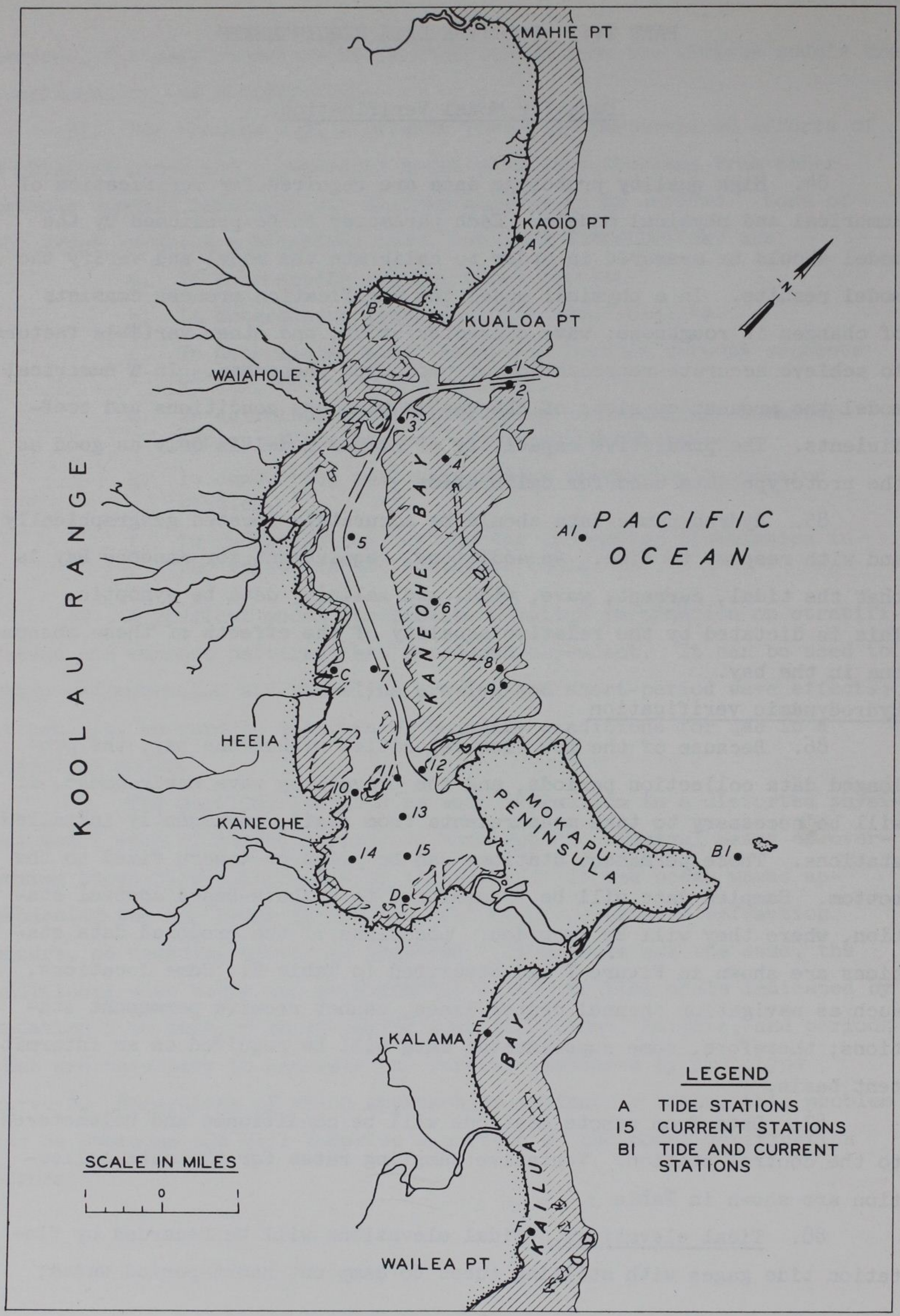

Figure 7. Prototype data stations

these gages can use either a drum-type paper chart recorder or transmit data via telephone lines.

89. Waves. The required ocean wave data will consist of wave heights, periods, and directions of propagation. Also needed will be the location of breaking waves and the degree to which breaking waves reform over the reef. Wave heights and periods can be obtained with submerged pressure transducers or from knowledge of the water depth where breaking occurs. To supplement transducer data and provide the other data desired, aerial photography should be used, but it must be controlled with respect to time and location. Such photography can also provide information on the wave climate within Kaneohe Bay.

90. Statistical wave data will be necessary for use in design of model testing programs.

91. Wind. Wind data from shore readings will not be reliable due to topographic effects. Therefore, wind recording devices will be located on several of the permanent stations and will telemeter wind speed and direction back to the control station. As with waves, statistical wind records will be needed.

92. Currents. The permanent velocity stations will be equipped with current meters at a varying number of depths. This number will depend on the degree of flow stratification expected at each station, with the least number of meters at the stations with no stratification. Therefore, the southeast basin of the bay will require the greatest number of readings over depth, while the ocean will require the least number. The speed and direction of the currents will be telemetered ashore. The current meters should be electromagnetic induction meters because of their low threshold velocities and nonfouling characteristics. The current data obtained from the permanent stations will be supplemented by measurements taken at the intermittent stations and possibly by drogue studies.

93. Freshwater inflows. The discharge hydrographs of the major streams will be necessary. Some of the streams have stage-discharge curves available, and other curves can be developed for the other streams. The hydrographs will be required for two weeks prior to the beginning of

other data collection and will continue throughout the survey period. Sewage discharge rates for the three outfalls in the bay will be required for the same period.

94. Sediment samples. Bottom samples will be taken in those portions of the bay where sedimentation is believed to be a problem. Stream and reef samples should be taken as necessary to establish the sources of sediments in the bay. Previous sediment sampling programs[4,5] will provide much of this information. Measurement of suspended sediment concentrations in the streams during flood flows will be desirable. Analysis of the sediment samples should include grain size distribution and X-ray diffraction.

Dispersion verification

95. The first step in calibrating a hydrodynamic model of the dispersive characteristics will be to verify the nondispersive model. Where salinity gradients (vertical or horizontal) are great enough, they may be used as a tracer from which dispersion can be verified. Otherwise, some artificial tracer must usually be employed.

96. The most commonly used artificial tracers are conservative fluorescent dyes, such as Rhodamine WT. Verification of physical models can be accomplished with either instantaneous or continuous dye injections, but continuous injections are usually preferred in order to maintain easily detected high concentrations. For verification of the numerical model of Kaneohe Bay, instantaneous injections are preferred.

97. Dye concentrations are obtained by analyses of water samples, either discrete or by flow-through techniques. Other measurements, such as salinity and DO, are most readily made on discrete samples. These may be collected by boat.

Data for Model Applications

98. There are some measurements of biological importance which will provide additional data to the dispersion model but will not be necessary for verification of the hydrodynamic models. These are the aqueous concentrations of nitrogen, phosphorus, carbon, and chlorine

forms, which should be considered in the supplemental data collection program accomplished in boats.

99. Other elemental forms and micronutrient compounds, such as metallic ions and vitamins, are present in the system, possibly in significant aqueous concentrations. But the analytical expense and data interpretation difficulties attendant with their measurement exclude them from all but the most exhaustive study. It is therefore not recommended that they be included in the baywide data collection program.

100. A feasible approach to a study of the metals budget of the bay will involve the periodic sampling of sewage effluents from the Kaneohe Marine Air Station and Kaneohe municipal sewage treatment plants and the collection of surface samples taken along transects relative to these plants. These samples can be analyzed for total zinc, copper, lead, chromium, cobalt, nickel, iron, and manganese content with relative ease by well-developed analytical procedures. This data can provide significant information on the input of these elements from the sewage outfalls and their transport through the bay system. As stated previously, DO concentrations can be measured easily in samples taken during supplemental data collection from boats. DO will be measured just below the surface (approximately 1 ft), at middepth, and just above the bottom. DO stations will be the same as those for salinity, temperature, and current velocity in the supplemental surveys.

Survey Conditions

101. The ideal conditions for data surveys will be those that permit straightforward identification of the forcing phenomena, i.e., a period without significant wave action, prolonged winds, or high freshwater runoff so that the water elevations and flow velocities can be attributed mainly to tidal action. Similarly, periods of dominance of each of the other phenomena would be desirable. However, the timing of these periods can be predicted only approximately at best, and insurmountable difficulties will be encountered in temporary mobilization of this kind of survey; thus, an alternate approach will be necessary. It

is suggested that all permanent data stations be monitored continuously for a 4-month period, preferably March through June, and that the auxiliary measurements be scheduled several times within that period. Should a storm providing large freshwater runoff occur during that time, salinity and discharge data should be collected immediately to permit evaluation of freshwater accumulation in the bay.

PART V: CONCLUSIONS AND RECOMMENDATIONS

102. Of the possible solutions to problems presently experienced in Kaneohe Bay, at least two do not require additional study to determine their worth. These are improved watershed land management and cessation of sewage effluent discharges into the southeast basin. Although it is desirable to know the rate at which the bay will flush the residual pollutants once sewage discharges have stopped, establishing the value of such an action is not necessary.

103. Other improvement plans, such as those intended to improve circulation within the bay, should be carefully evaluated before implementation. The high cost of coastal construction and the potential for harmful side effects discourage trial and error improvement works. If, as seems likely, the removal of sewage effluent from the bay is accomplished by means of an ocean outfall, then the location and design of the discharge manifold should be studied to insure that the effluent plume does not contaminate nearby beaches or reenter Kaneohe and/or Kailua Bays. These and other considerations provide the motivation for development of an adequate predictive capability in the Kaneohe Bay area.

104. The characteristics of the bay and its problems are of such complexity that only physical and numerical modeling techniques offer any promise for successful prediction. Each has advantages and limitations inherent in its use, as discussed in Part III. The major differences in capabilities are that wind waves and stratification can be accommodated only in the physical model and that currents and setup induced by the wind can be included only in the numerical model. Thus, the two techniques are complementary rather than competitive.

105. The prototype data requirements for either model are essentially the same. For a highly reliable model of either kind, a prototype data program only slightly less ambitious than that described in Part IV is the minimum acceptable. A more generalized numerical approach might be realized with less prototype data if the sacrifices in detail and confidence were acceptable. A smaller physical model can be achieved only through an increase in distortion, which might prevent the inclusion of

wind waves and sediment studies. A more highly distorted model can be used to examine current patterns due to tidal action and density differences.

106. The choice of models will be based upon the improvement works expected to be proposed and the type and quality of the information desired. Prior to implementation of any circulation improvement plans, it is recommended that, as a minimum, a prototype data program similar to that described in Part IV be implemented and a numerical model similar to that described in Part III be developed. For detailed analyses of improvement plans and bay responses, a physical model in conjunction with a numerical model is recommended.

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Table 1

Concentrations of Some Trace Metals in Wastewater and Seawater

Metal	Wastewater from Los Angeles, Calif.[14]*	Seawater[15]
Cr	610	0.05
Mn	80	2.00
Fe	7300	10.00
Cu	1100	3.00
Zn	1400	10.00
Cd	22	0.11
Pd	190	0.03

Note: All values are in micrograms/liter (parts per billion).

* References are listed on pages 45-46.

Table 2

Proposed Permanent Stations and Instrumentation

for Prototype Data Collection*

Station		Type and Number of Instruments Required			
Location	Approximate Depth, ft	Transducers	Current Meters over depth	Flotation Tide Recorder	Wind Velocity Meter
A	6			1	
B	6			1	
C	6			1	
D	10			1	
E	6			1	
F	6			1	
A1	50	1	1	1	
B1	30		1	1	1
1	35	1	3		
2	35		3		1
3	46		2		
4	12		1		
5	50		3		1
6	1-3		1		
7	42		2		
8	20	1	2		
9	20		2		
10	50		3		
11	50		3		
12	50		3		
13	50		3		
14	40		3		
15	50	—	3	—	1
Total	--	3	39	8	4

* See Figure 7 for station locations.

Table 3

Data Sampling Requirements

Meters	Sampling Period min	No. of Samples per Period	Period Frequency
Transducer	20	4800	4 times/day
Current meter	1	12	Hourly
Wind velocity meter	20	1200	4 times/day

APPENDIX A: APPLICATION OF THE NUMERICAL HYDRODYNAMIC MODEL

1. To obtain an indication of the relative importance of tidal currents and wind-driven currents in Kaneohe Bay, the hydrodynamic portion of the program was run at WES on a Honeywell G-635 computer for the no-wind condition and then with a typical trade wind. A grid size of 1000 ft was selected as giving sufficient spatial resolution for the purposes of the investigation. The grid is illustrated in Figure A1. Note that essential features of the bay can be reasonably well represented by this size grid. A time step of 90 sec was selected, based upon previous usage of the model. No stream inflows were included in these runs.

2. A tidal cycle for 14 July 1966 (Figure A2)[1*] was selected as a representative tide. A wind of 15 mph blowing into the bay at 90 deg was selected as representing an average wind condition. The hydrodynamic model was run for two tidal cycles for both a no-wind condition and for the 15-mph wind. Two cycles were run to allow system transients to decay. These transients were induced by starting the calculations with incorrect tidal heights and velocities at interior points of the bay. The second cycle was taken as a satisfactory solution for the tidal cycle with wind conditions considered. Based upon the results obtained, it might have been sufficient to run one and one-half tidal cycles since excellent agreement exists between the second half of both tidal cycles. Plots of the velocity field in the bay at 19 different times in the tidal cycle are shown in Figures A3-A21 for the no-wind condition. Corresponding diagrams for the 15-mph wind at 90 deg are shown in Figures A22-A40. The times in the second tidal cycle represented by these velocity plots are indicated in the figures. The dot on the velocity vector represents an arrow. General agreement exists between these results and available prototype current patterns and volume transport in the bay. This general agreement is encouraging and suggests that valuable information can be obtained from the numerical model.

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* References are listed on pages 45-46.

These results do not include the effects of short-period waves, which could not be considered in the model.

3. According to the numerical results, wind-driven currents in Kaneohe Bay are certainly significant in magnitude and may occasionally dominate. Of course, these initial numerical efforts were based upon a constant wind with no time or space variation, a condition which would never be exactly obtained in the prototype. There also were other approximations in the numerical model, the effects of which are not completely known. Additional numerical efforts can resolve some of these difficulties and refine the numerical model's representation of prototype conditions.

4. The small currents and poor flushing characteristics of the southeast basin are readily apparent in the numerical results. Almost no tidal currents and only small wind-driven currents are developed in this area. It is apparent that the barrier reef is an effective obstacle to flow entering the bay. Even the wind-driven currents are primarily turned parallel to the reef with little flow across the reef line. The wind does, however, produce significant currents on the shallow reef surface.

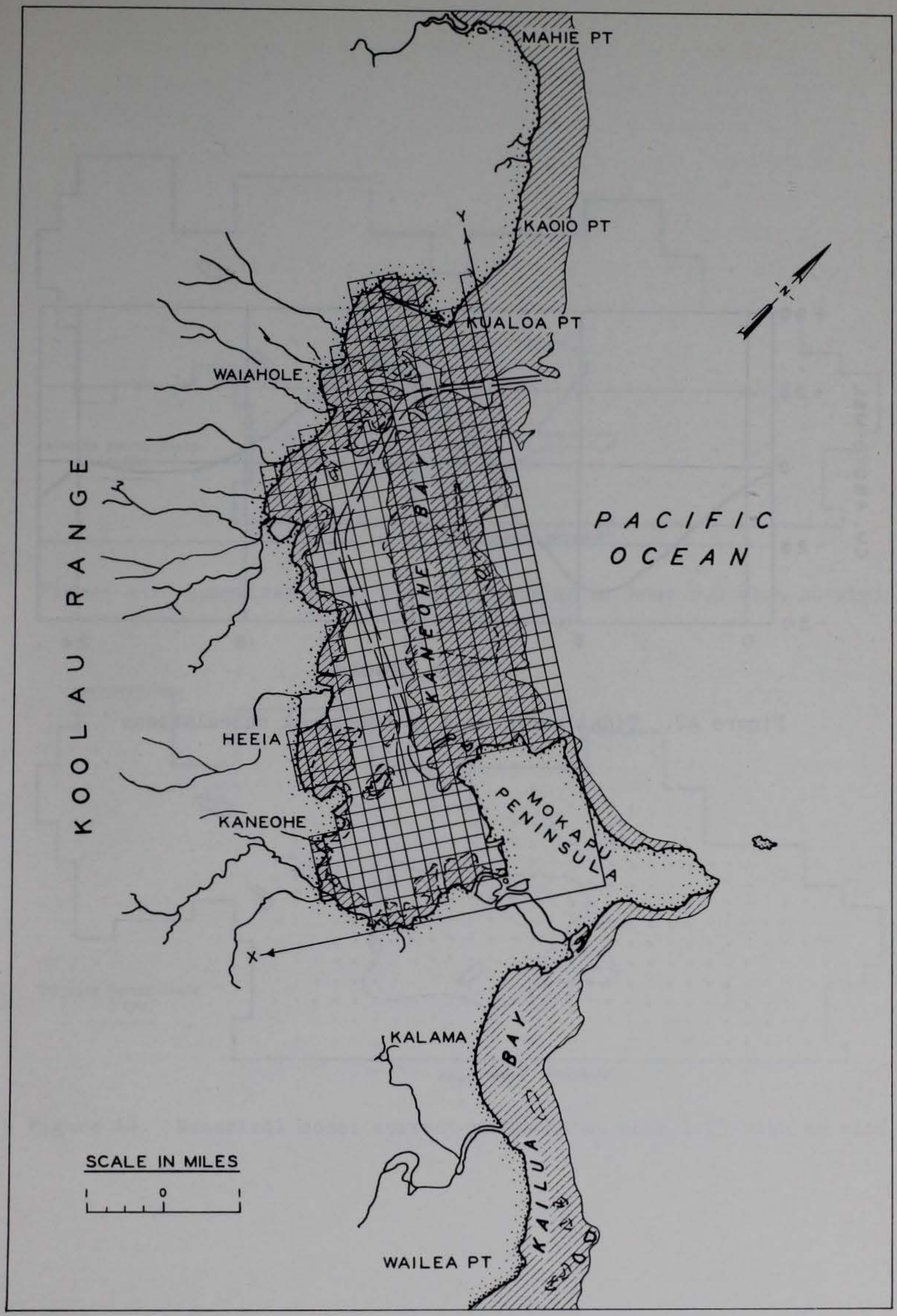

Figure A1. Computational grid for Kaneohe Bay

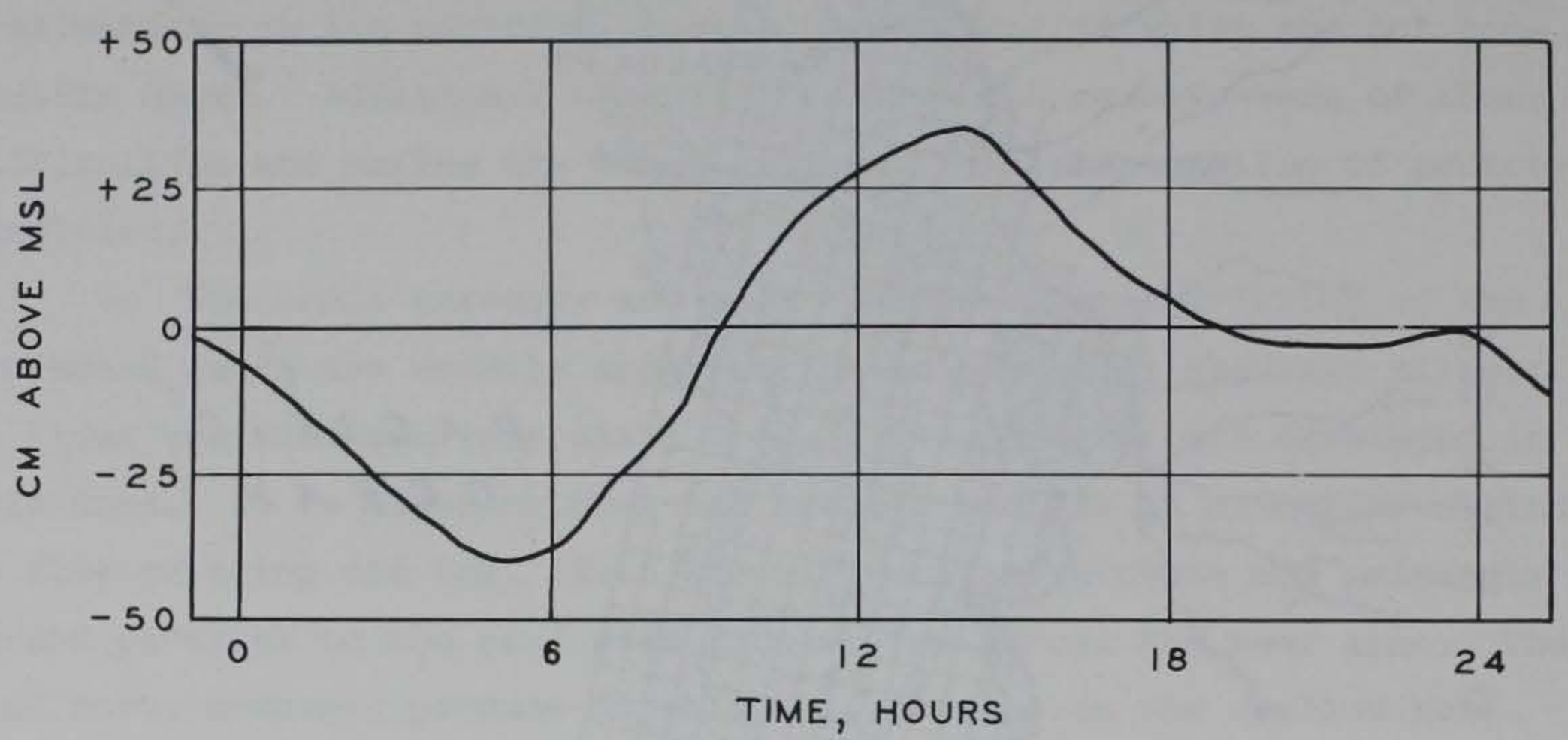

Figure A2. Tidal curve used in numerical calculations

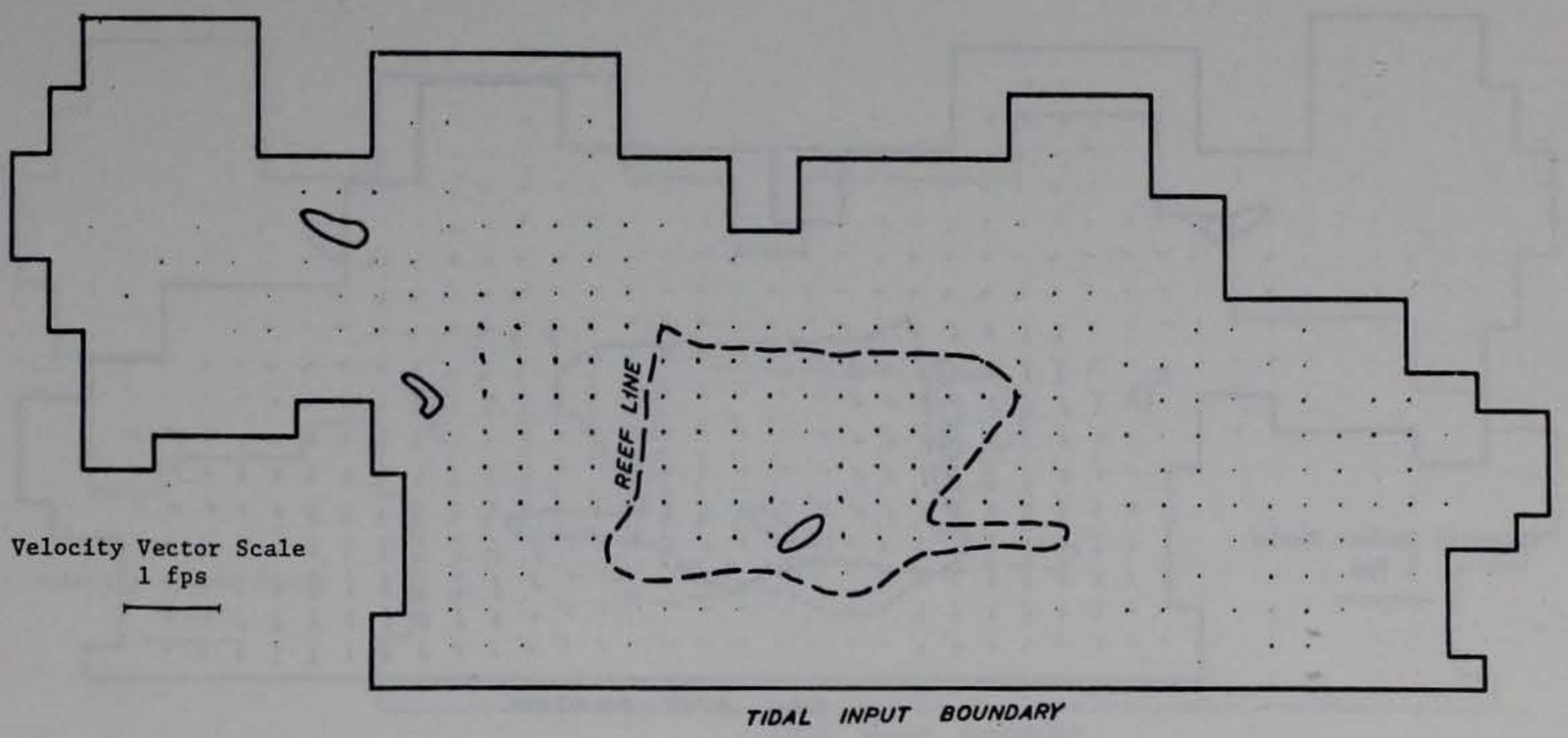

Figure A3. Numerical model current patterns at hour 0.0 with no wind

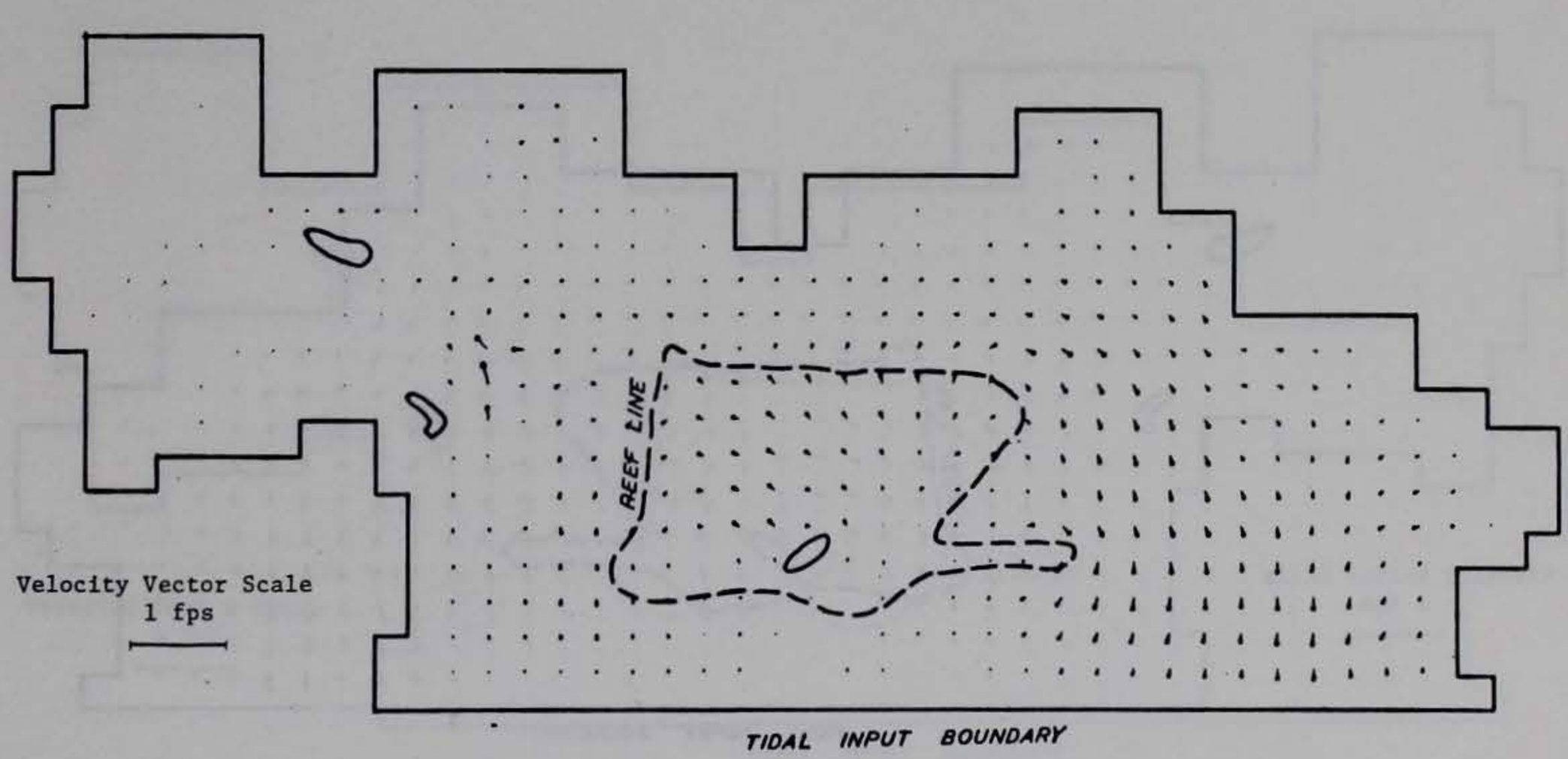

Figure A4. Numerical model current patterns at hour 1.25 with no wind

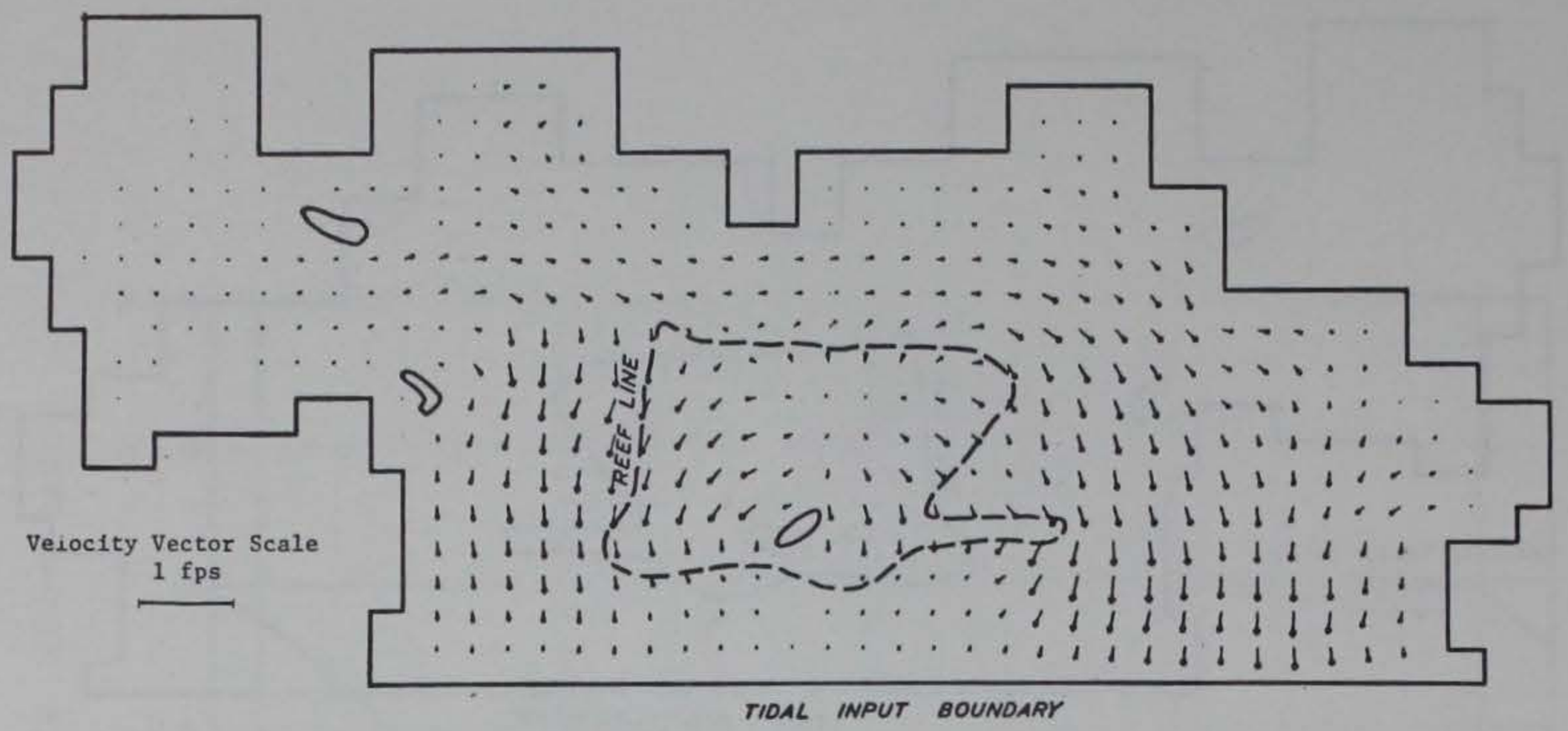

Figure A5. Numerical model current patterns at hour 2.5 with no wind

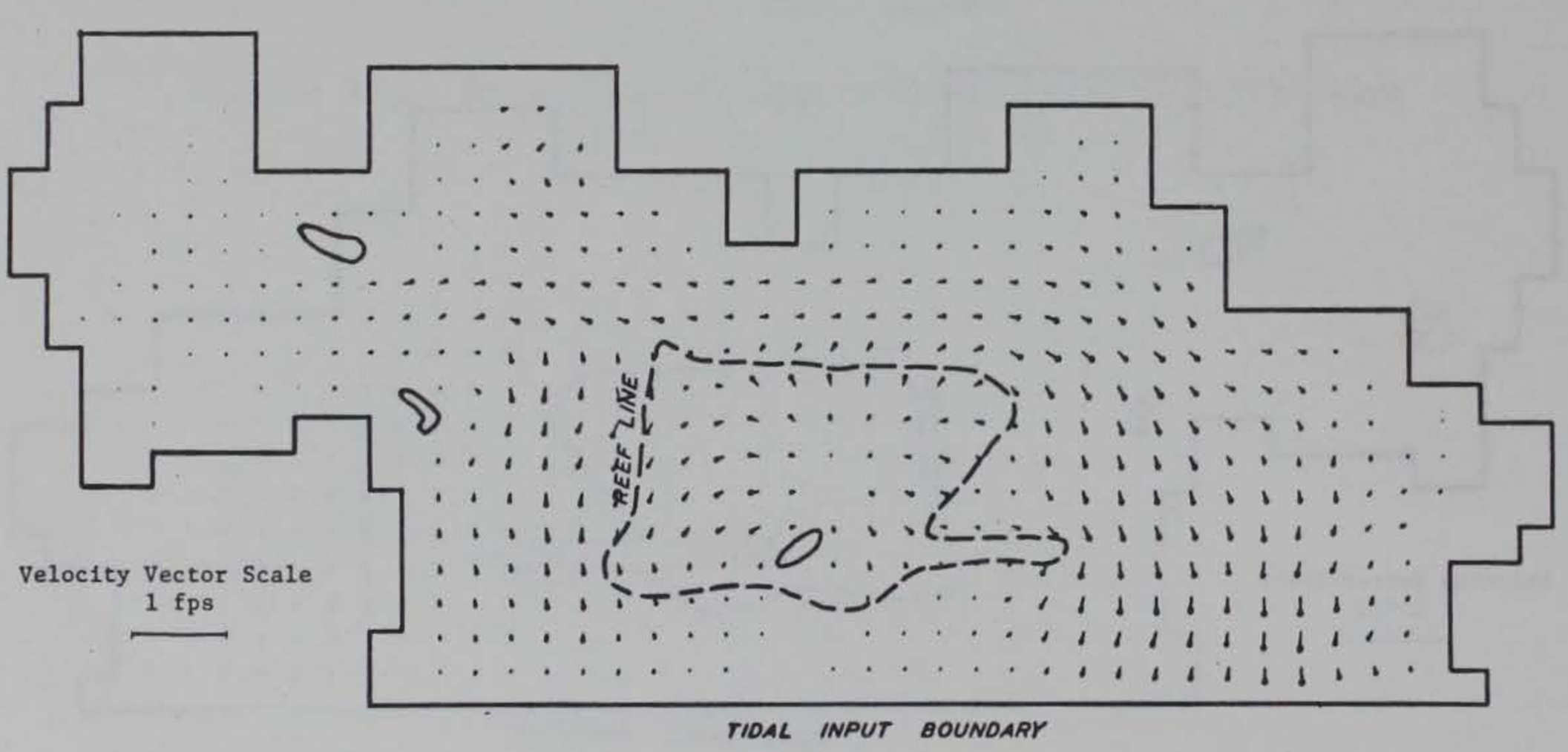

Figure A6. Numerical model current patterns at hour 3.75 with no wind

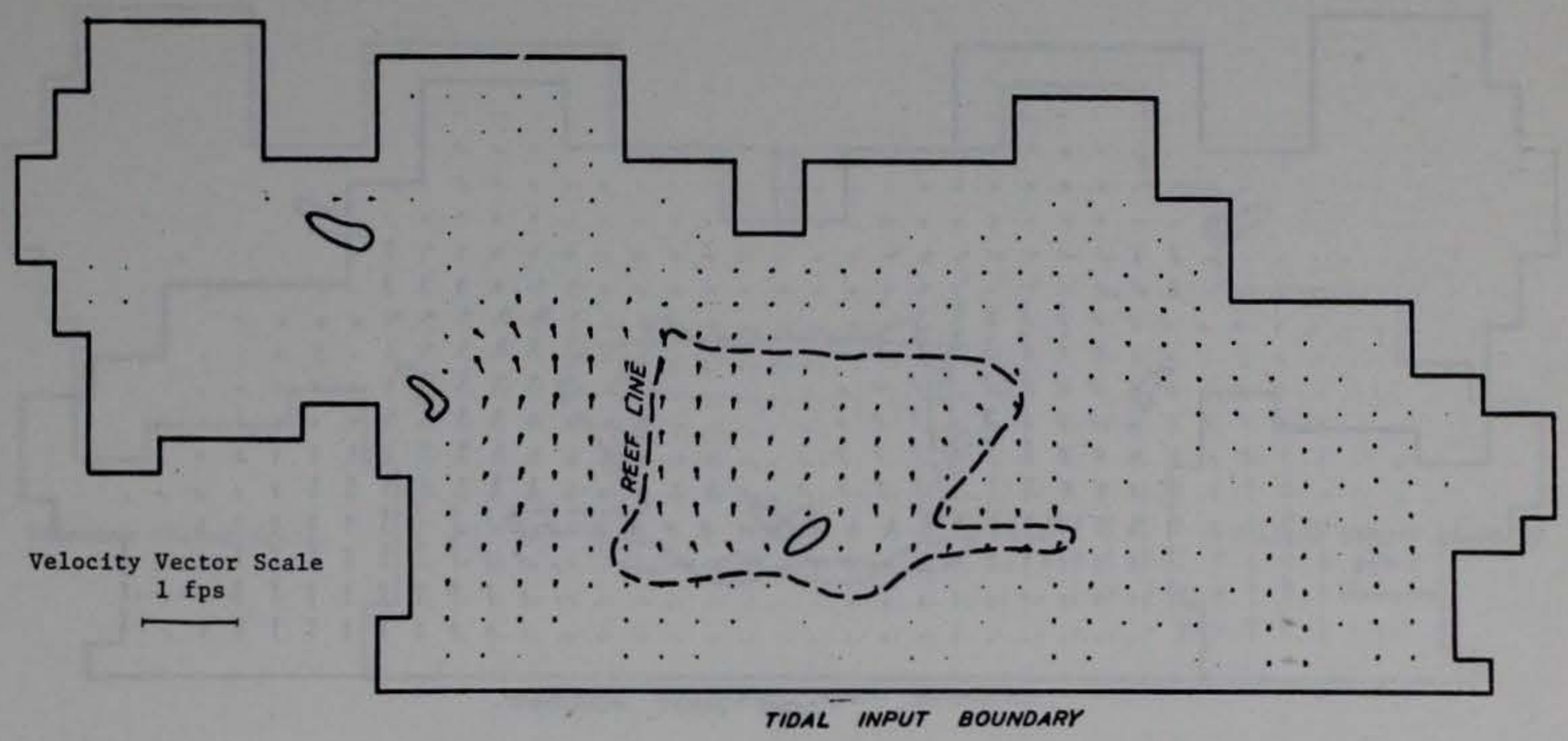

Figure A7. Numerical model current patterns at hour 5.0 with no wind

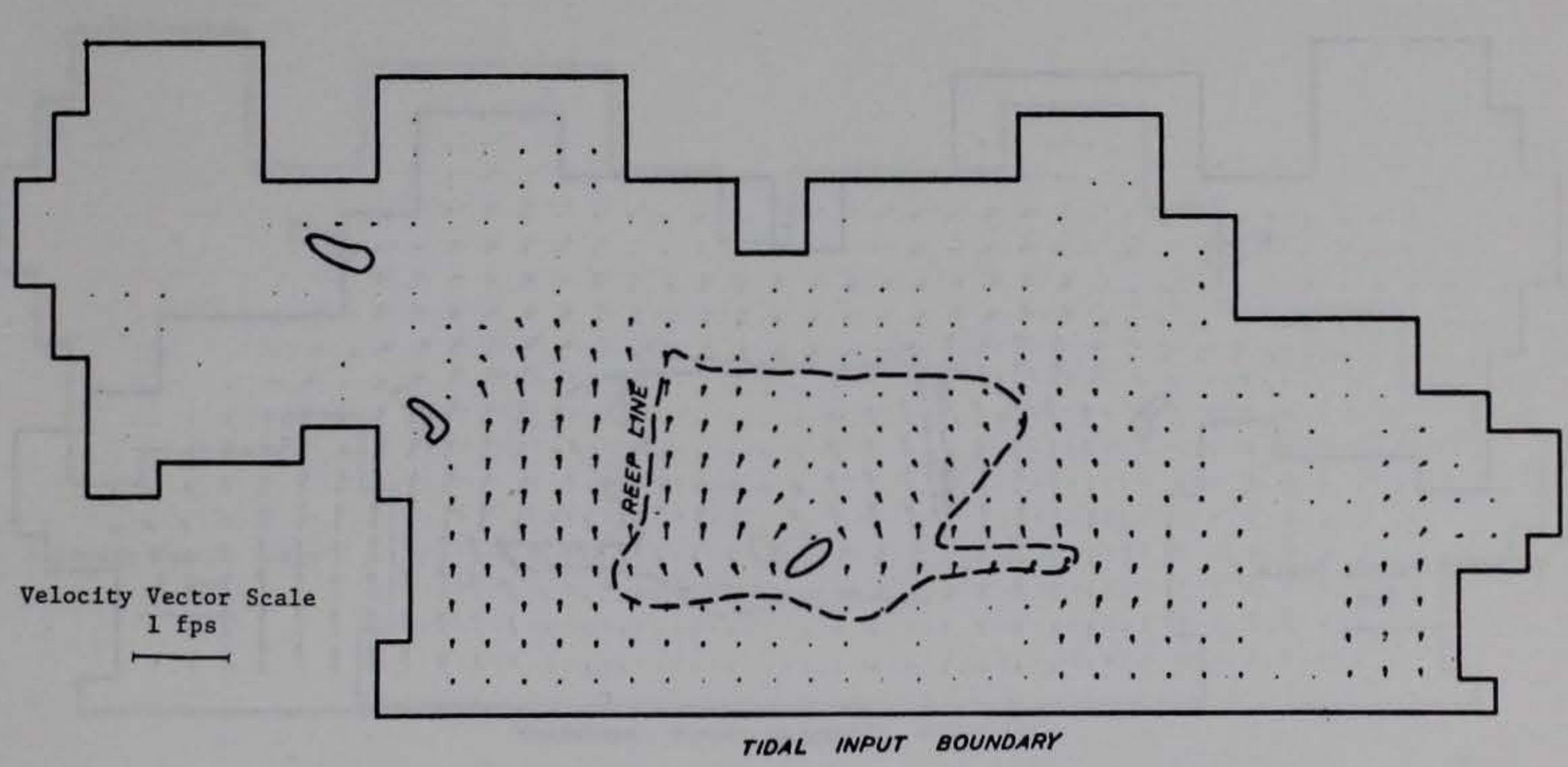

Figure A8. Numerical model current patterns at hour 6.25 with no wind

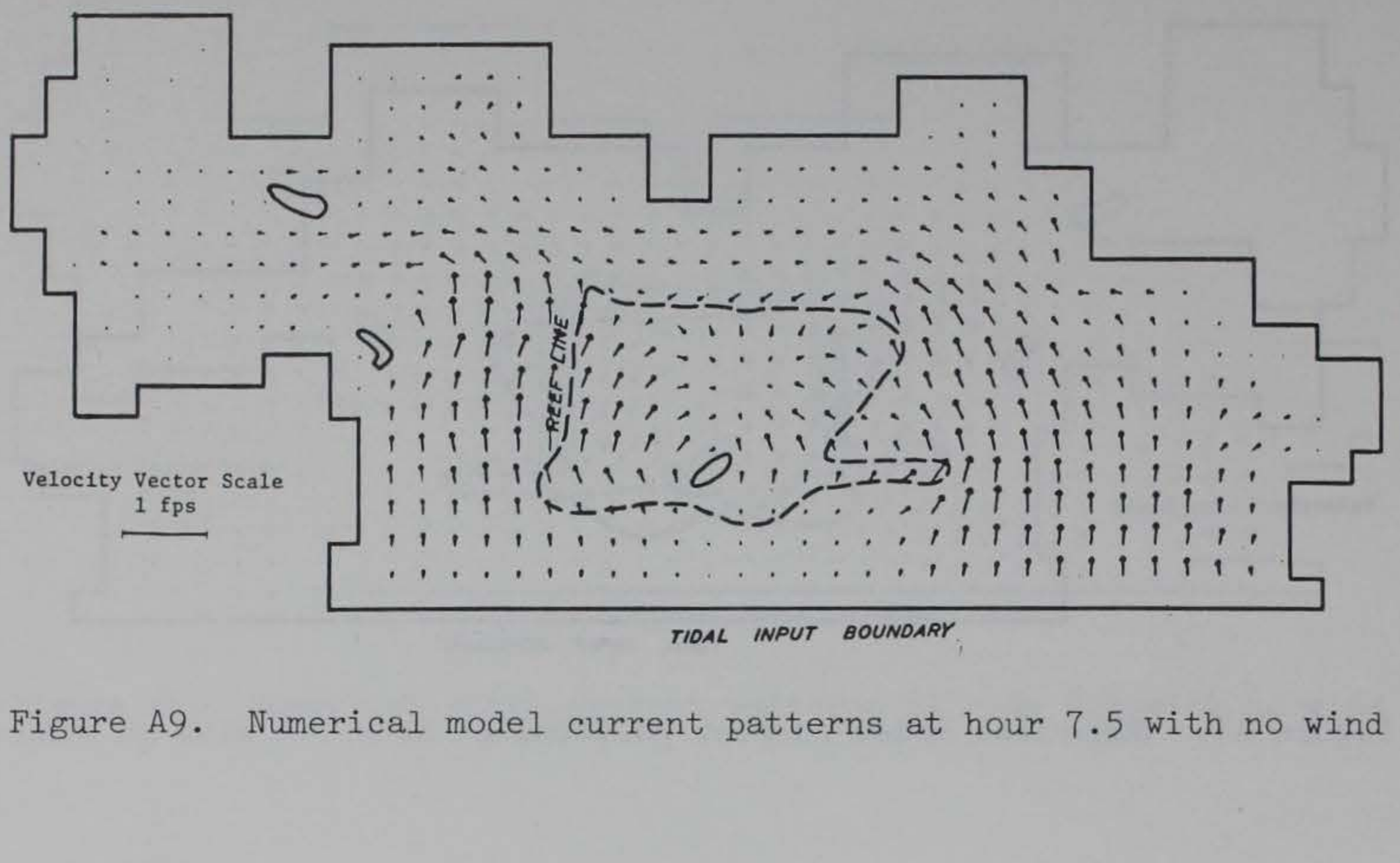

Figure A9. Numerical model current patterns at hour 7.5 with no wind

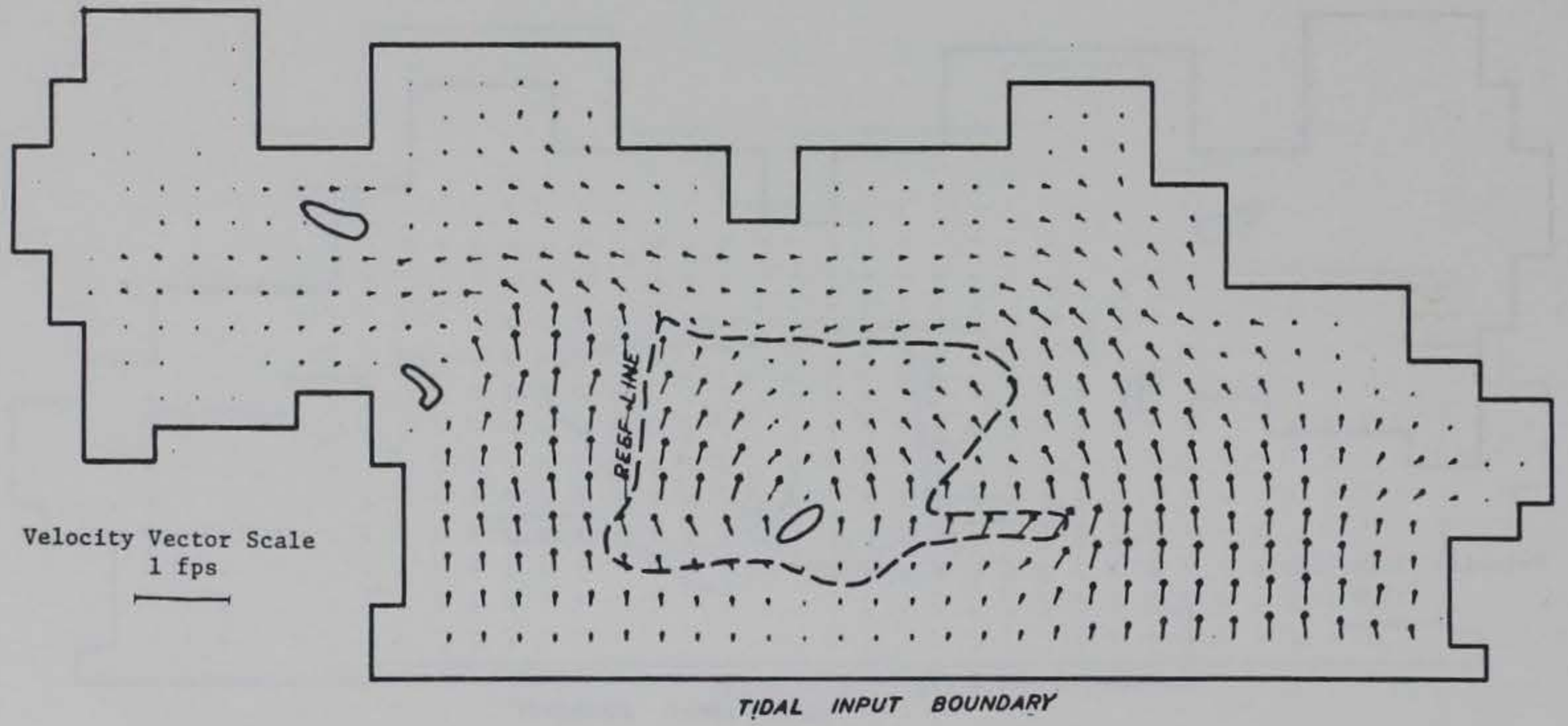

Figure A10. Numerical model current patterns at hour 8.75 with no wind

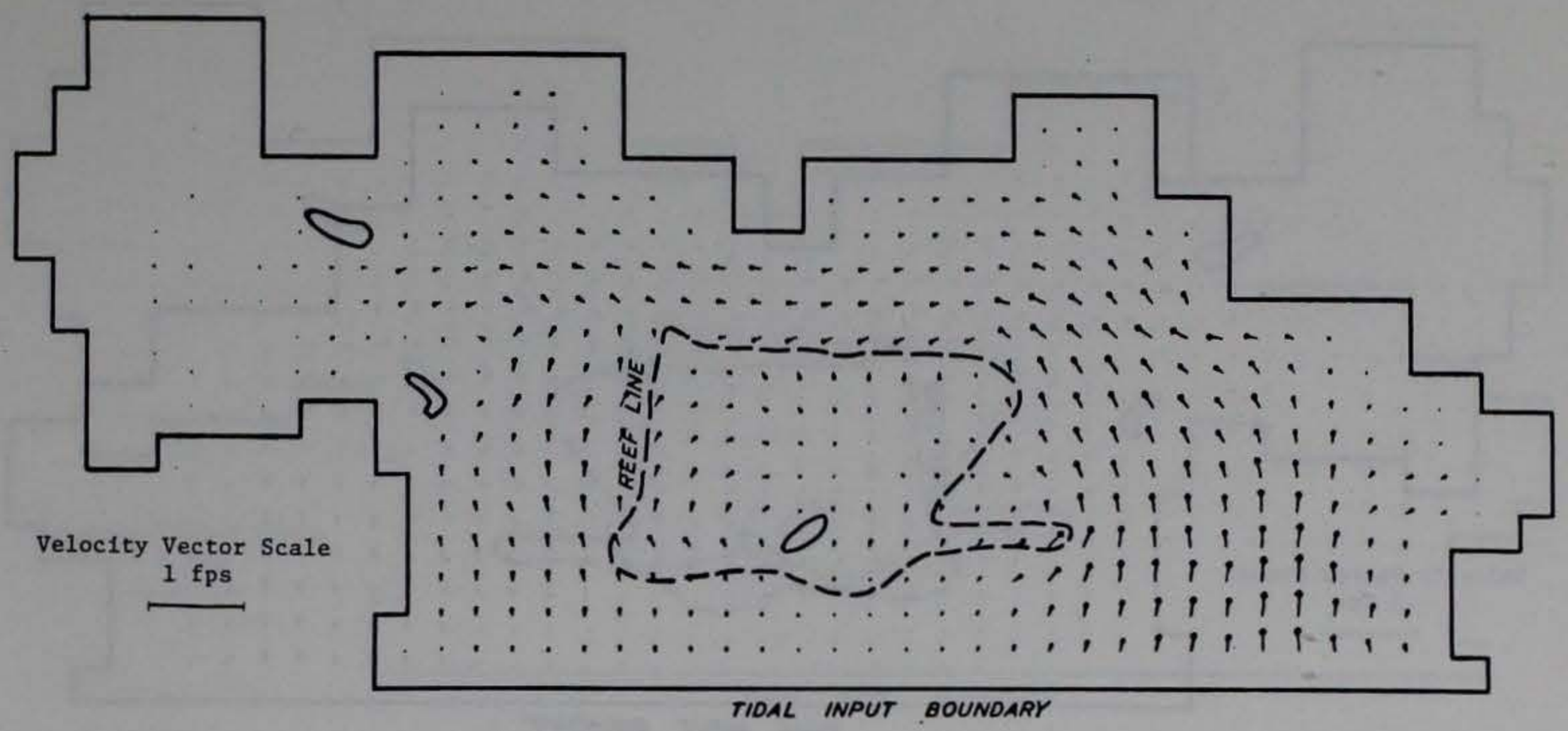

Figure A11. Numerical model current patterns at hour 10.0 with no wind

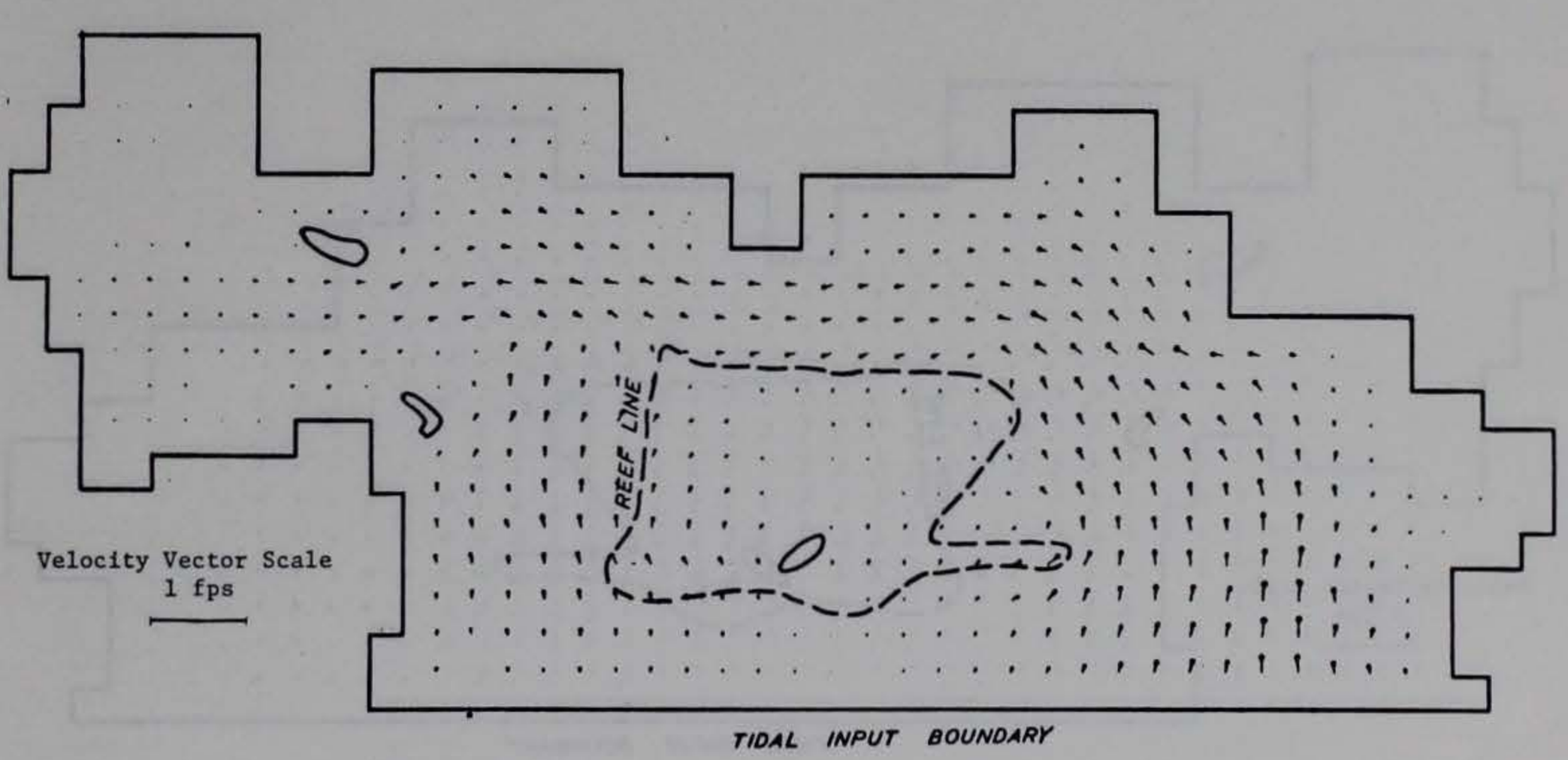

Figure A12. Numerical model current patterns at hour 11.25 with no wind

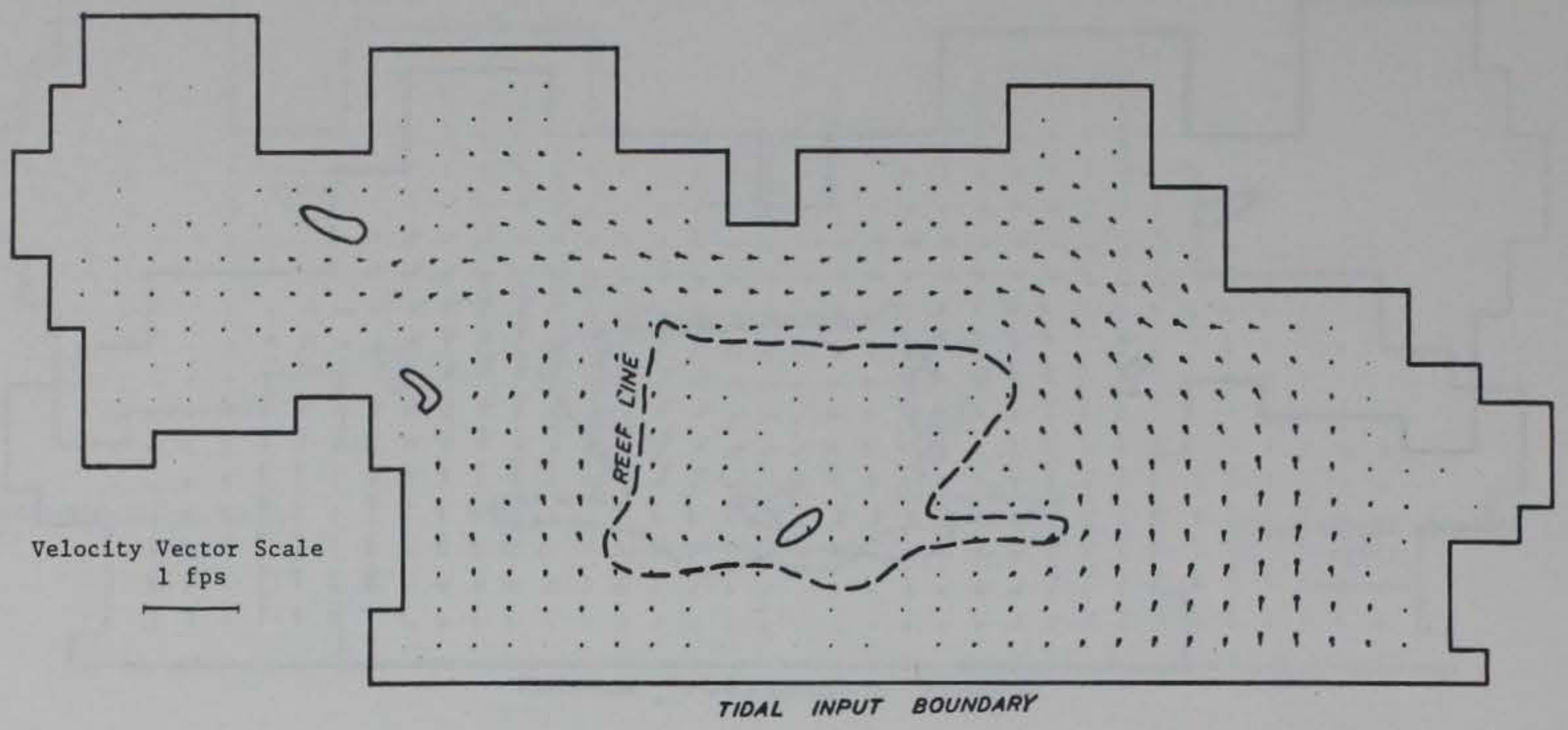

Figure A13. Numerical model current patterns at hour 12.5 with no wind

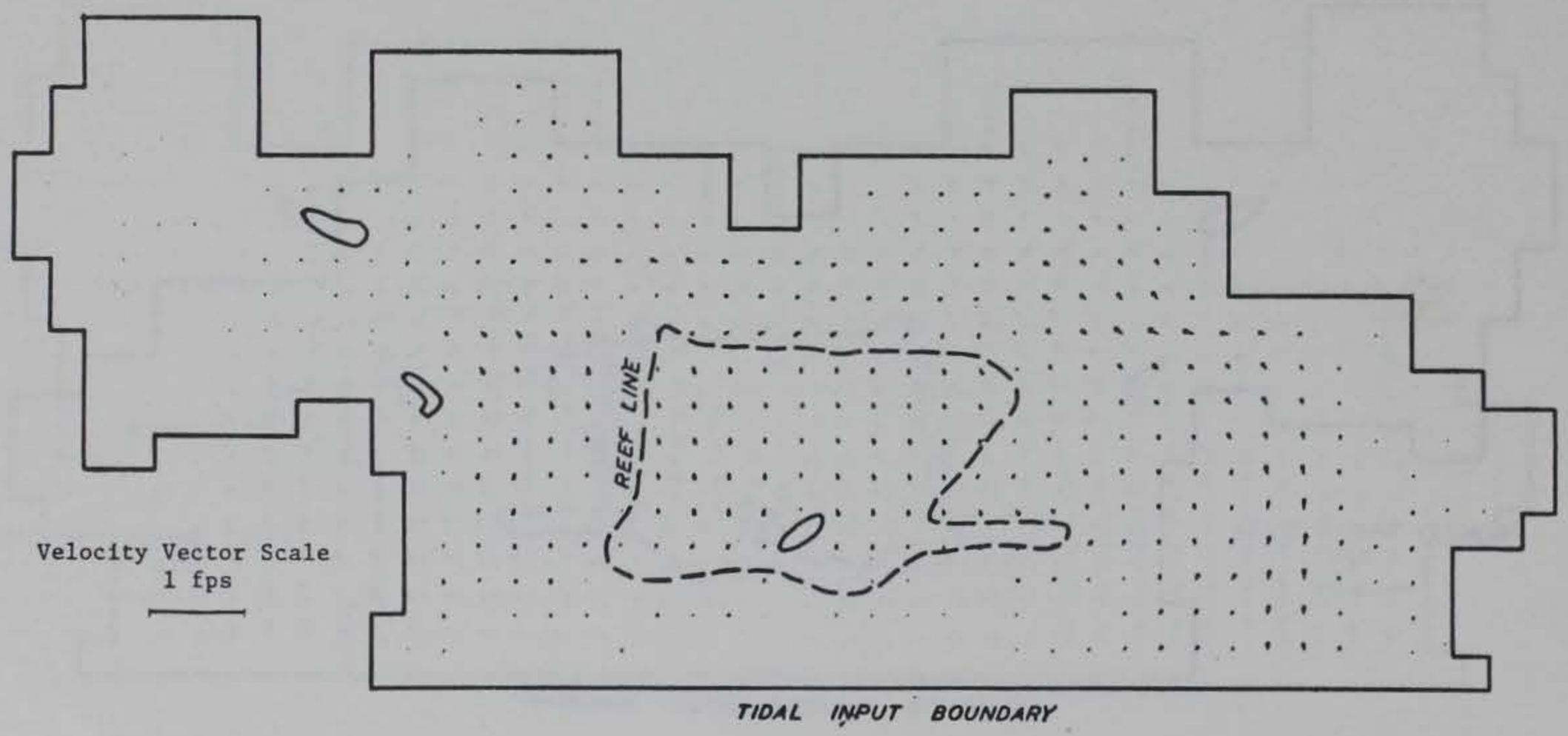

Figure A14. Numerical model current patterns at hour 13.75 with no wind

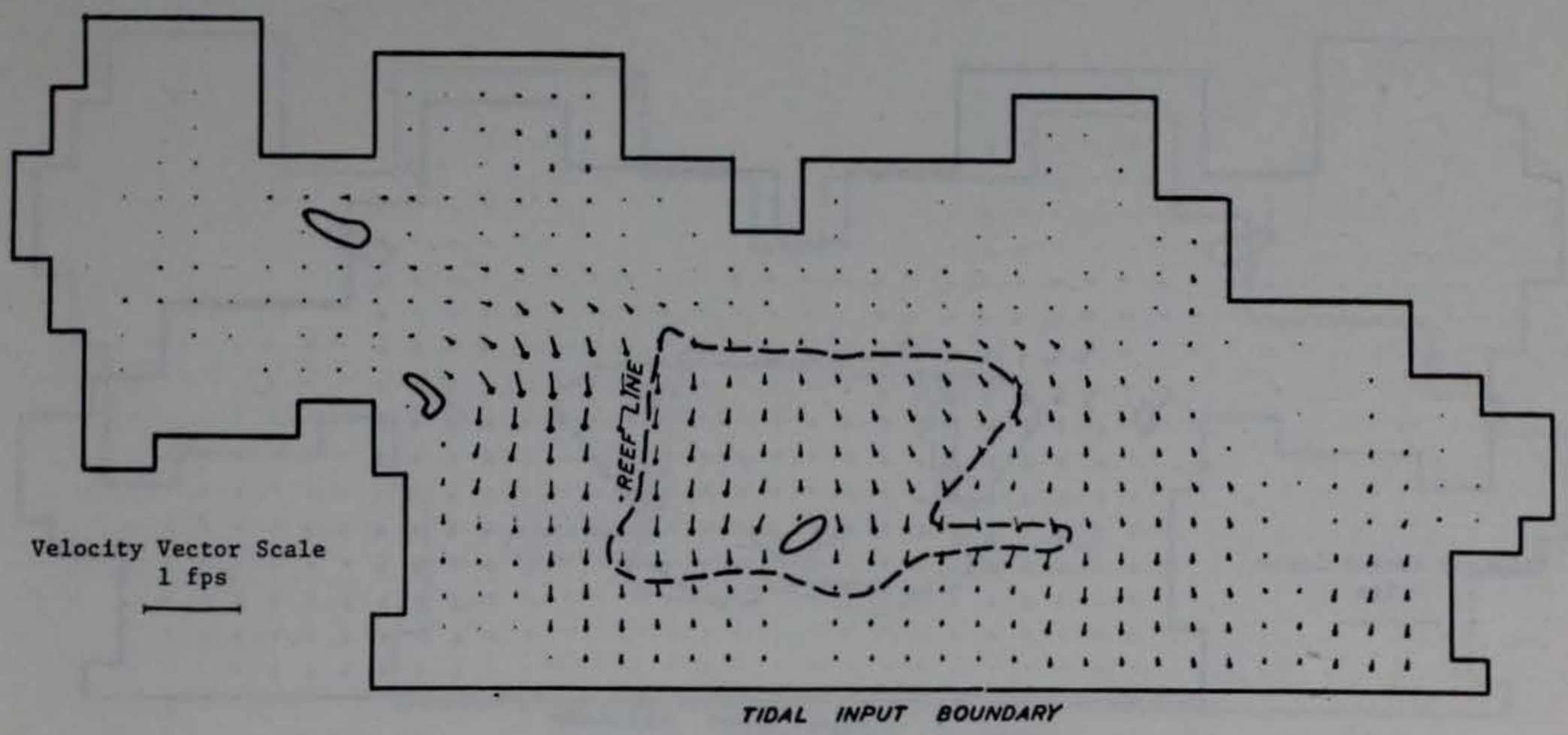

Figure A15. Numerical model current patterns at hour 15.0 with no wind

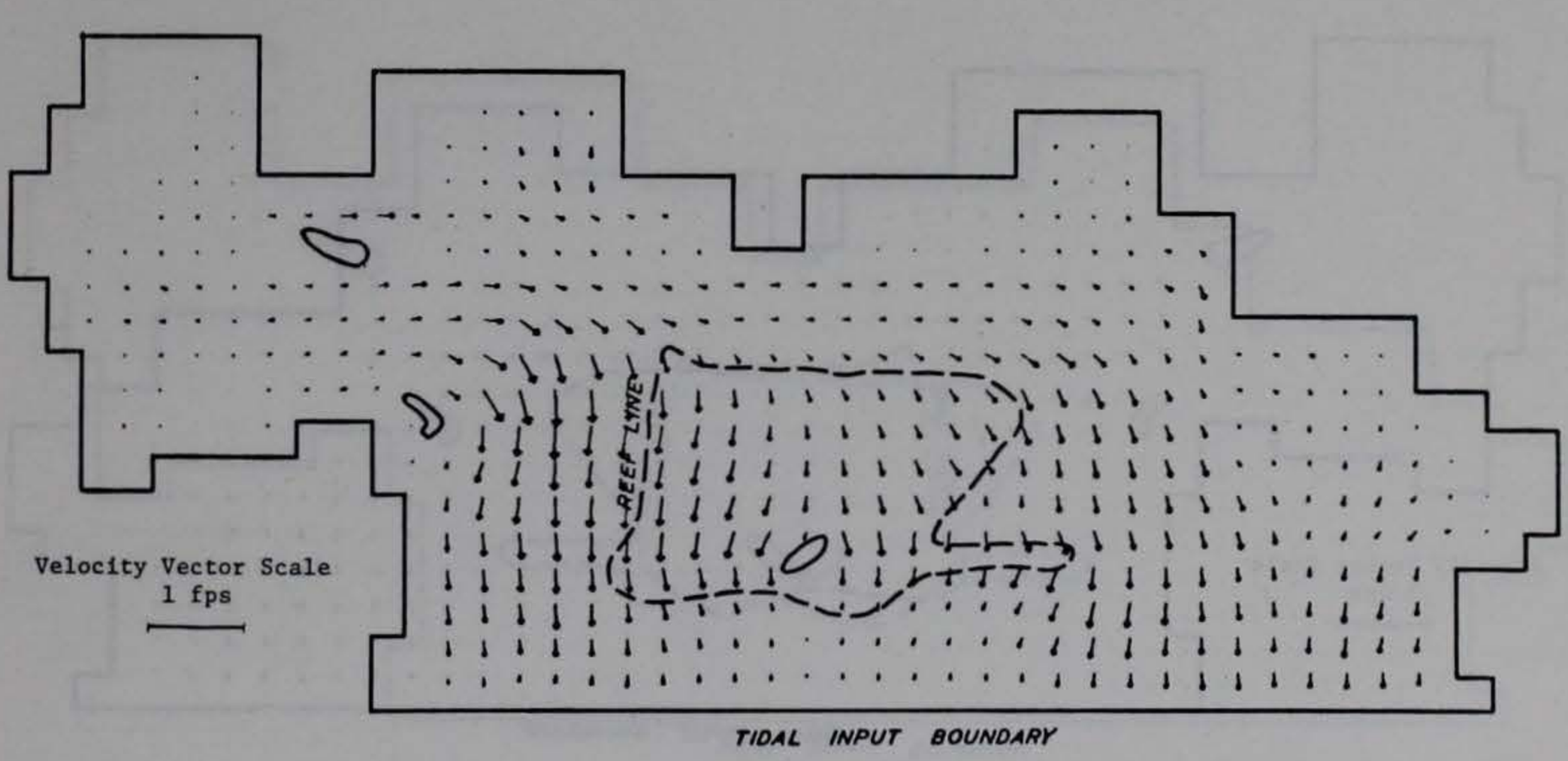

Figure A16. Numerical model current patterns at hour 16.25 with no wind

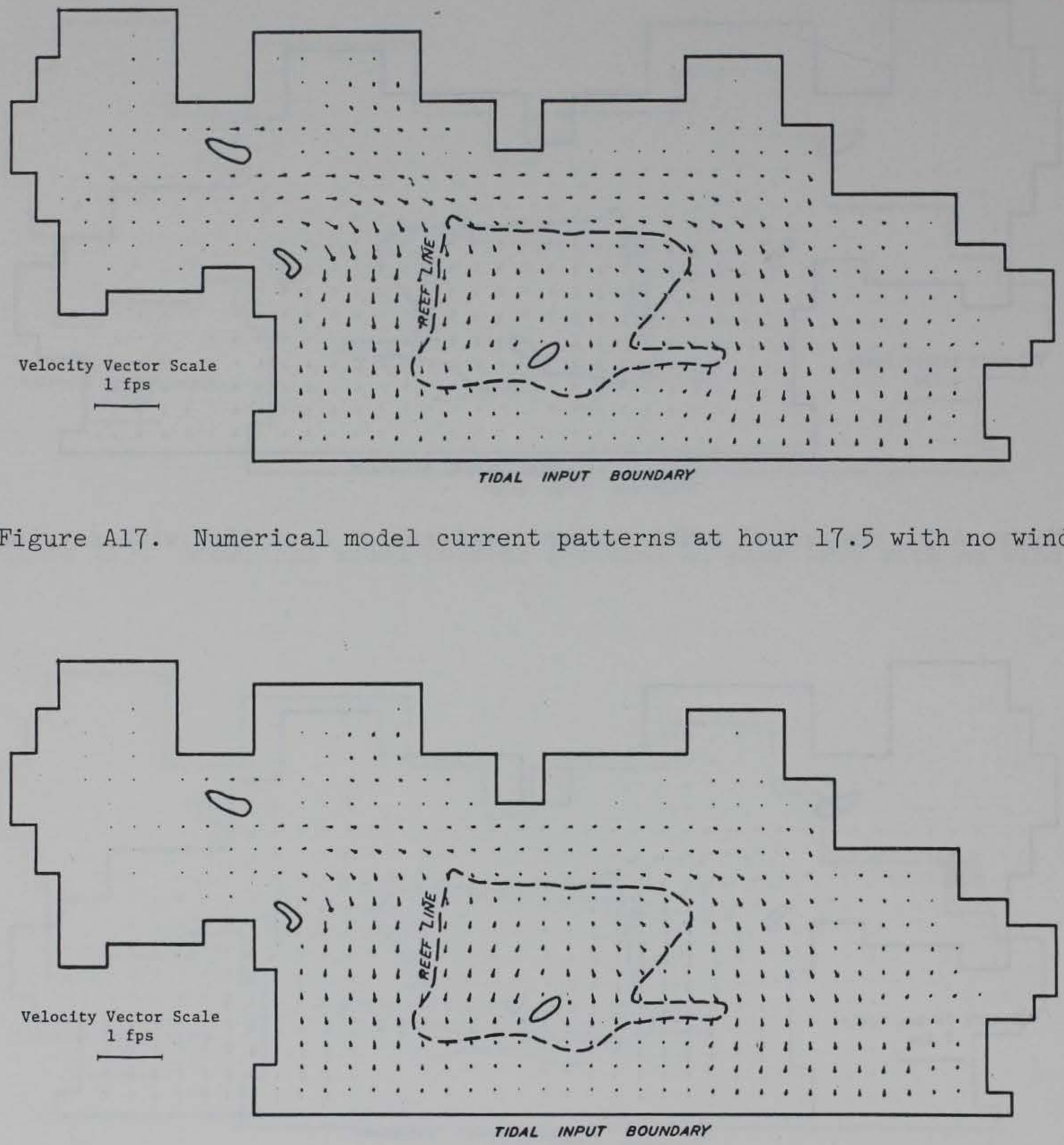

Figure A17. Numerical model current patterns at hour 17.5 with no wind

Figure A18. Numerical model current patterns at hour 18.75 with no wind

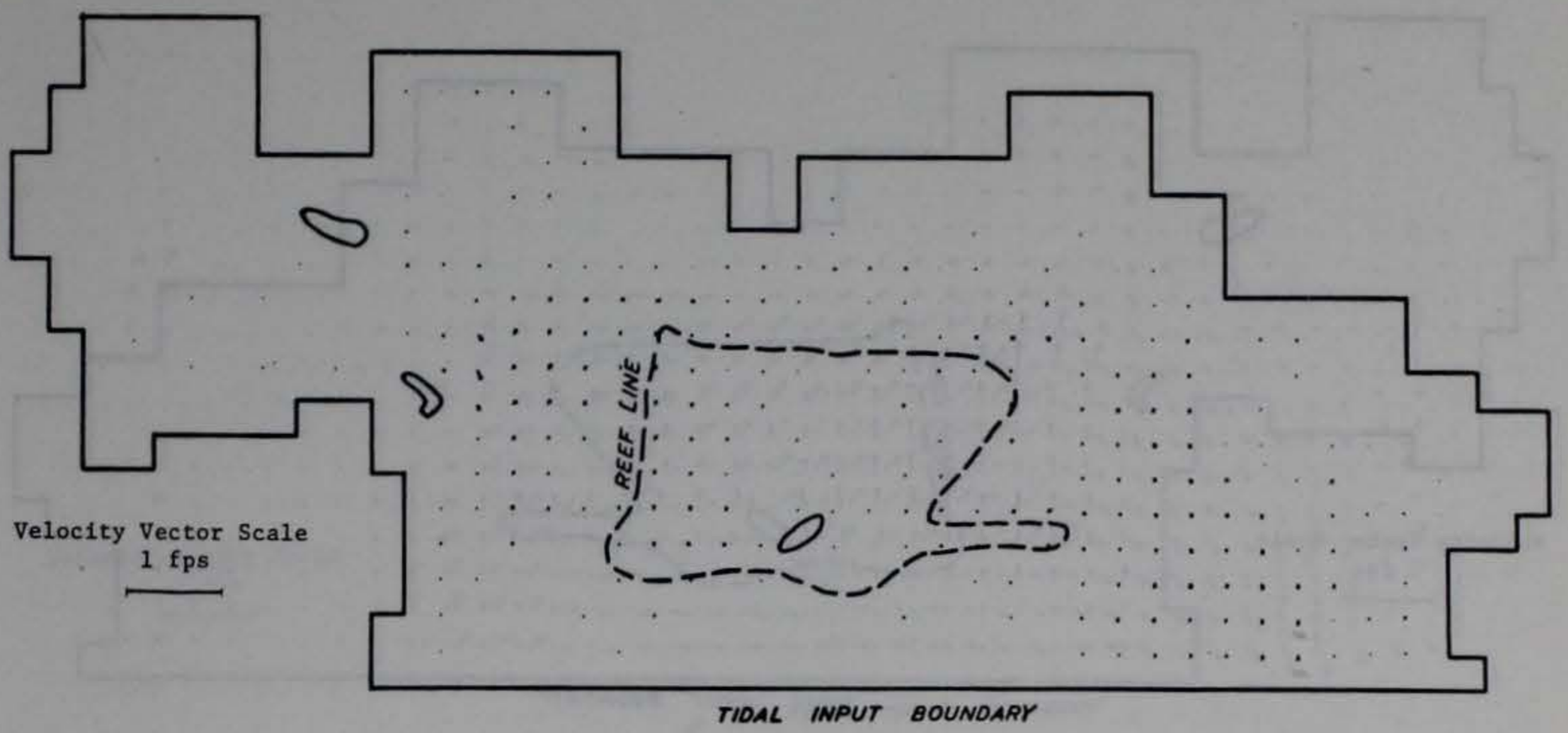

Figure A19. Numerical model current patterns at hour 20.0 with no wind

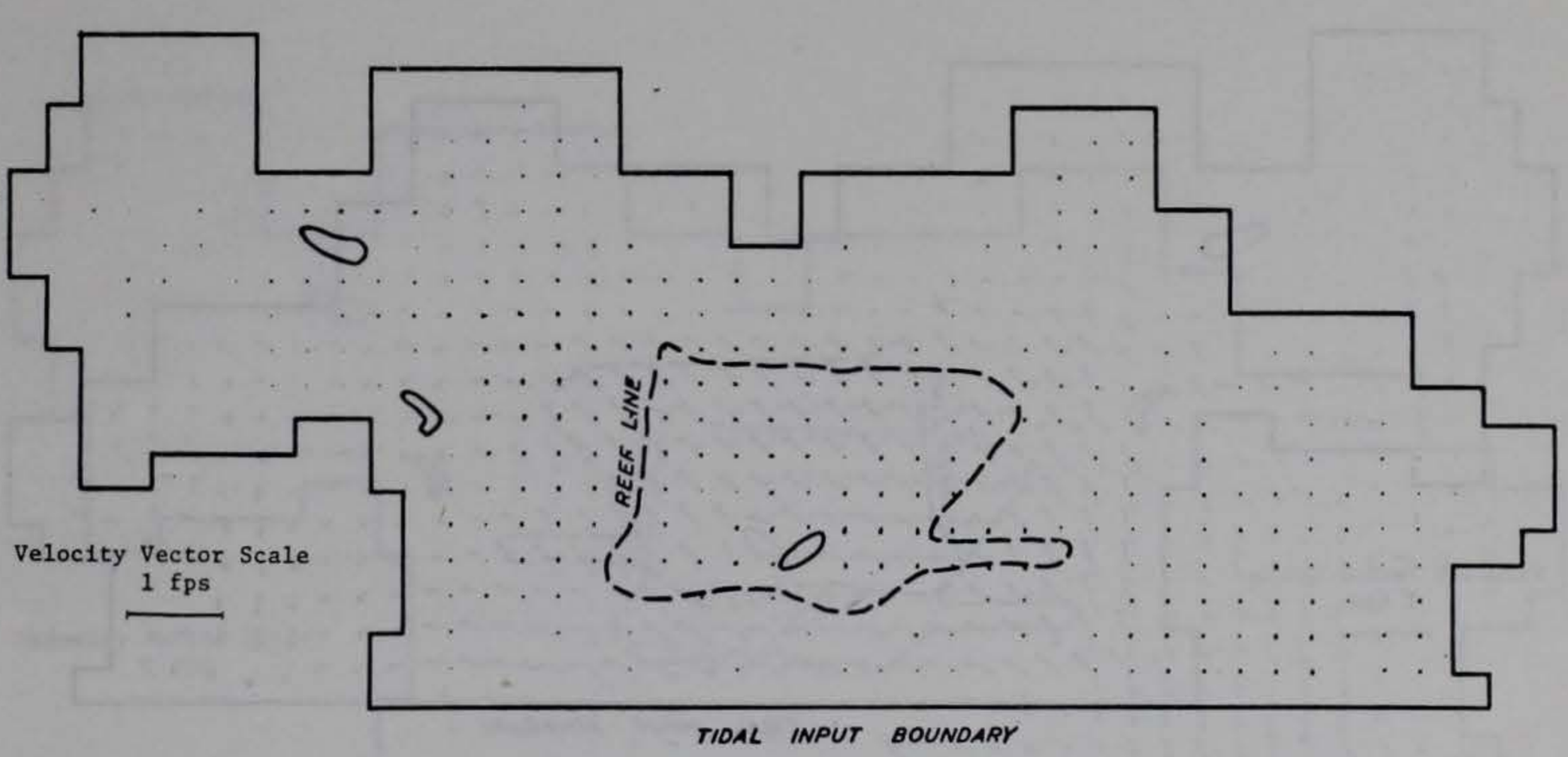

Figure A20. Numerical model current patterns at hour 21.25 with no wind

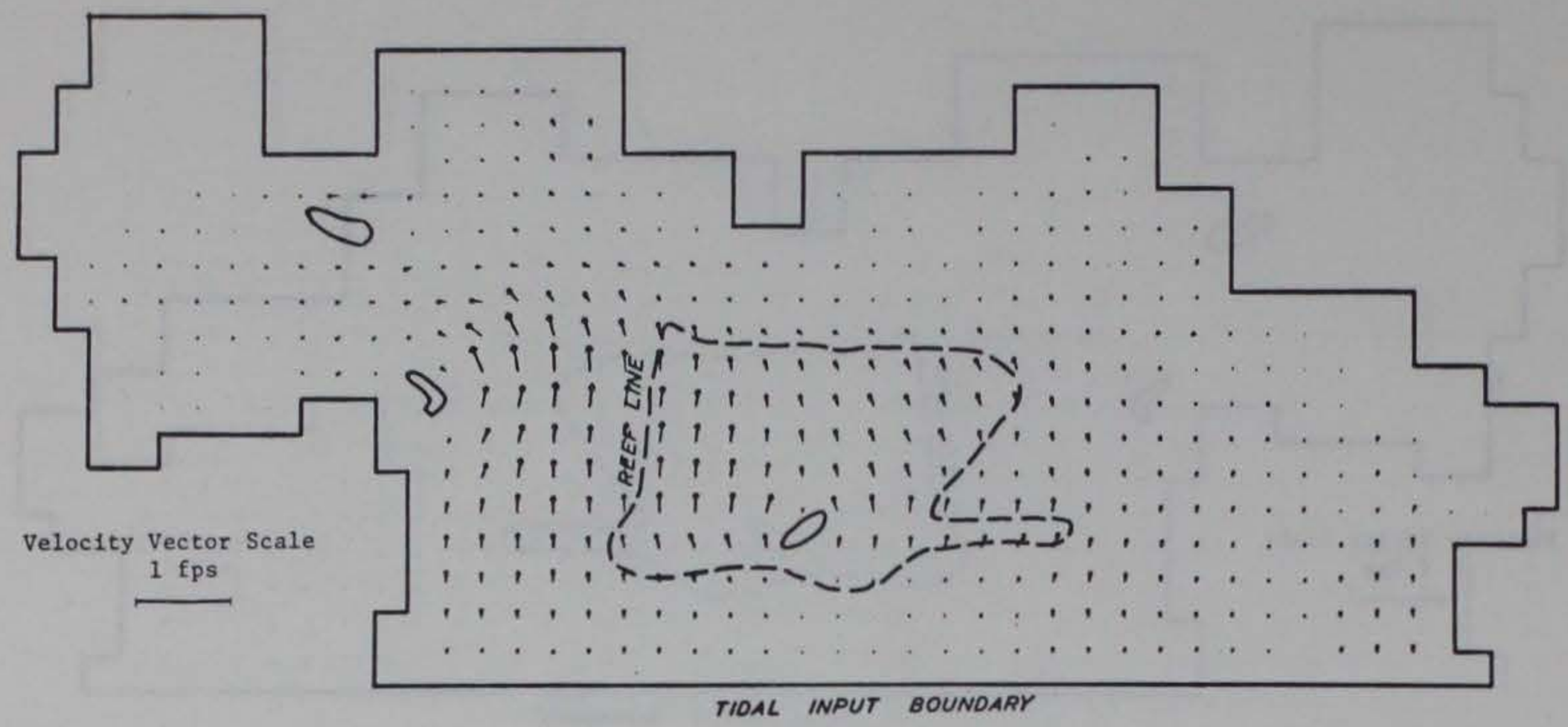

Figure A21. Numerical model current patterns at hour 22.5 with no wind

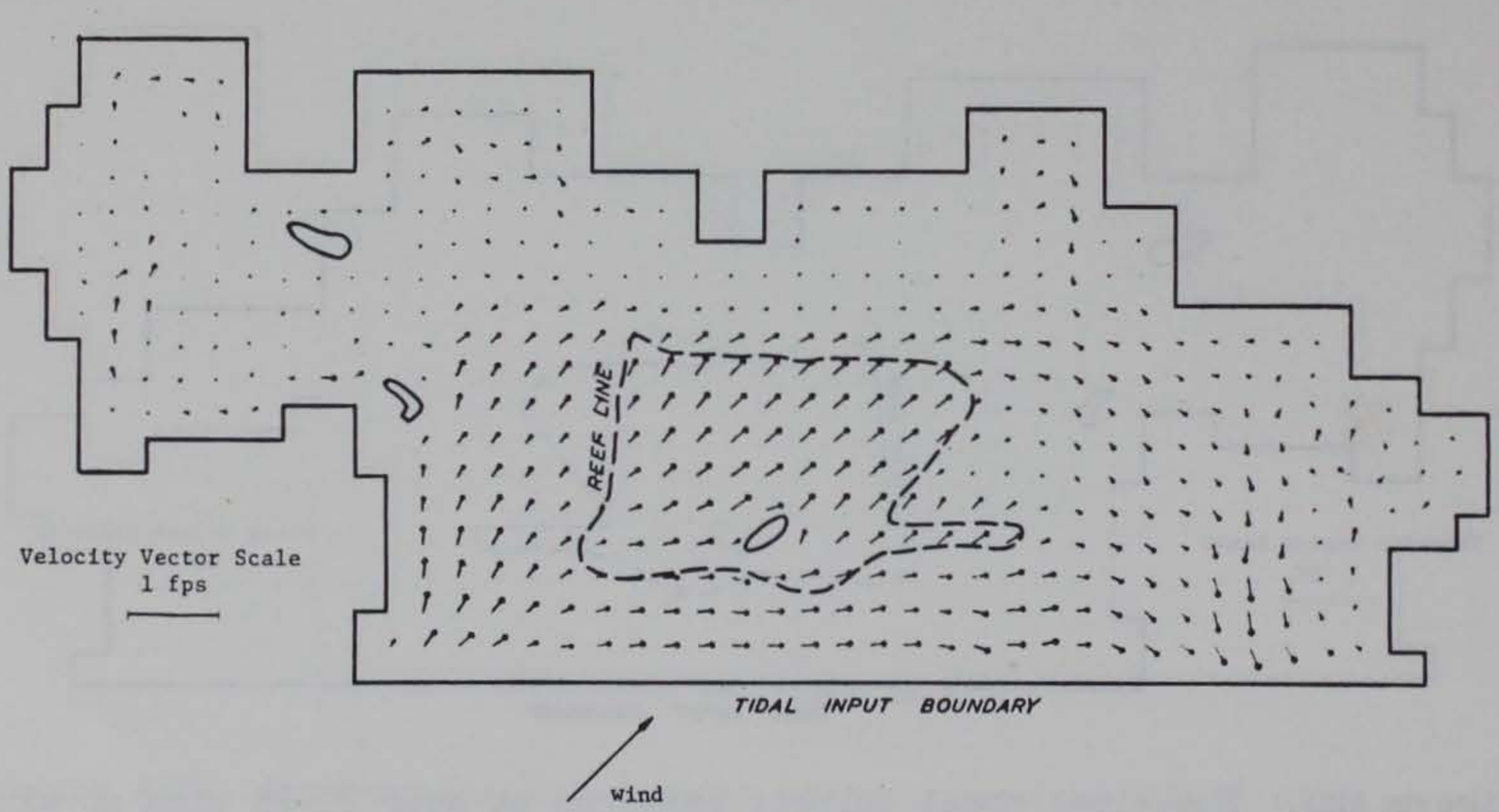

Figure A22. Numerical model current patterns at hour 0.0 with 15-mph wind at 90 deg

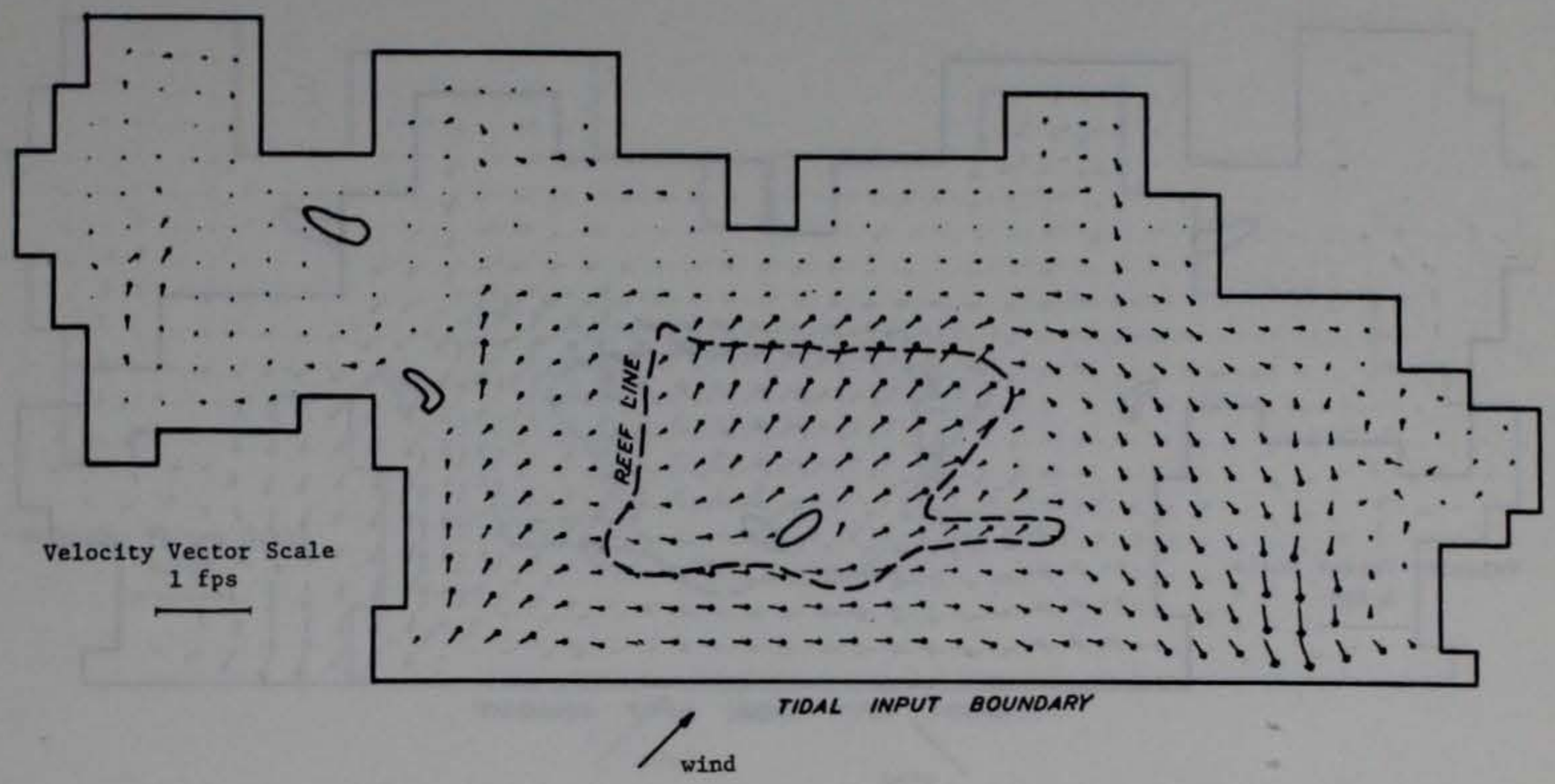

Figure A23. Numerical model current patterns at hour 1.25 with 15-mph wind at 90 deg

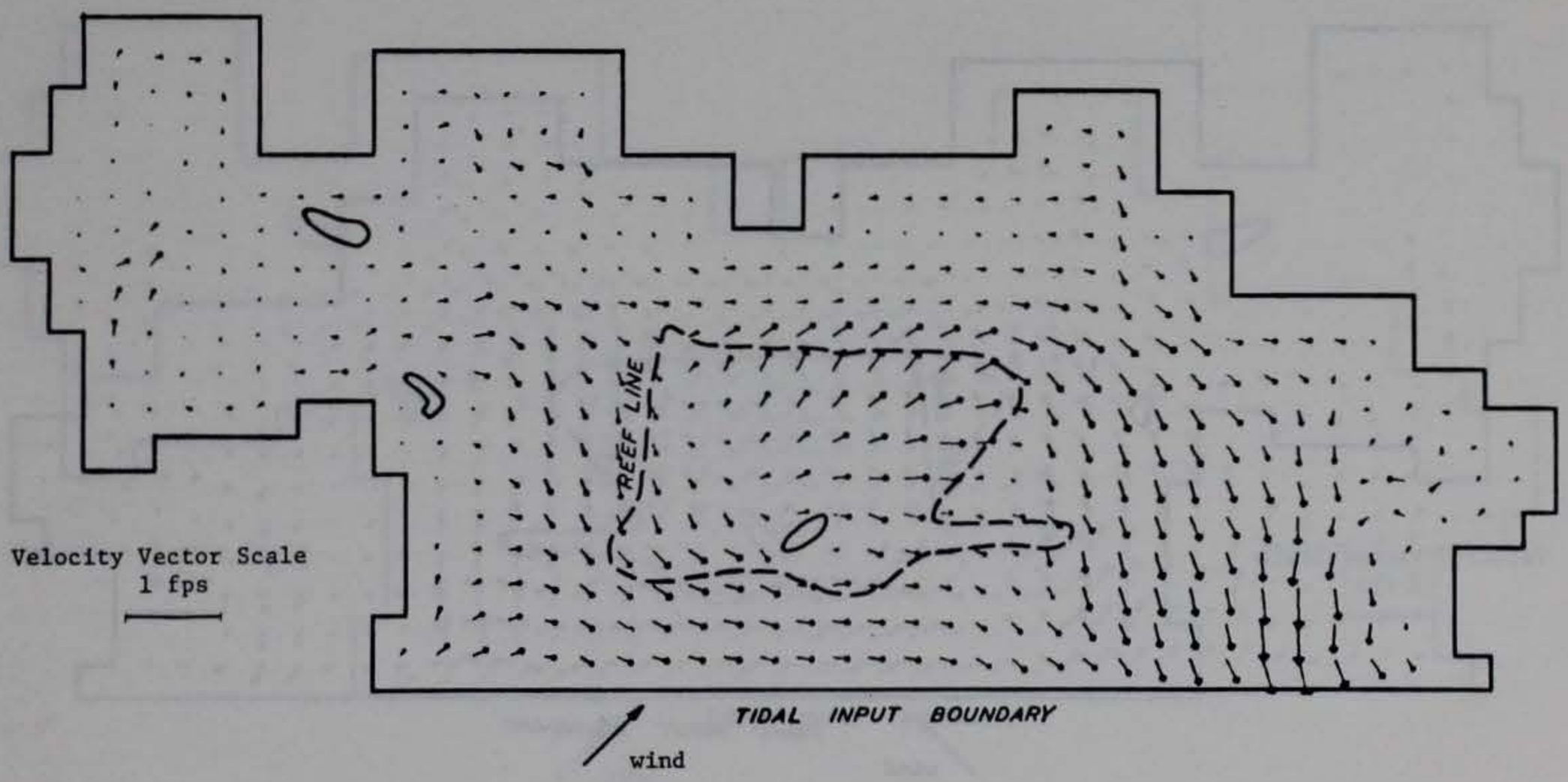

Figure A24. Numerical model current patterns at hour 2.50 with 15-mph wind at 90 deg

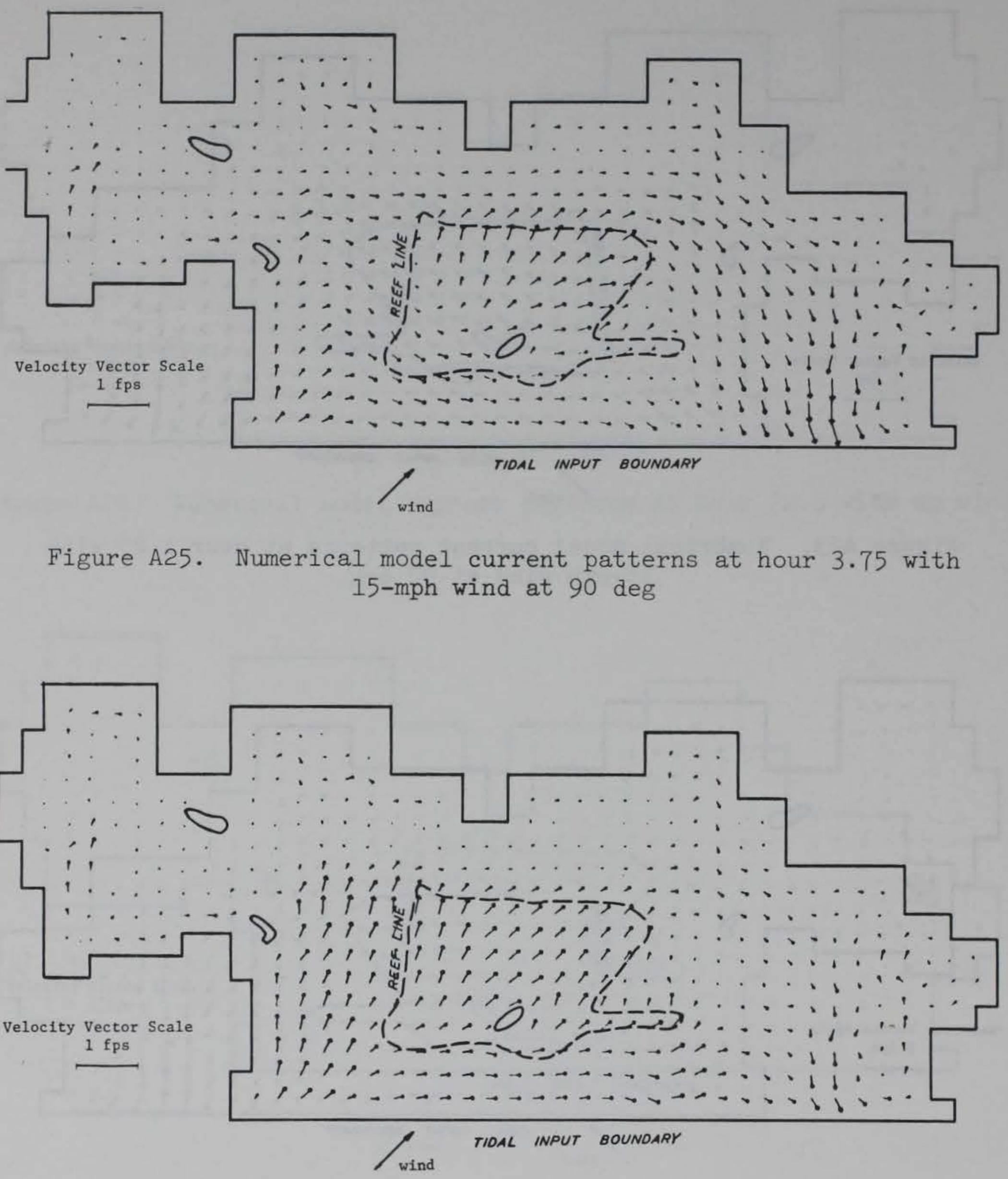

Figure A25. Numerical model current patterns at hour 3.75 with 15-mph wind at 90 deg

Figure A26. Numerical model current patterns at hour 5.0 with 15-mph wind at 90 deg

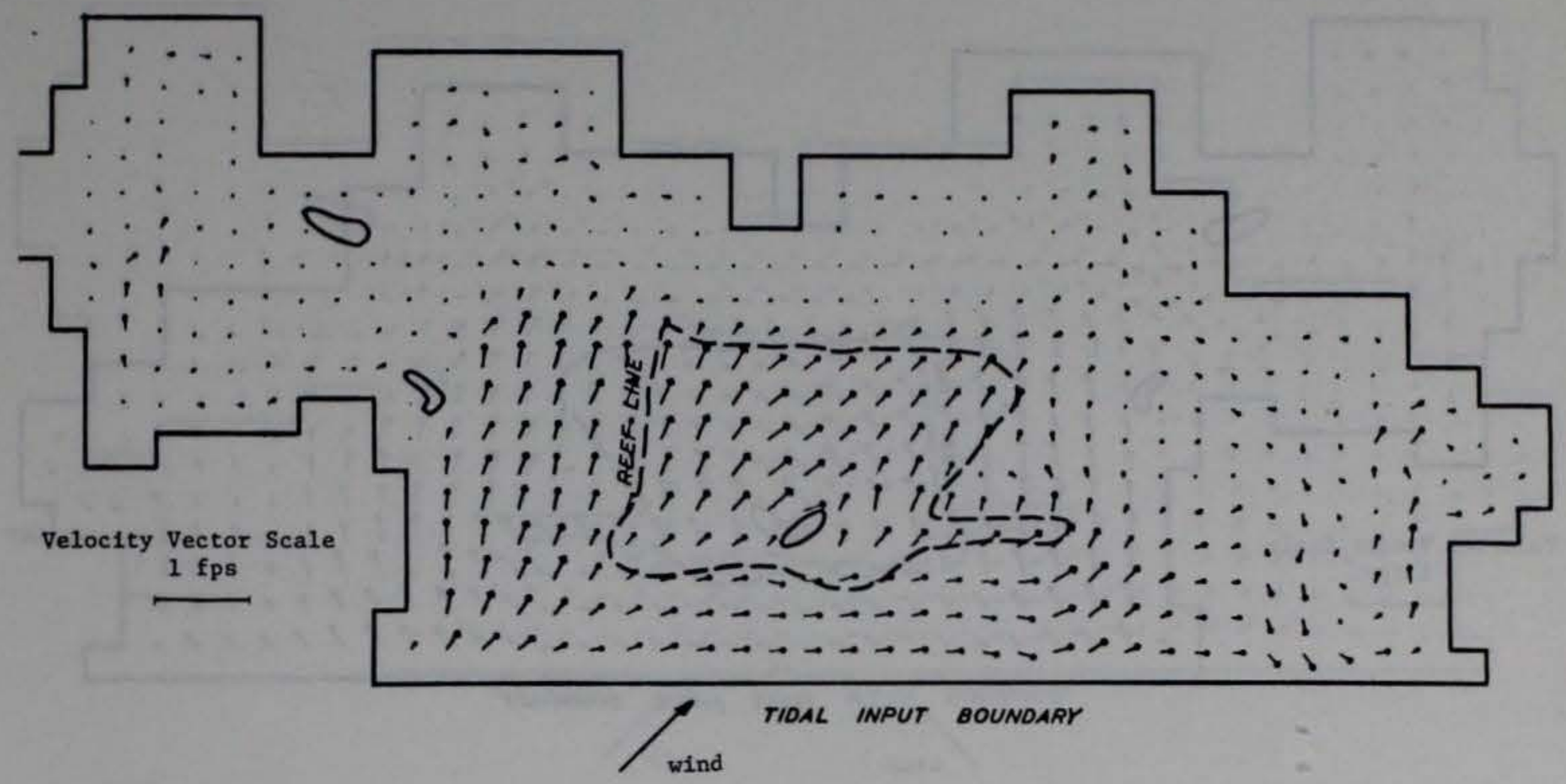

Figure A27. Numerical model current patterns at hour 6.25 with 15-mph wind at 90 deg

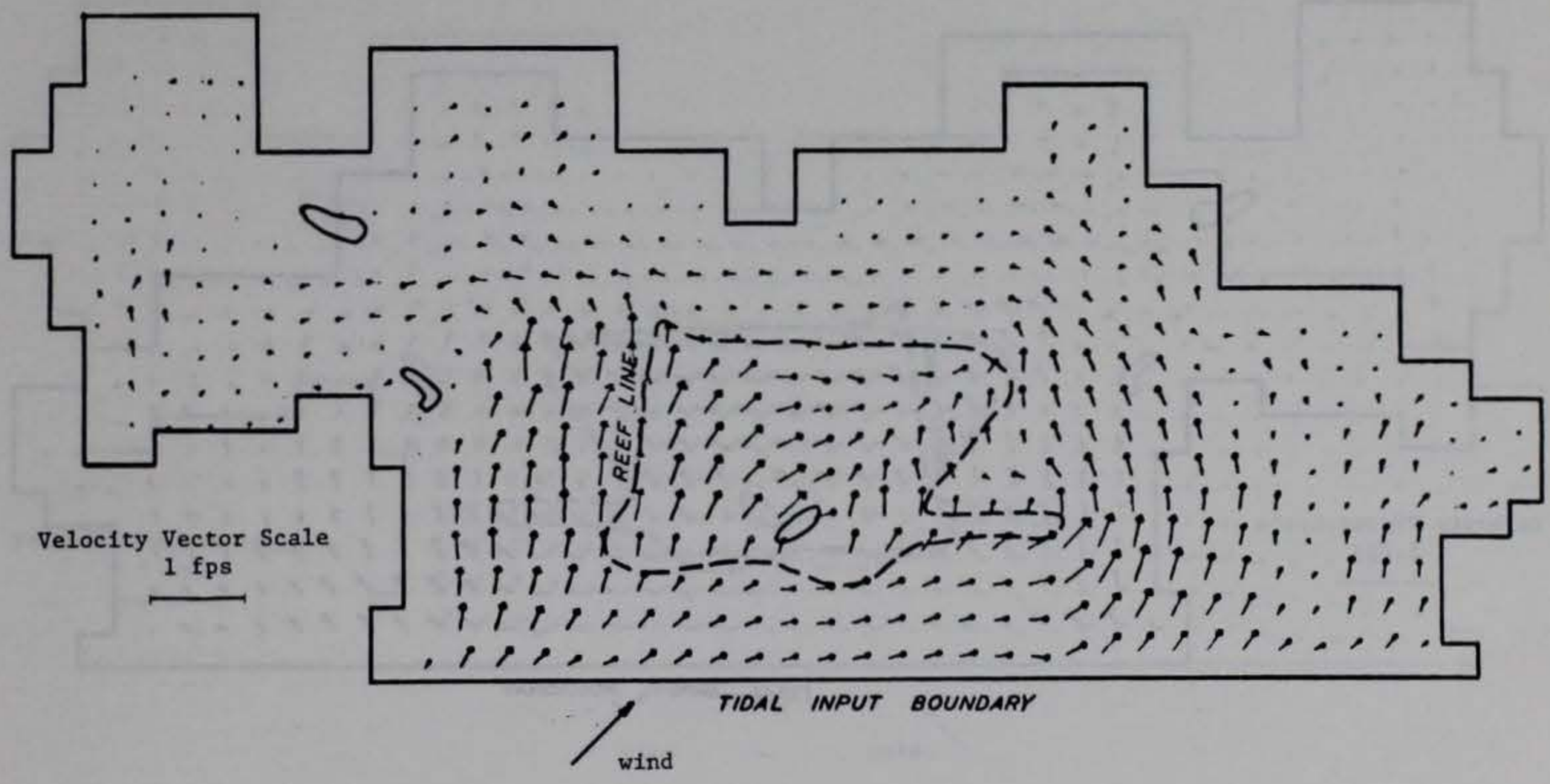

Figure A28. Numerical model current patterns at hour 7.5 with 15-mph wind at 90 deg

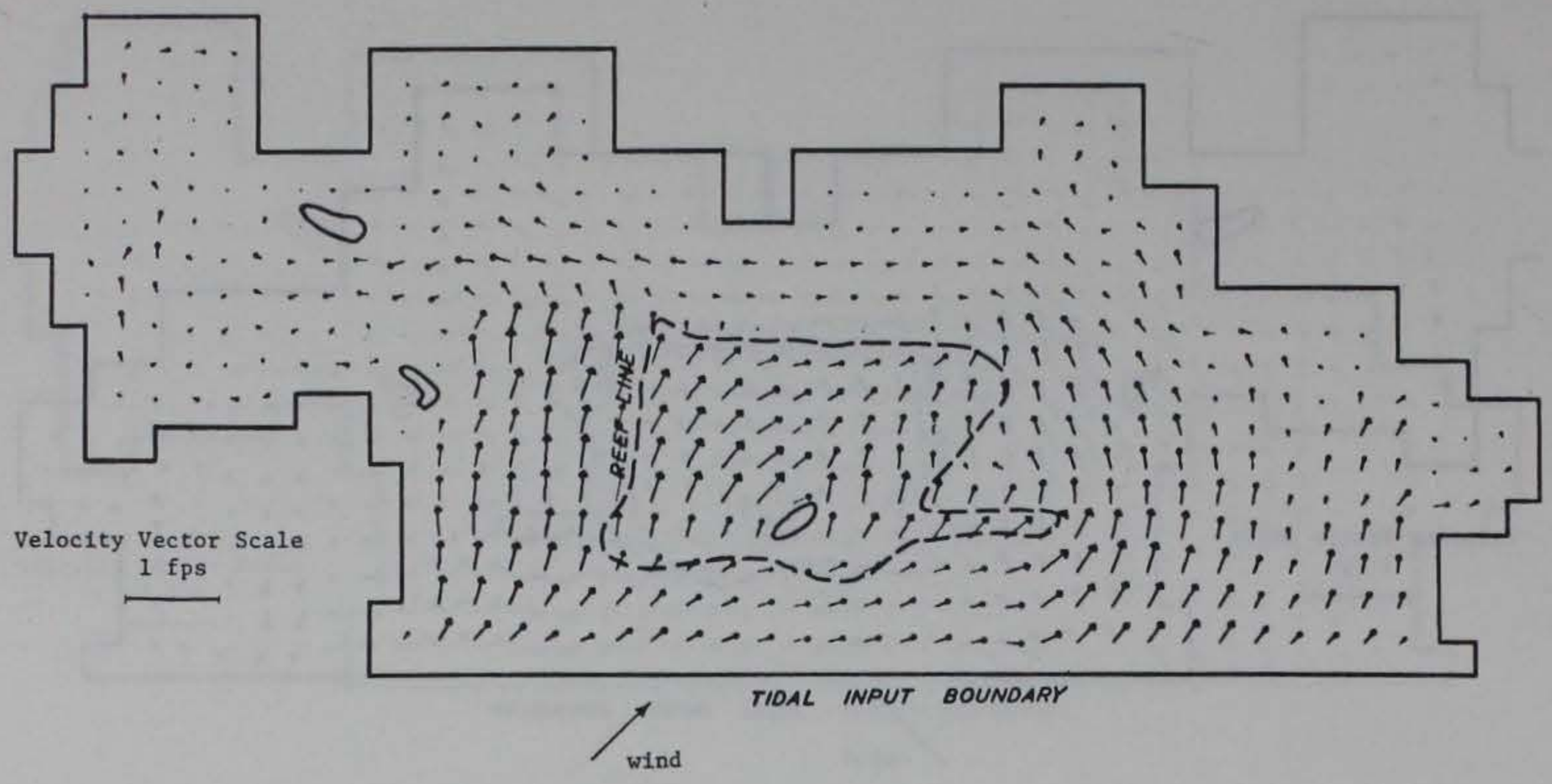

Figure A29. Numerical model current patterns at hour 8.75 with 15-mph wind at 90 deg

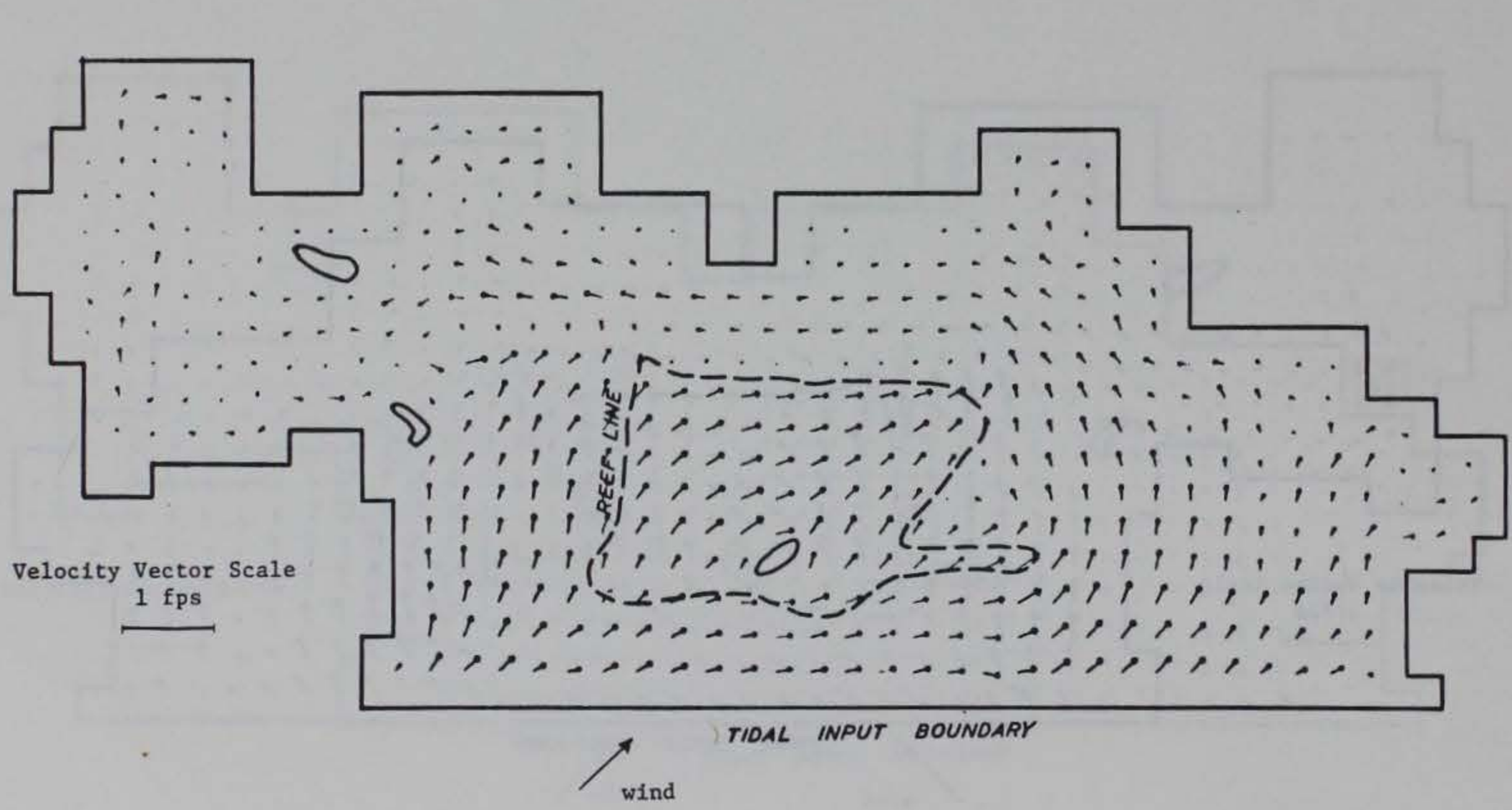

Figure A30. Numerical model current patterns at hour 10.0 with 15-mph wind at 90 deg

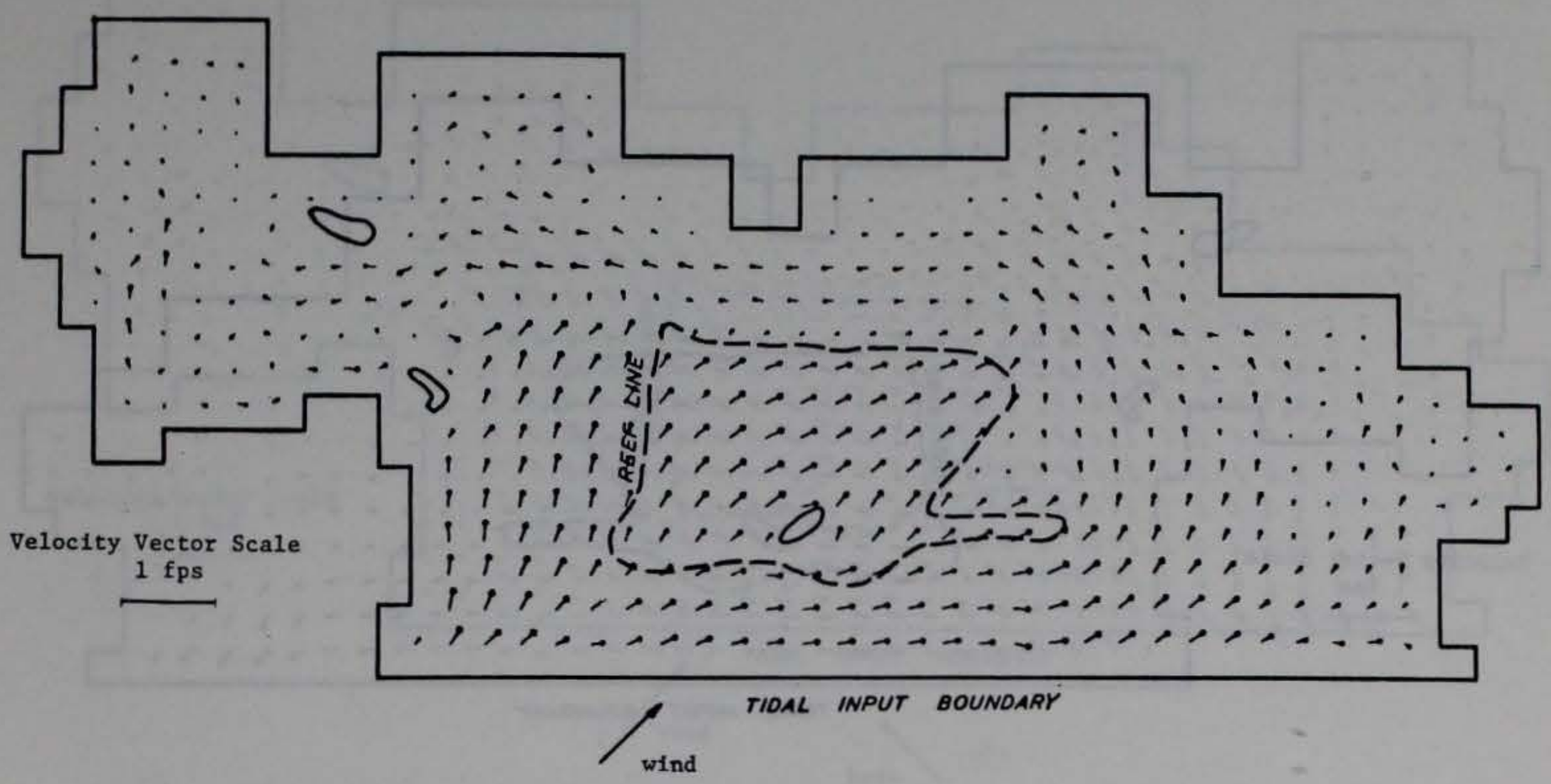

Figure A31. Numerical model current patterns at hour 11.25 with 15-mph wind at 90 deg

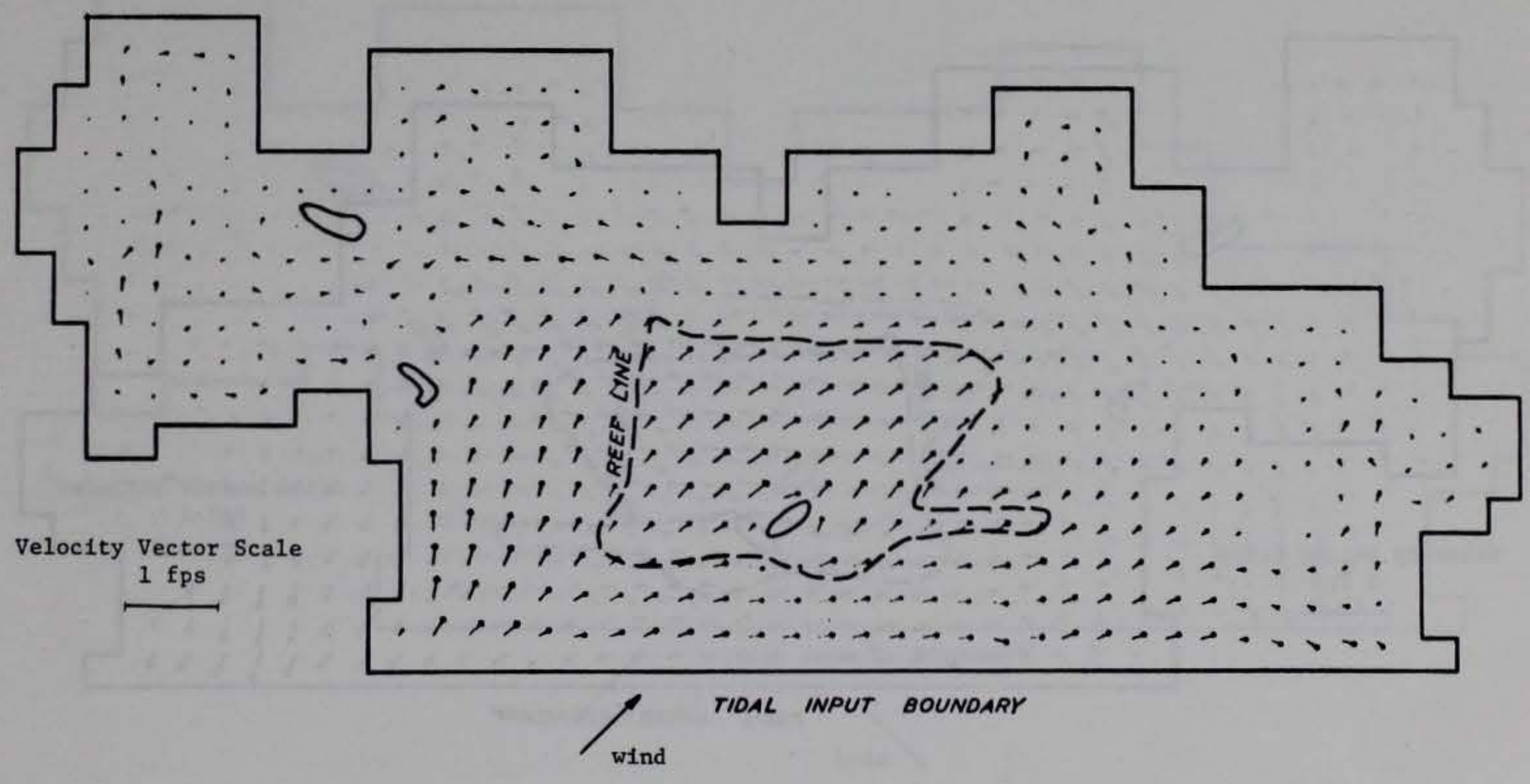

Figure A32. Numerical model current patterns at hour 12.5 with 15-mph wind at 90 deg

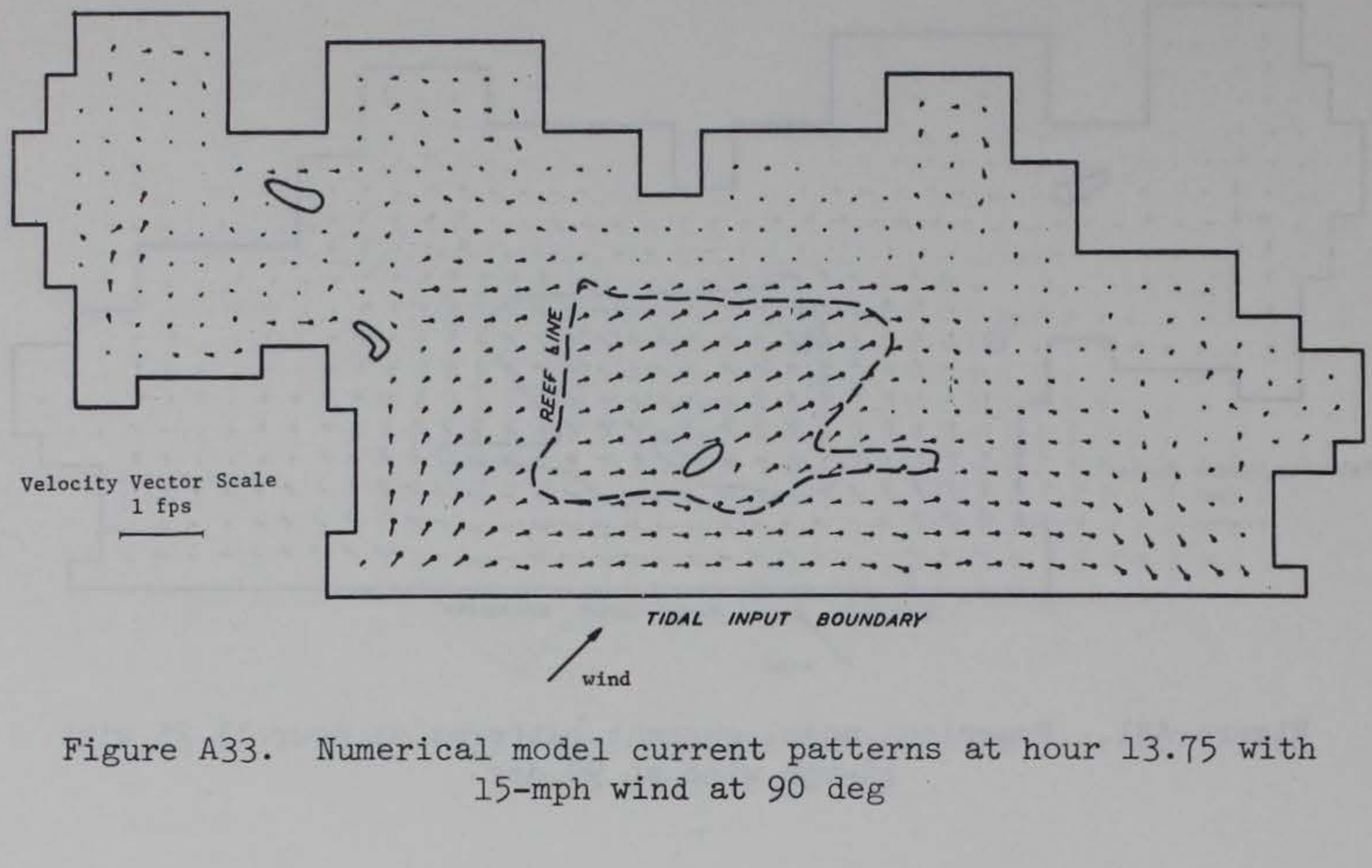

Figure A33. Numerical model current patterns at hour 13.75 with 15-mph wind at 90 deg

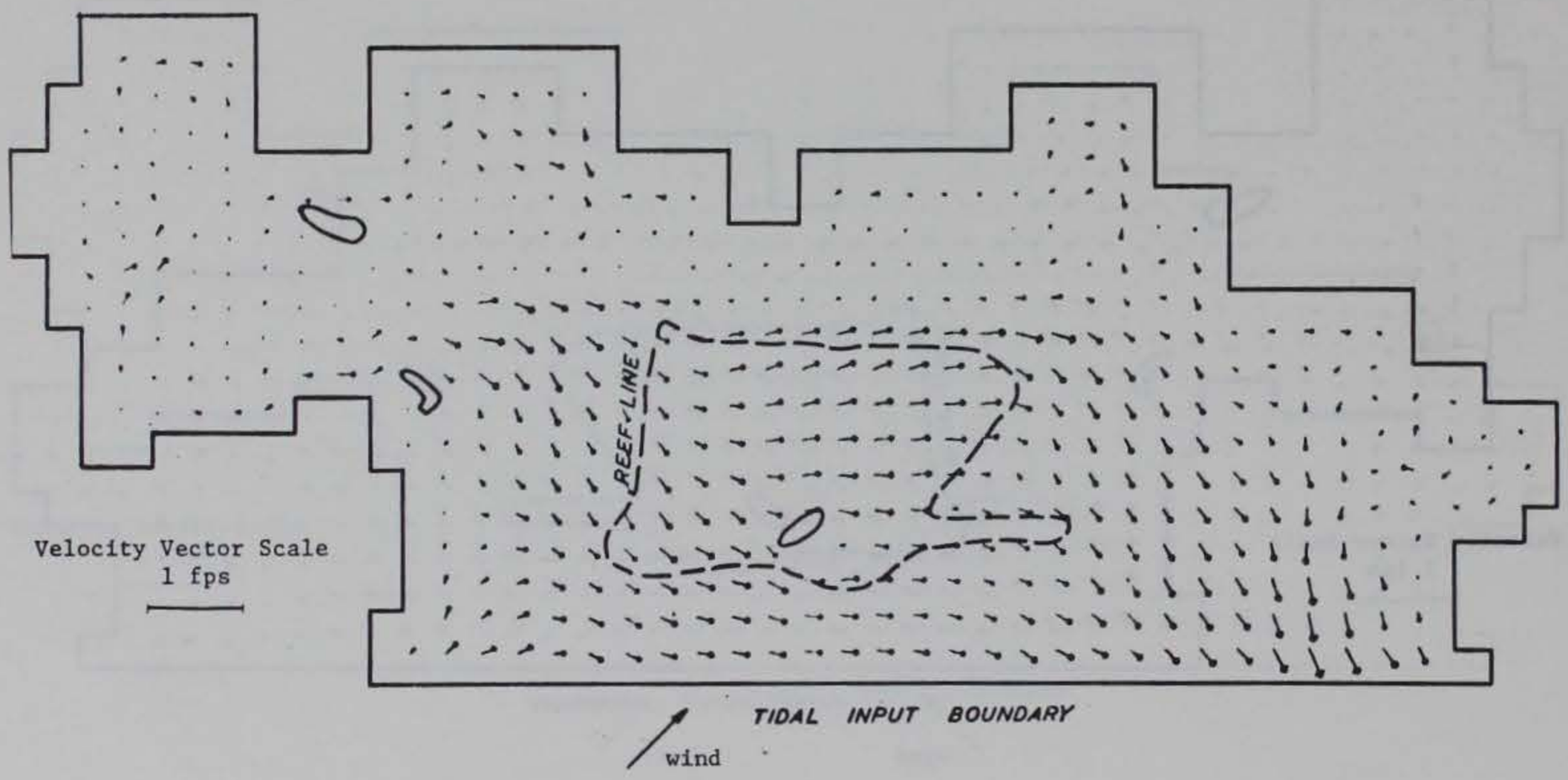

Figure A34. Numerical model current patterns at hour 15.0 with 15-mph wind at 90 deg

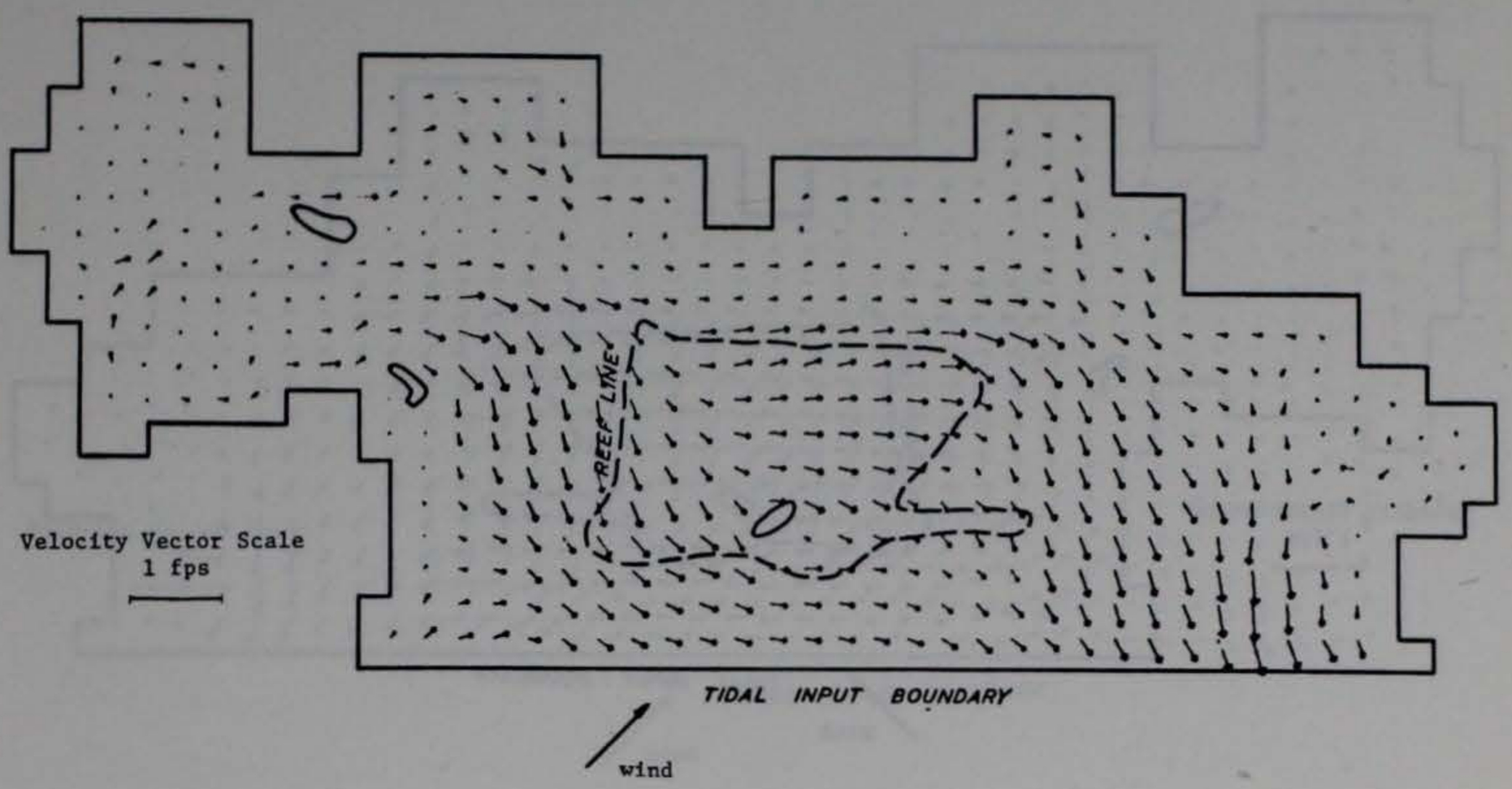

Figure A35. Numerical model current patterns at hour 16.25 with 15-mph wind at 90 deg

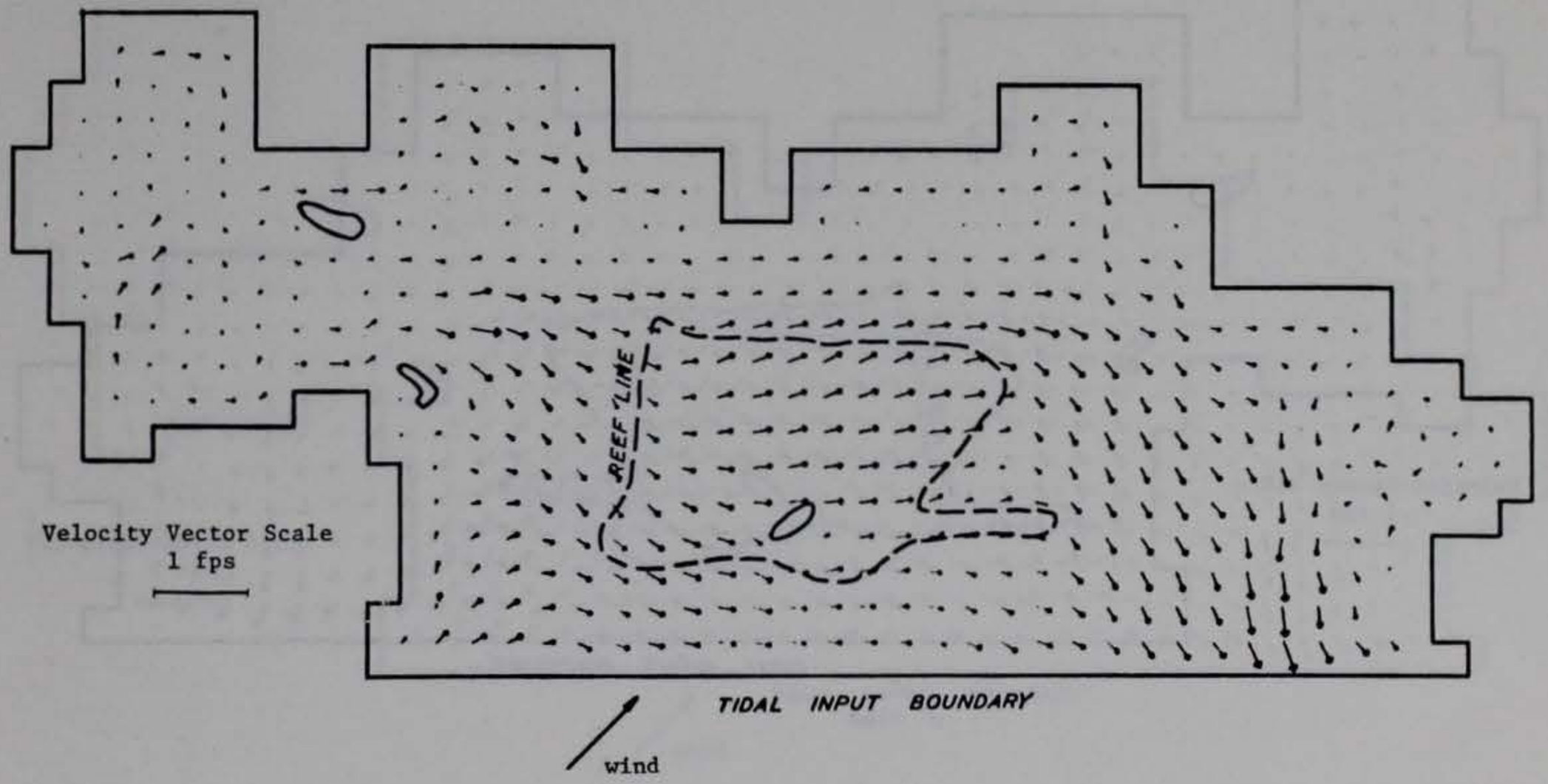

Figure A36. Numerical model current patterns at hour 17.5 with 15-mph wind at 90 deg

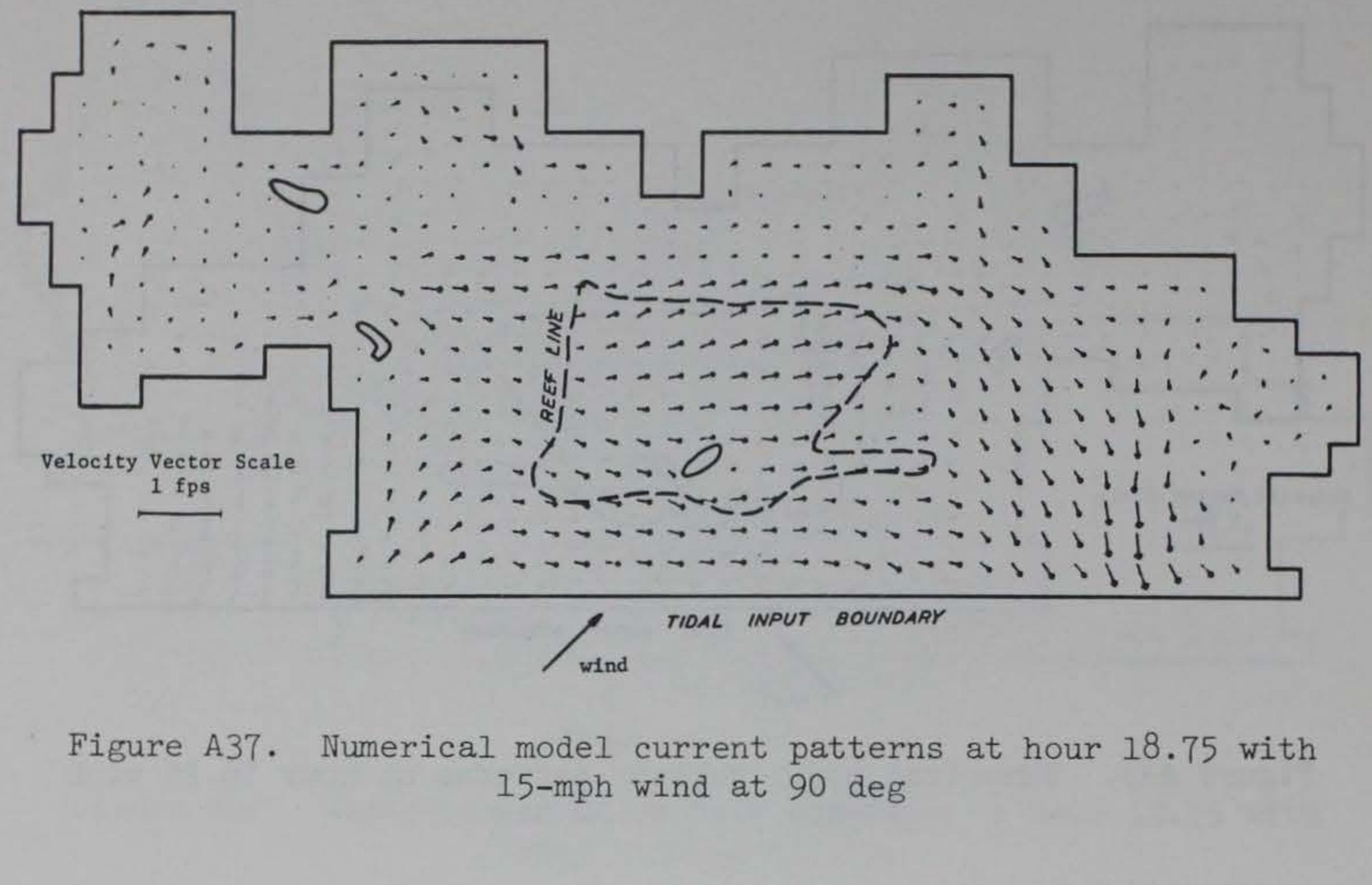

Figure A37. Numerical model current patterns at hour 18.75 with 15-mph wind at 90 deg

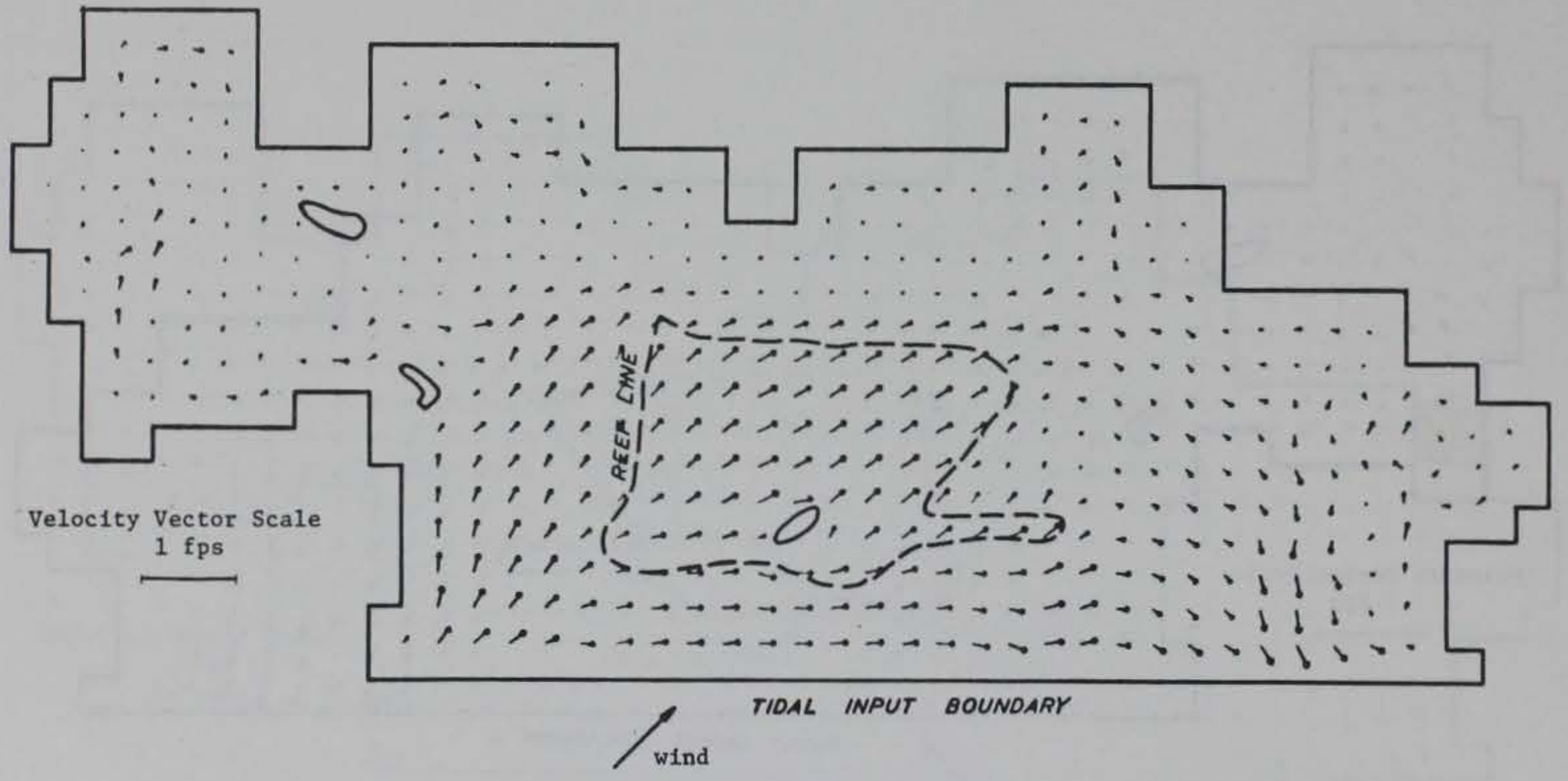

Figure A38. Numerical model current patterns at hour 20.0 with 15-mph wind at 90 deg

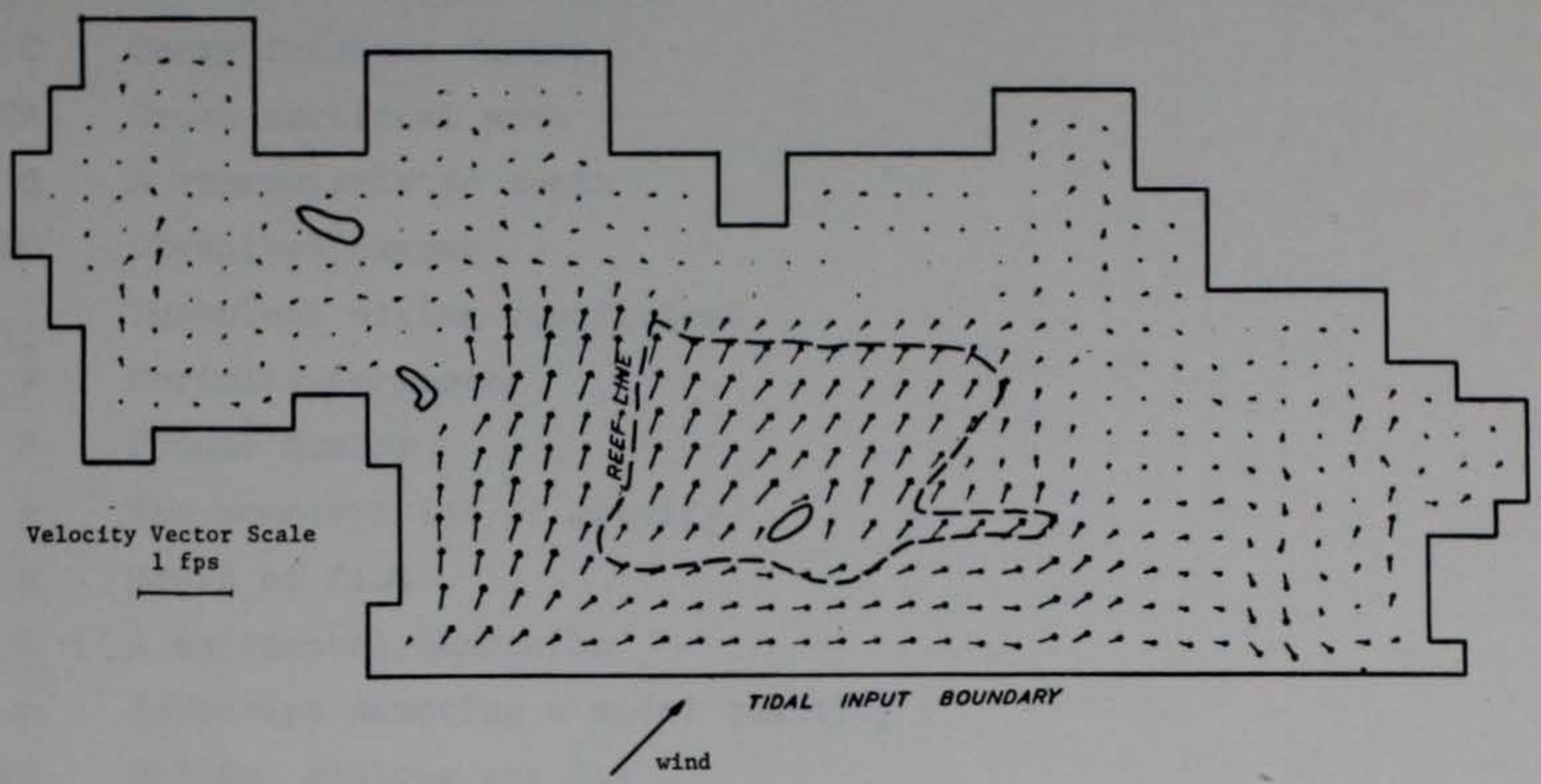

Figure A39. Numerical model current patterns at hour 21.25 with 15-mph wind at 90 deg

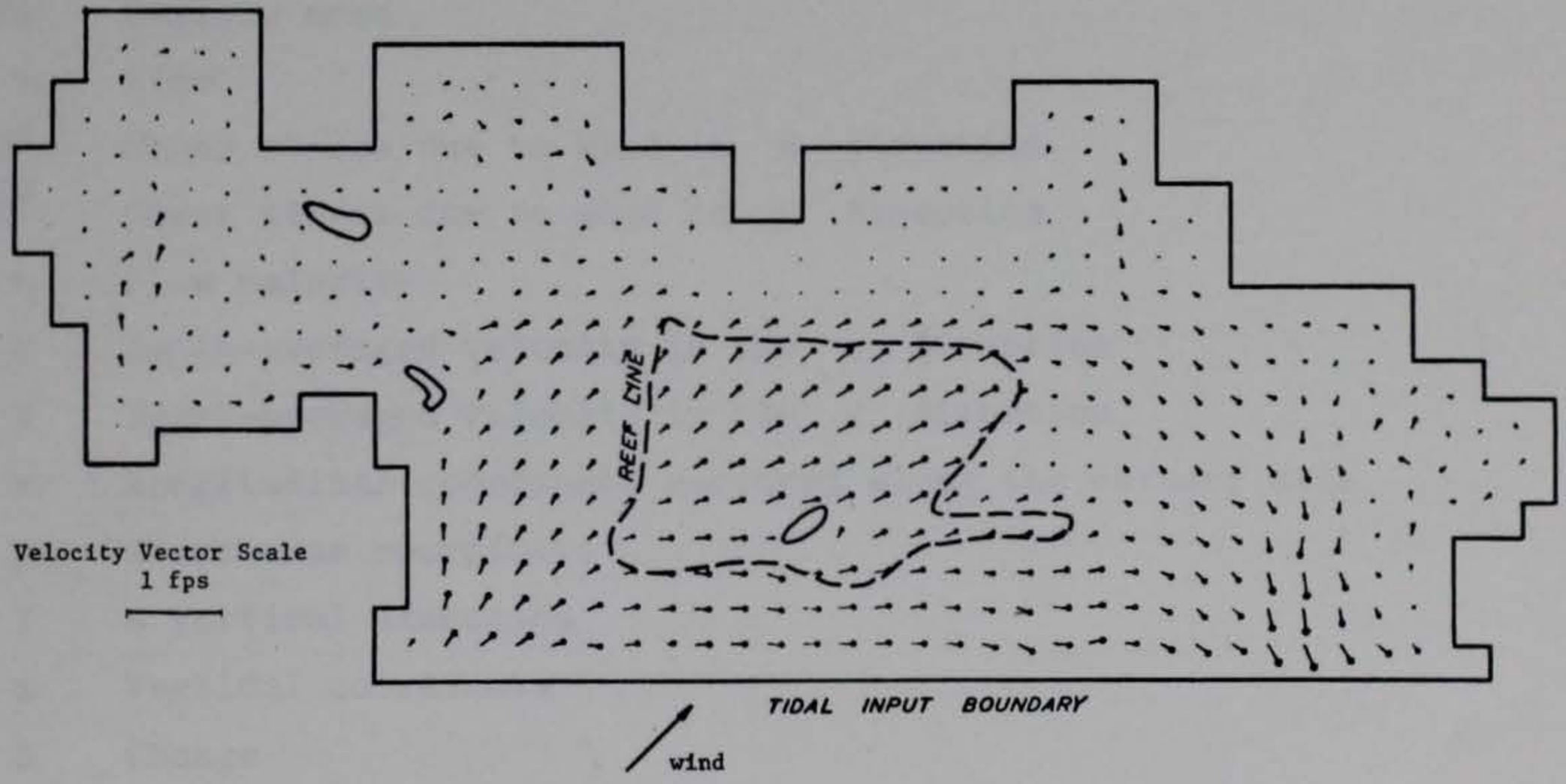

Figure A40. Numerical model current patterns at hour 22.5 with 15-mph wind at 90 deg

APPENDIX B: NOTATION

BOD	Biological oxygen demand
C	Chezy friction factor
CA	Cross-sectional area
d	A characteristic depth
DO	Dissolved oxygen
E_{ij}	Turbulent mixing coefficient
f	Coriolis parameter
F	Froude number
g	The acceleration of gravity
h	Depth of flow
L	A horizontal dimension
m	Subscript denoting a model quantity
mgd	Million gallons per day
p	Subscript denoting a prototype quantity
Q	Discharge
r	Denotes a model to prototype ratio of the subscripted parameter
SA	Surface area
t	Time
T^x	Shear stress due to wind in x direction
T^y	Shear stress due to wind in y direction
u	Flow velocity
U	Depth-averaged velocity in the x direction
V	Depth-averaged velocity in the y direction
x	Longitudinal coordinate measured along the estuary axis
y	Transverse coordinate
Y	A vertical dimension
z	Vertical coordinate
Δ	Change
λ	Wave length
ρ	Density of water
+	Increase
-	Decrease