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CALIFORNIA COASTAL PROCESSES STUDY - LANDSAT II
FINAL REPORT
LANDSAT INVESTIGATION #22200

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April 1977

Final Report

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

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16. ABSTRACT

This study reports on the continued use of Landsat data in the analysis and description of long and short-term littoral and nearshore processes along the California coast. The effects of these processes on natural and modified shorelines and the capability to demonstrate the utility of Landsat derived information are important considerations of U.S. Army Corps of Engineers in coastal protection, coastal zone management and engineering planning. The processes studied include sediment transport, river discharge, nearshore currents, and estuarine flushing. Landsat data as well as aerial photography and surface data covering a four year period were analyzed to determine the variability of coastal processes.

The specific objectives of this investigation included the determination of sediment transport parameters measureable in the Landsat data and application of this information to everyday coastal planning and construction.

By using suspended sediments as tracers, other specific objectives were met by the qualitative definition of the nearshore circulation along the entire coast of California with special study sites at Humboldt Bay, the mouth of the Russian River, San Francisco Bay, Monterey Bay, and the Santa Barbara Channel. Although Landsat primarily imaged fines and silts in the surface waters, the distribution of sediments allowed an examination of upwelling, convergences, and coastal erosion and deposition. In Monterey Bay and Humboldt Bay these coastal phenomena were used to trace seasonal trends in surface currents. These charts may now be used as a source of basic trends and current patterns in establishing detailed surveys. Coastal managers may utilize these charts as a data source for planning locations of outfall structures or other coastal construction projects.

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PREFACE

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1.0 INTRODUCTION AND SUMMARY

The overall objective of the investigation was to continue using Landsat data to analyze and describe long and short term littoral and nearshore processes along the California coast. The effects of these processes on natural and modified shorelines and the capability to demonstrate the utility of Landsat derived information are important considerations of the U.S. Army Corps of Engineers. Areas of prime interest include the applicability of Landsat derived information to coastal protection, coastal zone management and engineering planning. The processes studied included sediment transport, river discharge, nearshore currents, and estuarine flushing.

Landsat data as well as aerial photography and surface data, covering a four year period were analyzed to determine the variability of coastal processes. By using suspended sediments as tracers of surface dynamics, the specific objectives of the study were met. The first objective was to determine the sediment transport parameters measureable in the Landsat data and apply this information to everyday coastal planning and construction. It was possible to detect details of surface patterns by both manual and computer enhancement techniques. Figure 1-1 is an image of the northern California coast in which the density levels that encompass the suspended sediment were stretched to allow the investigator to make a detailed interpretation. This and other image processing techniques were applied to the Russian River Comprehensive Study, the Salinas Basin - Monterey Bay Metropolitan Area Urban Study Program, the San Francisco Bay Dredge Disposal Study, the Humboldt Harbor and Bay Study and the Channel Island Harbor Data Collection Study.

The Russian River information derived from satellite and aircraft imagery is now part of the data available to the water resource managers and will be used to help to define dam release volumes necessary to maintain river fish environments at an optimum level as well as to maintain the recreational and water resource potentials of the Russian River. Although Landsat primarily imaged fines and silts in the surface waters, the distribution of sediments allowed an examination of upwelling, convergences, coastal erosion, and other coastal engineering concerns. In Monterey Bay these coastal phenomena were used to trace seasonal trends in surface currents; and, although reconnaisance in nature, the current charts are available to oceanographers and coastal engineers. These charts may be used as a source of basic trends and current patterns to be used in establishing detailed surveys. Coastal managers may utilize these charts as a data source for planning locations of outfall structures or other coastal construction projects.

Figure 1-1 Computer Processed - Northern California Coast

This image of the Cape Mendocino area was density stretched to enhance the many subtle patterns in the ocean resulting from the heavy river discharge. The program for this process is termed ASTRETCH and the digital numbers on the tape were stretches from 0-40, 3 times (3X) to 0-120. The digital numbers on the tape represent data values that are linear with brightness and range 0 to 127. Coastal process features are represented by only a small portion of this range (about 25) so this computer enhanced image allows for a much more accurate interpretation. NASA/Landsat 1977-18103-5

At Humboldt Bay a comprehensive oceanographic survey has recently taken place as part of a plan to locate a sewage discharge diffuser offshore. All of the present reports for the area indicate a lack of detailed information on the dynamics of the offshore ocean. The Landsat imagery for the last four years presents the basic trends of the coastal processes. From this information seasonal and yearly changes in the transitory coastal currents are detectable. Numerous exceptions to the predicted current patterns were noted. This information is being utilized in the modeling of the expected transport of the planned sewage plume outside of Humboldt Bay. In the San Francisco estuary the same interpretation techniques were used but the results were combined with the ongoing dredge disposal study which provided sea truth data. The area of San Francisco Bay which was investigated was San Pablo Bay or northern San Francisco Bay. This is where the Sacramento, San Joaquin Rivers discharge into the bay. It is also the location of Mare Island Naval Base, numerous private terminals and marinas plus the channel to Carquinez Strait, Suisun Bay and Sacramento. The material from dredging operations in the area was marked, discharged and monitored for distribution. Correlation with the Landsat imagery from the same time period was investigated. Although a high degree of correlation was not always reached because of differences in the data sampling operations and the Landsat overpasses, it was possible to chart sediment transport and distribution patterns. The possibility exists for using the techniques developed with a precise sampling/ Landsat overpass correlation.

The overall sediment transport along the California coast, as detected in the Landsat imagery (Figure 1-2) was used to map the seasonal current periods. Since four years of imagery are now available, the results are much more detailed than during the Landsat I investigation. In general the current seasons may be divided into the Oceanic Current Period (July - November), the Davidson Current Period (November - February), and the Upwelling Current Period (February - July).

One location along the coast, Santa Barbara Channel, was investigated in detail utilizing not only Landsat, but also aircraft and shipboard collected data. Complex surface current patterns were present which changed dramatically with the current seasons. Lenses of sediments in surface waters were discovered during oceanographic data collection traverses across the channel. The Landsat imagery provided an unparalleled means of detecting the source material for such lensing. The ramification of this ability for monitoring oil spills, effluents, pollutants, etc., presents a valuable use of Landsat imagery.

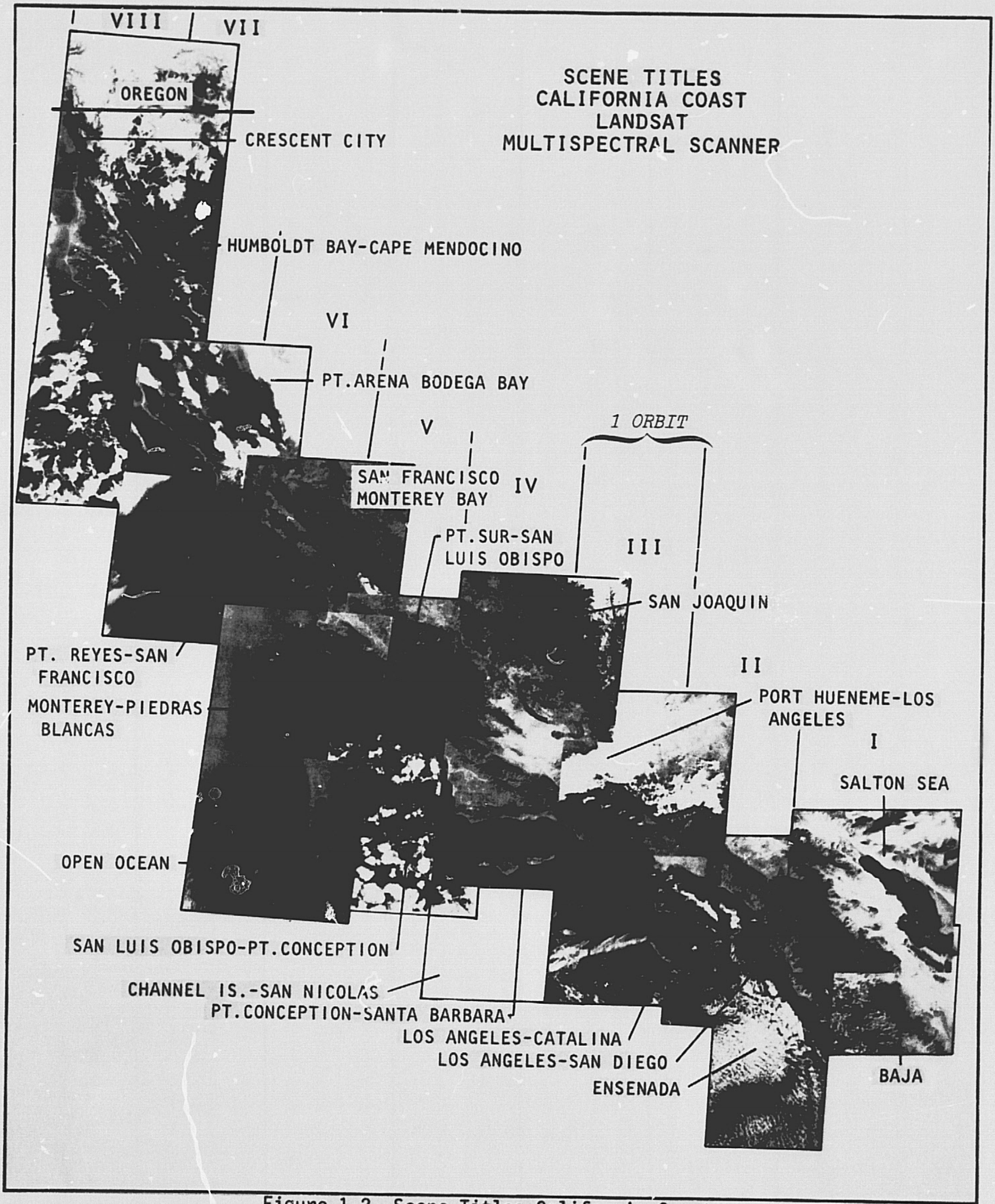

Figure 1-2 Scene Titles California Coast

2.0 CALIFORNIA NEARSHORE SURFACE CURRENTS

This section presents a discussion of nearshore California surface currents and techniques utilized in the application of remotely sensed data to the charting of the coastal current seasons of California.

The imagery analyzed in this study came from the Landsat I and II (formerly called ERTS) satellites of late 1972 through mid-1976, NASA Ames U-2 flights of 1972 through 1975, as well as NASA's Johnson Space Center (JSC) aircraft flights of 1969 through early 1974. These data sources, in addition to Army sources, provided unique views of the coastal currents spread over the three current seasons. High altitude and satellite imagery produced extremely complete, near synopic and clear images of the oceans's surface and revealed large scale phenomena and relationships that often cannot be seen from a low altitude - below 5,000 meters, (16,400 feet) or from a surface perspective. Coastal engineers and oceanographers may now trace the primary coastal current systems along the California coastline since suitable data are now available to set down, with reasonable confidence, the primary current trends observed during the three California coastal seasons. Thousands of individual image frames were analyzed to extract the bits of current vector directions that have been assembled into generalized seasonal current charts. Figure 2-1 gives the geographical sites noted.

Every year along the coast of California there are the three successive current seasons: Oceanic, Davidson and Upwelling. These nearshore currents are important in connection with various coastal processes and have a strong influence on the industrial, recreational and engineering activities in the coastal zone. During the Oceanic Period from July to November, the southward flowing California Current dominates the nearshore current patterns. Commencing about the middle of November and extending to February, the Davidson Current, a northward moving countercurrent, is the dominant inshore transporter of water and suspensates. The phenomenon of upwelling is prevalent during the period from the middle of February to the end of July.

With the advent of quality films and multispectral imaging systems for both aircraft and satellite, remote sensing techniques have gained widespread acceptance and utilization in coastal processes studies. The Landsat satellites provide repetitive and high resolution multispectral imagery of the earth's surface. With respect to nearshore currents, Landsat permits synoptic, repetitive coverage with acceptable resolution capability for detecting current directions and horizontal distribution, upwellings, current blockages, offshore movements, gyres, and sediment sources (Pirie and Steller, 1974).

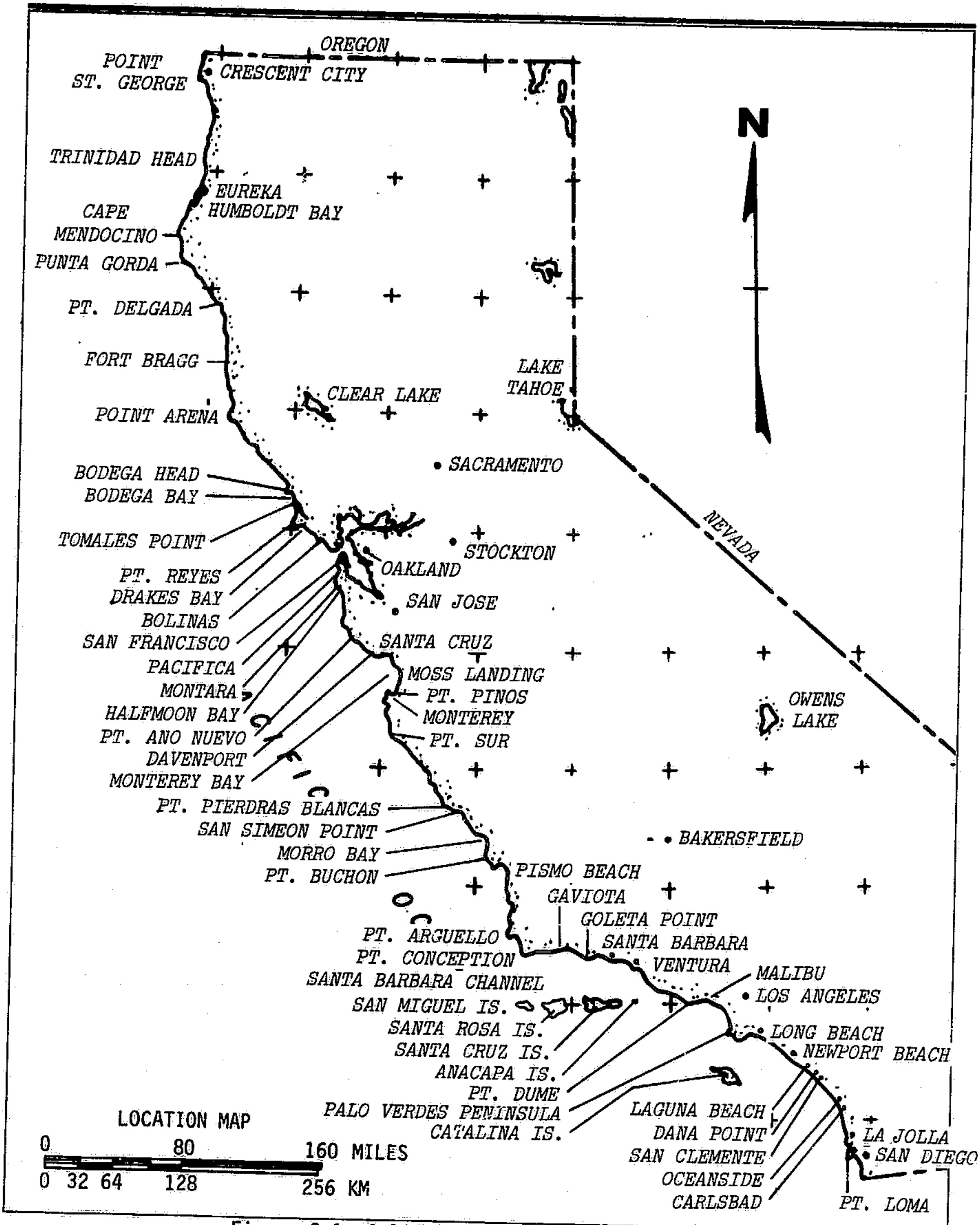

Figure 2-1 California Coast Location Map

Utilization of the 0.5 to 0.65 micrometer band of the electromagnetic spectrum provides the best definition of the California nearshore and offshore currents which carry suspended sediments. The suspensates act as current pattern tracers and originate primarily from riverine discharges, estuarine flushing, and shore erosion. During periods of little or no runoff, especially in southern California, the lack of appreciable quantities of suspended materials makes detection of sea and coastal currents difficult. In order to obtain maximum information from transparencies and computer tapes, enhancement techniques may have been applied to expand density ranges. It is also possible through multi-channel computer processing to enhance water density differences between the various multispectral channels in order to enhance suspended sediment and current features.

2.1 GENERAL OVERVIEW AND RESULTS OF PREVIOUS INVESTIGATIONS

Although a fully integrated picture of all factors influencing the nearshore surface currents along the coast of California has yet to be developed, the most important force imparting motion to the surface waters is the wind. As described by Sverdrup (1942) and others, there is generally a clockwise current circulation in the North Pacific Ocean caused by the strong westerly winds in high latitudes which move the waters eastward and the trade winds farther south which push the waters westward in a return flow. The California Current lies at the eastern, southward-flowing side of this Pacific Ocean circulation pattern. The current flows southeastward between one cell of high atmospheric pressure to the west and another cell of high pressure on the landward east side. Winds over the California Current are generally from the north and west. These winds are strong when the two high pressure cells are close together and intense. Conversely, winds are weak when the cells are farther apart and moderate. Both these cells are weakest in winter. The high to the west moves north in spring and summer as it grows slightly stronger. In the fall it weakens and moves south. The low pressure cell over the land is a semi-permanent feature with a wider range of seasonal variations. Changes in the strength and location of the cells cause seasonal changes in the winds along the California coast. From spring to fall the winds mainly have a northerly component and in the winter this northerly component either weakens or reverses.

Other forces which affect the ocean waters are pressure gradients, Coriolis and gravity. They produce geostrophic flow, or gradient currents. Gradient currents are due to the action of gravity flow outward from topographic bulges of water found primarily at the center of surface wind gyres. Differences in the level of the sea produced by lighter density water overlying denser water, especially if there exists a sharp interface between the water bodies, induce slope currents. During the fall and winter months, river discharge quantities, particularly in Northern California, are of sufficient magnitude to cause slope currents.

2.1.1 DESCRIPTION

The California Current system is a part of the general clockwise circulation of the North Pacific Ocean. At high latitudes the waters move eastward under the influence of the "roaring forties" and near the coast of North America, south of the Aleutian Islands, divide into branches. The smaller part turns northward into the Gulf of Alaska, and the larger part turns southeastward to become the California Current. The water which is transported south by the California Current is cooler than the waters farther offshore. This current with a usual speed of less than 0.25 meters (0.82 feet) per second, is modified by upwelling, solar heating, river discharge and exchange with estuaries and embayments as it traverses the shoreline of western North America. As it nears the latitude of 25 degrees north it begins to turn westward and its waters become part of the west-flowing North Equatorial Current. On the inshore side of the current, numerous variations of the circulation occur. A permanent counter-clockwise eddy, the Southern California Countercurrent, is found inside the submerged peninsula that extends southeast from Point Conception and includes Santa Rosa Island, San Nicolas Island and Cortes Bank (Sverdrup and Fleming, 1941).

2.1.2 OCEANIC AND UPWELLING SEASONS

Along the coast of California, winds from the north and northwest prevail during the spring and summer months. The nearshore southward flowing surface waters are turned from their movement along the coast to a direction offshore. Some part of the waters which move offshore are replaced by colder waters from below. This replacement, known as upwelling, is important because of the surfacing of waters rich in nutrients. These nutrients support the abundant and diverse biological activity in the coastal waters.

The period of strongest upwelling differs along various sections of the coast. For San Diego, McEwen (1934) gave the upwelling period as April to September with a maximum during June and July. Skogsberg (1936), for Monterey Bay, gave the upwelling period as the middle of February to the beginning of September. Maximum upwelling occured before the end of July in his investigations. Reid and others (1958), suggested that upwelling is the strongest when the north and northwest winds are most marked. This is in April and May off Baja California, May and June off Southern California, June and July off Northern California, and August off Oregon. Wyrtki (1958) said that upwelling off Baja California occurred all during the year.

A theoretical consideration for large scale upwelling was given by Yoshida and Mayo (1957). They used their equation for vertical velocity in the surface layers to show that intense upwelling should occur only in the spring in southern and Baja California waters, because of the positive values in the curl of the wind stress. Intense upwelling also should occur, state Yoshida and Mao, only during the summer and fall in the northern areas, when the curl of the wind stress has appropriate positive values.

Skogsberg (1936) indicated that upwelling was limited normally to the upper 300 meters (984 feet); but, during years of intense upwelling, the depth could be greater. Sverdrup and Fleming (1941) indicated this figure to be about 200 meters (656 feet). Roden (1962) using statistical data off Northern California, concluded that water from depths greater than 100 meters (328 feet) could not extend frequently to the sea surface.

Sverdrup (1938) found evidence of coastal upwelling out to 100 km (62 miles) from the coast. Yoshida and Mayo (1957) implied that upwelling of a large horizontal extent could occur out as far from the coast as 500 km (310 miles). Yoshida's (1955) theory of coastal upwelling described a narrow strip of upwelling about 50 km (31 miles) in width close to the coast. The width of the coastal upwelling being controlled by two parameters. The first is the axis of the northerly winds; when the axis is closer to the shore, the upwelling zone width will be narrower and vice versa. The second parameter is the latitude; the calculations presented from Yoshida's model showed that the upwelling area width decreased with increasing latitude.

Sverdrup and others (1942) indicated centers of upwelling along the coast at 24° N, 35° N, and 41° N. Hidaka (1958) suggested that since his velocity components all included the sine of the latitude in the demoninator, the intensity should increase with decreasing latitude. Reid and others (1958) noted that upwelling was more intense south of capes and seaward extensions (Cape Mendocino and Point Conception). Pattullo and Burt (1960) reported a similar situation off the coast of Oregon, while Dawson (1951) reported this effect off the coast of Baja California. Arthur (1965) using Dawson's equation for upwelling velocity, showed theoretically why this occurs. The planetary vorticity term is always negative on the west coast of continents. The relative vorticity is positive north of a point or cape (opposing the planetary vorticity) and thus contributes to a higher upwelling velocity. Holly (1968) showed that the most persistent areas of coastal upwelling seem to be where the continental shelf slope is the greatest. These are approximately 29° N, 31° N, and 33° N.

During the period from April to September, coastal upwelling is the principal controlling factor of sea surface temperature within 100 km (62 miles) of the west coast of North America; large scale upwelling is an influential factor in the California Current region further offshore. Comparing coastal and large scale upwelling, coastal upwelling is smaller in scale but more intense. These two types of upwelling frequently occur at the same time and are separated by a trough of sinking water. The nearshore circulation resulting from coastal upwelling is determined mainly by the wind stress; but the stratification of the water, bathymetry and latitude are influential factors.

2.1.3 DAVIDSON CURRENT SEASON

During the period of approximately November to February each year the Davidson Current, a northward moving countercurrent, is the dominant inshore transporter of water and suspensates. The Davidson Current is generally a deep countercurrent below 200 meters (656 feet) which flows to the northwest along the coast from Baja California to some point beyond Cape Mendocino (Edmisten, 1974). It has been observed as far north as 50 degrees north latitude (Burt and Wyatt, 1964) and brings warmer, more saline water great distances northward along the coast through the year. When the north winds are weak or absent in late fall and early winter, this countercurrent forms at the surface on the inshore side of the main stream of the California Current.

2.1.4 CURRENT MEASUREMENT

Commencing in the late 1950's, direct measurements of the California Current were made using various measurement techniques. Improved radar and radar reflectors made it possible to track many drogues at one time and thus measure the currents over wider areas with only one ship. Such a technique was employed in March 1958 to gain a detailed picture of the California Current for a four day period off Point Sur in the vicinity of Davidson Seamount. The current set was to the southeast at an average velocity 0.25m/sec. (0.82ft/sec)with rapidly moving streams with maximum velocities of 0.90m/sec (2.95ft/sec)observed (Jennings and Schwartzlose, 1960). Direct measurements of the nearshore surface currents were again made in October 1958 and January 1959 for the same location off Point Sur. Parachute drogues were used to determine current direction and speed. In October the coastal waters were just beginning to flow northward and velocities measured by both drogues and the geostrophic approximation indicated some irregularity. In January the northwest flowing Davidson Current was well established. It was about 90 km (55.8 miles) at 36 degrees north, and speeds of

0.10 to 0.25 m/sec (0.33 to 0.82 ft/sec) were observed. Flow maintained quasi-periodic fluctuations of approximate diurnal and semidiurnal periods. Geomagnetic electrokinetograph (GEK) measurements substantiated fluctuations in flow.

In addition to the direct measurements obtained by drogues and the GEK, drift bottles have been used extensively to study nearshore currents along the coast of California; and except for remote sensing, few other data show as clearly the existence of the Davidson Countercurrent during the late fall and winter months.

The results from drift bottle studies of inshore currents along the coast of California have been reported by a number of investigators (Tibby, 1939; Reid et.al, 1958; Fofonoff, 1960; Schwartzlose, 1963; Hamby, 1964; and Crowe and Schwartzlose, 1972). Other related drift bottle studies have been made (Dodimead and Hollister, 1958; Burt and Wyatt, 1964; and Wyatt et. al., 1971). In late 1954 Scripps Institution of Oceanography's component of the California Cooperative Oceanic Fisheries Investigations (CalCOFI), the Marine Life Research Group, began using drift bottles to study seasonal variation in the inshore portion of the California Current. From 1955 through 1971, a total of 148,384 drift bottles were released and approximately 3.4 percent (4,995) were recovered (Crowe and Schwartzlose, 1972). The northern most return was from Montague Island, Alaska (August 1968), the southern most came from an area just north of Acapulco, Mexico (May 1959), and the western most return was from the island of Hawaii (September 1969). An interesting feature of the drift bottle results, is that few bottles put over more than 75 km (46.4 miles) offshore have returned to the coast. This result is consistent with the assumption that the surface waters are nearly always moved offshore by the prevailing wind.

2.1.5 GEOSTROPHIC FLOW CALCULATIONS

In the open ocean waters away from regions of effective boundary friction, unaccelerated and frictionless flow is called geostrophic (earth turned). The only effective forces acting per unit mass are the pressure gradient, the Coriolis (to the right in the northern hemisphere) and gravity. Currents produced as a result of the slope of isobaric surfaces, which are a function of the density distribution of the water, are called gradient currents. In order to express these density distributions as currents, it is necessary to make certain assumptions. These are that the currents and density distribution are steady, there are no effects of friction either at the bottom or from wind at the surface, there is some depth - perhaps 1,000 m (3,280 feet) at which there is no motion and to which the density measurements can be referenced, and above this level all movement is horizontal and east to west. The geostrophic flow, calculated from temperature, salinity and depth data, provides a reliable approximation of the actual motion of the water from time frames exceeding a day (Wylie, 1966). However, currents computed from density are not as reliable for nearshore waters since the basic assumptions and boundary conditions are not so well fulfilled, and other factors, such as coastline configurations, varying depth, variable winds, upwelling and the oscillations of internal waves influence the nearshore currents.

2.2 DESCRIPTION OF SURFACE CURRENT SEASONS FROM REMOTE SENSING

From 1970 to mid-1976 the National Aeronautics and Space Administration (NASA) obtained a wealth of imagery of the ocean off California with their Landsat satellites, U-2 high altitude remote sensing aircraft and low and mid-altitude aircraft. These and other image data sources have provided unique views of the coastal currents, from macro to micro in scale spread over the various oceanic seasons; and have given coastal engineers and oceanographers a tool with which the primary coastal current systems may now be traced in detail. High altitude imagery produces extremely complete, near synoptic and clear images of the ocean's surface, revealing large scale phenomena and relationships that often cannot be seen from a low altitude- below 5,000 meters (16,400 feet) or from a surface perspective.

Because coastal water is a complex mixture of solubles, colloids, suspensoids and biologic substances, visible light is absorbed, scattered and reflected in the water column in different spectral bands and in varying amounts. These differences create variations in colors, brightness, texture and contrast boundaries on imagery. Oceanic masses are distinguished by these imaged spectral variations. Major difficulties in obtaining field observations of nearshore currents exists because the current systems extend to the broad area in and near the surf zone. In the investigation of sediment transport in the littoral zone, it is required not only that the wave characteristics such as height, period and direction be defined, but also that the current field and bathymetry in, and offshore of, the littoral zone be understood to insure that models developed to predict sand transport confidently reflect the coastal parameters that exist in the prototype. It is not uncommon for field observers to note that a net sand transport for any particular site will be opposite that predicted by wave characteristics alone because of the dominance of the oceanic current system over the wave transport system. What is needed is the development of models that superimpose wave induced drifts with oceanic current induced drifts. Therefore, a good statistically reliable knowledge of the nearshore oceanic current vectors is basic. Unfortunately, quantitative as well as qualitative data pertaining to nearshore coastal currents off the shores of the United States is sorely lacking at the present time.

As by-products of attempts to define the nearshore currents that affect littoral transport mechanisms, valuable inputs have been obtained for studies concerning the locating of sewage or thermal outfalls to minimize adverse environmental effects and maximize the utilization of nutrient or thermal levels in needy oceanic areas. It has been demonstrated that along the California coast there are areas where oceanic current systems tend to move offshore during the various ocean seasons. This observation means nutrients that would , if introduced in the nearshore zone, cause red tide blooms or other equally environmentally destructive effects, could be directed offshore to areas where natural nutrient levels are low; and therefore, increasing these nutrient levels would increase the biological productivity leading to new fisheries and other commercial concerns. Analyses of oceanic current systems will make it possible to determine the areas where sediments containing pollutants, introduced by rivers, find their way into areas of upwelling. They may possibly reduce the expected productivity of these areas.

2.2.1 CALIFORNIA COASTAL CURRENTS

Very little is really known about the specifics of the seasonal variations of the California nearshore current systems. However, NASA remote sensing technology has provided data suitable for current definition and sufficient imagery to set down, with reasonable confidence, the primary current trends observed during the three California coastal seasons. Thousands of individual image frames were analyzed to extract the bits of current vector directions that have been assembled into generalized seasonal current charts in this section. It must be emphasized that the surface current systems presented herein are those observed during the period of 1969 through mid-1976 and primarily during late 1972 through mid-1976, and that cyclic meteorological and thermal trends as well as short term climatoglogical perturbations have not been filtered to provide long term trends. It is hoped that future acquisition of satellite and high altitude aircraft imagery will provide sufficient data that, when correlated with climatological variations, will provide a sample of current analyses that can be utilized for temporal projections. In addition to outfall and sediment transport studies, current projections are seen to be increasingly important in environmental impact studies dealing with offshore oil production as well as the myriad problems encompassing coastal development.

Figures 2-2, 2-3, and 2-4 show examples of the Landsat, Ames U-2 aircraft and NASA Houston (JSC) aircraft imagery utilized in the coastal current analyses. The use of the U-2 aircraft platform for imagery scales of 1:130,000 was found to be most useful for detection of nearshore structures and overall definition. The JSC-supplied imagery with scales between 1:10,000 to 1:40,000 was

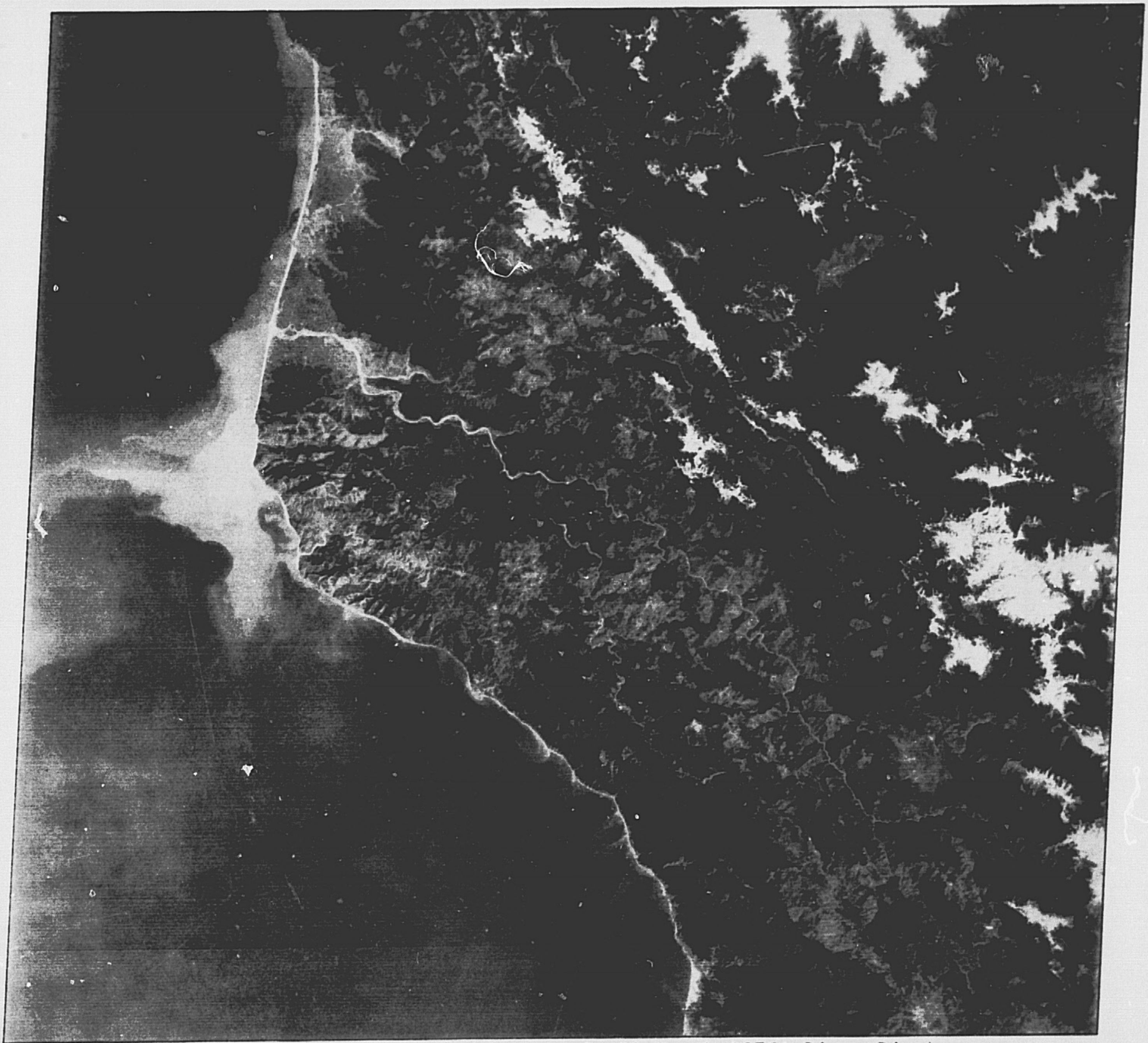

Figure 2-2 Landsat II Image 2415-18131-4, 12 March 1976, River Discharges at Cape Mendocino, California.

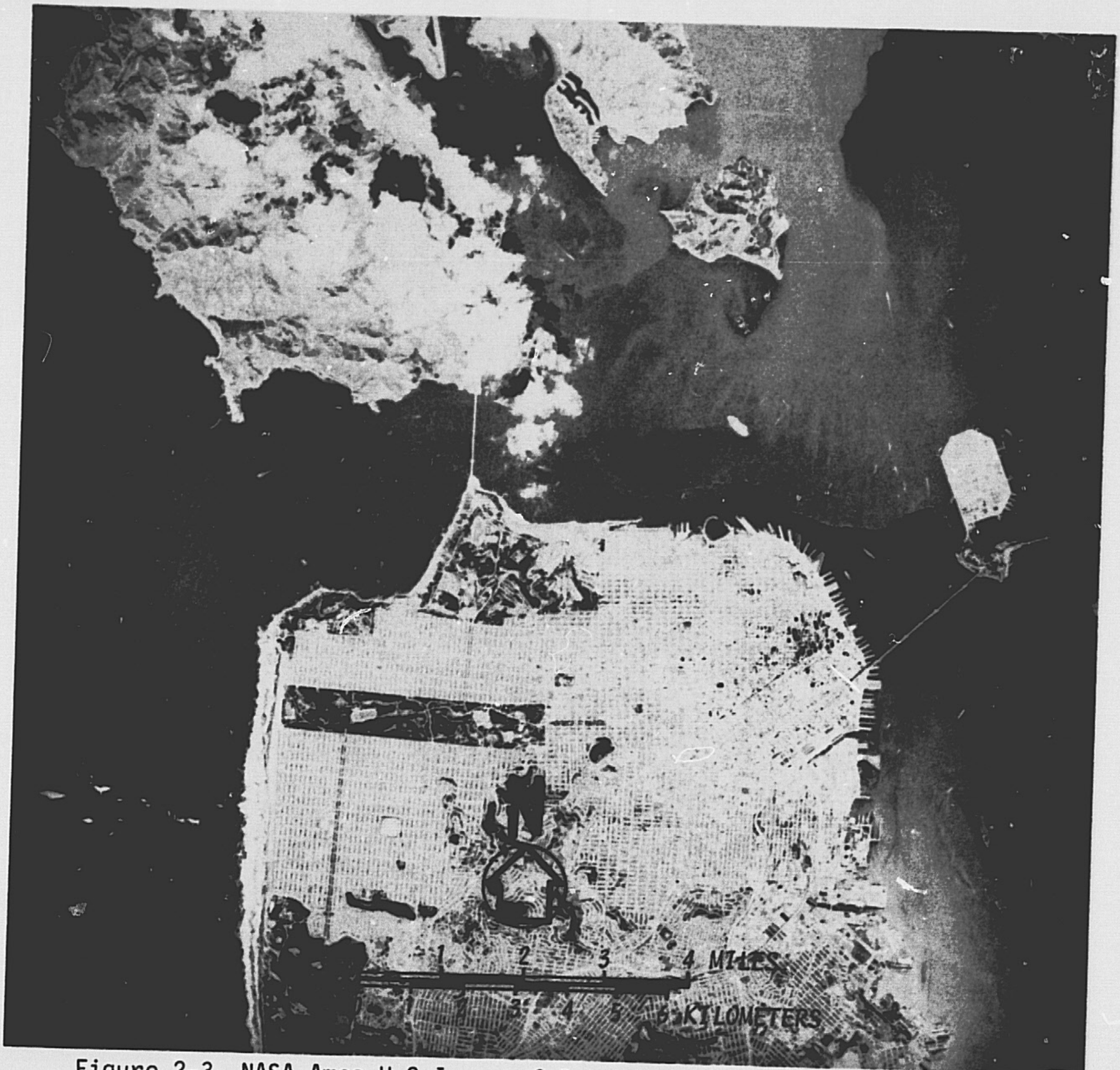

Figure 2-3 NASA Ames U-2 Image of San Francisco Bay, California, 21 March 1975, Accession No.2022, Frame 3502, Original in Color Infrared

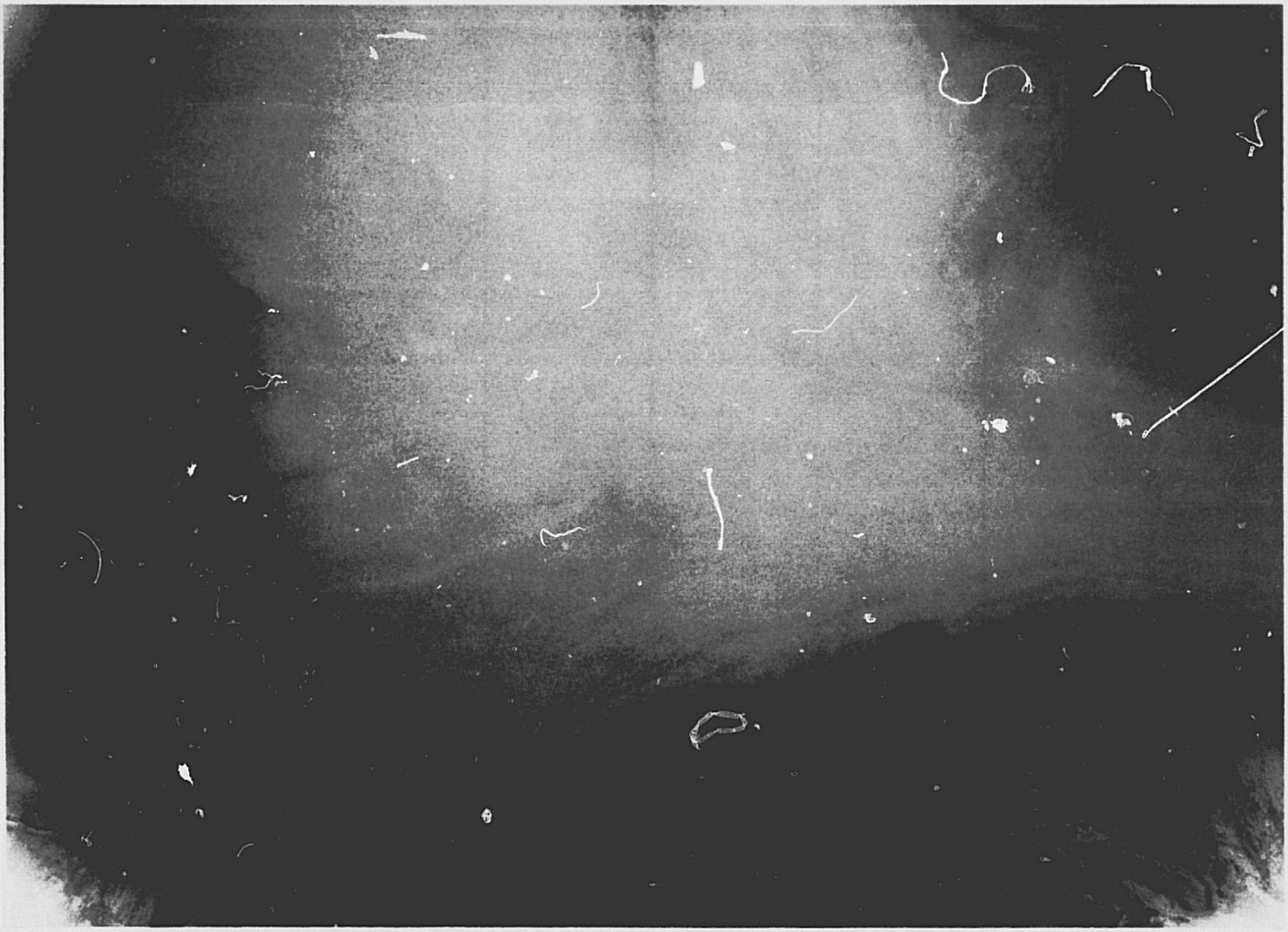

Figure 2-4 Delgada Submarine Canyon.

NASA Houston JSC image of upwelling area south of Cape Mendocino, California. Print from positive transparency used to enhance suspended sediment. 26 Sept 1973, Mission 253, Roll 118, Frame 266.

excellent for littoral zone analyses and the Landsat scale of 1:1,000,000 was appropriate for the macro and offshore tendencies.

The techniques used to define current directions, upwellings, and other basic surface parameters ranged from the simple use of photographic transparencies on standard light tables to complex digital processing of satellite computer compatible tapes. The machine processing techniques were useful when it was necessary to contrast and enhance data to bring out the subtle variances in densities and patterns that were used in describing ciruclatory systems. Multispectral ratioing and other algebraic functioning, allowed for theoretical depth of sediment, lensing, and sediment concentration analyses (Pirie and Steller, 1974). Because of the cost of machine processing, the majority of current interpretation was restricted to photographic transparency interpretation using either a light table with stereoscopic viewing or a variable scale projector. With the simpler viewing systems, the interpreter must view the coastal images, screen out wind, wave, and bottom topography effects, and organize the sediment density patterns into a current pattern. To do this effectively, the interpreter must be knowledgeable in the spectral response of the transparency that he is viewing, the magnitude and reflective characteristics of the noise and parameters of interest; and also have a good "seat of the pants" knowledge of the area being studied. Wind effects were probably the most difficult form of noise that was encountered. Complex wind patterns can often be confused with upwellings, internal waves or island wakes. It is important that the interpreter utilize all his experience as well as all the spectral channels at his disposal to eliminate confusing noise.

Figures 2-5 through 2-10 are the results obtained from the analyses of the three primary coastal current circulation patterns off the coast of California. The basic generalized current patterns were found to be in general agreement with the results of oceanographic studies previously discussed. However, never before had the complexity of the relatively stable nearshore circulation been so graphically defined.

2.2.2 DAVIDSON CURRENT PERIOD

The complex movements of the various currents which occur during the Davidson Current Period are illustrated in Figures 2-5 and 2-6. Normally, the main influencing current on the coast is the California Current; however, during the period of approximately November to February each year, the Davidson Current, a north moving countercurrent, is the dominate inshore transporter of water and suspensates.

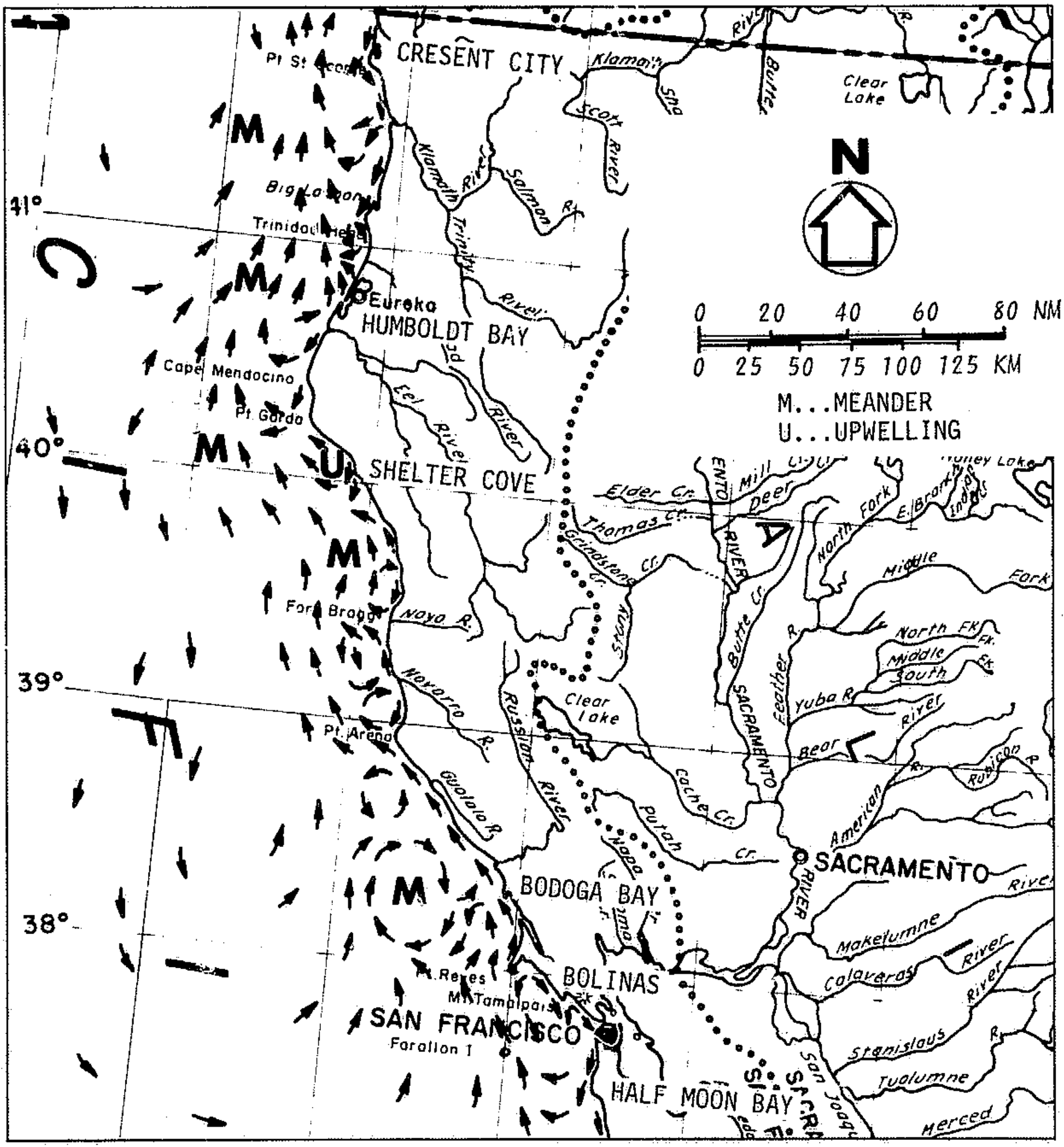

Figure 2-5 Generalized Northern California Surface Currents for the Davidson Season.

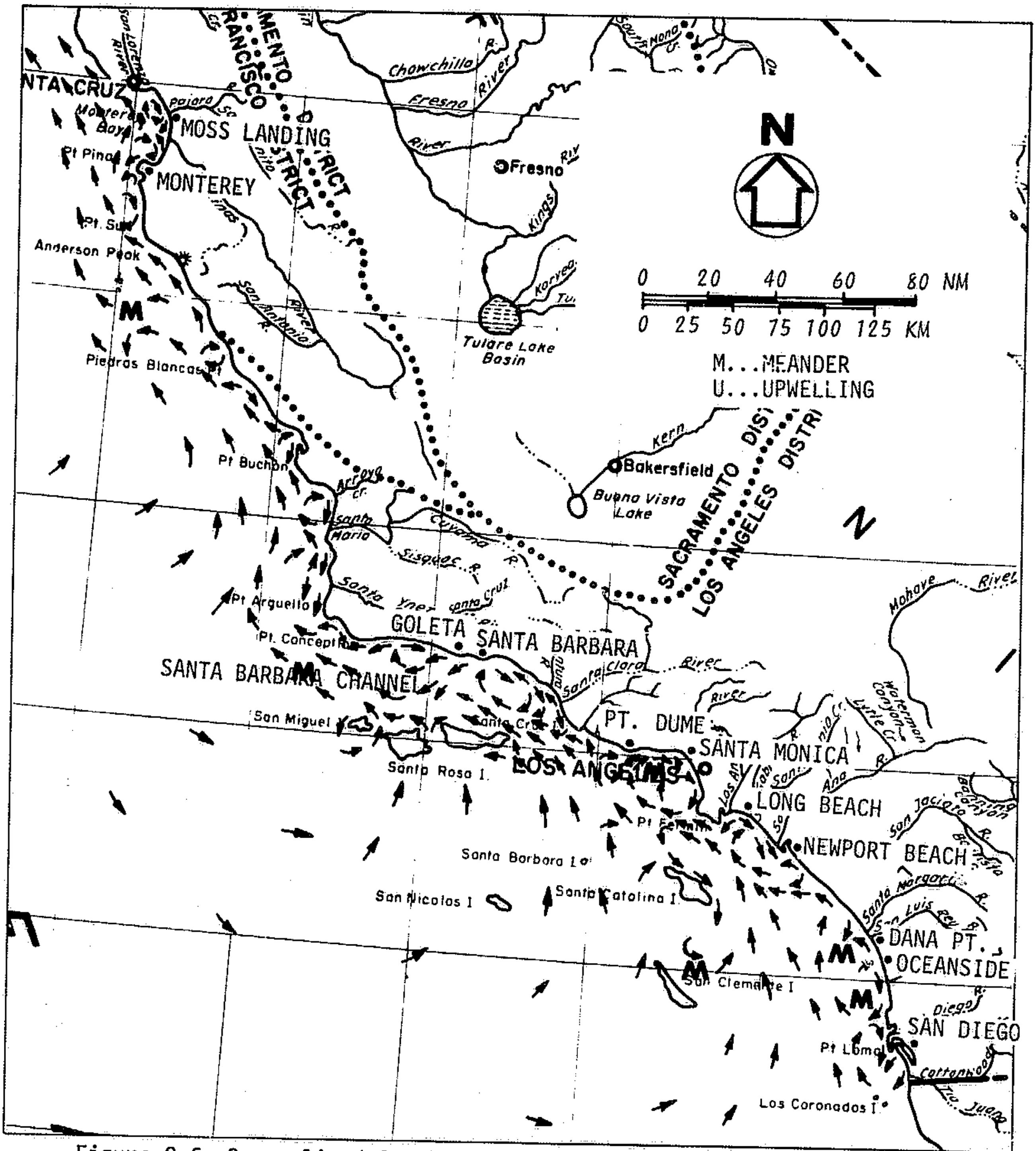

Figure 2-6 Generalized Southern California Surface Currents for the Davidson Season.

The Davidson Current is generally a deep countercurrent below 200 meters (656 feet) which flows to the northwest along the coast from Baja California to some point beyond Cape Mendocino. It brings warmer, more saline water great distances northward along the coast. When the north winds are weak or absent in late fall and early winter this countercurrent forms at the surface, well on the inshore side of the main stream of the California Current. The evidence for this current is visible on the Landsat imagery and supported by temperature contours in the eastern Pacific bend to the north along the coast during the height of the Davidson Current activity with the most dramatic changes taking place in February.

Generally Figures 2-5 and 2-6 illustrate the greatest concentrations of nearshore northerly moving sediment tagged water within approximately 30 km (18.6 miles) of the coast with high concentrations of lines and silts within 10 km (6.2 miles) of the coast. At several points, notably Cape Mendocino, Point Arena and Point Conception, significant quantities of surface waters are transported offshore to mix with the southward flowing California Current.

The effects of the Davidson Current on the nearshore waters of the coastal reach between the Oregon border and Cape Mendocino are strongest about 40 km (24.8 Miles) offshore and directed toward the north. The currents past 100 km (62 miles) offshore are to the south with meanders ("M" on the figures). Coastal currents are primarily tidal, wave and wind shear induced with a net southerly transport except near Humboldt Bay where the Davidson periodically sweeps into shore. This northerly transport at Humboldt Bay is especially common during winters of heavy storm activity when the California Current is further offshore and the Davidson strongest. At Cape Mendocino and Punta Gorda there is an offshore transport of surface waters containing high concentrations of silts and clays. The severe changes in bathymetry in the Cape Mendocino region caused by the Mendocino Fracture Zone are probably responsible for the landward component of current drift to the north of the Cape and the offshore component to the south.

The currents between Punta Gorda and Point Arena are structurally similar to those just discussed but exhibit more near coast eddies and meanders caused by the variable winter winds. One interesting upwelling site has been repeatibly observed on the LANDSAT imagery during the late Davidson Current season as existing at the head of the Delgada and Spanish Submarine Canyons ("U" on the figure depicts an upwelling area). These two nearshore submarine canyons between Punta Gorda and Shelter Cove may be responsible for the shoreward channeling and surfacing of deeper Davidson Current waters.

The currents for the reach between Point Arena and Point Reyes are discussed in Section 6 and shown on Figures 6-2, 6-3, and 6-5 as well as being illustrated in this section to be clearly influenced by the net northward currents alongshore with meanders offshore and a seaward flow of sediments at Point Arena.

In the Gulf of the Farallons a complex surface current and sediment transport system is present. A large clockwise gyre is present off the Golden Gate Bridge reaching from the San Francisco area northwest to the vicinity of Bolinas.

From Halfmoon Bay to Point Conception the offshore currents are northward and effective to at least 40 km (24.8 miles). Back eddies are commonly observed at any coastal indentation to the north of headlands and along high energy and wave facing (northwest facing) beaches. The Monterey Bay surface waters are reported to be exceedingly uniform during the Davidson Current period. The temperature difference between any pair of stations averages a little less than 0.25° C. No regular pattern of temperature distribution is discernible. The general northern trend of the suspended sediment, however, appears to continue in Monterey Bay with the area from Moss Landing to Santa Cruz containing two clockwise gyres. Additional Monterey Bay current information is to be found in Section 4.

Off Point Conception the California Countercurrent in the area between the mainland and the Channel Islands appears to pick up suspended particles and transports them offshore into a complex pattern region that is influenced by the California Current.

In the Los Angeles Harbor area materials from the Los Angeles, San Gabriel and Santa Ana Rivers move offshore and westward under the influence of the Davidson Current. Inside the harbor an east-southeastward current is in effect. Once outside the Los Angeles breakwater a slow moving westward current appears to dominate the nearshore sediment movement. Suspended sediments in Santa Monica Bay ring the bay with a 4 to 8 km (2.48 to 4.96 miles) wide border. This band of sediment appears to be escaping the bay area to the west around Point Dume and to the south at Point Vincente.

From Newport to the Mexico border the Davidson Season currents are effectively northward offshore with meandering eddies nearshore.

2.2.3 UPWELLING PERIOD

During the Upwelling Period (March through August) winds parallel to the coast move surface waters offshore allowing deeper ocean water to surface. This effect seems to be intensified near submarine canyons and south of capes and points which extend out into the current stream. On the current plots, Figures 2-7 and 2-8, the process of upwelling is illustrated with a "U". These colder upwelling waters are often rich in nutrients with the additional result that plankton blooms often accompany this period in the spring and again in late summer.

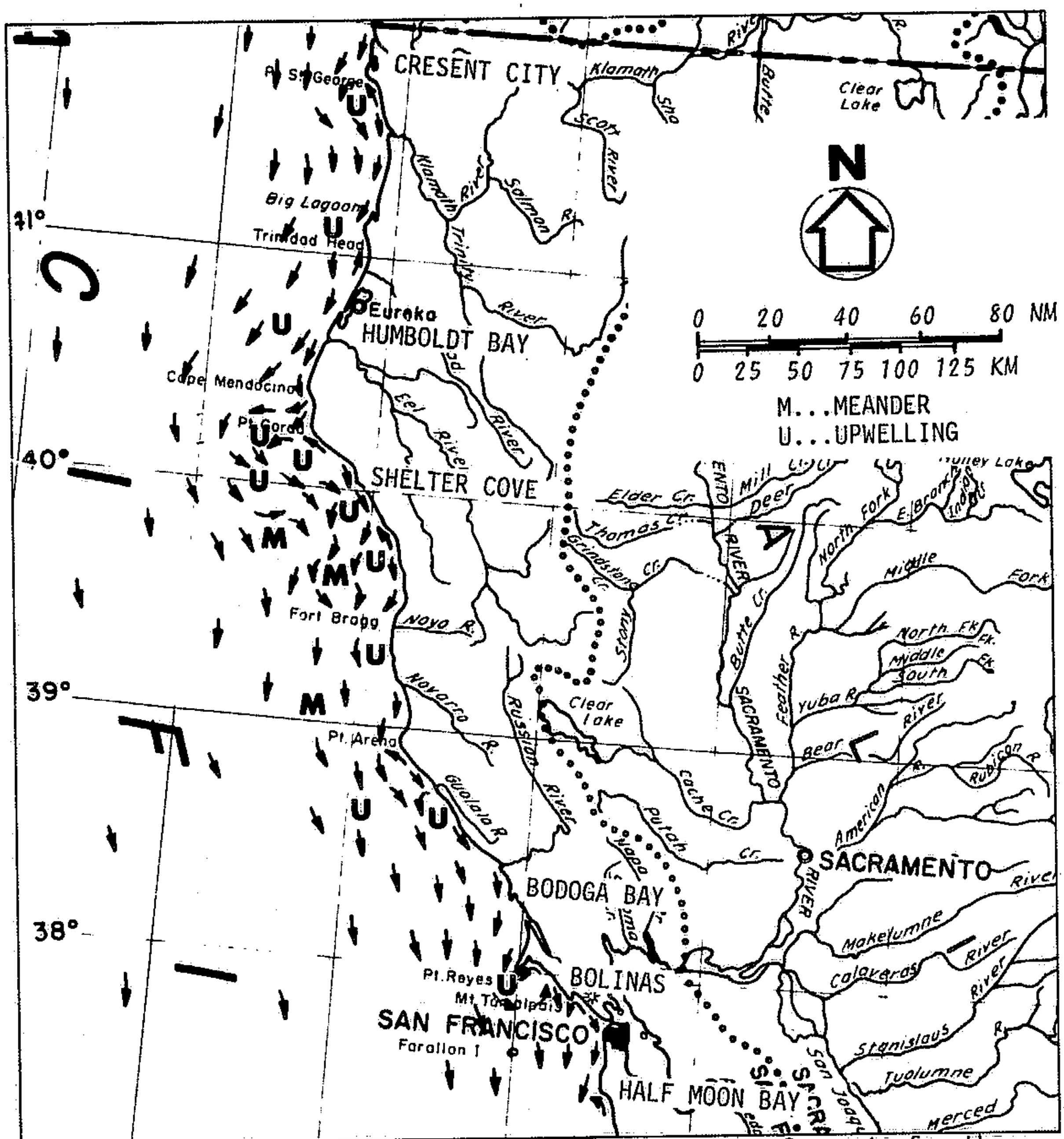

Figure 2-7 Generalized Northern California Surface Currents for the Upwelling Season.

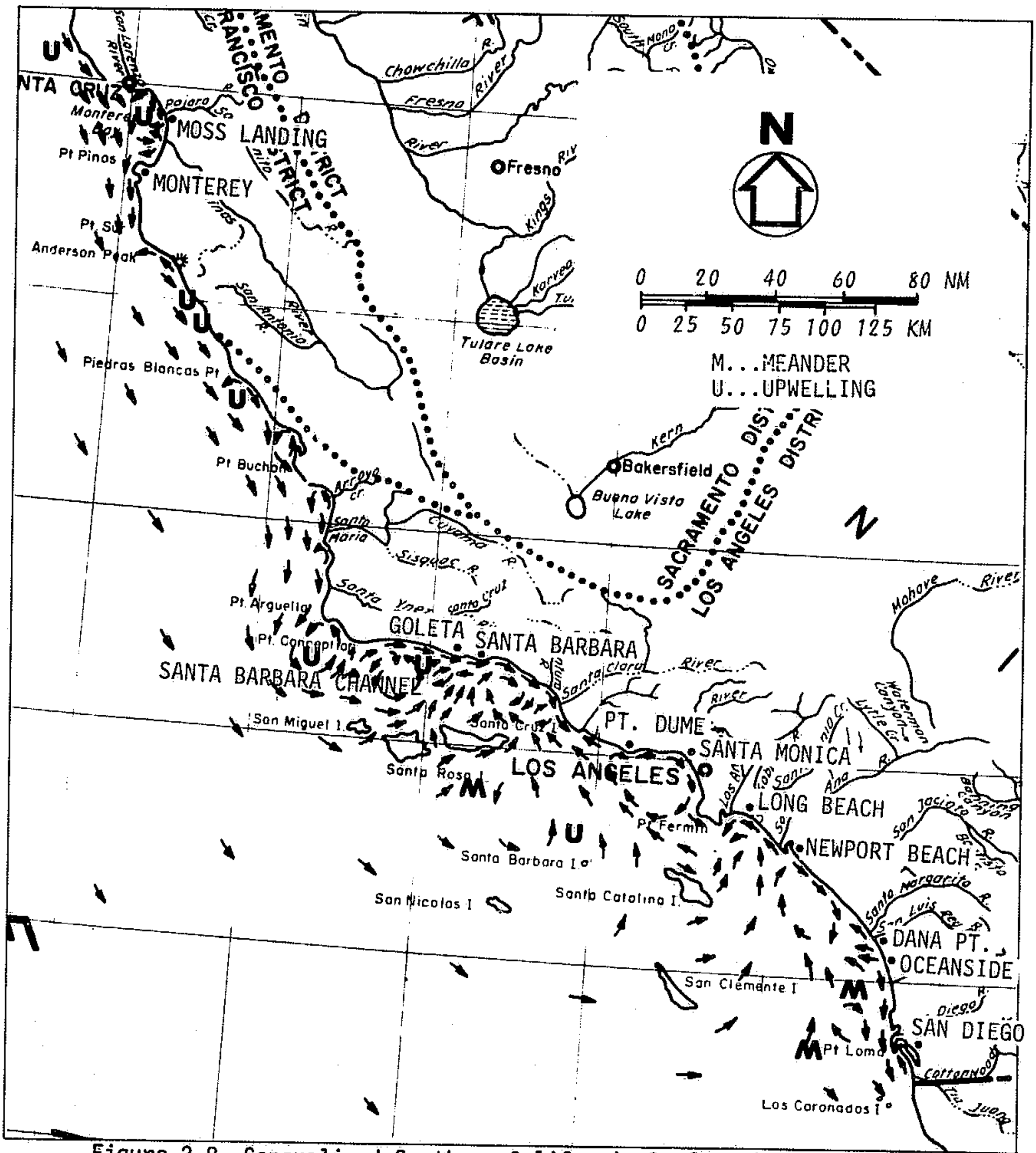

Figure 2-8 Generalized Southern California Surface Currents for the Upwelling Seasons.

During spring a gradual warming of surface waters normally takes place along the coast with the exception of the Cape Mendocino area. An extensive offshore upwelling extending from Cresent City to south of San Francisco forms a variation in the general warming trend. Similar features on a more local scale are detectable by studying nearshore tonal changes on the Landsat imagery.

From the Oregon border to Punta Gorda the California Current sweeps close in toward land with gyres and upwellings off the points. Sediment transport out to sea is found primarily at Point St. George and at Cape Mendocino. At Punta Gorda the coast changes direction to more NW-SE tending; and, with the strong NW winds of spring there develops between Punta Gorda and Fort Bragg a series of strong nearshore upwellings that appear on the high altitude and Landsat imagery as extremely clear waters adjacent to trapped sediment laden coast waters. Figure 2-2 Landsat image 2415-18131-4 of 12 March 1976) illustrates the effect of the California Current becoming effective to the north of Cape Mendocino but not yet dominant between the Cape and Fort Bragg. However, upwellings are evident near the coast.

The winter of 1975-1976 was one of the driest of all times on the California coast. This lack of storm activity as well as the lighter than normal winds of spring and summer resulted in Landsat images depicting weaker currents and many more meanders than during "normal" years.

Between Point Arena and Bodega Bay another NW-SE tending coastline exists and displays many of the same upwelling tendencies as the Mendocino-Fort Bragg reach but seems to have less obvious and less powerful surfacings. This may be due to the broader shelf in the nearshore region.

In Southern California another NW-SE cliff backed coast is found between Point Pinos near Monterey and Point Buchon near Morro Bay. The narrow continental shelf, southwestward current and northwest wind combine to provide a wealth of sealife of upwelled watered kelp forests.

At Point Conception the coast takes a sharp bend to the east and sets up a gyre and suspected upwelling. As shown on Figure 2-8, the upwelling season in the Santa Barbara Channel is generalized as being made up of two counter rotating gyres with upwellings nearshore along high cliff or hill backed coasts that channel the winds parallel to the shore. From Point Dume to Mexico the currents shown on the generalized figure were weak and unclear because of the low contrasts of sediments in the imagery. However, enough images depicted the same trends to develop the representation on the lower portion of Figure 2-8.

2.2.4 OCEANIC PERIOD

The California Current system dominates the nearshore surface current patterns during the Oceanic Period from July to November. In the offshore area, this current is the driving force of open ocean waters throughout the year.

The coastal current effects during the Oceanic Period are shown on Figures 2-9 and 2-10. The California Current is the southward component of the clockwise circulation of the North Pacific Ocean. As this current slowly meanders southward at speeds generally less than 0.25 m/sec (0.82 ft/sec), it becomes warmer under the influence of the sun and mixing with the warm waters to the west. On the inshore side of the current are found the numerous local disturbances which are of interest in this study. By comparing Figures 2-9 and 2-10 with Figures 2-7 and 2-8, one may observe that the seasons are similar except for a general lessening of current strength because of low surface wind and wave forces.

Off Point St. George a large gyre is normally found offshore from the sandy beaches extending south for a distance up to 40 km (24.8 miles).

In the Humboldt Bay area the sediment being transported comes mainly from the Mad and Eel Rivers and has been observed moving southward and offshore to a distance of 100 km (62 miles) from the entrance to Humboldt Bay.

Between Cape Mendocino and the San Francisco Bay entrance a number of sediment gyres are set up moving fine material directly offshore. At Point Arena a linear plume of material moves westward for a distance of about 25 km (15.5 miles). The first 5 km (3.1 miles) of this feature appears to be heavily laden with sediment. Further offshore, settling and mixing of the material causes the gradual decrease in this visible pattern. This feature appears to be the result of a small clockwise gyre set up just north of Point Arena. Similar processes are present off Shelter Cove.

At Bolinas Bay, about 15 km (9.3 miles) northwest of the Golden Gate the predominant direction of littoral drift past the entrance of the lagoon is from east to west. Reinforcement of drift occurs during storms when the wind and waves are from the southeast and during the Davidson Current Period. A clockwise gyre is often present off the San Francisco Bay entrance which brings sediment from the Bay system northward into the Bolinas area. This is part of the overall Gulf of the Farallons current and transport cell.

Some of the most complicated local currents occuring along the California coast take place near the entrance to San Francisco Bay. They result from high current velocities through the Golden Gate

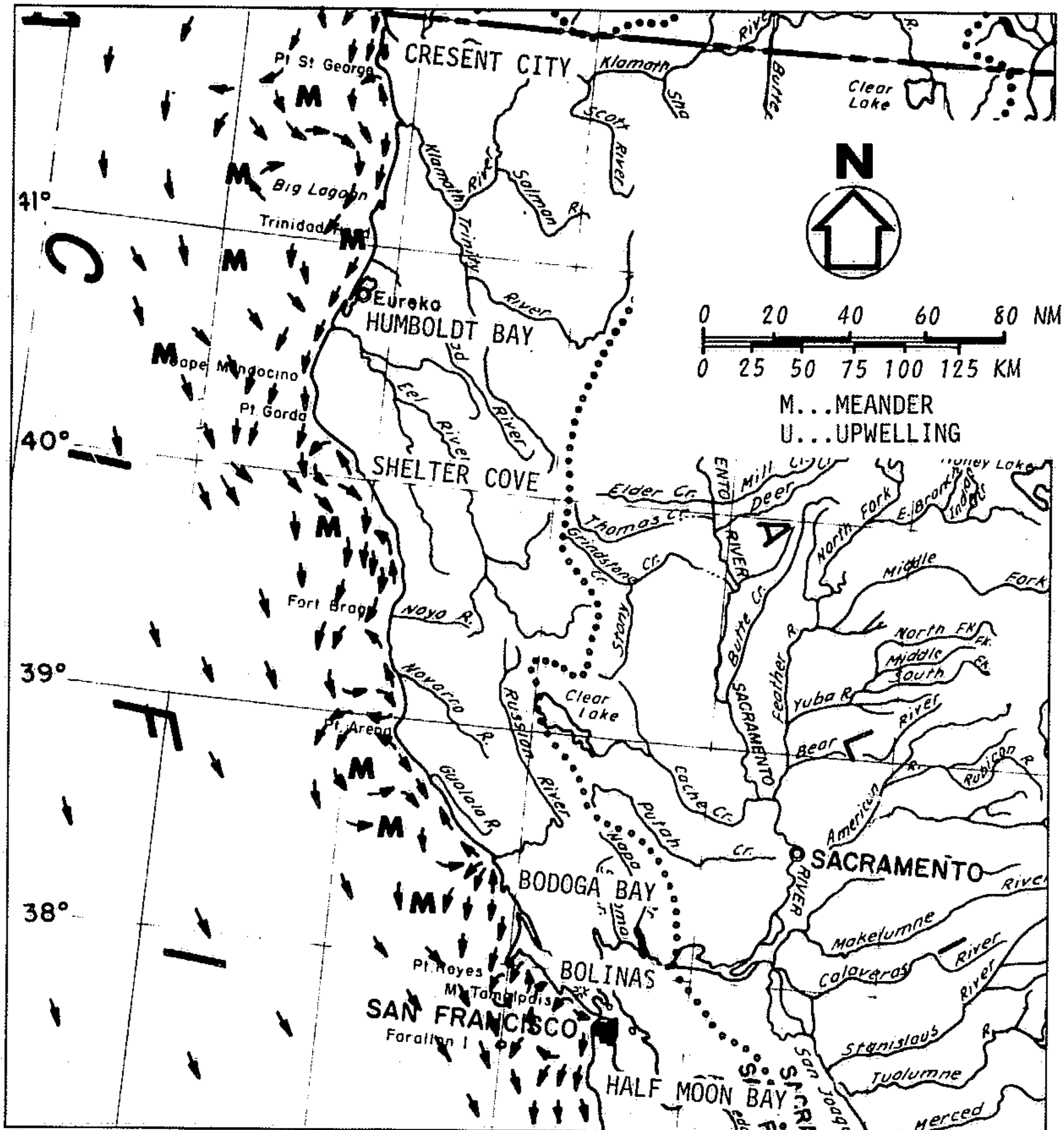

Figure 2-9 Generalized Northern California Surface Currents for the Oceanic Season

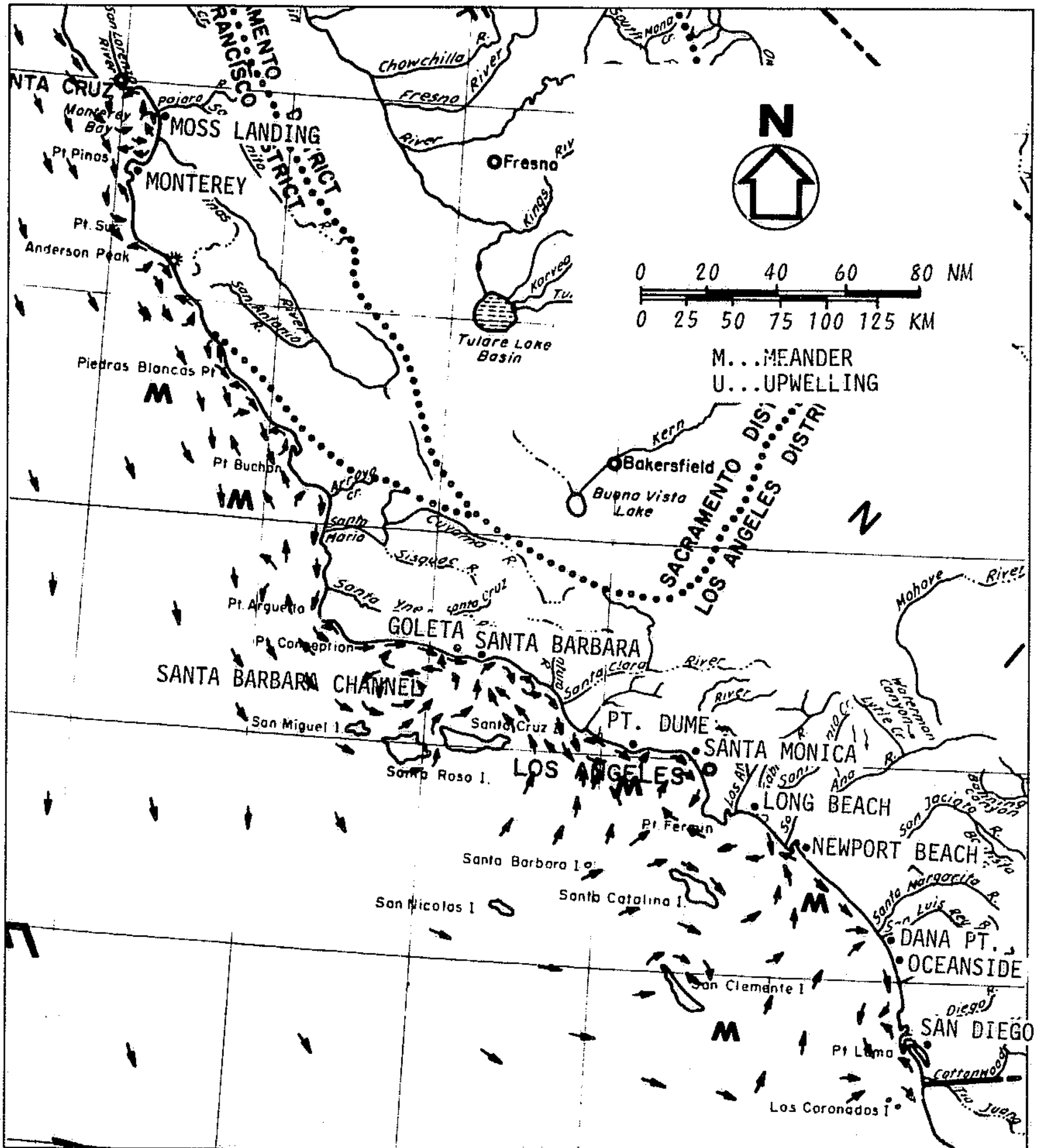

Figure 2-10 Generalized Southern California Surface Currents for the Oceanic Season.

during flood and ebb tides, variations in bottom topography and the highly variable wind drift all imposed on the coastal currents. It should also be noted that rough water conditions which are often present in the Gulf of the Farallons have always made detailed survey ship operations extremely difficult.

In Monterey Bay the nearshore area out to about 3 km (1.86 miles) contains suspended sediment which forms a crescent shaped pattern similar to the contour of the bay. Two breaks occur in this pattern, however. The first, 8 km (4.96 miles) north of Monterey and the second over the Monterey Submarine Canyon off Moss Landing. These breaks appear as areas of clear water in the nearshore suspended sediment pattern. The Monterey Submarine Canyon is the location of numerous upwellings which are indicated by lower temperature lenses which move to the north and south of the canyon. The feature 8 km (4.96 miles) north of Monterey appears to be a divergence between a small clockwise gyre in the southern end of the bay and a counter-clockwise gyre north to the Monterey Canyon.

The coastline between Point Conception and the Mexican Border is considered as a single system which has been described as the Southern California Bight. It is caused by the sharp eastern break of the coast to the south of Point Conception and the resulting indentation that extends for 575 km (356.5 miles) to Cabo Colmett on the Baja California coast. This Bight modifies the southern flow of the dominating California Current. The hydrodynamic discontinuity forms a return eddy and a semi-independent system of water circulation within the Bight. This is called the Southern California Countercurrent and is a combination of converging southern, western, northern and upwelling waters. What is generally seen during the Oceanic Period in the Bight is a counterclockwise gyre which passes northward through the eight Channel Islands.

In the Oceanic Period a small plume of suspended material moves south and southeast around Point Conception - Point Arguello. This represents the split between the south moving California Current and the material entering the California Countercurrent gyre in the western Santa Barbara Channel. This counterclockwise movement is apparent along the Channel Islands and then coastward to a point between Point Conception and Goleta Point. At the same time the nearshore sediment transport is to the east.

Within the Santa Monica Bay, the currents and sediment transport are clockwise along the coast to Point Vicente. Very little material rounds the pensinsula because of the combination of the Santa Monica Submarine Canyon sediment capture and the offshore sediment movement.

South of Long Beach transport is mixed or northwest. In the vicinity of Dana Point and Oceanside, current transport is often offshore to about 3 km (1.86 miles) then southeast. Although the waters off San Diego contain little suspended sediment, the transport is normally seen to be southward.

2.3 CONCLUSIONS

The nearshore surface currents along the coast of California have been seriously studied by numerous investigators for the last fifty years. Early investigators could only obtain localized current data, and spatial and temporal characteristics were inferred by assembling mosaics of local observations. Within the last few years, aircraft and satellite remote sensors have obtained the synoptic "big picture" with respect to nearshore surface currents along the coast of California.

The surface currents are driven and affected by gravity, friction, forces due to pressure gradients and Coriolis accleration. Nearshore water movements, however, which overlie the continental shelf are affected to a greater degree by wind, tidal forces, and irregularities in the ocean bottom. The features which are of particular interest in this study and are often visible on high altitude imagery, lie within this continental shelf zone. Before the use of remote sensing systems, it was often found during studies of local currents, that shelf effects, combined with seasonal run-off, distorted the nearshore currents to such a degree that it was difficult to determine the regional circulation. Landsat and U-2 imagery graphically illustrate the California Current as well as the nearshore currents, when suspended material acts as a detectable tracer.

Recently evolved techniques applied to the expanding data bank of imagery afford greater definition of sea surface dynamics. Concurrently, surface observations have assumed a new importance as they are required to provide "sea truth" for the observed sea surface phenomena.

In this study we have demonstrated the capability of LANDSAT and aircraft sensor systems to be utilized to define the oceanic and nearshore surface currents. At this time we do not know that what we have observed can be stated to be 100 percent correct in generalized content. However, we do feel the observations and analyses performed for the California nearshore surface current seasons make up as good an evaluation of the nearshore currents as can be found. We recommend the use of the remote sensing tool for any nearshore study where large spatial reaches are to be observed. The questions raised as to the absolute velocities and directions of our coastal currents will only be answered after much more surface data are taken and compared with additional aircraft and satellite imagery.

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3.0 SANTA BARBARA CHANNEL

The Santa Barbara Channel area is an essential part of the Southern California coast which is being subjected to development. The oil finds and associated oil spills have been well publicized and there are plans for future petroleum developments. Along the coast are several popular harbor and marina areas plus the northern Channel Islands. This area, as shown in Figure 3-1, is defined as the northern end of the California Continental Borderland which stretches from Point Conception eastward to Port Hueneme and seaward to include the four northern Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa). There are four major harbor areas including Santa Barbara, Ventura, Channel Island, and Port Hueneme. Each of these harbors has its own particular sedimentation problem. Sixteen kilometers (10 miles) of coastline considered to be eroding at a critical rate are located in this area (National Shoreline Study, 1971). The objective of this study is to determine what impact man's activities, such as offshore drilling and pollution, have on the marine environment. This is also of great importance to Channel Islands National Monument which now includes Anacapa and San Miguel Islands in the Santa Barbara Channel area plus Santa Barbara Island further southeast. The Landsat satellite provides continuous data which is usable as a valuable source of ocean surface information for these areas. On several of the Landsat overpass days, sea truth information was collected and aircraft photographs were taken. This information was used for calibrating and interpreting the Landsat imagery. It is in such an area with its diverse and often conflicting usage requirements for coastal waters that Landsat can be most beneficial.

3.1 SANTA BARBARA CHANNEL CURRENT PATTERN

The general surface circulation over the Santa Barbara Channel and surrounding borderland is dominated by a permanent cyclonic Southern California Eddy. The eddy is formed as the California Current water passes southward into the lee created by the eastward turn of the coast along the Transverse Range (Point Conception). The cold California Current sweeps into the Santa Barbara Channel. The eastern edge of the current beyond Point Conception bathes San Miguel Island with cold water, some of which is deflected into the Santa Barbara Channel (Neushul, 1967). The main stream of the California Current continues its southeasterly direction to San Nicolas Island where some of the water from its eastern edge enters the semipermanent counterclockwise Southern California Countercurrent. Seasonal variations in this pattern have been well documented (Reid and others, 1958; Emery, 1969). In the spring and

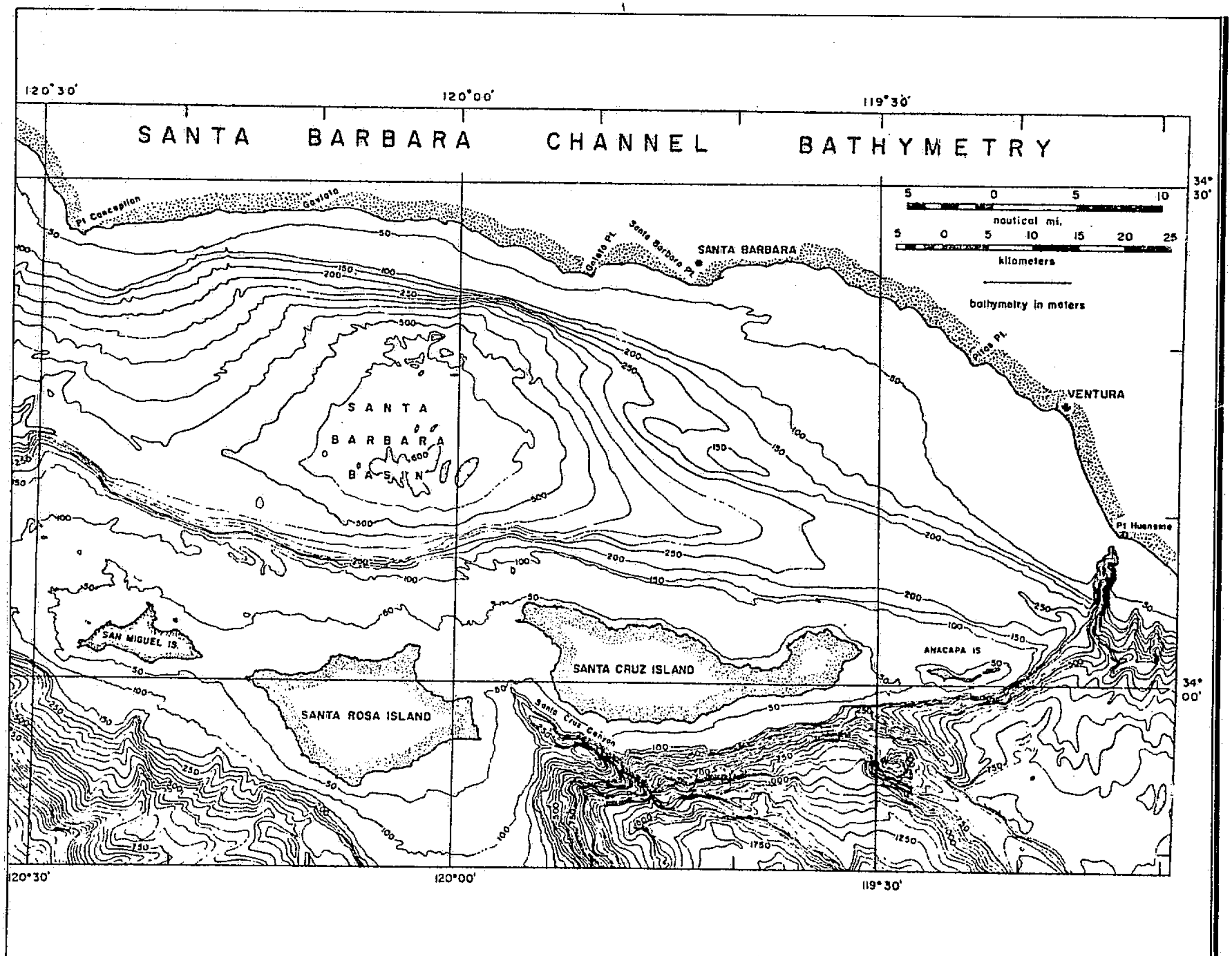

Figure 3-1 Santa Barbara Channel Location Map.

summer the North Pacific high pressure cell is well established and generates consistant northwest winds which tend to drive the California Current eastward toward the coast. In the fall and winter months, the high pressure cell degenerates and splits into two smaller highs located off Baja California and over Nevada. In response to the wind change the axis of the California Current moves farther offshore allowing a coastal counter current of warm water to develop. This current, called the Davidson Current or California Countercurrent, has been detected along the Pacific Coast as far north as Oregon (Sverdrup and Fleming, 1942).

The inflow of water at either end of the Channel is partially blocked by current action. This is significant to the suspended sediment system. The trapped eddy in the western sector serves to partially halt rapid escape of water flowing westward from near Ventura. Runoff and suspended sediment supply by streams to the south of Oxnard is always lower than local supply from the Santa Clara and Ventura Rivers (Rodolfo, 1970 and Gorsline, 1968). The Anacapa Current from the east (Drake, 1972) is generally relatively clear and does not add appreciable quantities of particulate matter to the area but it has the important hydrologic effect of blocking the southern escape of material to the southeast.

The affect of the ocean circulation on the Channel Islands is of special interest to the marine life evaluations in the Santa Barbara Channel. The California Current continues southeasterly after passing Point Conception. San Miguel, the western half of Santa Rosa, and San Nicolas are all strongly influenced by the cold California Current, whereas, Santa Barbara Island, Santa Cruz, Anacapa, and the eastern half of Santa Rosa receive both cold water from the California Current and warmer water from the south, moving up along the Southern California coast. Further south, Santa Catalina and San Clemente Islands are bathed throughout the greater part of the year by the warmer southern waters. Current and circulation in the island area are further complicated by local upwelling in the summer months.

3.2 LANDSAT-SANTA BARBARA CHANNEL

The Landsat imagery of Santa Barbara Channel, when studied in conjunction with the collected aircraft imagery and sea truth data, gives a clear and reliable picture of surface oceanographic information (Figure 3-2). Because of the land usage in this area, the oceanographic information is essential as a basis for water survey and shore protection operations. The main feature which is detectable is the reflectivity or coloration changes at or near the water surface. The reflectivity changes are caused by the sediment in suspension, water body characteristics, sun angle, wave patterns, water depth, pollutents, floating fauna and flora, and bottom characteristics.

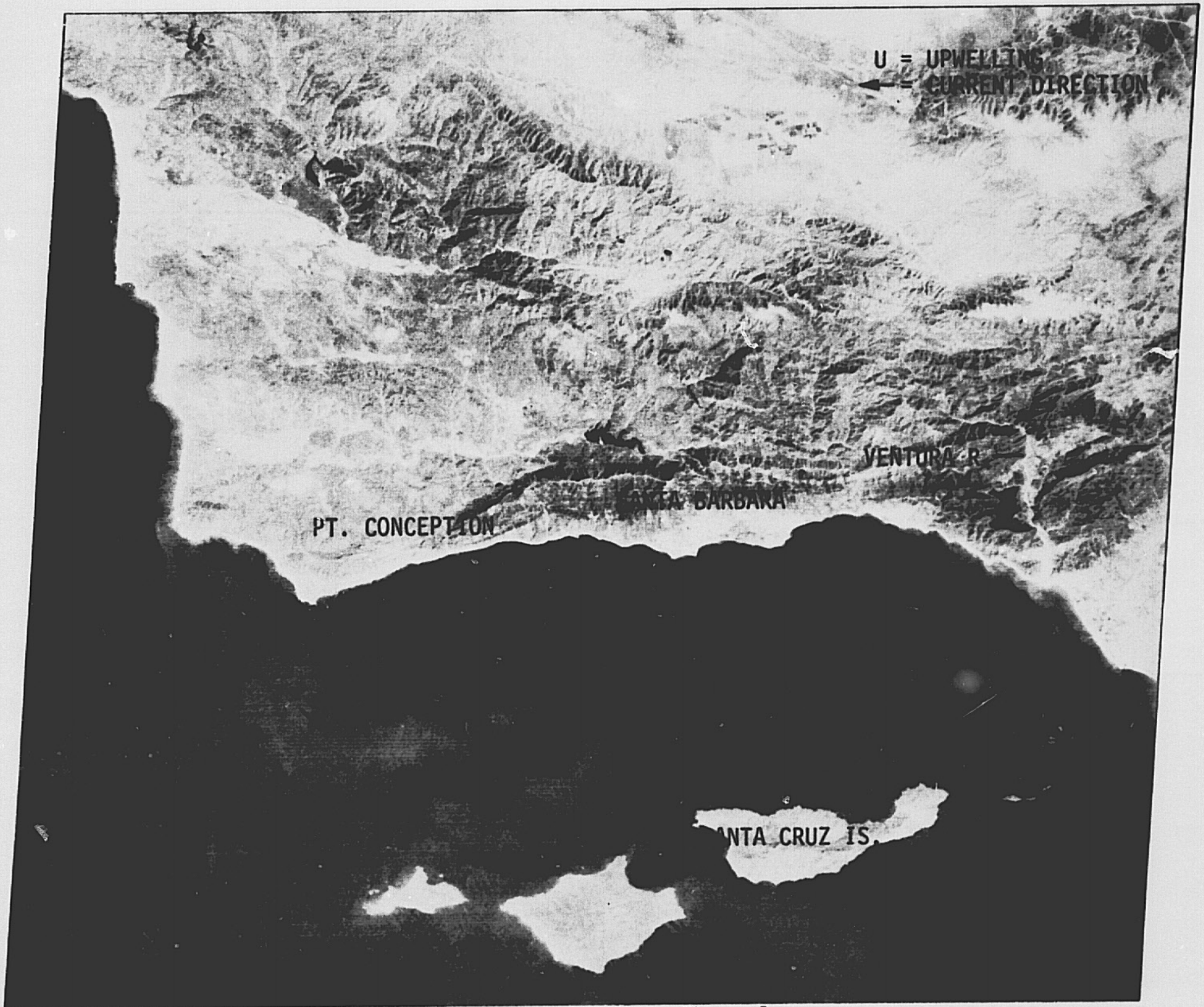

Figure 3-2 Santa Barbara Channel

This April 2, 1973, image from the upwelling current period illustrates the affect of a large upwelling south of Pt. Conception. Note the wind induced lineations south of Santa Rosa Island. NASA/LANDSAT 1253-18075-5

Landsat imagery was considered from the standpoint of providing a synoptic view of currents in the channel, the source of sediment from fluvial discharges and longshore drift and finally the transport of mainland sediment offshore. Band 4 and 5 are interpreted for water penetration differences. The film density differences in the water are interpreted as being mainly due to the variable load of suspended sediment. The turbidity plumes visible in the enhancement of the LANDSAT imagery originates along the mainland and bathes the entire east end of Anacapa Island. A principal contributor to the suspended materials is the plume often appearing from the Santa Clara and Ventura Rivers and their agricultural watersheds (Figure 3-3). It is likely the pesticides from these agricultural lands are absorbed in the soils that erode into the rivers and subsequently flow into the ocean. Reproductive failures as in the Anacapa Island population of the brown pelican have been linked with exceptionally high levels of DDT (Delong et.al., 1973). The California Sea Lion has also experienced problems with premature births which have been traced to high organochlorine pollutants. The offshore transport noted in Figure 3-3 is often detectable in the Landsat imagery.

3.2.1 IMAGERY SUMMARY

In viewing all of the Landsat imagery available for the Santa Barbara Channel several striking features are apparent (Table 3-1). There is a considerable period of the year during the dry season when most of the suspended sediment is located only in the nearshore area. This is a result of littoral drift, offshore winds and suspension of particles caused by heavy swells. During periods when the rivers and streams are flowing, the resulting plumes are greatly affected by complex offshore current patterns. A large countercurrent is often present between the Northern Channel Islands and the mainland causing westward current along the coast. In the period between November and February, the Davidson current is also visible moving suspended material westward along the coast. In the majority of the images, the dominant current is eastward.

Table 3-1 gives a short review of some of the features located on the indicated imagery.

Summary of Table 3-1

81 Total Landsat picture interpretable
56 East current dominant
14 West current dominant
10 Offshore sediment plumes
17 Clouds
2 Dark
15 Upwelling detected

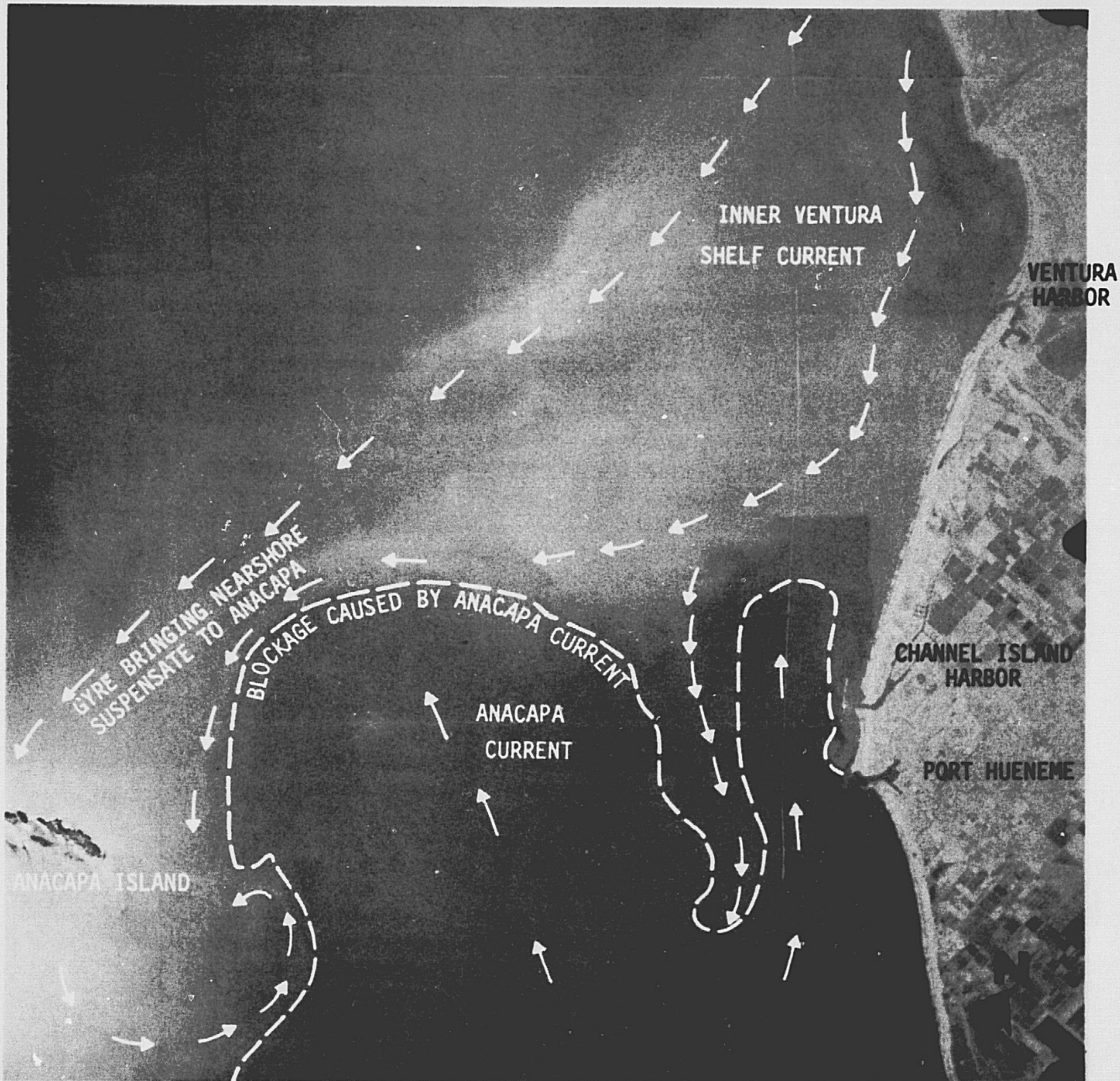

Figure 3-3 Anacapa Current

This color picture was taken on December 13, 1974, at 1245PM PST. The Anacapa Current blocks the movement of suspended sediment into Santa Monica Bay to the southeast. Sediment and polluents from the mainland are forced seaward where they bathe the shore of Anacapa Island. This is part of the Channel Islands National Monument where the Brown Pleican and California Sea Lions populations were adversely affected by pollutents. NASA/AMES 13 Dec 74 FLT 74-206 ACC 1981

TABLE 3-1

SANTA BARBARA CHANNEL
LANDSAT COVERAGE

LEGEND

E	East Current	V	Ventura Harbor	VR	Ventura River
W	West Current	A	Anacapa Island	SM	Santa Monica
PH	Port Hueneme	SC	Santa Cruz	PC	Point Conception
SB	Santa Barbara	SCR	Santa Clara River	SLO	San Luis Obispo

	LANDSAT ID	DATE	REMARKS
1	1055-18064	16 Sep 72	E Clouds, minor sed visible
2	1073-18064	4 Oct 72	E Plume off PH 10 km excellent
3	1090-18012	21 Oct 72	E Minor seds
4	1127-18073	27 Nov 72	W Plume, lineation V to SC Island off V nodal Pt.
5	144-18015	14 Dec 72	W Plume, wind blown lineation
6	1163-18072	2 Jan 73	W Offshore plume VR and SCR 8 km
7	1180-18013	19 Jan 73	E Offshore plume SB to SM Bay
8	1217-18074	25 Feb 73	W 20 km plume off Ventura, PC west
9	1252-18021	1 Apr 73	E Hazy - clouds
10	1253-18075	2 Apr 73	E Moderate seds coastal (7 km) plume
11	1270-18021	19 Apr 73	E Offshore plume 16 km
12	1271-18075	20 Apr 73	E Offshore plume PC reverse gyre
13	1288-18020	7 May 73	E Clouds
14	1289-18074	8 May 73	E Fog
15	1324-18014	12 Jun 73	E Minor seds
16	1342-18012	30 Jun 73	Clouds
17	1396-18004	23 Aug 73	E Small gyre SCR-VR, PH lineation
18	1415-18060	11 Sep 73	E Clouds minor seds
19	1432-17595	28 Sep 73	E Minor seds
20	1469-18045	4 Nov 73	E Minor seds excellent
21	1486-17590	21 Nov 73	E Blockage Anacapa Channel, excellent plume PH
22	1504-17585	9 Dec 73	W Minor seds, plume VR excellent

TABLE 3-1 (Continued)

	LANDSAT ID	DATE		REMARKS
23	1505-18043	10 Dec 73	W	Minor seds, plume VR excellent
24	1523-18041	28 Dec 73		Clouds
25	1541-18034	15 Jan 74	E	Nearshore W is Anacapa Channel N SLO
26	1577-18024	20 Feb 74	E	Nearshore W offshore - Anacapa Channel excellent (upwelling PH)
27	1594-17564	9 Mar 74	E	Nearshore blockage Anacapa Channel - W
28	1595-18022	10 Mar 74		Clouds
29	1631-18014	15 Apr 74		No seds visible, Excellent wind shadow islands
30	1666-17545	20 Apr 74	E	Band of seds approx. 10 km wide
31	1702-17535	25 Jun 74	E	Minor seds
32	1703-17593	26 Jun 74	E	Minor seds Channel Islands and coast Leeward pattern (wind)
33	1720-17531	13 Jul 74		Clouds
34	1721-17585	14 Jul 74		Clouds
35	1757-17574	19 Aug 74		Clouds leeward patterns Channel Islands inland
36	1774-17511	5 Sep 74		Clouds, seds L.A. Harbor, good terrain resolution
37	1792-17502	23 Sep 74		Excellent, gyre PH, nearshore seds SB
38	1828-17495	29 Oct 74		Excellent, plume half way to A blockage
39	1865-17540	5 Dec 74	E	Nearshore seds, SB to PA to 7 km
40	1882-1747	22 Dec 74	W	Nearshore east movement, gyre Goleta
41	1883-17532	23 Dec 74	W	Anacapa Blockage large eddy Santa Barbara
42	1900-17465	9 Jan 75		Low haze, sediment pattern
43	1901-17523	10 Jan 75	E	Current reverse, since Dec. nearshore sed out to 5 km
44	1936-17452	14 Feb 75	E	Long nearshore discharge pattern through A channel
45	1937-17510	15 Feb 75	E	Nearshore pattern out to 7 or 8 km
46	2033-17555	24 Feb 75	E	Gyre off PH and Mugu 10-15 km offshore plume
47	2051-17554	14 Mar 75	E	PC gyre heavy sed concentration nearshore 5 to 7 km

TABLE 3-1 (Continued)

	LANDSAT ID	DATE	REMARKS
48	1973-17492	23 Mar 75	E Excellent PC to Mugu, 5-8 km gyres
49	2087-17553	19 Apr 75	E Seds nearshore, wind shadow effect
50	5009-17473	28 Apr 75	E Seds nearshore 6-8 km
51	2104-17495	6 May 75	E Seds nearshore V to Pt. Dume then offshore
52	5027-17464	16 May 75	E Clouds SB east
53	5062-17390	20 Jun 75	E Light seds minor nearshore
54	2158-17495	29 Jun 75	Clouds Santa Monica Bay east cloud free
55	2159-17554	30 Jun 75	E Minor seds, wind shadow effect
56	5080-17375	8 Jul 75	E Minor seds clouds
57	5081-17433	9 Jul 75	E Clouds
58	2176-17494	17 Jul 75	E Minor seds clouds PH east
59	2212-17484	22 Aug 75	E Clouds
60	2249-17541	28 Sep 75	E Clouds
61	2266-17482	15 Oct 75	E Minor seds P/C flight
62	2284-17481	2 Nov 75	E Minor seds clouds
63	2285-17535	3 Nov 75	E Clouds
64	2302-17480	20 Nov 75	E Seds starting to show plume (8 km) V
65	2303-17534	21 Nov 75	E Seds plume (V)
66	2320-17474	8 Dec 75	W Minor seds
67	2321-17533	9 Dec 75	W Minor seds
68	2339-17532	27 Dec 75	W Minor seds clouds
69	2374-17471	31 Jan 76	E Minor seds clouds current reversal
70	2375-17525	1 Feb 76	E Plume V, nearshore clouds offshore
71	2392-17464	18 Feb 76	E Clouds offshore minor seds
72	2410-17461	7 Mar 76	E Nearshore plumes SB to PH
73	2428-17454	25 Mar 76	W Nearshore seds plume PH
74	2429-17512	26 Mar 76	W Nearshore seds plume PH
75	2447-17505	13 Apr 76	E Nearshore plume PH (6-8 km)
76	2464-17443	30 Apr 76	E Minor seds

TABLE 3-1 (Continued)

LANDSAT ID		DATE	REMARKS
77	2464-17450	30 Apr 76	E Minor seds
78	2465-17502	1 May 76	E Minor seds, clouds
79	5386-17183	9 May 76	Dark, coulds
80	5387-17241	10 May 76	East, dark coulds
81	2482-17441	18 May 76	Clouds

At times when heavy river discharge is taking place from the Ventura and Santa Maria Rivers, it is possible to see the effect of the Anacapa Current. The sediment laden water and the clear Anacapa current waters provide striking patterns detectable on the Landsat imagery. Figure 3-2 is a prime example. At the time this image was taken, the surface component of the Anacapa Current is obviously offshore while a southeast current is transporting the nearshore sediments.

This southeast current is part of the California Current which brings cool, low salinity water into the Santa Barbara Channel from the west and southwest. In response to seasonal changes in winds and the position of the California Current, the intrusion is at a maximum in the spring and summer and generally restricted to the southwest corner of the area in the fall and winter months. Although most of the suspended sediment in the channel is contributed by local runoff at certain times of the year, nearshore wind-driven turbid plumes around Point Conception (Figure 3-4) enter the area. Suspended sediment concentrations have been found to exceed 1.0 mg/l (Drake, 1972) in these plumes.

3.3 SANTA BARBARA CHANNEL SEA SURVEY OPERATIONS

As part of the Landsat analysis of the Santa Barbara Channel three oceanographic data collecting surveys were carried out. The surveys took place simultaneously with Landsat overpasses on October 16, 1975 (Oceanic Current Period), February 18, 1976 (Davidson Current Period), and May 27, 1976 (Upwelling Current Period). (Table 3-5). During the first two surveys simultaneous aircraft remote sensor data was also collected (see Appendix A). The ocean surveys (Figure 3-5) were used for collecting water samples, Secchi disk measurements and water temperature. The percentage of suspended solids present in the water samples were determined using the micropore filter technique. The information from the surveys were utilized in analyzing the suspended particles detected on the simultaneously collected Landsat and aircraft imagery. The first survey started from the Ventura Marina while the second and third survey started from Channel Island Harbor near Port Hueneme. In each case they ended near the lighthouse on the eastern tip of Anacapa Island. The tip of Anacapa Island was a good offshore reference point for locating the ocean stations on the satellite imagery. This was a valuable asset during the interpretation phase of the study.

Water samples, transmissivity profiles and Secchi disk readings were taken every mile between the coast and the east end of Anacapa Island. The chlorophyll-a, total suspended load, and particle size spectra were also measured. Due to the limited amount of data it is possible to make only point source correlations with the Landsat data.

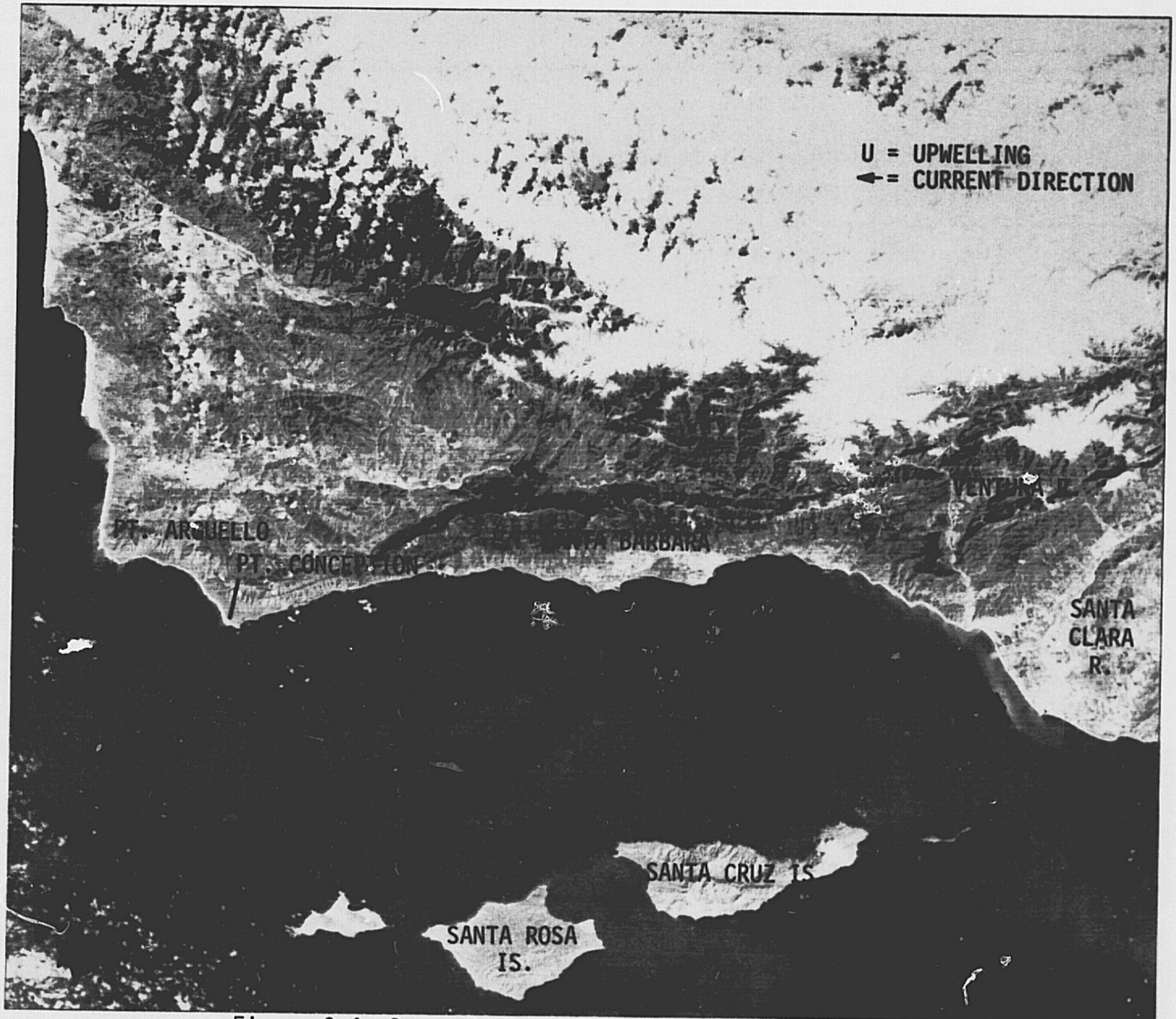

Figure 3-4 Santa Barbara Channel Wind Driven Sediments

TABLE 3-2 SANTA BARBARA CHANNEL - OCEAN SURVEY SUMMARY

	16 October 1975						18 February 1976					27 May 1976			
	Nautical Miles	Ocean Sta	Temp ^{O}C	Secchi M	Mg/l		Nautical Miles	Ocean Sta	Temp ^{O}C	Secchi M	Mg/l	Nautical Miles	Ocean Sta	Secchi M	Mg/l
Ventura Harbor	0	1	16.1	3.0	1.5										
	1	2	16.0	4.5	1.5										
	2	3	16.4	4.0	1.6										
	3	4	16.5	6.0	1.5	Channel Is. Harbor	0	1	14.0	5	1.5	0	1	5.0	3.9
	4	5	16.4	6.5	1.4		1	2	14.0	9	1.5	1	2	---	2.9
	5	6	16.5	7.0	1.5		2	3	14.2	10	1.5	2	3	8.5	1.9
	6	7	16.5	7.5	1.4		3	4	14.4	12	1.5	3	4	9	.7
	7	8	16.4	8.0	1.5		4	5	14.5	17	1.5	4	5	10	1.9
	8	9	16.8	9.5	1.4		5	6	14.4	16	1.5	5	6	10	.5
	9	10	16.8	10.0	1.4		6	7	14.2	16	1.5	6	7	10	1.3
	10	11	16.8	10.0	1.4		7	8	14.4	14	1.5	7	8	12	1.5
	11	12	16.8	10.5	1.3		8	9	14.5	15	1.5	8	9	14	1.3
	12	13	16.8	11.0	1.3		9	10	14.1	15	1.5	9	10	12	1.7
	13	14	16.7	12.5	1.4		10	11	13.8	17	1.5	10	11	16.5	.7
Anacapa Island	14	15	16.4	13.0	1.4	Anacapa Is.	11	12	13.8	19	1.5				
	15	16	17.3	19.0	1.4										

See Figure 3-5 for ocean station locations.

No Temperatures Available

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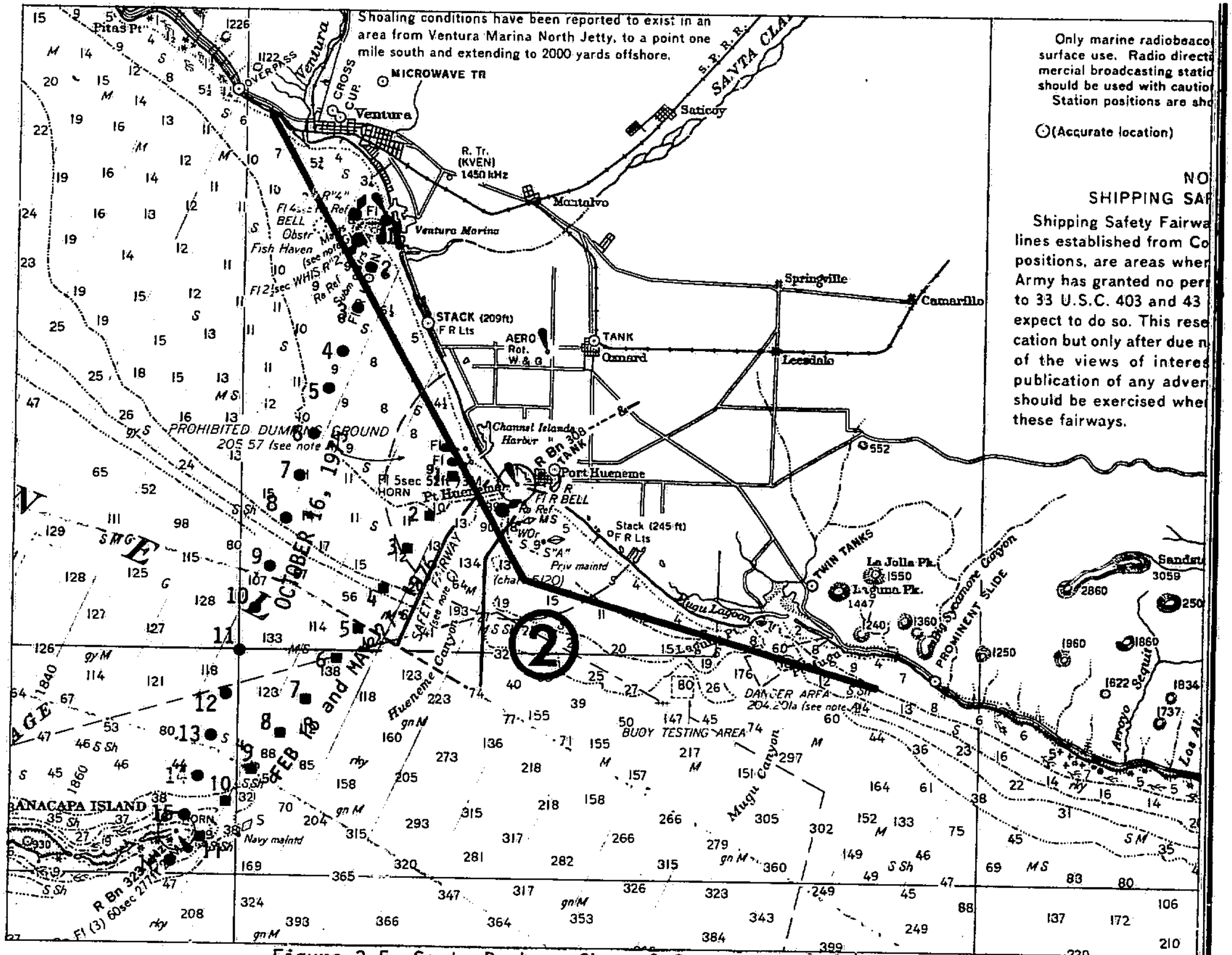

Figure 3-5 Santa Barbara Channel Survey Operations

Transmissivity measurements were made using a Hydro Products transmissometer with 1 meter (3.28 feet) path length. The output was recorded on an X-Y plotter as transmissivity vs. depth measurements. Measurements were taken at 5 foot (1.52 meters) down to a maximum of 50 feet (15.2 meters). The 5 foot (1.52 meters) measurements were used in correlation with the surface water samples.

Surface water samples for the total suspended load measurement and the particle size spectra were taken at each station and approximately one quart of sea water was added to 1.5 oz. of formaldehyde (~5% formaldehyde as preserver). Bottle samples were kept cool and in the dark until they were analyzed. Total suspended load determinations were obtained by initially weighing each filter twice (mean Δ weight of two determination was ≃0.019 mg) filtering approximately 750 ml through a Whatman GF/C glass filter and re-weighing dried filters. Two determinations were again made (~ΔW = 0.024 mg).

The particle size spectrum was determined using a coulter counter to electronically count particle sizes. The procedure used is essentially that found in Strickland and Parson, 1972. A 100 micrometers aperture was employed, thereby allowing particles in the range of 5-20 micrometers to be measured. Measuring times were for 30 sec. and 60 sec., and the data appropriately averaged.

Two chlorophyll-a samples were collected at each station and analyzed on a Turner Fluorimeter. The collection procedure was to immediately filter 100 ml of surface water through a Whatman GF/C glass filter, place filter in 10 ml of 90% acetone and stored on ice.

3.3.1 RESULTS OF SEA SURVEY OPERATIONS

The transmissometer profiles for May 27, 1976 from nearshore waters out 3.7 kilometers (2 nautical miles) showed a low % of light transmission on the surface and at depth of approximately 40%. This corresponded with the suspended particles content as determined in the collected water samples. Outside the Channel Island breakwater suspended particle content of 3.9 mg/l was found and at 1.85 kilometers (1 nautical mile) the reading was 2.9 mg/l. From the three mile station (5.5 kilometer) out to Anacapa Island the % of light transmission at the surface and at depth increased to about 60% and then stayed approximately equal. All of the volume readings were between 0.5 and 1.9 mg/l indicating the very low amount of suspended particle during May of 1976.

Surface temperature profiles across the Anacapa Channel indicates slight, but signicicant, changes in the surface water movement patterns. In October 1975 there was a warming trend toward Anacapa Island. Near Ventura the water was 16.1°C and off the Anacapa light 17.3°C. The Southern California Eddy appears to be bringing cooler water inshore with the possibility of an upwelling northwest of Port Hueneme. In February 1976, the cooler surface waters were inshore (14.0°C) and off Anacapa Island (13.8°C). In between, warmer water (14.5°C) appears to be entering the area from the south.

The suspended particle content was unusually low throughout the year. This was mainly due to a low precipitation level (7" rainfall in Los Angeles as opposed to the 14" average) throughout the 1975-1976 climate year. In October and February, the surface concentrations across the channel were about 1.5 mg/l. In the nearshore concentrations were higher, although no rivers or streams were running in the area. Near the coast the concentration was about 3.0 mg/l and out beyond 3 miles (4.8 kilometers) about 1.0 mg/l. Overall, a very low particle transport year as compared to recent studies.

The chlorophyll-a measurements indicated a low concentration in May 1976 with the lone exception of the nearshore sample. In the shallow water (5 meters or 16.4 feet) outside the Channel Island Harbor breakwater a reading of 4.96 mg/l chlorophyll-a was recorded. The rest of the readings were between 0.77 and 1.49 mg/l. The high nearshore reading is probably the result of nutrient input from the coastal land area and/or upwelling in the immediate nearshore area.

3.4 SANTA BARBARA CHANNEL CONCLUSIONS

The Landsat imagery illustrates the complex surface current patterns as they change from season to season (Figures 3-6, 3-7, and 3-8). Although 1975 and 1976 were years of low runoff, the littoral currents and plankton provide sufficient "tracers" for analyzing the current movement. During the Upwelling Current Period the countercurrent in the Santa Barbara Channel rotates across the entire basin. In the Oceanic Current Period this countercurrent is mainly confined to the southwest corner of the basin. At certain times during the Davidson Current Period all coastal transport was toward the west and northwest. The Anacapa Current appeared to be active throughout the year moving westward from Santa Monica Bay into the Santa Barbara Channel.

The dominant eastward current transports material into all the major harbor areas. At Santa Barbara Harbor, Ventura Marina, Channel Island Harbor and Port Hueneme deposition of sand from the west requires periodic or continuous removal.

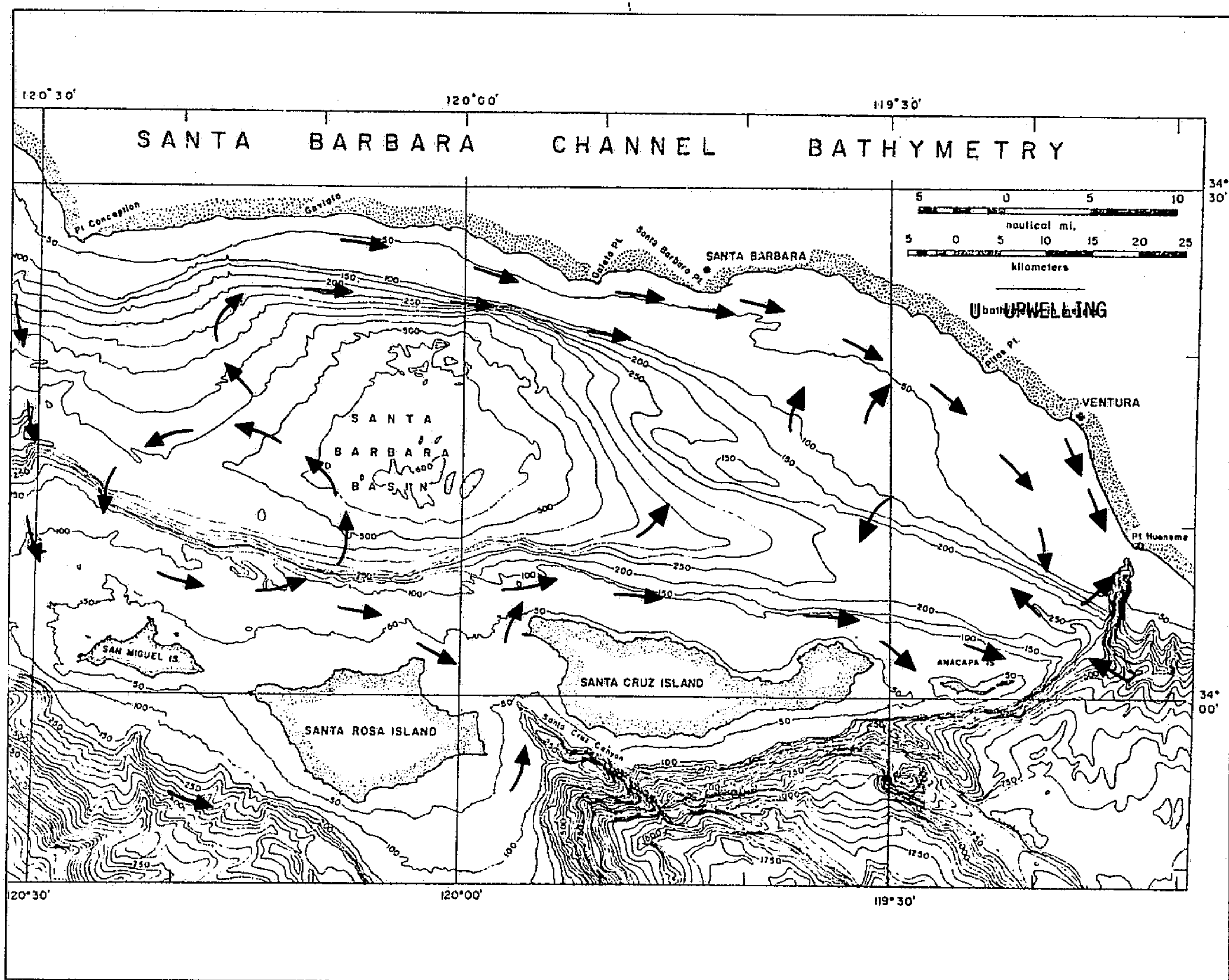

Figure 3-6 Oceanic Current Period - Santa Barbara Channel Composite

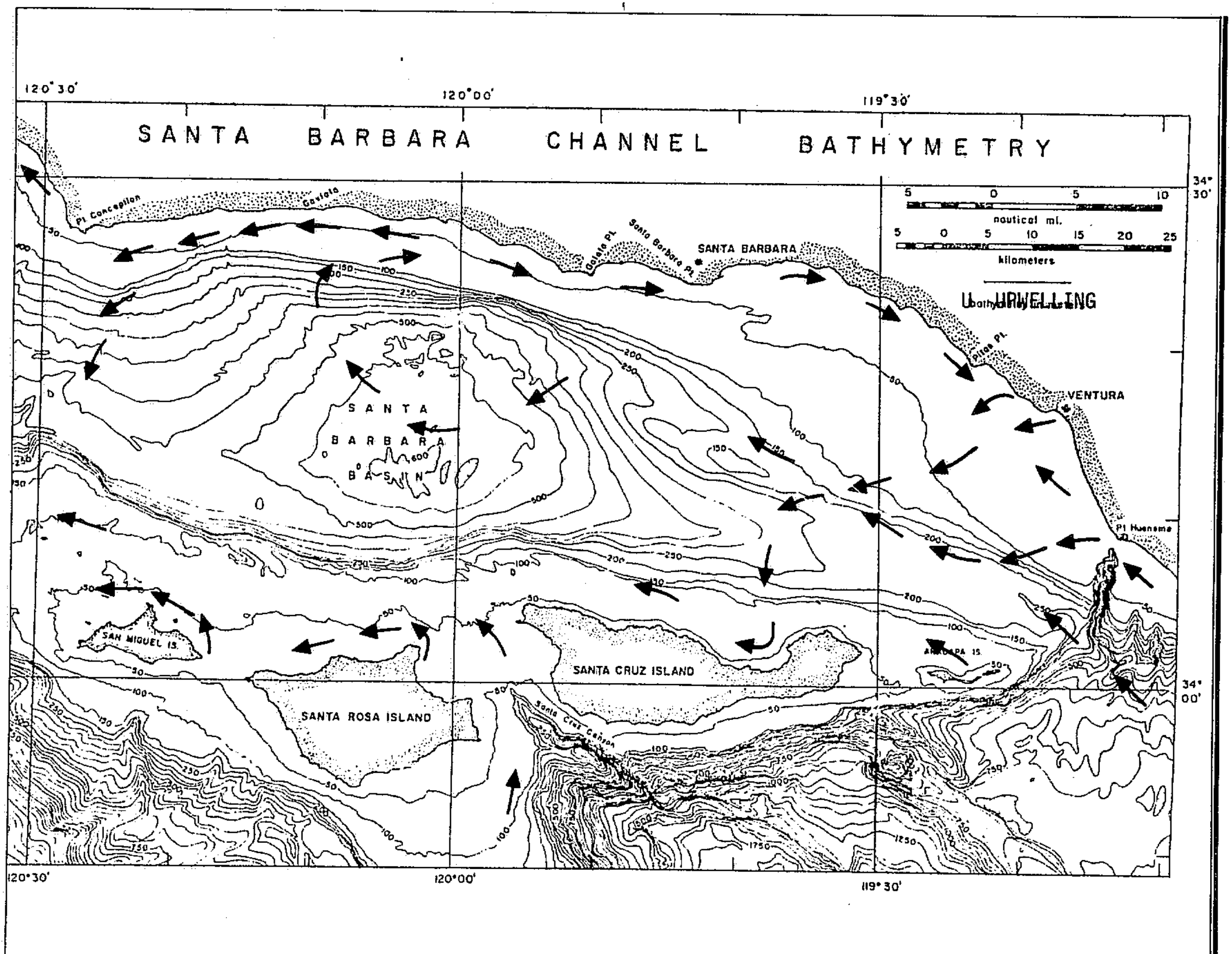

Figure 3-7 Davidson Current Period - Santa Barbara Channel Composite

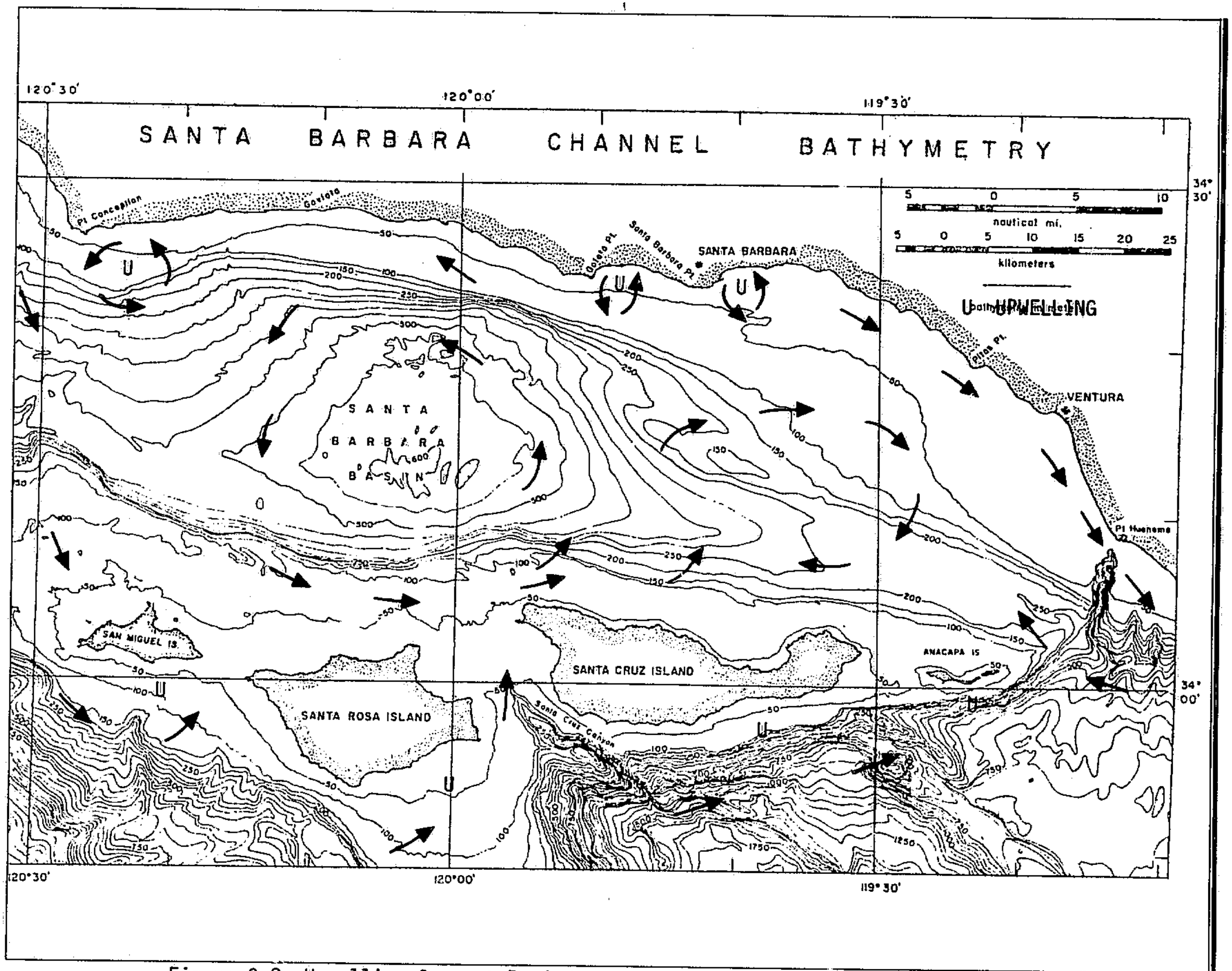

Figure 3-8 Upwelling Current Period - Santa Barbara Channel Composite

Sea truth surveys across the Santa Barbara Channel from Channel Island Harbor to Anacapa Island indicate complex current and transport patterns. These patterns were confirmed on the May 1976 Landsat imagery. A west moving current in the center of the channel is bracketed by east moving currents along the coast and Anacapa Island. This movement pattern was further complicated by a gyre near the coast.

Landsat imagery presents a readily available means of positioning oceanographic stations for collecting base line information at optimum locations. These locations can be positioned according to the investigators needs (i.e., plankton, sediment transport, current velocity or pollution) rather than merely in a grid pattern as has been the common previous practice.

There are complex gyres often present off the Ventura area. The sea truth measurements confirmed lenses of sediment which were probably transported from the Ventura or Santa Clara Rivers to the offshore ocean stations. A counterclockwise gyre often results from strong Anacapa Current action trending westward or opposite to the east moving waters in the channel.

3.5 REFERENCES

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4.0 MONTEREY BAY CURRENTS

Monterey Bay is a unique and beautiful feature of the California coast. It is not surprising that many of the residents of the communities bordering the bay are concerned with maintaining their lovely environment. Proposals or plans to modify the environment in any way become the subject of a great deal of public interest and discussion. Disposal of sewage from the area is no exception. Concern with the existing arrangements for sewage disposal became increasingly evident during the late sixites and led to several of the cities of Monterey Bay forming the Monterey Peninsula Water Pollution Control Agency for the purpose of planning and implementing new sewage treatment and disposal systems. Concern for river borne sediment and pollutants, thermal discharge patterns and harbor circulation is also evident in the planning organizations of the Monterey Bay area.

To best position future outfalls and manage resources, all planning agencies require a knowledge of the Monterey Bay water circulation patterns. The purpose of this study is to extend the knowledge of the surface water circulation of Monterey Bay by building on the previous nearshore oceanographic studies of numerous investigators with the relatively new tool of remote sensing data interpretation. Known literature on Monterey Bay circulation has been reviewed, compared and is presented and followed by a description as viewed from space with Landsat imagery, high altitude or U-2 aircraft data; and mid-altitude Army, NASA, and commercial aircraft imagery. The authors believe that the remote sensing analysis of the various Monterey Bay circulation seasons, although probably not 100% correct, present as good an evaluation of the generalized current systems as is now available. However, since our current descriptions have not been rigorously field checked, they should be used with caution.

4.1 DESCRIPTION AND SEASONS

Monterey Bay is a nearly semi-elliptical embayment (see Figure 4-1) on the coastline of central California. It is approximately 35 km (21.7 miles) long from north to south and has a maximum indentation into the open coast of about 18 km (11.16 miles).

The bay is an area of wide flat continental shelf bisected by the deep intrusion of the Monterey Submarine Canyon which has its head very close to shore off Moss Landing. It can be considered to be composed of three physiographic units: the northern and southern shallow shelves and the canyon. The shallow regions are less than 100 meters (328 feet) deep and exceedingly flat while the submarine canyon has very steep sides and reaches depths of over 1,500 meters (4,920 feet) within the bay. The presence of the canyon allows deep oceanic water access along the center of Monterey Bay.

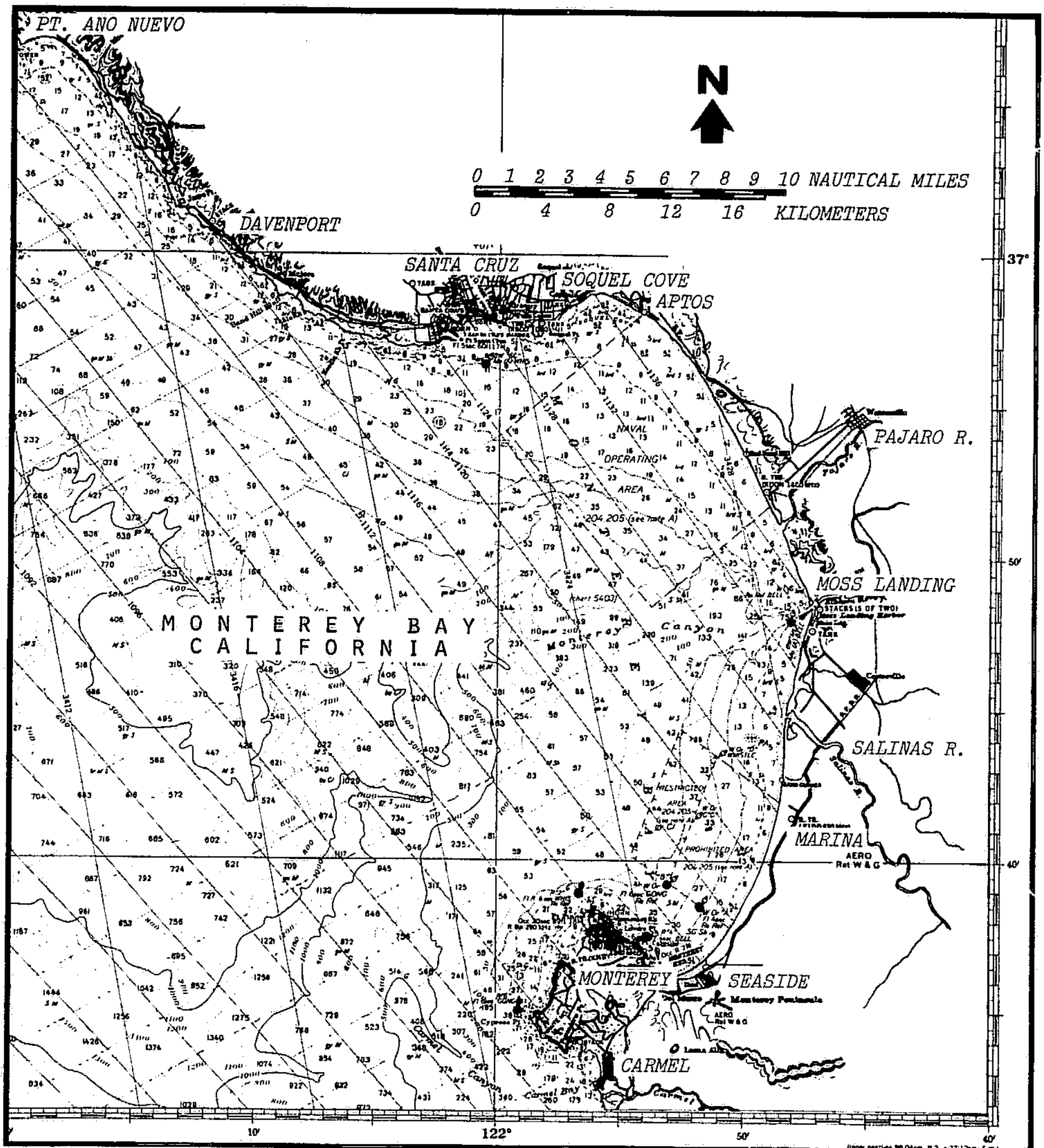

Figure 4-1 Monterey Bay Location Map

Water movements at a specific nearshore location result from the complex interaction of a number of factors: the nearshore component of the main ocean circulation pattern; local wind-driven currents; tidal currents; wave-induced longshore currents; and rip currents.

In the context of riverborne silts and ocean outfall location, wave-induced longshore currents and rip currents are of minor importance because they are primarily restricted to the surf zone. Tidal effects are of little importance because of the exposed nature of the greater part of Monterey Bay, which precludes the development of strong tidal currents beyone one km (.62 miles) from shore. Some investigators (Dooly, 1968; Gatje and Pizinger, 1965; and Njus, 1968) have found that the currents near the bottom at the head of the Monterey Submarine Canyon offshore of Moss Landing were related to the tidal stage and flowed down canyon during flood tide and up canyon during ebb tide. However, Glenn and Webb (1966) could find no relationship between surface longshore currents near the head of the Monterey Submarine Canyon and bottom currents in the canyon head, and could find no relationship between the longshore current measured at Moss Landing and the direction of tidal flow.

Skogsberg (1936) made the first comprehensive oceanographic investigation of the circulation regimes in the Monterey Bay. He occupied 23 stations located in the bay, taking measurements of temperature, salinity, and other chemical parameters. From his study, he was able to divide a year into three oceanographic seasons. These have been standarized as the Upwelling Period, the Oceanic Period, and the Davidson Current Period. Bolin (1963), in a study of one station over the Monterey Submarine Canyon for a five-year period, confirmed Skogsberg's work and refined the definition of these oceanographic seasons. Present opinion among physical oceanographers is that the concept of oceanic seasons is somewhat arbitrary in view of the observed variability of ocean conditions and the time of occurrence from year to year. However, the generalizations do presist.

Skogsberg's exhaustive study of thermal conditions prevailing in Monterey Bay from 1929 to 1933 showed that, due to the open nature of the bay, water movements in a large part of the bay are similar to those at open coastal locations. Water masses moving either north or south along the coast pass through the outer bay in the form of large eddies. Relatively small, closed eddies are formed close to Monterey Harbor and at Soquel Cove. Thus the nearshore component of the main ocean circulation pattern and local wind-driven currents are the principal factors determining the current regime of the Monterey Bay area (Engineering-Science, Inc. 1976). Drift card studies in Monterey Bay (Blaskovich, 1974; Griggs, 1974) show that the surface flow traced by drifters follows the wind almost directly at about three to four percent of the wind speed.

The prevailing winds in the area tend to correspond with the direction of the Oceanic Current. During the Davidson period, the prevailing winds are from the south or southwest while during the rest of the year, when the California Current dominates, the coastal circulation, north or northwest winds predominate.

It is expected that rotary tidal currents occur in the bay, but they have never been measured in situ. The tides exhibit a diurnal inequality with a mean range from mean high water to mean low water of 1.16 meters (3.80 feet) and a diurnal range between mean higher high water and mean lower low water of 1.68 meters (5.51 feet).

In this section the oceanic seasons have been averaged over a number of years, and for an individual year the time of onset and termination of these seasons may vary by as much as a month or two due to changes in the driving forces that cause them.

The Upwelling Period in Monterey Bay generally begins in mid-February or March and extends to late August or early September. Upwelling reaches a maximum in April or May and begins to decrease in June. The Upwelling Period is characterized by the ascending of cold subsurface water from depths as great as 150 meters (492 feet) causing the depths of the various isotherms to become shallower. The surface water temperatures are between 10° and 11° C in much of the bay.

The Oceanic Period tends to be rather short, usually occuring from September to mid-November. It is characterized by a strong vertical temperature gradient in the upper 100 meters (328 feet) and the highest sea surface temperatures of the year reaching over 13° C. Both the Upwelling and the Oceanic periods are associated with the southerly flow of the California Current along the coast.

From mid-November to mid-February or March the northward-flowing Davidson Current is in effect. During this period, the countercurrent flows at the surface near the coast. There are some indications from CalCOFI or geostrophic computations (Wylie, 1966) and drift bottle results (Crowe and Schwartzlose, 1972) that there may sometimes be a northerly flow at the surface at other times of the year. During the Davidson Current period, the upper 50 meters (164 feet) tend to be well mixed with a weak vertical temperature gradient. Surface temperatures are usually lower than in the Oceanic Period, but not as low as those occuring during the Upwelling Period.

4.2 OCEAN CURRENT MODELS

Garcia (1971) developed a theoretical model of the circulation pattern of Monterey Bay using the shear flows of the ocean currents that occur off the bay as the sole driving mechanism. The open coast circulation varies throughout the year in a manner described by the three oceanic seasons, as discussed previously. Accordingly, the bay circulation was expected to respond seasonally as well.

During the Upwelling Period and the Oceanic Period, the offshore current flows southward along the coast. Collectively, these two periods are called the California Current season after the predominant offshore current. During the Davidson Current season, the offshore current flows toward the north.

The southerly California Current was expected to produce a counterclockwise circulation pattern in the bay. Either a single gyre or a two gyre pattern appeared probable. Because of the symmetry of the bay, the division between the two gyres was expected to occur in the area of the Monterey Submarine Canyon with a northern gyre flowing in the same direction as the southern gyre.

The circulation in the bay during the Oceanic Period was expected to be different from that occurring during the Upwelling Period even though the offshore current direction was the same. The lack of upwelling during the Oceanic Period and the associated decrease in the intensity of the northwest winds along the Pacific coast were important in causing a difference in the bay circulation between the Upwelling and Oceanic Periods.

The northward flowing Davidson Current was expected to cause the water in the bay to circulate in a clockwise pattern. For this time of the year either a single or a two gyre pattern was expected.

These shear-flow driven models have been adopted as the most probable general circulation patterns expected to occur seasonally in Monterey Bay and were used as a guide in interpreting drift bottle studies, drogue studies and remote sensing reaearch.

4.3 DRIFT BOTTLE STUDIES

In order to examine the variations of Monterey Bay current seasons, Reise (1973) conducted bottle drops that were divided into three groups that were to represent the oceanic seasons. The time limits of the seasons were categorized according to the expected times of the seasons and supported by the results of the CalCOFI drift bottle study (Crowe and Schwartzlose, 1972) and a geostropic current study (Wylie, 1966) for the period of time of the drift bottle survey.

Drift bottle results for the Upwelling Period indicated a variable current along the northern shore of the Monterey Peninsula. The current turned northward and flowed upcoast from Monterey Harbor. There was a separate circulation in the northern bay.

The circulation along the coast was similar to that predicted by Garcia's model if extended to the nearshore regions. The model predicted a counterclockwise gyre or two counterclockwise gyres when a southerly current flowing offshore as occurs during the Upwelling Period.

Drift bottle results from the Oceanic Period suggested that the current in the southern bay was in the same direction as during the Upwelling Period, but with a weaker circulation. The bottle drift in the southern bay suggested a counterclockwise current pattern along the shore similar to that predicted by Garcia's shear-flow model. The returns from the northern bay were too few to indicate whether or not a separate current gyre existed there. The returns to the north of the bay suggested that the Davidson Current may have been present part of the time.

The drift bottle results from the Davidson Period appeared to fit Garcia's ocean current shear model as a description of the movement along the coast of the drift bottles. A clockwise current pattern with a southerly current along the coast which turns west and flows along the north shore of the Monterey Peninsula appeared to exist and suggested a two gyre model with one gyre in the northern bay and the other in the southern bay.

During the Davidson Period, the surface circulation seemed to be contained within the bay since few bottles left the bay. Those that did were only transported as far as the seaward side of the Monterey Peninsula. Also supporting the view of a relatively closed circulation was the fact that no bottles were found to the north of the bay even though the predominant direction of the offshore current was northward.

4.4 OTHER CURRENT STUDIES

While it is difficult to compare measurements made using different methods and done at different times, there are several studies of the circulation in or near Monterey Bay which are useful for comparison with the results of this study.

A current drogue study was done by Stevenson (1964) in the southern part of Monterey Bay. Stevenson observed the simultaneous movement of drogues at depths of 0.6, 1.2, 2.5, and 4.3 meters (1.97, 3.94, 8.2, and 14.0 feet) for periods not exceeding six hours. He conducted two surveys in August and October 1963 and eight more between January and March 1964.

Stevenson found his drogues to move in directions to the right of the wind for wind directions other than northwest. For moderately strong southwest winds, his drogues moved substantially to the left of the wind direction.

In a period of light winds during the Davidson Period. Stevenson's results show the drogue tracks to be much farther to the right of the wind than would be expected for pure wind drift. The extra movement to the right may have been due to the clockwise gyre predicted by the Garcia model for this time of the year. These results are interpreted here as wind drift superimposed on the oceanic component driven by the Davidson Current. It is considered that the diminished wind drift due to weak winds allowed the oceanic component to be more visible than at times of stronger winds. It was concluded in both Stevenson's study and in drift bottle studies that, except during periods of calm, the dominant driving force of the surface circulation is the wind in the shallow waters of the bay.

Stoddard (1971), in a study to test the feasibility of shore-based radar in tracking current drogues in Monterey Bay, released a total of 41 parachute drogues. The drogues were set at a mean depth of about 14 meters (46 feet) and were tracked for periods of 6 to 20 hours and occasionally longer. Most of the drops were in the southern bay, but a few were in the northern bay and some seaward of the bay. The period covered in his study was from August to November, 1970. Current speeds measured by the drogues were generally between 0.1 m/sec to 0.2 m/sec.

Stoddard's results seem to indicate a clockwise pattern in the bay during the Davidson Current period and a counterclockwise gyre during the time of the California Current. The oceanic current prevalent at these times were determined from drogues tracked seaward of a line between Santa Cruz and Point Pinos. He concluded that the oceanic currents were probably the dominant driving force of the bay circulation, with the possibility of tidal forces being important in the shallower regions of the bay. It should be noted that at the depth at which drogues were placed the wind-driven effect was probably weak except at times of sustained high winds. It may thus be expected that the effects of the ocean currents should dominate the current pattern. Stoddard's results generally agree with the bay circulation model of Garcia and the drift bottle observations.

Drogue studies were also carried out by personnel of the Naval Postgraduate School and from the Association of Monterey Bay Area Governments (AMBAG) from June to August, 1972. In two drogue studies in June and July, a clockwise circulation was indicated for the southern bay. This is opposite to the counterclockwise circulation which is predicted by Garcia's model for the southerly oceanic current expected for this time of year. Drogues tracked in the northern part of Monterey Bay in early August indicated a counterclockwise circulation cell in the northern bay, with flow out of the bay along the northern coast past Santa Cruz and to the northwest. Drogues tracked in late August in both the northern and southern bay appeared to indicate a counterclockwise gyre for the whole bay with flow out of the bay to the north.

In June and July, as stated, the results were contrary to Garcia's model if the direction of the ocean current flowing along the open coast were southerly. The supposition of a southerly ocean current during these months may have been incorrect for 1972 since variability has been shown to exist from year to year by the CalCOFI drift bottle study (Crowe and Schwartzlose, 1972). Three of the four AMBAG drogue studies appeared to indicate a two gyre current pattern while the other defined a single gyre for the whole bay. The average speeds were similar to those obtained from the drift bottle results. the AMBAG drogues were designed to show the influence of ocean currents, as Stoddard's results did, rather than wind-driven transport.

A regular CalCOFI drift bottle station was located in the seaward edge of Monterey Bay off Santa Cruz (Crowe and Schwartzlose, 1972). Upon occasion, drift bottle returns from this station suggested a counterclockwise circulation pattern extending from Monterey Bay to Ano Nuevo Point or possibly further north. The drop of April 1976 appears to be a good example of this. Five to twelve days after being dropped, bottles were found along the coast north of Santa Cruz to be about 80 km (49.6 miles) south of San Francisco. Bottles from the same drop were found in southern Monterey Bay 37 to 94 days later. The oceanic current at that time appeared to be directed southward according to the returns from other nearby drop stations.

Lammers (1971) and Moomy (1973) deduced the geostrophic circulation of the bay from the temperature structure of the water. Lammers' results appear to agree with the Garcia's proposed bay circulation pattern for October through April, but differ for the period of May to September. Moomy's results for geostrophic currents determined from surface segment values appear to agree with the current gyres predicted from Garcia's model during all three oceanic seasons, with the drift bottle study, and with a number of the AMBAG drogues tracked at the same time as Moomy's study.

The methods used by Moomy and Lammers may not work at times due to failure of the assumption for geostrophy. Salinity variations, which were not considered by Lammers, can significantly affect the determination of geostrophic currents. Additionally, Monterey Bay surface currents are weak and may be perturbed by local winds, bottom topography, or tidal forces. Changes in offshore eddies or meanders may also cause these approaches to circulation determination to be misleading.

4.5 WIND

The seasonal wind regime on the California coast, including the Monterey Bay area, is reflected in the seasonal offshore current patterns. When considered on a short-term basis, the winds blowing over Monterey Bay are variable in speed and direction in response to the changing synoptic weather conditions and to the local sea-land breeze circulation in the vicinity of the coast. These local winds create wind-driven currents in the bay of a relatively transient nature. It is to the transient systems that the following discussion is directed.

The dominant wind direction in Monterey Bay, as on most of the California coast, is from the northwest. This may be attributed in large part to the presence of the quasi-permanent subtropical high pressure cell that is centered off the California coast. In addition, a diurnal pattern of onshore-offshore winds is present along the Monterey coast during most of the year. The stronger afternoon seabreeze component is characteristically from the northwest while the low wind speeds found at night and in the early morning are usually offshore.

The Ekman wind-drift model predicts that in the absence of a coastal barrier, a water mass will tend to move in a direction 45 degrees to the right of the wind in deep water in the northern hemisphere. As the water gets shallower, the angle diminishes until for shallow depths the water moves in the direction of the wind. The water depth is actually a relative depth governed by the wind speed, so that as the wind speed increases the relative depth becomes smaller (Neumann, 1968).

The angle between the current direction and the net wind direction over intervals has been determined. Careful examination of the data showed that southern Monterey Bay currents moved significantly to the left of the wind (by as much as 80 to 100 degrees) when associated with a northwest wind direction and that for other wind directions current drift was generally approximated by the Ekman model. It is hypothesized that a northwest wind induces a strengthening of the northward longshore flow in the extreme southern end of the bay.

The components of the bay currents caused by winds and by the offshore currents may act to reinforce or oppose each other. Reinforcement appears to occur frequently in the southern bay for northwest winds during the months when the California Current flows along the outer coast. Winds seem to be the primary cause of transient surface currents in southern Monterey Bay.

In summary, although the effect of the Garcia-type model is evident, the apparent direction of current movement in the bay is determined by the wind direction much of the time.

4.6 WAVES

For the case of wind waves, it appears from Stokes third-order theory that the surface transport due to waves is less than a tenth of that produced by the wind (Wiegel, 1964, pp. 324). Accordingly, the mass transport due to wind waves may be considered a part of the wind-driven transport. It is therefore considered that winds alone effectively represent the combined effects of waves and wind in moving the surface water.

4.7 TIDES

Tides can be an important current-causing force in coastal waters. Tides in Monterey Bay, as for most of the Pacific coast of the United States, are of the semi-diurnal mixed types. This pattern of tides leads to a rather complicated pattern of tidal currents. Tidal currents on the open continental shelf in the northern hemisphere are rotary, turning clockwise and completing a cycle every 12.4 hours. Because of the inequality of the tide heights and times, the two tidal current cycles per day differ in their speeds and their rate of change of direction. However, from one day to the next, the diurnal pattern approximately repeats itself so that little net tidal transport of water occurs. Tidal currents of this character occur off the entrance of San Francisco Bay and it is probable that a similar tidal current pattern exists in Monterey Bay.

No successful attempt at measuring the tidal currents over the broad shelves of Monterey Bay has been made, although tidal currents with velocities of up to 0.5 m/sec have been observed in the Monterey Submarine Canyon (McKain and Booenkow, 1972). Tidal current tables for the Pacific coast describes the tidal currents in the bay as weak and variable. Lazanoff (1971), in an unsuccessful attempt to verify Hansen's hydrodynamic-numerical model for Monterey Bay, concluded from his examination of current data that he could make no direct statement about tidal current velocities and directions, but suggested that the currents are probably less than 0.05 m/sec.

From Dorman's (1968) drogue study results it appears that tidal currents are not an important factor in net long-term movement of the water in Monterey Bay, and therefore, because of their rotary nature, have a negligible affect on the average flow.

4.8 MONTEREY BAY CURRENTS FROM REMOTE SENSING DATA

From the preceding sections it may be observed that the Monterey Bay surface current circulation system is complex, difficult to model and poorly understood. Utilization of the remote sensing imagery of

Monterey Bay was undertaken to clarify the mixture of models and study results and to present a qualitative picture of the generalized seasonal current systems observed during the time period from October 1971 to June 1976. Flights over the site on 102 separate occasions produced data appropriate for current studies. Of these, 74 were from the Landsat satellites, 17 from the NASA U-2 aircraft and 11 from either NASA or commercial mid-altitude aircraft. Because of film density and spectral selection characteristics of the Landsat satellites only 18 images could be considered excellent in current evaluating quality. However, 13 of the 17 U-2 flights produced excellent current presentations as did 9 of the 11 mid-altitude aircraft flights. It was found that a high resolution color film filtered to be dominant in the yellow range of the visible spectrum and overexposed at least two f-stops over the normal land exposure produced the best current images for film products as did the 0.5 to 0.6 micrometer channel of the Landsat multispectral scanner.

Imagery selected for analysis represented all three oceanographic seasons with an assortment of wind and wave conditions. Seasonal sets were produced and from these sets, three currents charts (Figures 4-2 to 4-4) were developed to represent the generalized current patterns expected to be produced at the height of the particular season. The U-2 photographic imagery was found to be best suited to this site study because of its scale characteristics (1:130,000) and resolution. Landsat imagery was best suited to oceanic processes that affected the bay's circulation.

During the Monterey Bay Oceanic season, surface currents were observed to be dominated by the driving force of the California Current. Two large counterclockwise gyres were commonly observed to be split by the Monterey Submarine Canyon with a smaller third clockwise pattern directly off of Moss Landing Harbor. Drift along the northern side of the Monterey Peninsula varied from eastward to westward and divergence of currents between Marina and Seaside and off the mount of the Pajaro River were common. Convergent currents near the Salinas River mouth and most coastal points were also frequently observed. The Oceanic season plot (Figure 4-2) seems to agree well with the primary results of the drift bottle study as well as the drogue studies. Also it can be seen that the dual gyre circulation could be misconstrued to be a simple gyre because of the Moss Landing cell transport link.

All currents observed during the Oceanic season seemed to be rather weak with wind effects present but transitory. Red Tide conditions were observed during the Oceanic Period and may have resulted from the poor circulation of the surface waters coupled with the influx of nutrients and solar heated surface layers. Circulation was minimal off Seaside during October 1971 when large blooms of Red Tide were imaged (Figure 4-5).

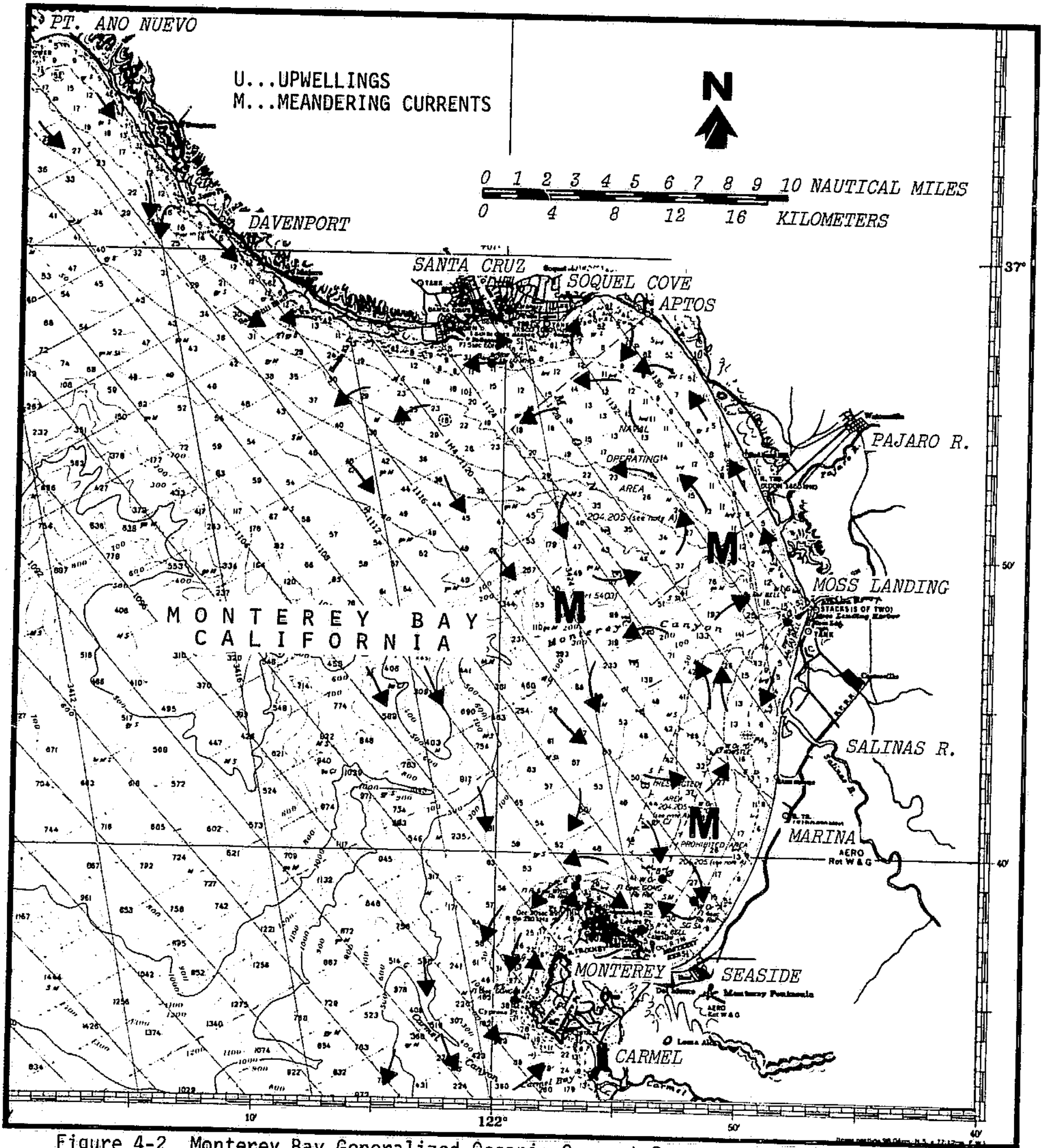

Figure 4-2 Monterey Bay Generalized Oceanic Current Season - Surface Currents

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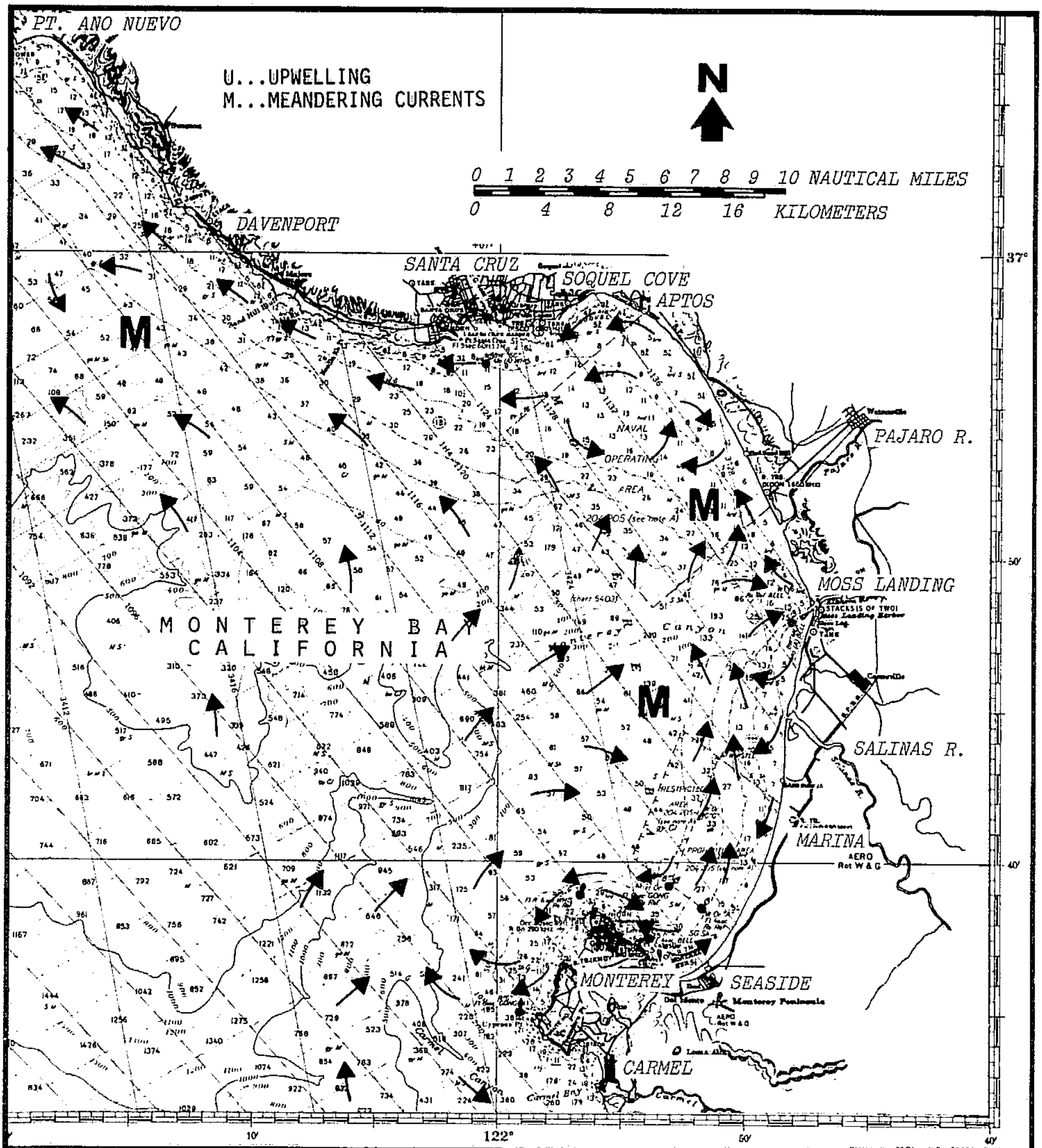

Figure 4-3 Monterey Bay Generalized Davidson Current Season - Surface Currents

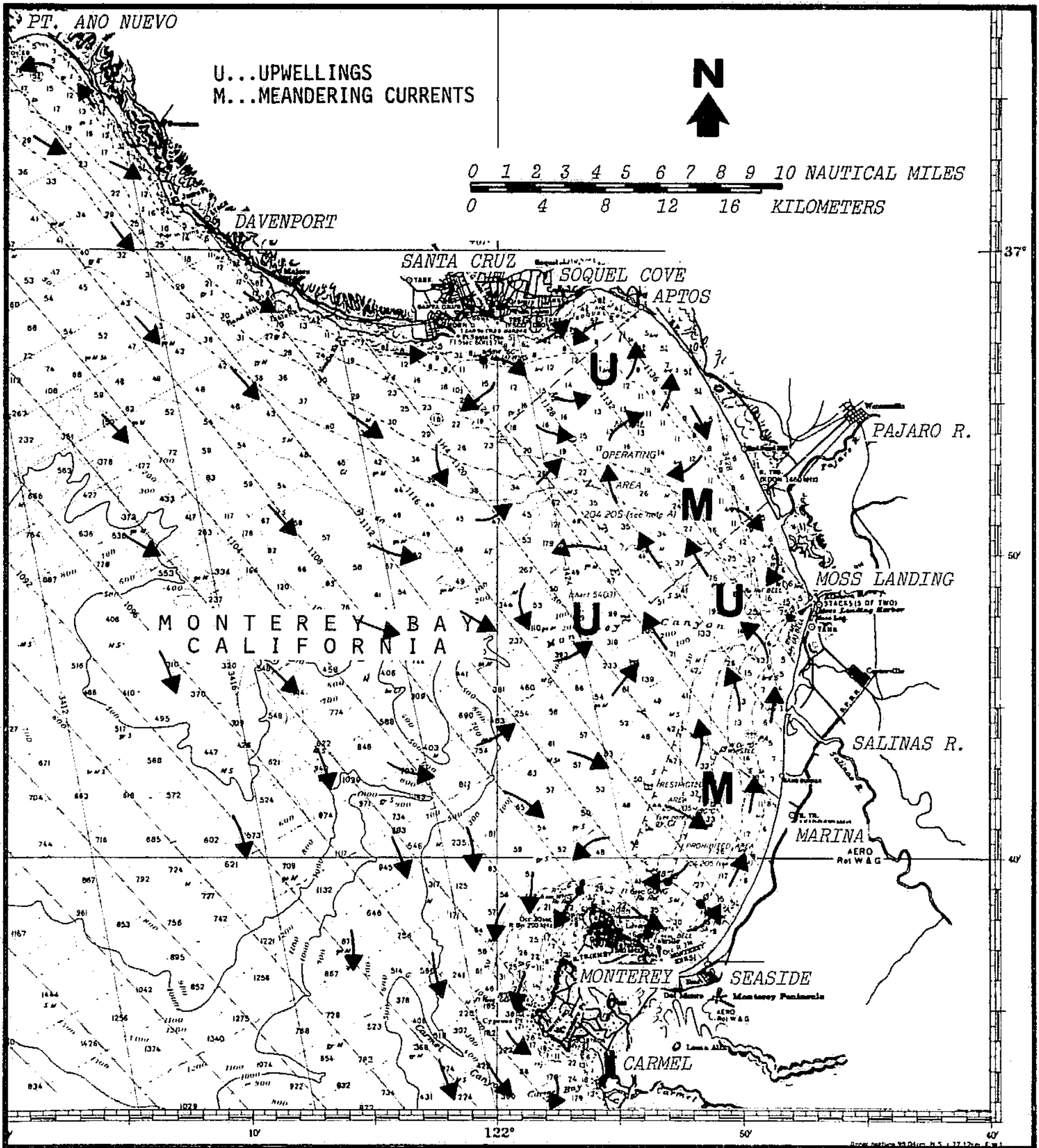

Figure 4-4 Monterey Bay Generalized Upwelling Current Season - Surface Currents

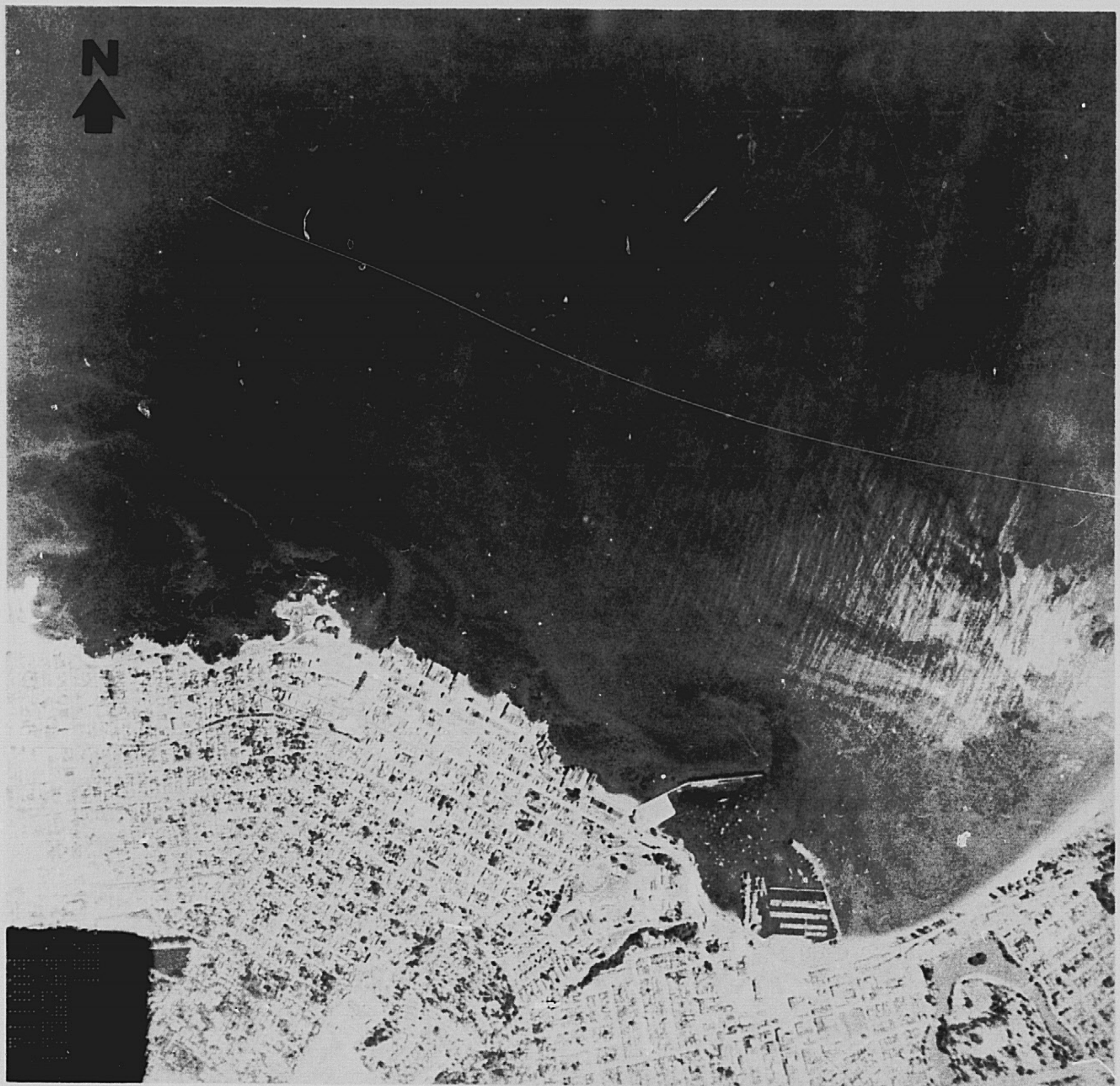

Figure 4-5 Southern Monterey Bay and Monterey Harbor Area Imaged on 4 Oct 1971, from NASA Mission 186, Altitude of 10,000 Feet. Original Photography was in Yellow Filtered Color and Defined Currents, Sediments and Red Tide Bloom.

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The Davidson Current season during winter is represented by Figure 4-3. This season finds Monterey Bay currents being driven by a northward flowing coastal current that protrudes into the bay. Inshore of this current, three gyres form, the most massive of which is present off Moss Landing Harbor. Because of the high velocity of both north and south winds expected during winter conditions, Ekman wind-drift phenomena linked with the driving power of the Davidson Current produce clockwise cells in the inner eastern portion of the bay. The Monterey Submarine Canyon plays an important part in the development of the Davidson season circulation by channeling a high volume of water deep into the bay. A high correlation exists between current plots and bathymetry. Figure 4-7 shows Pajaro River sediments.

This description of the Davidson currents in Monterey Bay tends to disagree with earlier field investigation. The clockwise circulation in the southern end of the Bay is similar to that expected by Garcia and Stoddard but the northerly tending flow (Figure 4-6) seen off of Moss Landing and the Salinas River is opposite to their predictions. The weak counterclockwise circulation off of Soquel and the meandering streams off the mouth of the Pajaro River were also unexpected. Both the Pajaro's and the Salinas' mouths are at locations where meanders and tidal influenced currents were observed in the imagery. See Figure 4-6 for a late Davidson season Landsat image.

The Upwelling season (Figure 4-4) is of importance to the bay because as the southward flowing California Current establishes itself in spring and summer and the north and northwest winds freshen, upwelling of cold and nutrient rich water occurs over the submarine canyon and off of Aptos. In the aircraft imagery the vertically moving waters appear darker than the normal surface waters with wave-like rings being common. The three upwelling areas presented on the Upwelling season current plot have been observed from Landsat as well as by mid and high altitude aircraft and surface measurements. The principal current trends are the formation of gyres similar to those of the Oceanic Period but shifted to the north and stronger. The authors interpretation of the current directions during this season is different from and more complex than the previously referenced results. Generally, the mass transport of water seems to be in the bay south of the canyon, entrapment and gyres in the north bay, and exiting near the Monterey Peninsula. The wind does seem to play an important role in the transport of south bay water up into the north bay with the primary divergence being offshore of Marina.

4.9 CONCLUSIONS

The nearshore surface currents along the coast of California have been seriously studied by numerous investigators for the last fifty years. Early investigators could only obtain localized current data, and spatial and temporal characteristics were inferred by

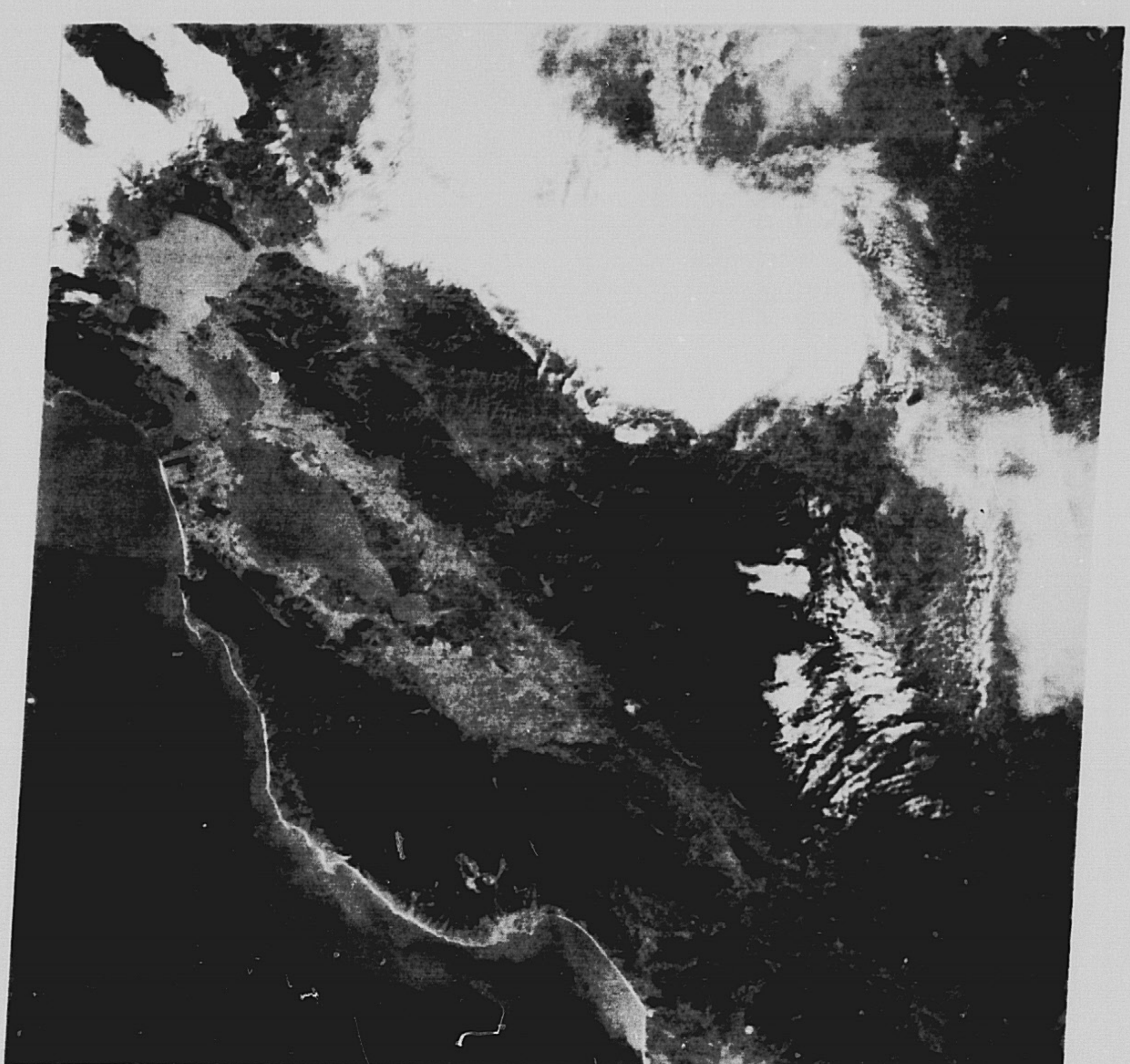

Figure 4-6 Landsat Satellite Image 1183-18175-4, 22 Jan 1974, of California Coast from San Francisco to Monterey.

Figure 4-7 NASA Ames U-2 Photograph of Moss Landing Area.

Image taken on 4 April 1974. Upper sediments are from the Pajaro River, darker center sediments are from Moss Landing harbor, and lower sediments are from the Salinas River.

assembling mosaics of local observations. Within the last few years, aircraft and satellite remote sensors have obtained the synoptic picture with respect to nearshore surface currents along the coast of California. Recently evolved techniques applied to the expanding data bank of imagery afford greater definition of sea surface dynamics.

In this section we have demonstrated the capability of different sensor systems to be utilized to define the oceanic and nearshore surface currents. At this time we do not know that what we have observed can be stated to be 100 percent correct in its generalized content. However, we do feel that the observations and analyses performed for the California nearshore current seasons make up as good an evaluation of the nearshore currents as found anywhere. We recommend the use of the remote sensing tool, especially high resolution satellite and U-2 imagery, for any nearshore study where large spatial reaches are to be observed. The questions raised as to the absolute velocities and directions of our coastal currents will only be answered after much more surface data is taken and compared with additional aircraft and satellite imagery.

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5.0 SAN FRANCISCO BAY AREA

The waters of San Francisco Bay and adjacent coastal areas are used by millions of people. These include not only those who inhabit the area but visitors from around the world. These people use the bay for recreation, commerce, municipal and industrial sewage disposal, and as a source of aesthetic pleasure. Keeping the quality of the water in a state that will continue to be compatible with these uses is essential to the people. In investigating the literature on the bay area it is obvious that many and detailed studies have been accomplished both before and during the advent of Landsat. What is also obvious is that the detailed reports often required time consuming and expensive data collection and survey methods. This applies to methods ranging from collected sediment samples from the mud flats, water and gravel samples from shipboard, to photography from aircraft. The major problem with each of these methods is that during a point source data collection operation concerning water processes, some feature or parameter was changing in other parts of the bay. The repeatable Landsat imagery shows the Bay and offshore waters all at one instant of time. Even with the resolution restrictions, these Landsat images present a powerful tool to the investigator. One of the other advantages is that surface parameters are "frozen" at one instant of time for later analysis. This is not a new tool since aerial photography has provided such information for years. What is new is the large area covered and the repeatability of the satellite (Figure 5-1).

The major usable feature which is visible on the Landsat imagery in the bay are the patterns of suspended sediment in the surface and near surface waters. These patterns change as a result of, or are influenced by, fresh water discharge, tidal cycle, bottom topography, wind action, currents and to some extent sanitation and waste water discharges. In Landsat bands 4 and 5 the materials in the water are clearly detectable. The band 4 imagery was the most useful in detecting the maximum amount of sediment because of the water penetration capability of this blue green band. This allows the viewer to analyze the surface patterns and subsurface features down to 10 meters (32.8 feet) (Polcyn, 1973). Two problems are associated with the band 4 imagery which must be considered during evaluation. The problem of determining the depth of the features that the viewer is evaluating must be appraised. Is the patterns of sediment transport on the surface or further down in the water column? Possibly the pattern extends from the surface beyond extinction depth. Part of the answer to this problem can be answered by utilizing band 5. Band 5 is useful for detecting the surface and nearsurface suspensate and can be compared with band 4 to differentiate the deeper materials.

Figure 5-1 Offshore San Francisco

The complex offshore sediment plumes resulting from heavy river discharge. South of Pt. Reyes a counterclockwise gyre is present. NASA/Landsat 2432-18074-4, 29 Mar 76.

5.1 CIRCULATION AND PARTICULATE INPUT

More than 90 percent of the mean annual river discharge (840 m^3/sec) entering San Francisco Bay system is contributed to north bay by the combined inflows of the Sacramento and San Joaquin rivers (Carlson et.al. 1975); about 5 percent is contributed directly into south bay by the small local streams. This mean annual discharge, 4 m^3/sec, is less than that of the wastewater flows, 10 m^3/sec (220 million gallons/day), contributed directly into south bay by the heavily populated surrounding communities (Hines, 1973). High river runoff occurs during the winter months and reflects the high precipitation in the surrounding drainage basin.

The diurnal tidal range varies from 1.7 meters (4.13 feet) at Golden Gate to 2.7 meters (7.46 feet) at the south end of the bay system (U.S. National Ocean Survey, 1976). Waves generated in response to high winds and the long fetch within the south bay play a significant role in sediment transport. The observed frequency of wave heights of 0.5 to 1 meter (1.64 to 3.28 feet) is at least 50 percent (Conomos, 1963).

The water turbidity, expressed as Secchi disc depths, typically ranges from less than 0.25 meters (.82 feet) in the shallow areas to over 3 meters (9.84 feet) in the channels nearest Golden Gate. The high turbidity is partially caused by wind, wave and current resuspension of fine-grained sediment in the shallow areas. In north bay, river-borne suspended particles are a dominant factor in increasing the turbidity. In south bay, secondary sources of turbidity are the streams and sewage effluents, and low salinity high turbidity river water transported southward from north bay (McCulloch and others, 1970; Carlson and McCulloch, 1974).

Dilution of Pacific Ocean water by Sacramento-San Joaquin river discharge decreases the salinity and increases the turbidity in north bay. In south bay the small streams and wastewater flows have only local effects in decreasing the salinity. Water salinity varies greatly both spatially and seasonally. At Golden Gate, for example, winter salinities typically range from 18 to 26 $^{0}/_{oo}$ and reflect the high river inflows, while summer salinities are somewhat higher, ranging from 29 to 32 $^{0}/_{oo}$. Salinity stratification is present during winter (vertical differences of up to 10 $^{0}/_{oo}$) in most portions of the bay system. In the south bay during summer, however, little low-salinity water is present and the water column is well mixed by tidal currents and wind generated waves.

Water temperatures vary seasonally and are generally controlled by ocean and river water temperatures and insolation effects. In the channels, typical winter temperatures are 7 to 9°C; summer temperatures often exceed 20°C.

The circulation in the San Francisco Bay estuary is controlled by tidal and non-tidal water movements (Figure 5-2). In geometrically simple estuaries, unlike the San Francisco Bay, fresh water enters the estuary from one end and ocean water from the other. These waters are mixed by several processes within the estuary, principally by tides, and because the river discharge produces a net outflow of these tidally mixed waters, the estuary is flushed. The south bay does not enjoy this normal flushing pattern, for there is no large fresh water discharge at its head near San Jose. Instead the south bay is dependent upon water that enters it from the rest of the estuary system for its flushing. Tidal currents often in excess of 100 cm/sec (3.28 ft/sec), mix and move water which in turn transports and resuspends bottom sediments. Non-tidal circulation, generated by water density differences and wind is generally less than 10 cm/sec (.33 ft/sec). For describing this non-tidal circulation, the bay system can be divided into (1) a north bay -- central bay -- Gulf of the Faralloner region that demonstrates a permanent circulation cell typical of a partially mixed estuary, and (2) a south bay region that has seasonally reversing but sluggish near-bottom and surface currents (McCulloch and other, 1970; Conomos and others, 1971).

The fresh water discharge of the Sacramento River is the major control of the salinity and suspended sediment of San Francisco Bay. During years of high rainfall when the Sacramento River discharges is high, flushing significantly removes undesirable constituents from the south bay, but in low rainfall years the concentration of pollutants increases, sometimes reaching dangerous levels (Morse and others, 1968).

5.2 LANDSAT

The Landsat imagery from the San Francisco Bay area is summarized in Table 5-1. At times during the four years from which this imagery was taken, the sediment discharge into San Francisco Bay from the Sacramento and San Joaquin Rivers was so heavy it obliterated normal surface current patterns. This was the case in the spring of 1974. Of the 80 images reviewed, 47 had total or partial cloud/fog cover over San Francisco Bay. This is a common occurance at 10:00 AM in the San Francisco Bay area. Overall, however, the imagery provided a good basis for detailed analysis of the water surface in the bay and offshore waters. Flushing patterns are detectable as are complex gyres and eddies, wind effect and some man made features (effluent discharge). To the limit of resolution (80 meters or 262 feet) the Landsat imagery provides a detailed, instantaneous view not available to an investigator in any other way.

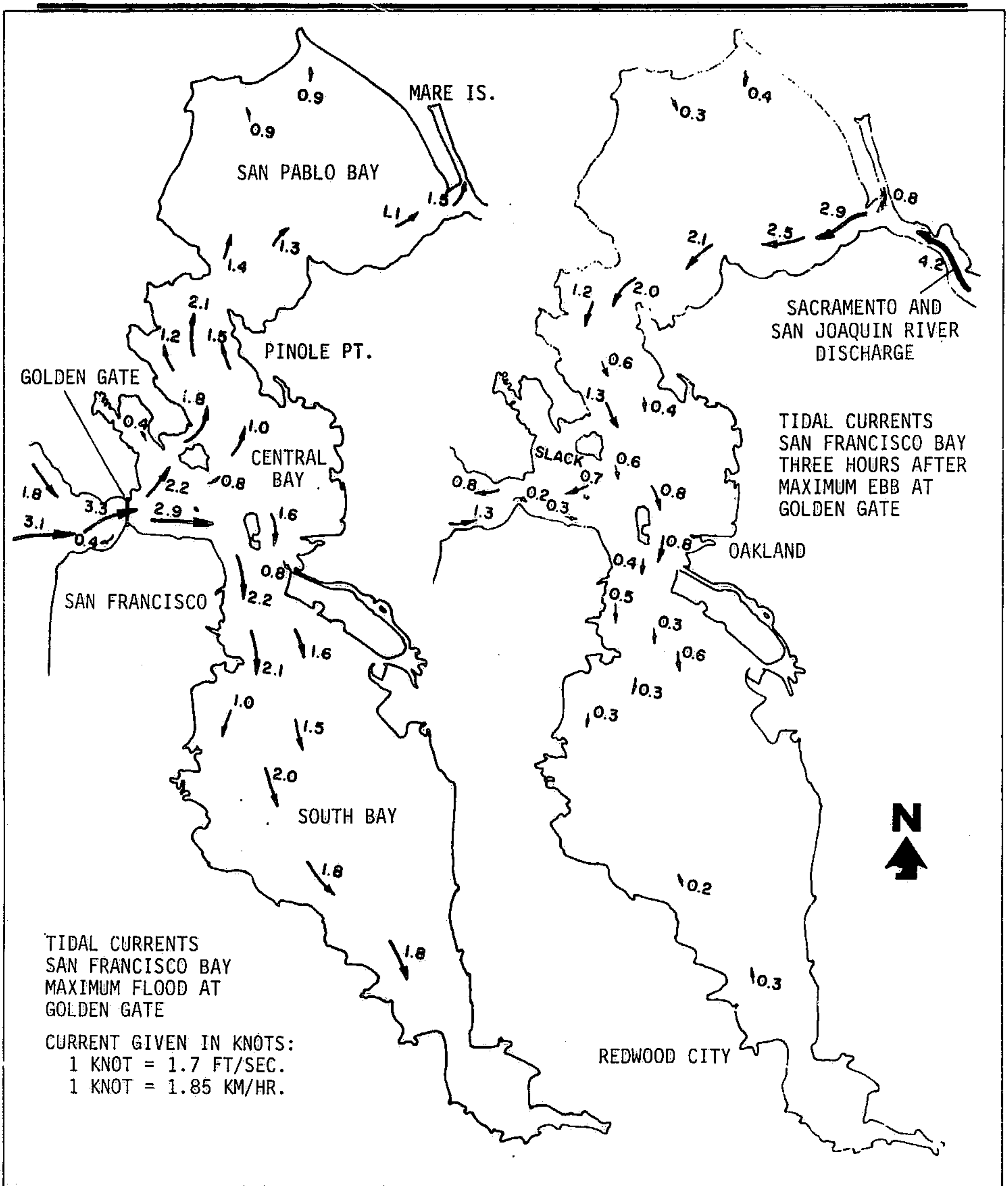

Figure 5-2 San Francisco Bay Tidal Currents (Smith, 1966)

TABLE 5-1

SAN FRANCISCO BAY AREA
LANDSAT COVERAGE

LEGEND

Mont. - Monterey Bay
SP Bay - San Pablo Bay
GG - Golden Gate
SF - San Francisco Bay
SB - South Bay
Seds - Sediment Transport

	LANDSAT ID	DATE	REMARKS
1	1003-18175	26 Jul 72	Clouds ocean, seds
2	1022-18230	14 Aug 72	Clouds
3	1039-18172	31 Aug 72	Minor seds, clouds
4	1075-18173	6 Oct 72	Clear, minor seds
5	1093-18173	24 Oct 72	SP minor seds, clouds central bay
6	1129-18181	29 Nov 72	Seds offshore, clouds SP Bay
7	1165-18174	4 Jan 73	Seds off GG, gyre off Ano Nuevo
8	1183-18174	22 Jan 73	Heavy seds, SF, Monterey Bay
9	1184-18234	23 Jan 73	Seds, clouds SP, Angel Island gyre
10	1238-18242	18 Mar 73	Excellent, large plume off Pt. Reyes, nearshore Pigeon Pt. seds
11	1255-18183	4 Apr 73	Excellent, large discharge plume off GG
12	1273-18183	22 Apr 73	Excellent, SP heavy seds, gyre Petaluma R.
13	1274-18241	23 Apr 73	Excellent, SP-lineation and entrainment patterns
14	1291-18182	10 May 73	Excellent, gyre Bolinas Bay, entrainments, plume GG, minor seds
15	1292-18240	11 May 73	Excellent, possible red tide Pt. Reyes to Devils Slide
16	1309-18181	28 May 73	Good sed patterns, clouds
17	1327-18180	15 Jun 73	Minor seds SP, Bolinas gyre, south bay flushing
18	1345-18174	3 Jul 73	Good patterns SF, especially south bay
19	1363-18173	21 Jul 73	Clouds GG, entrainment SP, south bay good
20	1264-18231	22 Jul 73	Minor seds, Bolinas gyre
21	1399-18170	26 Aug 73	Clouds offshore, Richmond entrainment

TABLE 5-1 (Continued)

LANDSAT ID		DATE	REMARKS
22	1436-18215	2 Oct 73	Seds SP, gyre Bolinas Bay
23	1489-18152	24 Nov 73	Excellent, seds SP, Berkeley Flats gyre
24	1525-18145	30 Dec 73	Excellent, heavy seds bay and coast gyre 40 km
25	1561-18133	4 Feb 74	Clouds, some seds
26	1562-18191	5 Feb 74	Clouds, fog, heavy seds 25 km gyre
27	1579-18131	22 Feb 74	Clouds, plume GG, SP seds
28	1580-18190	23 Feb 74	Heavy seds, gyre, GG, Pt. Reyes
29	1652-18173	6 May 74	Clouds off GG, heavy seds SP
30	1669-1811	23 May 74	Seds, clouds off coast
31	1670-18165	24 May 74	SP, off GG heavy seds, excellent, possible red tide
32	1687-18104	10 Jan 74	Clouds offshore to GG, entrainment SP
33	1688-18162	11 Jun 74	Clouds SP entrainment
34	1705-18100	28 Jun 74	Plume GG, jetting release Mare Island entrainment SP
35	1724-18151	17 Jul 74	Clouds offshore to GG, flooding pattern unique
36	1759-18081	21 Aug 74	Minor seds, clouds off GG
37	1760-18135	22 Aug 74	Clouds offshore, minor seds
38	1777-18073	8 Sep 74	Clouds at GG, minor seds, entrainment SP
39	1813-18063	14 Oct 74	Clouds at GG, minor seds, pattern SP
40	1831-18060	1 Nov 74	Clouds, no offshore seds
41	1867-18043	7 Dec 74	Clouds, south bay and south coast somewhat clear
42	1868-18103	8 Dec 74	Clouds SP, some seds
43	1886-18093	26 Dec 74	Clouds
44	1921-18022	30 Jan 75	Excellent, plume GG, sed patterns SP, South Bay
45	1939-18013	17 Feb 75	Clouds
46	1957-18011	7 Mar 75	Clouds
47	1975-17595	25 Mar 75	Clouds SB, heavy sed discharge
48	2072-18120	4 Apr 75	Clouds

TABLE 5-1 (Continued)

	LANDSAT ID	DATE	REMARKS
49	2089-18061	21 Apr 75	Clouds
50	5011-17580	30 Apr 75	Clouds offshore, heavy seds SP, GG plume
51	2107-18060	9 May 75	Clouds offshore
52	5029-17571	18 May 75	Clouds offshore GG, seds SP, some entrainment
53	5048-18015	6 Jun 75	Clouds
54	2161-18061	2 Jul 75	Clouds offshore GG, seds entrainment GG
55	5033-17541	11 Jul 75	Clouds, some seds SP
56	5084-17595	12 Jul 75	Light seds, entrainment SP, low tide
57	2179-18060	20 Jul 75	Clouds
58	2180-18114	21 Jul 75	Clouds offshore GG north SP, some seds
59	2197-18053	7 Aug 75	Light seds, minor patterns SP
60	2270-18183	19 Oct 75	Minor seds
61	2288-18101	6 Nov 75	Minor seds, entrainment SP and SB
62	2305-18042	23 Nov 75	Minor seds, entrainment SP patterns
63	2306-18100	24 Nov 75	Clouds, GG plume
64	2324-18095	12 Dec 75	Minor seds, some SP pattern
65	2341-18040	29 Dec 75	Minor seds and patterns
66	2342-18094	30 Dec 75	Minor seds and patterns
67	2359-18035	16 Jan 76	Minor seds, entrainment SP
68	2360-18090	17 Jan 76	Clouds
69	2378-18091	4 Feb 76	Minor seds, SB patterns
70	2395-18030	21 Feb 76	Clouds
71	2414-18081	11 Mar 76	Patterns and entrainment SP
72	2431-18020	28 Mar 76	Seds, clouds
73	2432-18002	29 Mar 76	Excellent seds, gyre Pt. Reyes and Devils Slide, GG linear pattern
74	2449-18012	15 Apr 76	Clouds, heavy seds
75	2450-18070	16 Apr 76	Excellent, heavy seds, pattern SP, band 7 good
76	2467-18005	3 May 76	Clouds GG, SP excellent patterns also SB

TABLE 5-1 (Continued)

	LANDSAT ID	DATE	REMARKS
77	2468-28063	4 May 76	Clouds
78	2485-18002	21 May 76	Clouds offshore, seds
79	2486-18061	22 May 76	Clouds, seds
80	5390-17403	23 May 76	Minor seds, gyre GG

Clouds 47/80 Excellent 12/80

5.3 DREDGE DISPOSAL STUDY - LANDSAT CORRELATION

Landsat imagery from 1974 was used in combination with a detailed dredge disposal study to determine sedimentation patterns in San Pablo Bay (northern San Francisco Bay). The Landsat film density patterns formed from the radiance levels in the bay waters were contoured. They were then compared with sedimentation patterns in the bay. These sedimentation patterns were determined as part of the U.S. Army Corps of Engineers Dredge Disposal Study, 1975. In San Pablo Bay, Carquinez Strait and Suisun Bay, 111 sediment samples stations (Figure 5-3 were monitored during the study. It was not possible to control the day the samples were taken in relationship to the Landsat overpass so there was up to a 2 week delay. However, during periods when samples were collected close to the Landsat overpass fairly close correlations were reached.

The San Francisco Districts Dredge Disposal Study of San Francisco Bay and Estuary was to identify possible environmental impacts resulting from dredging an aquatic disposal of dredged material. One part of this effort was a study to follow the initial movement and recirculation of material dredged from Mare Island Strait and disposed of at the Carquinez Strait disposal site.

To accomplish the tracing study, a joint program was initiated between the San Francisco District, the Explosive Excavation Research Laboratory (now the Explosive Effects Division of the Weapons Effects Laboratory, U.S. Army Engineer Waterways Experiment Station), and the Stanford Research Institute to quantify the horizontal and vertical extent of dredged material deposition and recirculation within San Pablo Bay, Mare Island Strait, Carquinez Strait and Suisun Bay. Tracing was accomplished by tagging 21,729 pounds of previously dredged material with 22 pounds (approximately 10 kilograms) of iridium. Then introducing these tagged sediments into approximately 500,000 long tons of Mare Island Strait dredge material and dispose of them off Mare Island. This took place in the February-March 1974 dredging period. Neutron activation of sediment samples collected from March through December 1974 was determined with a gamma-ray spectrometry. This was done to determine the quantity of iridium and, hence, dredge material in the samples. Volumes of dredged material were calculated, using simplifying assumption, for three layers (the top one inch and two succeeding 4-inch layers of sediment sample) for each sampling period. Sampling periods were designated by month.

The tagged material was added to the two dredge hoppers for each of the 706 dredging cycles in February-March 1974. For a calculated hopper volume of 2,300 yd^3 (1,758 m^3) a total volume of 1,623,800 yd^3 (1,241,437 m^3) was dredged. Using a wet density of dredged sediments of 81.2 lbs/ft^3 (1.3 g/cc), the total weight of dry sediment dredged was 5.06×10^{11} grams (500,000 long tons). Thus, the concentration of iridium in the disposed dredged sediments was 1.95×10^{-8} grams of dry sediment. The naturally occurring background concentration of

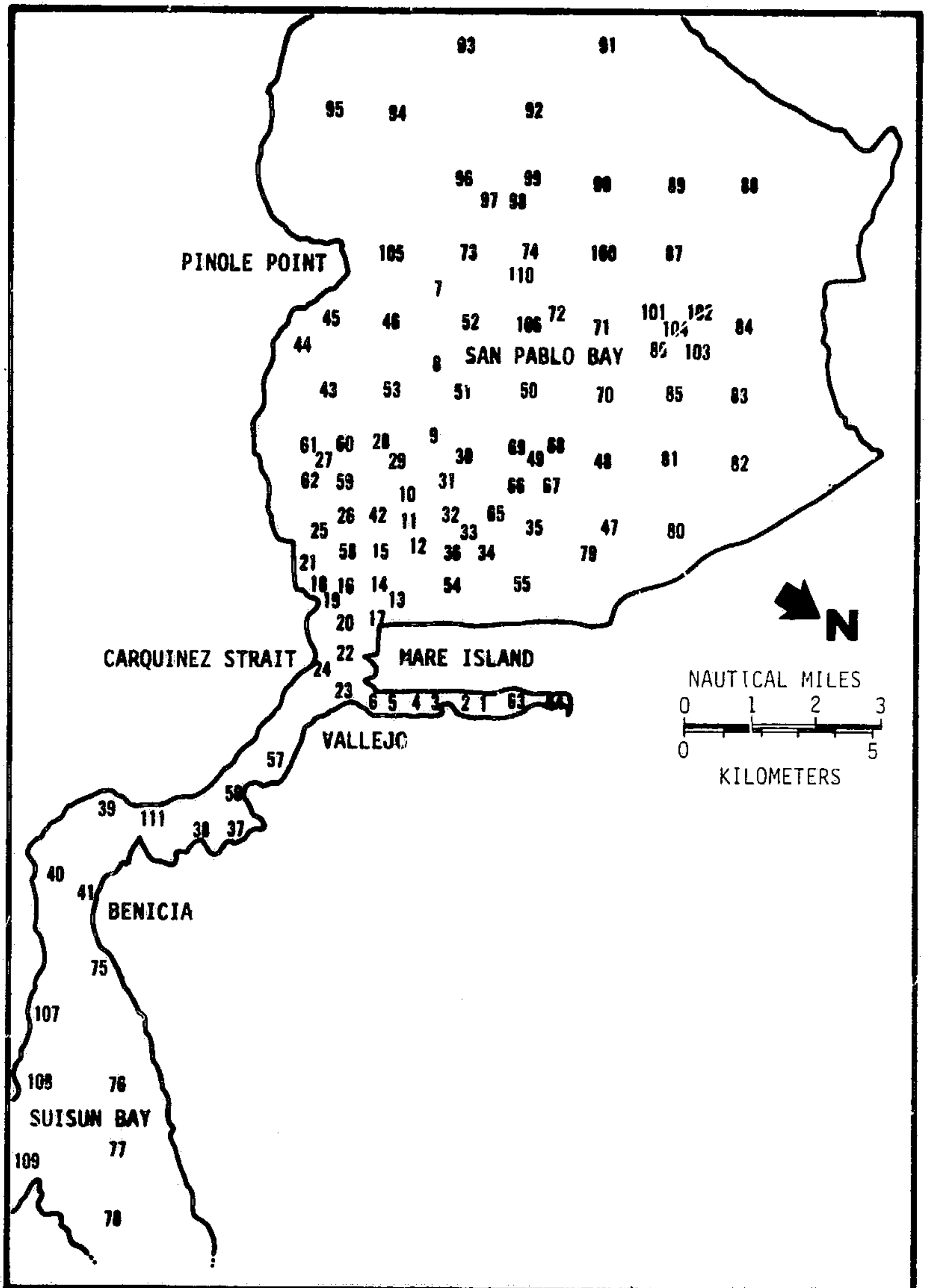

Figure 5-3 Dredge Disposal Study - Sampling Stations March-December 1974 (U.S. Army Corps of Engineer, 1975)

iridium (determined from sediment samples taken in Mare Island Strait, Carquinez Strait, and San Pablo Bay) is 5 x 10^{-10} gram Ir/gram of dry sediment. Thus, the concentration of iridium in the tagged sediments was approximately 40 times the background level.

The study period, March-December, 1974, was divided into 11 sampling periods. Not all 111 locations were sampled for each sampling period. The sampling periods selected were early March, late March, and each month from April-December 1974. For the two March periods samples were collected in Mare Island and Carquinez Straits and a limited number of stations in San Pablo and Suisun Bays.

Seven months of Landsat data from 1974 were used as the basis for the project (March, May, June, July, August, October and November). For each month density contour maps were made from the Landsat imagery for the San Pablo Bay -- Suisun Bay area. Spot densitometer readings were also taken from areas of maximum and minimum suspended sediment levels. These readings along with sediment distribution data and Landsat imagery density wedge levels were used as calibration. Figures 5-4 to 5-10 are enlargements of San Pablo Bay for the respective months. On each figure surface current patterns have been plotted along with detectable water boundaries and wind shear. In several cases during ebb tide the hydraulic release effect can be seen where the Sacramento River enters San Pablo Bay. Figures 5-11 to 5-17 are contour maps of the density plots from the Landsat imagery in Figures 5-4 to 5-10. These were made using a Data Color densitometer enhancements of the film negatives. In each case the higher the number of the contour the greater the amount of suspended sediment found in the imagery. These levels have not been assigned absolute suspended sediment concentration levels because the available data was taken from bay bottom samples. In many cases the samples were taken up to two weeks before or after the time of the Landsat overpass. The result was that only relative conclusions could be made from their correlation process. Once the samples stations' sediment cores were analyzed, the distribution patterns of suspended sediment from the source point off Mare Island were known. These patterns were then compared with the surface pattern visible on the Landsat imagery. Although this was only a cursory comparison it did allow the investigators to confirm the patterns noted on the Landsat imagery. Much of the fines from the sediment discharges from the Sacramento River is deposited on the flats in the north part of San Pablo Bay. Although a large quantity is transported directly through the Bay, a large volume remains behind on the flanks or sides of the main channel. During periods of high northwest winds much of the material deposited on the flats is resuspended by the wind and wave action. It is then transported to new locations within the Bay or swept out completely.

Figure 5-4 San Francisco Bay - 13 March 1974

Figure 5-5 San Francisco Bay - 24 May 1974

Figure 5-6 San Francisco Bay - 10 June 1974

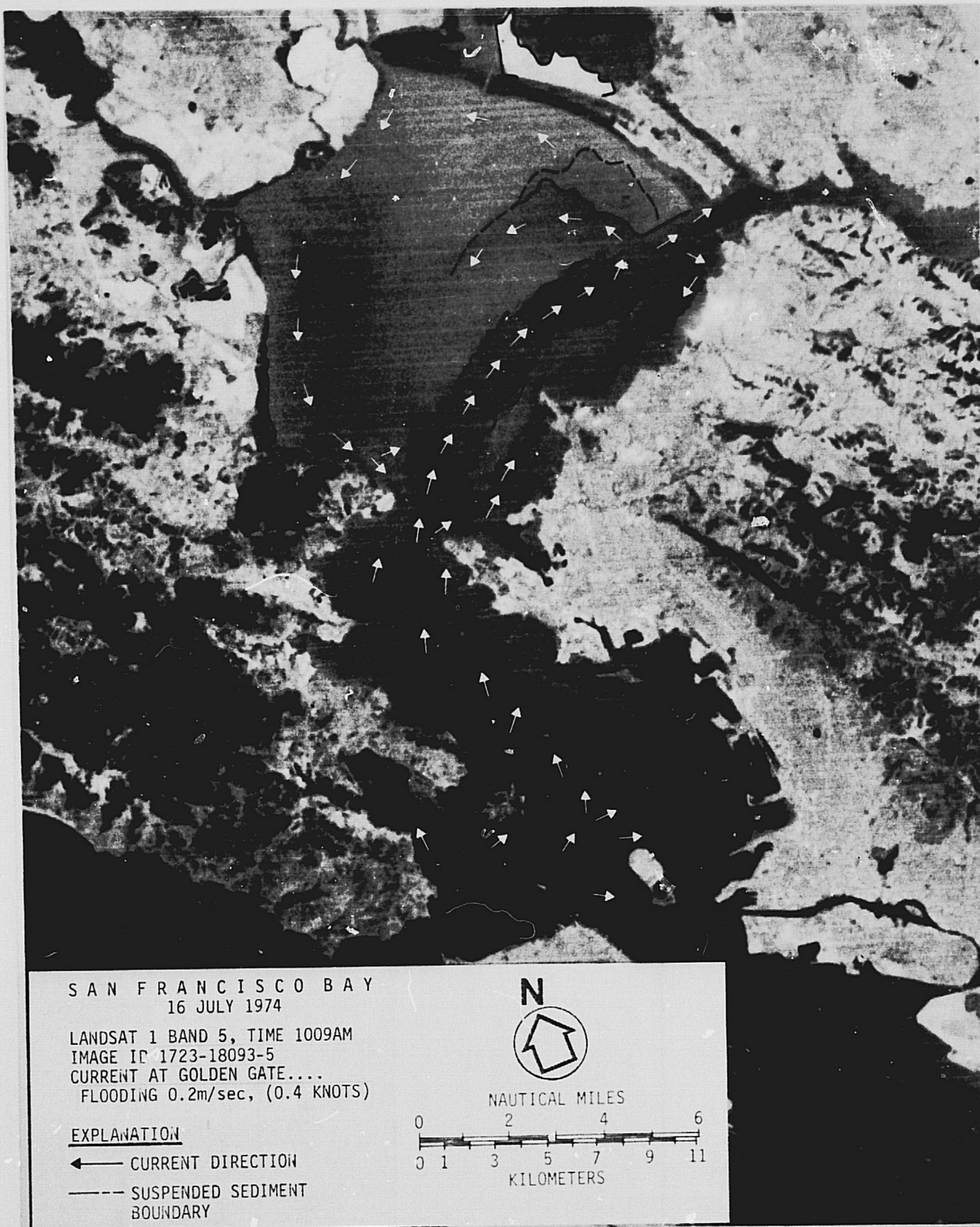

Figure 5-7 San Francisco Bay - 16 July 1974

Figure 5-8 San Francisco Bay - 21 August 1974

Figure 5-9 San Francisco Bay - 14 October 1974

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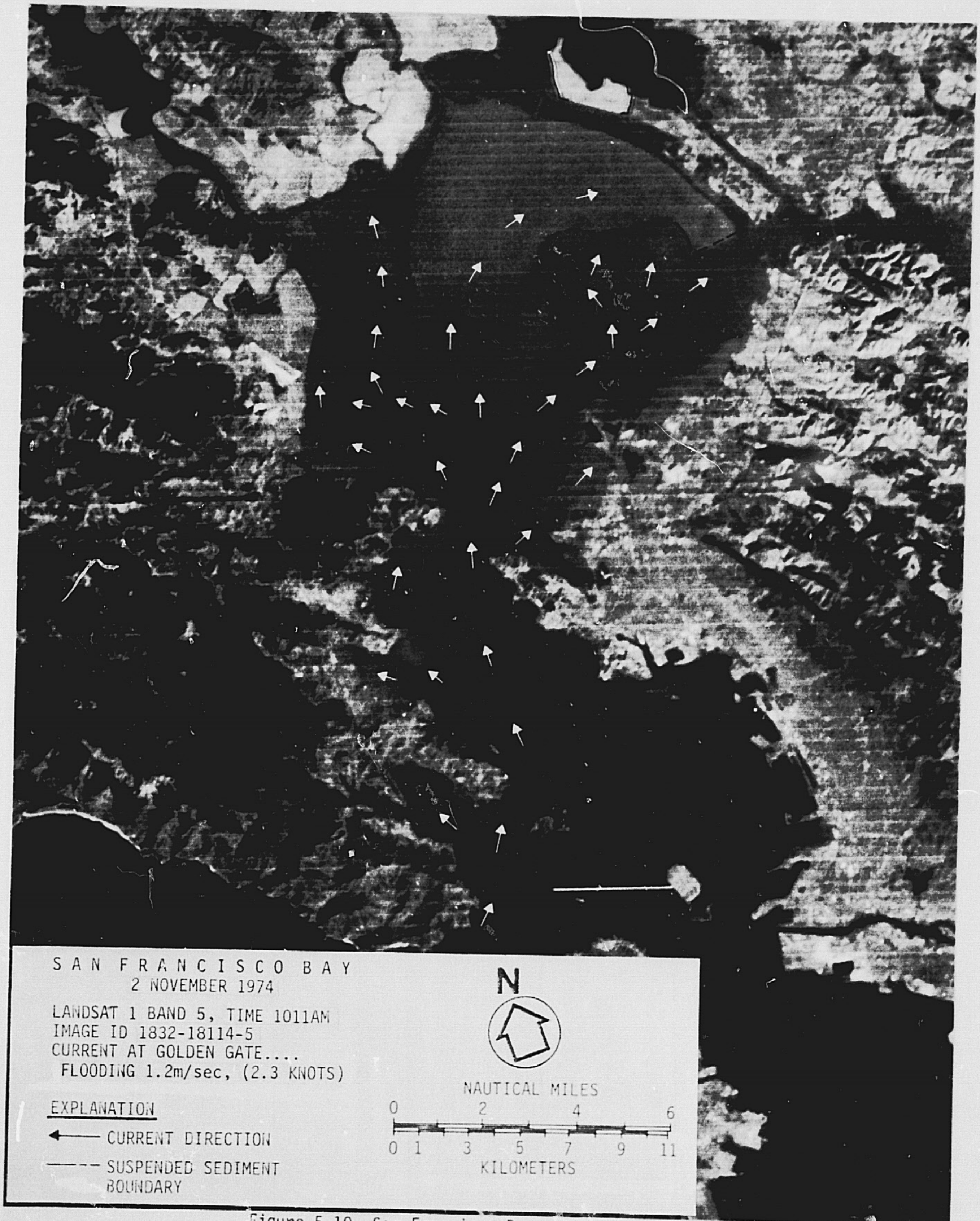

Figure 5-10 San Francisco Bay - 2 November 1974

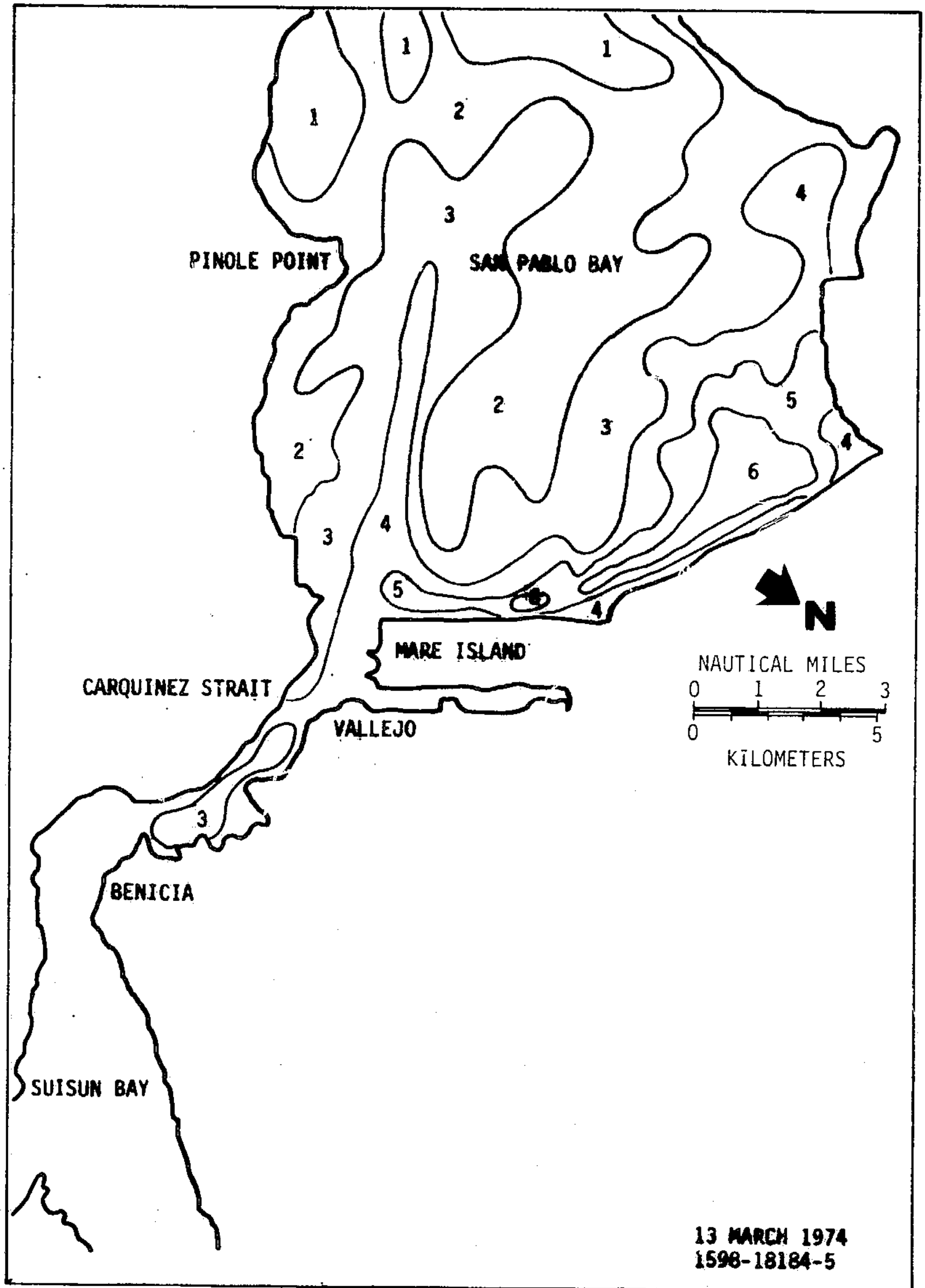

Figure 5-11 Density Contour - March 74

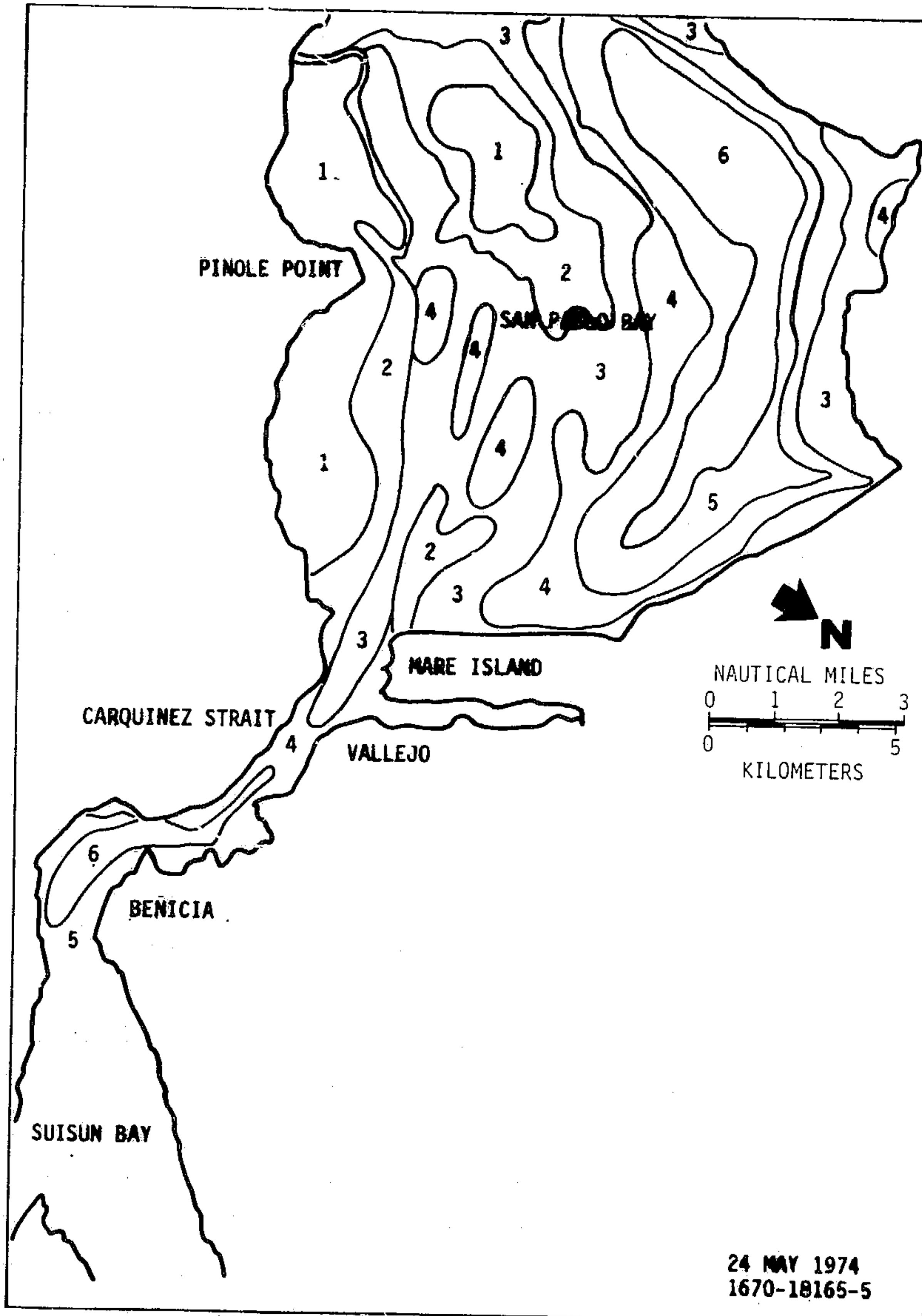

Figure 5-12 Density Contour - May 74 1974

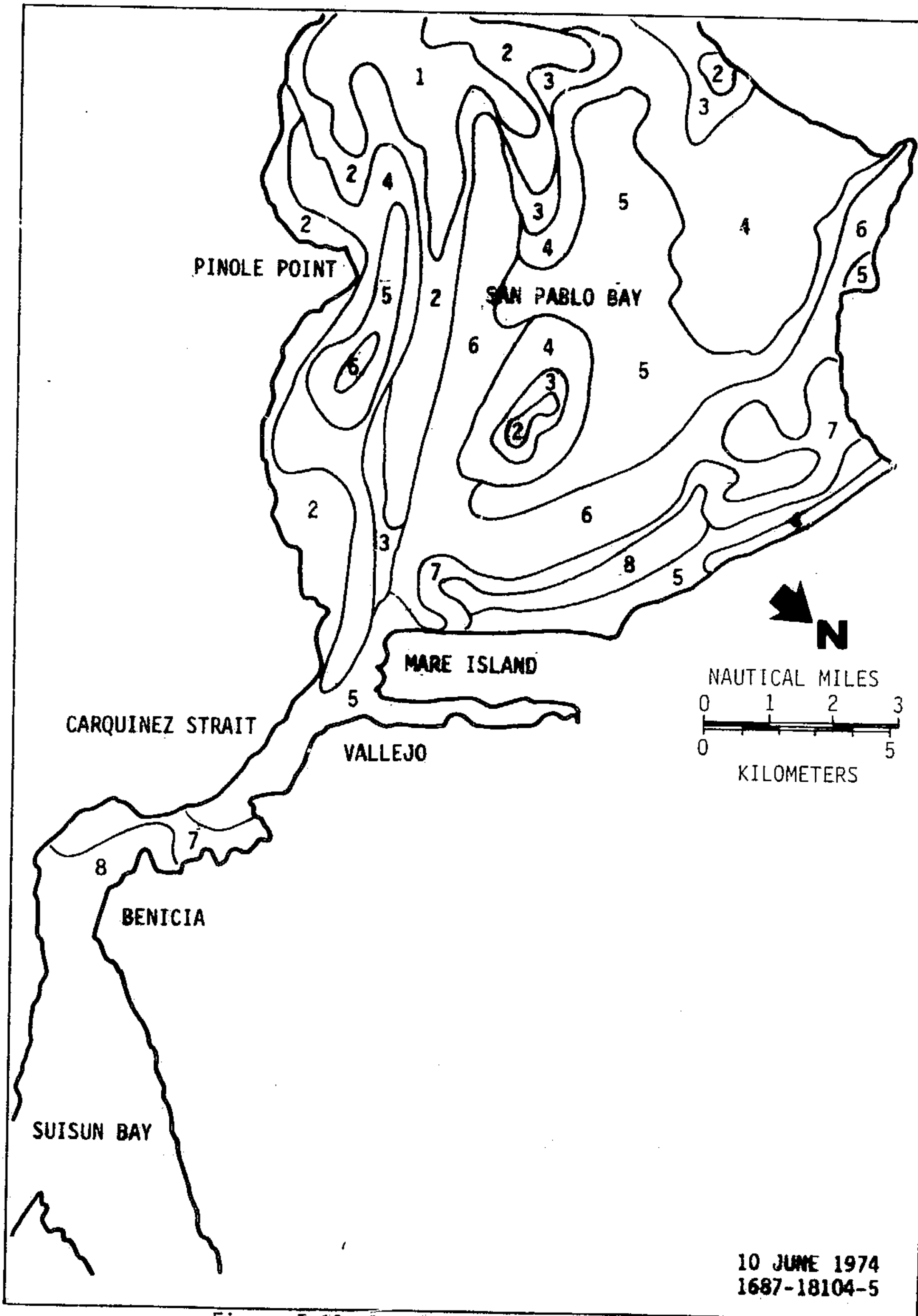

Figure 5-13 Density Contour - June 74

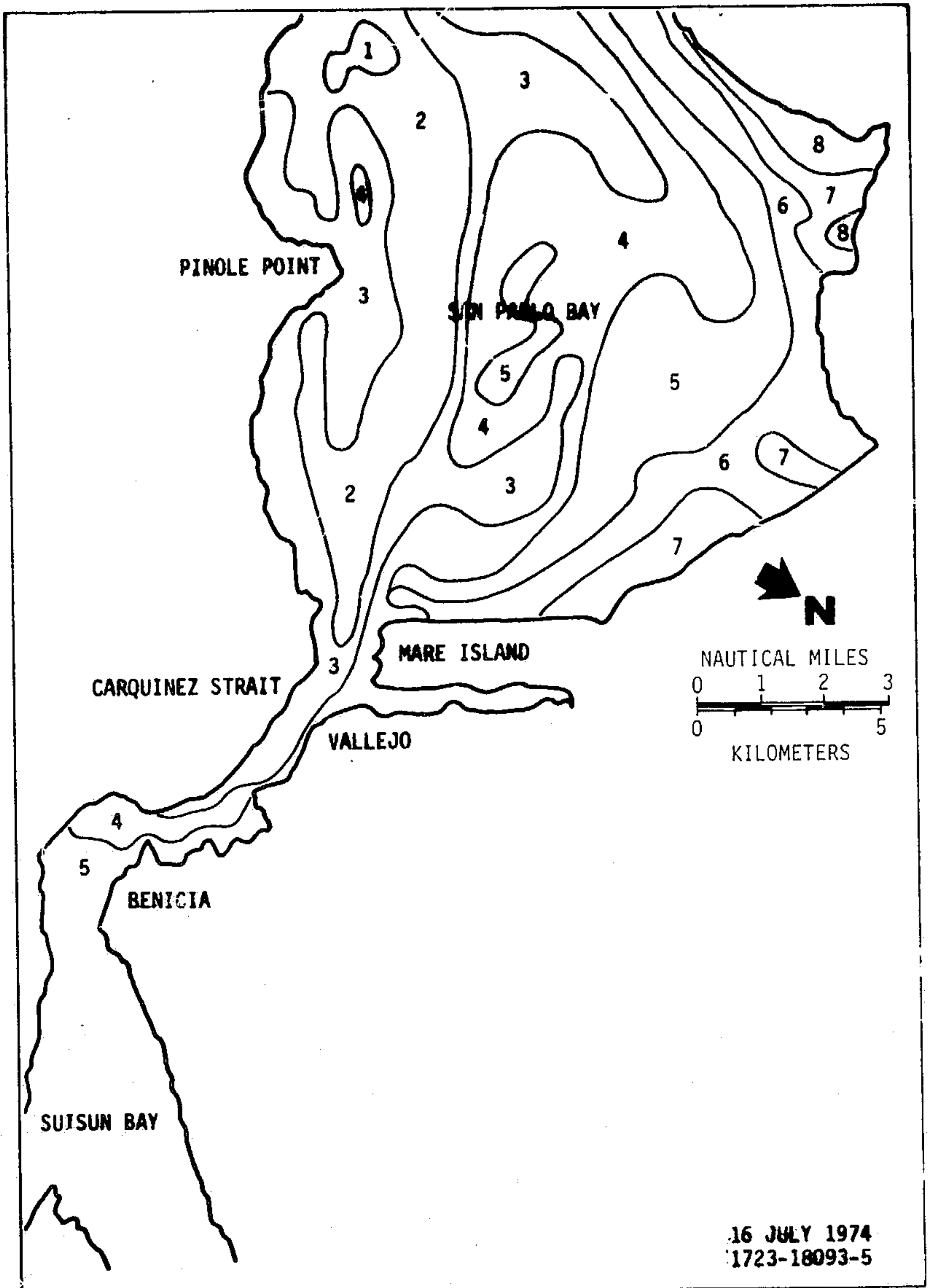

Figure 5-14 Density Contour - July 74

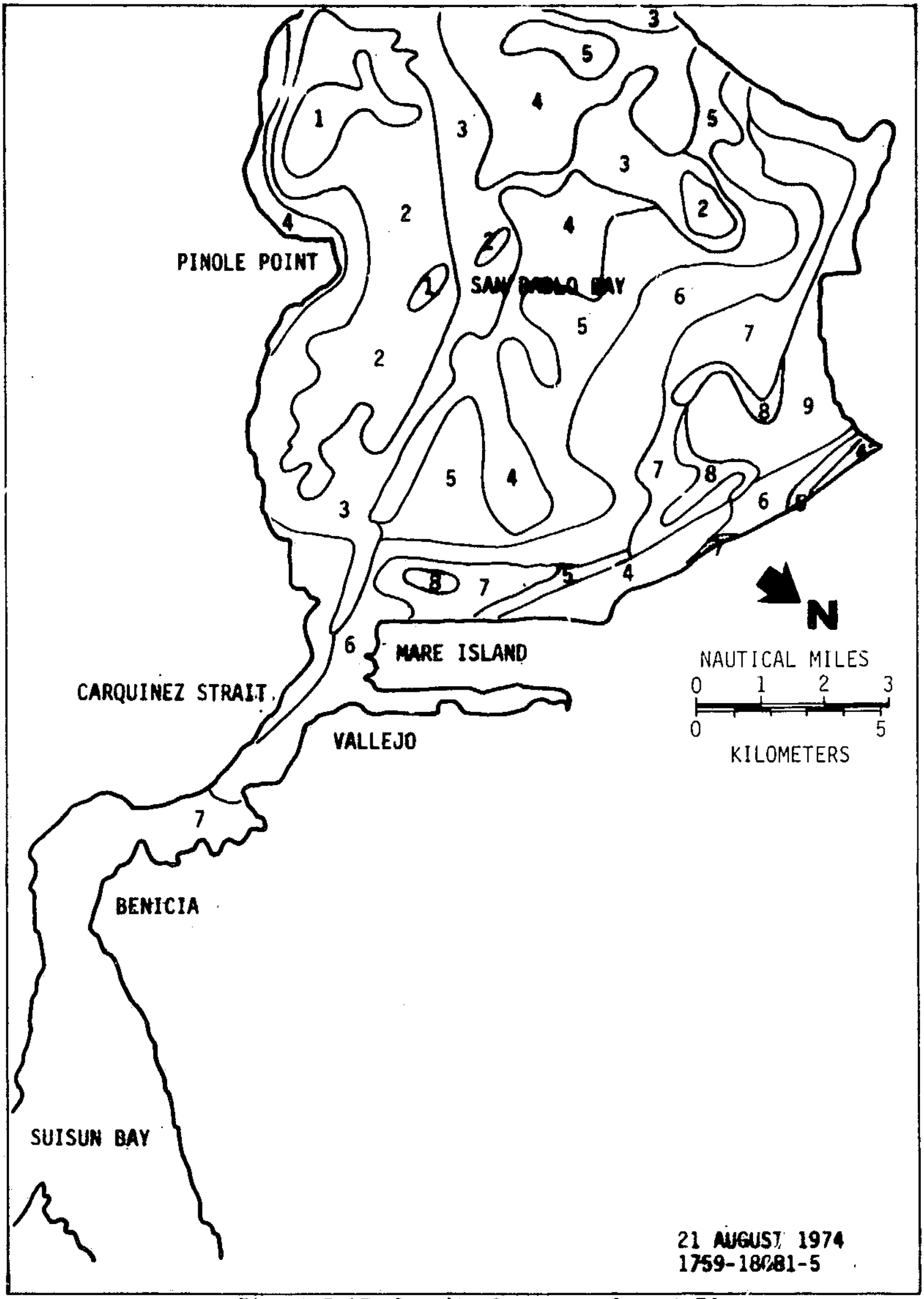

Figure 5-15 Density Contour - August 74

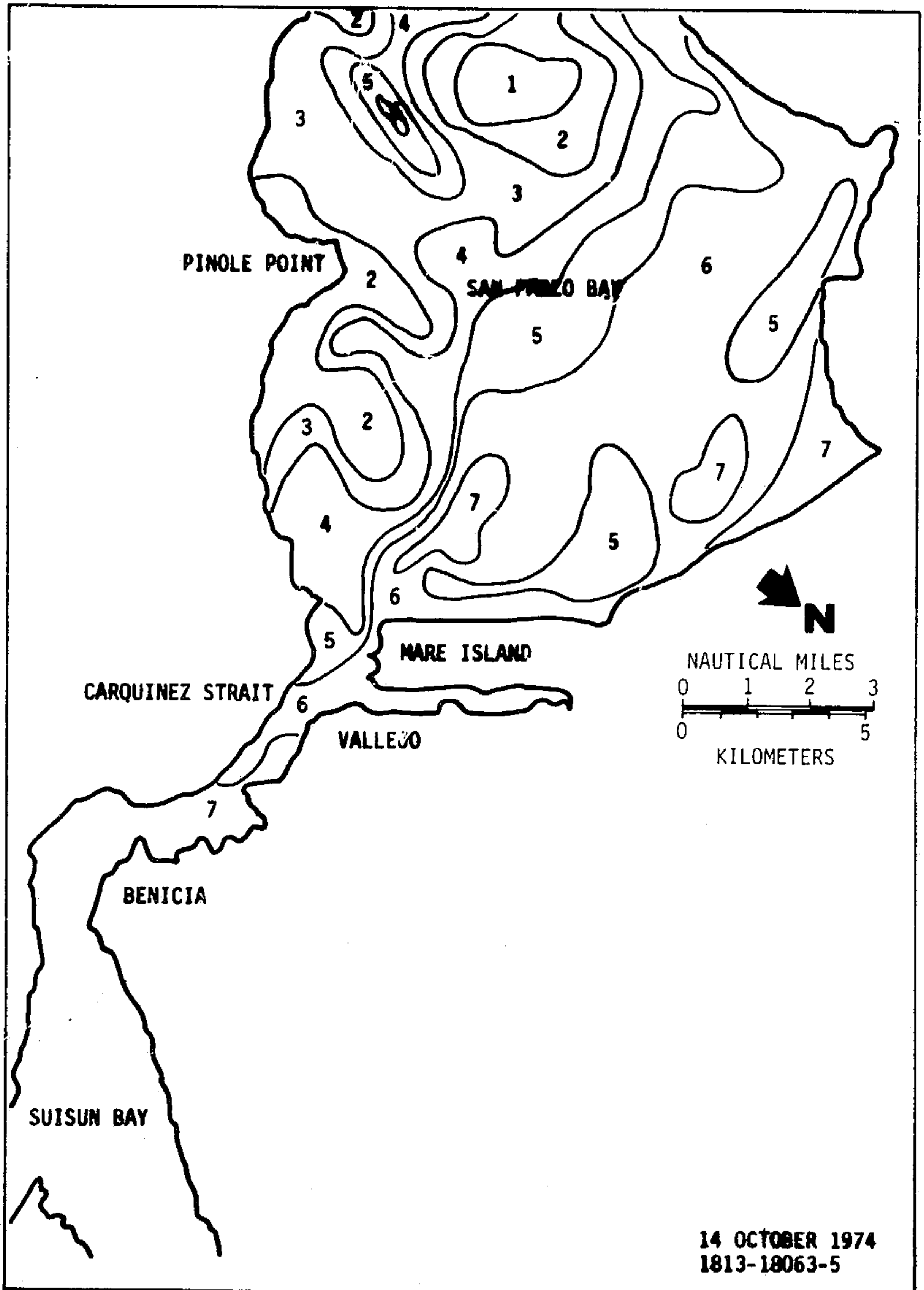

Figure 5-16 Density Contour - October 74

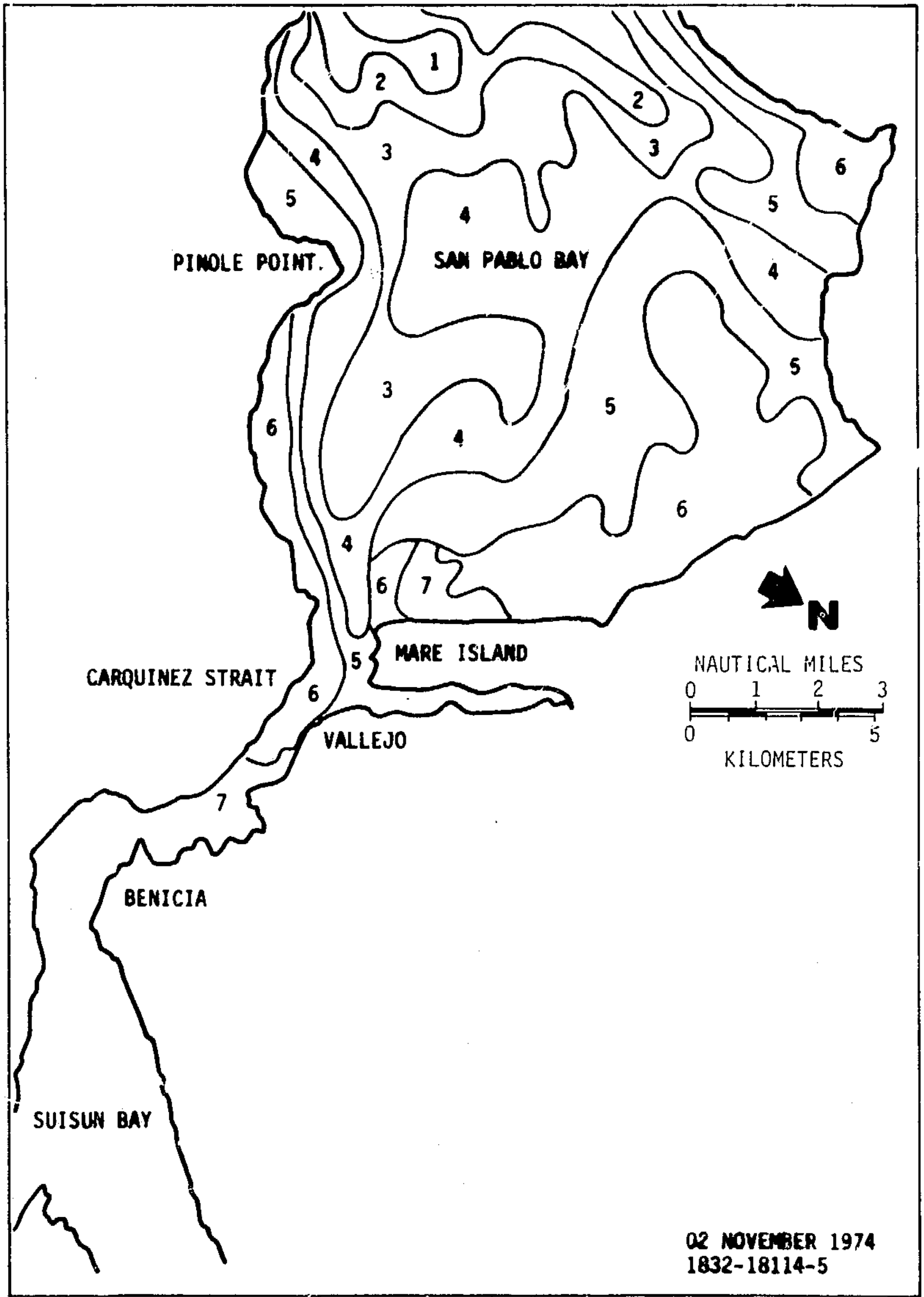

Figure 5-17 Density Contour - November 74

The dredge disposal sampling program presented the investigators with a wide spread network of station data for use in this Landsat study. This type of field data collection was impossible under the study's limited budget. Resulting information from the sampling and analysis provided a basis for understanding the complex movement of sediment within San Pablo Bay. The fact that coordination between the projects was not possible caused some obvious drawbacks. Some of the problems encountered include:

1) Delay between sediment sample collection and Landsat overpass.

2) No surface samples were taken, only bottom core samples. Thus, what is seen at the water surface station will not necessarily correlate with a core at the bottom from the same station.

3) At times when a number of cores were taken around a station differing results were found.

4) Material from the distribution point off Mare Island only was being monitored.

5) The densitometer spot size used for analyzing the Landsat imagery was the smallest available. It covered 3.1 sq km (1.2 sq miles) of the water surface. This is over 700 Landsat picture elements, a large ground area to compare to the point source sampling stations (70 mm film clip used).

6) The density step wedges on the film transparencies used for this experiment varied from frame to frame. Although the variation was often small, any variation would cause a large statistical error in expected results.

7) The surface material being analyzed was obviously moving in relationship to the bottom samples.

5.4 CONCLUSIONS

The Landsat imagery of San Francisco Bay provides a detailed synoptic view of the estuarine processes affecting the surface and nearsurface waters. Tidal current patterns, eddies, gyres, wind action and resulting sediment transport is detectable. Manual and automatic means of manipulating the imagery is useful in enhancing these patterns. Four years of imagery is now available for use as a historical record of the processes. Future investigators will have the opportunity to use techniques such as densitometer analysis and band to band comparison in evaluations and predictions of estuarine processes within the bay. This sould provide excellent background for marine construction, shore protection or environmental analyses.

The correlation of sediments collected at 111 stations throughout San Pablo Bay, with patterns on the Landsat imagery provided general background on sediment transport within the bay. This information will be useful in predicting the location of future deposition and erosion sites within this study area. Although closer coordination and timing between the sampling of water stations and the Landsat overpass would have been useful, the overall sedimentation patterns were detectable.

In future studies such as the San Pablo Bay experiment several sampling changes would provide much more usable background data. The recommended methods that follow could be easily accomplished at the same time a shipboard core sample was being collected. First use a calibrated transmissometer and lower it below the light extension depth. Collect water samples for use in determining the total suspended sediment load and for checking the transmissometer calibration. Make the data collections as close to the Landsat overpass as possible.

5.5 REFERENCES

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6.0 RUSSIAN RIVER

This section on the coastal processes in the vicinity of the Russian River is included to demonstrate the capability of Landsat and aircraft imagery to supplement standard coastal engineering data in the description of a coastal reach. The Russian River Basin, located in northern California (Figure 6-1) is a unique and valuable natural and economic resource. To preserve the basin's environment and protect, maintain and enhance the standard of living of residents, requires controlled and proper use of its natural resources. This can only be achieved through acquisition of data on these resources and development of proper management programs. As part of the development of resource data on the Russian River Basin, river mouth configurations, sediment transport and nearshore currents were studied and included with this Landsat work.

The study area is limited to those inland, coastal and offshore areas which would be affected by material discharged from the Russian River and extends from Point Arena to Point Reyes as shown in Figure 6-1. The coastline within this area has vast stretches of sandy beaches as well as many miles of intermittently rocky and beached shoreline. Aside from the broad sandy beaches, the coastline is backed by irregular cliffs ranging from 15 to 60 meters (50 to 200 feet) in height. Fronting these cliffs are narrow pocket beaches whose material is often composed of shingles. The foreshore is typically rocky. The shoreline is oriented in the northwest to southeast direction. The Russian River is the main discharge into the Pacific Ocean within this stretch of coastline. A few small creeks of unappreciable discharge are characterized by short, widely-spaced tributaries, alluvial valleys, gentle gradients, and barred estuarine mouths.

Historically the Russian River supported one of the major fisheries along the Pacific Coast. While hard data on the magnitude of this fishery is limited, personal and recorded historical information supports that such is true. Flow in the Russian River is critical for the maintenance of an adequate resident and anadromous fishery. Present operating criteria provides for maintenance of a minimum maintained flow of 3-5 cubic meters per second at a distance of 22 km (13.6 miles) from the mouth. The basis for this flow is questioned but studies to determine an optimum flow for fishery purposes have not been conducted. Determination of benefits to be achieved by lower flow rates and periods of maintained flow is needed.

Turbidity and sediment resulting from various watershed activities including construction, logging, gravel mining and water diversions among others are harmful to the water quality necessary for maintenance of the fishery. Insecticides, many mineral and

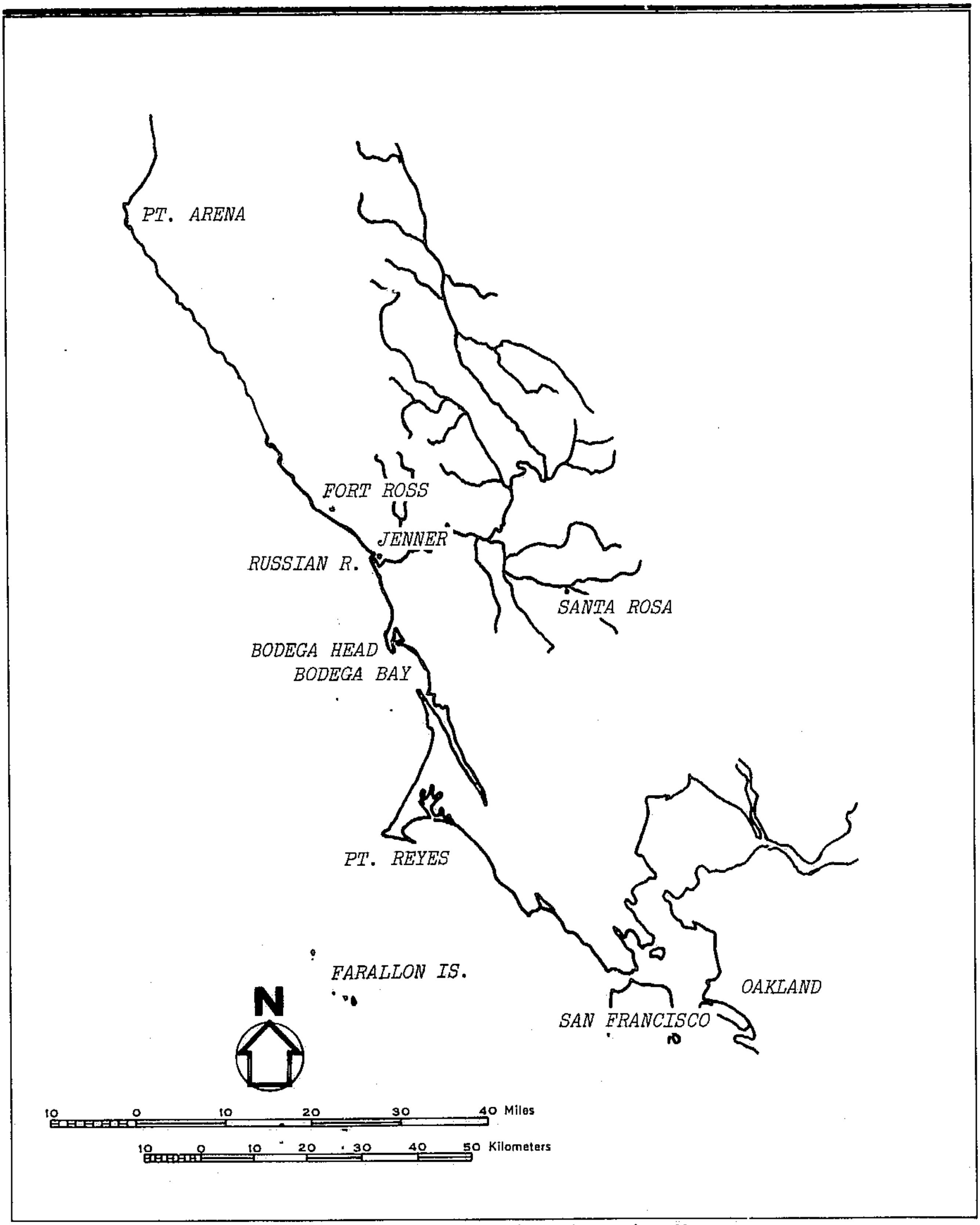

Figure 6-1 Russian River Location Map.

organic substances, some resulting from improper waste disposal, also threaten maintenance of acceptable fishery water quality.

The need for acceptable water quality in the Russian River Basin as recognized by water quality planning objective is common to most elements of the basin's environment. Since water is the environment in which fish must carry on all life processes, maintenance of appropriate water quality is critical to the existence of a healthy and diverse fishery. Increasing recreational usage of the river demands a clear, high quality water, but often the water quality is degraded by the activities of the recreationists themselves.

The findings of previous studies confirmed the obvious existence of extensive sediment in the Russian River resulting in frequent turbid river and ocean water conditions. Several sources and causes of this turbidity have been identified. These include rainstorms and consequent erosion, diversion of extremely turbid waters from the Eel River, sand and gravel mining operations, road construction and logging practices and algal blooms which tend to perpetuate the turbid conditions.

Excessive turbidity is known to have an adverse effect on the production of healthy salmon and steelhead as well as adversely affecting angling. These effects occur throughout the Russian River and appear to be particularly significant on the upper river. No studies or data are available to determine the magnitude of these adverse effects; however, they are considered to have contributed to the general decline in the overall Russian River fishery.

6.1 COASTAL CURRENTS

In the Russian River coastal area there are four principal sources of material for the formation of beaches:

1) stream-borne sediments,
2) erosion of alluvial deposits,
3) onshore movement of sand,
4) material moving laterally along the coast.

The Russian River is thought to annually discharge an average of 130,000 cubic meters of beach sand in addition to many times this amount in silts and clays. The deposition locations of the important beach sands are primarily dictated by wave energy distribution in conjunction with nearshore currents. The silts and clays, however, are not influenced as much by wave energy as by coastal currents and river flow.

Four types of nearshore currents affect the study reach and are caused by: tidal, wave, wind stress, and water density distribution. Currents resulting from density distribution and wind stress are the large scale ocean currents and are relatively feeble. Among these large scale ocean currents is the California Current (see Section 2.0). The California Current is a cold mass of water that flows from north to south along the California coastline and is the most important current adjacent to the western margin of the United States. The California Current is part of the large scale North Pacific gyre circulation pattern.

The Davidson Current is generally a deep countercurrent below 200 meters (656 feet) which flows to the northwest along the coast from Baja California to some point beyond Cape Mendocino. It brings warmer, more saline water great distances northward along the coast. When the north winds are weak or absent in late fall and early winter this countercurrent forms at the surface, well on the inshore side of the main stream of the California Current. The temperature contours in the eastern Pacific bend to the north along the coast during the height of the Davidson Current activity with the most dramatic changes taking place in February.

These two coastal currents, the Davidson and the California are the prime movers of the silts and clays that are flushed from the mouth of the Russian River each winter. The impact of man's activities on the make-up of the sediments is not really known at this time. Unfortunately the impact of these streamborne sediments on the anadromous fish populations is also unknown.

Salt in the ocean water acts as a flocculative agent which combines with the silts and clays in the rivers' stream flow and eventually this mixing of stratified nearshore waters results in deposition of flocs in the ocean bottom offshore in more tranquil waters. The settlement of flow may take place many kilometers to sea from the river mouth.

The imagery from the Landsat satellite was used to trace the nearshore currents out to approximately 50 km (31 miles) to provide data on the seasonal variations on plume location for future use by fishery researchers and geologists. The plume position is dependent upon the ocean current and stream flow prevalent at any particular time.

6.1.1 DAVIDSON CURRENT PERIOD

The complex movements of the Russian River plume during the Davidson Current period (normally between November and February) were obtained from Landsat imagery spanning the period from the winter of 1972 to spring of 1976. In the study area, the Davidson

Current is not strong but is effective in developing gyres that trap sediment laden river waters near shore behind water mass fronts. These gyres and fronts restrict the transport of silts and clays to an area between Point Arena and Point Reyes and tend to account for an initial winter flocculation and deposition of fines and muds out to 25 km (15.5 miles). Figure 6-2 depicts a generalization of the Davidson Current Season in the study reach.

6.1.2 UPWELLING PERIOD NEAR THE RUSSIAN RIVER

The Upwelling Period, between February and July, marks the period of strongest ocean currents with the California Current moving to the south along the coastal reach from Point Arena to Point Reyes. Strong winds parallel to shore support a coastal upwelling while point gyres support headland upwellings. Figure 6-3 illustrates these interesting features as well as sketching the normal position of the Russian River plume. Figure 6-4 is an excellent Landsat image of the period.

Although substantial quantities of rainfall occurs during December and January, Northern California's runoff intensifies during the early upwelling period. This increased runoff coupled with nutrient-rich upwelling waters is of interest to fishery researchers since any mixing of pollutants with nutrients in a fish production area may result in detrimental effects.

6.1.3 OCEANIC SEASON

From the end of July to the beginning of the winter storms in November, comes a period where currents are slow, poorly defined and tend to meander. Tidal effects seem to have as much to do with the surface currents as does wind stress. However, there is a southward tendency to the sluggish currents as the California Current is still in effect. Figure 6-5 illustrates the current meanders. It is interesting to note that during the winter of 1975-1976, Northern California received little rain. As few storm fronts crossed northern California, the upwellings and the spring currents were not as strong as usual. The Davidson Current did not develop as normal and the river runoff was far below normal. Although it is still too early to determine the effect of the lack of winter storms on the coastal fishery, it is possible that Landsat data will be used as a data source to assist in assessment of fishery statistics in the future. This is especially true if the 1976-1977 winter is as dry as the 1975-1976 storm season.

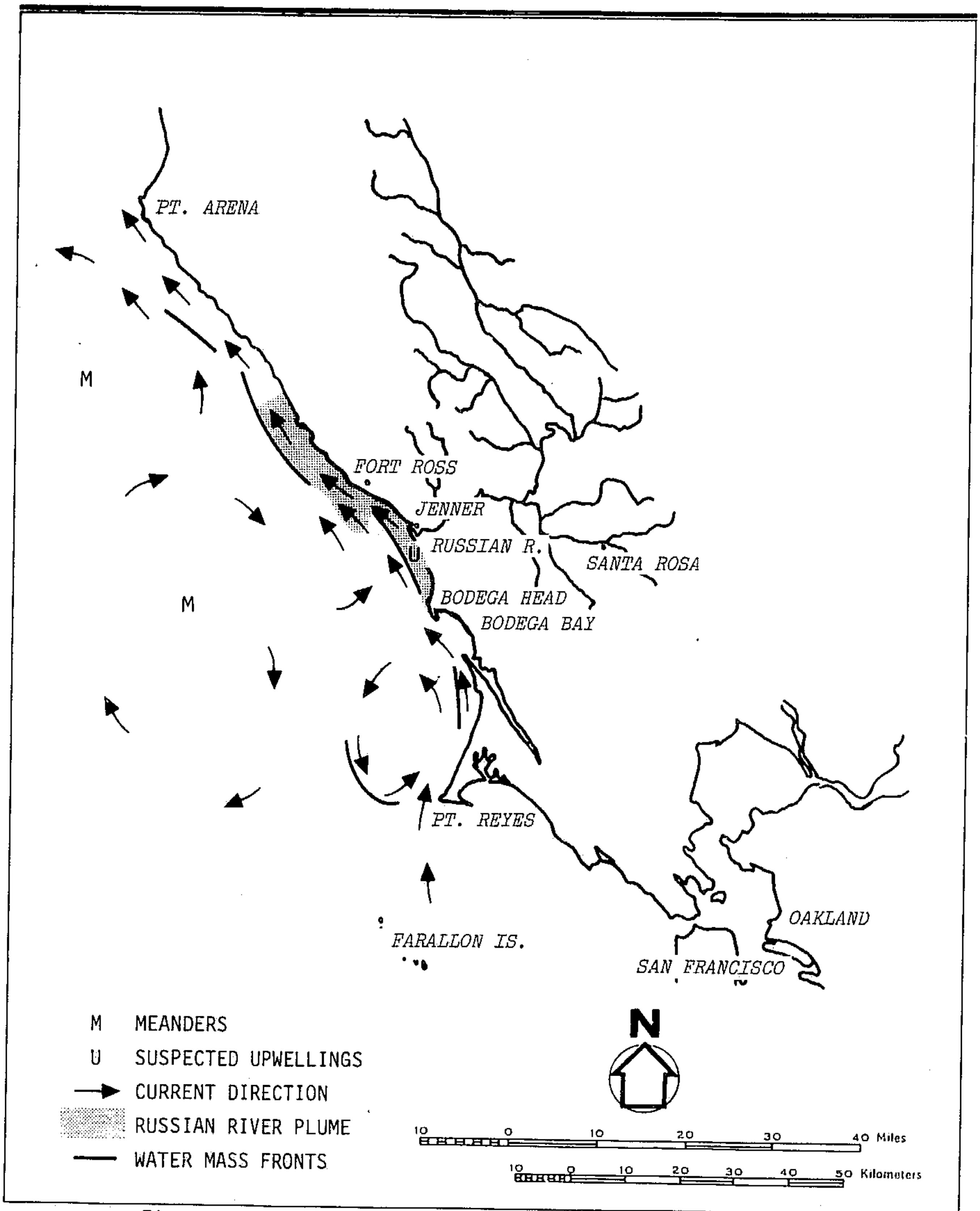

Figure 6-2 Generalized Russian River Surface Currents During Davidson Current Season.

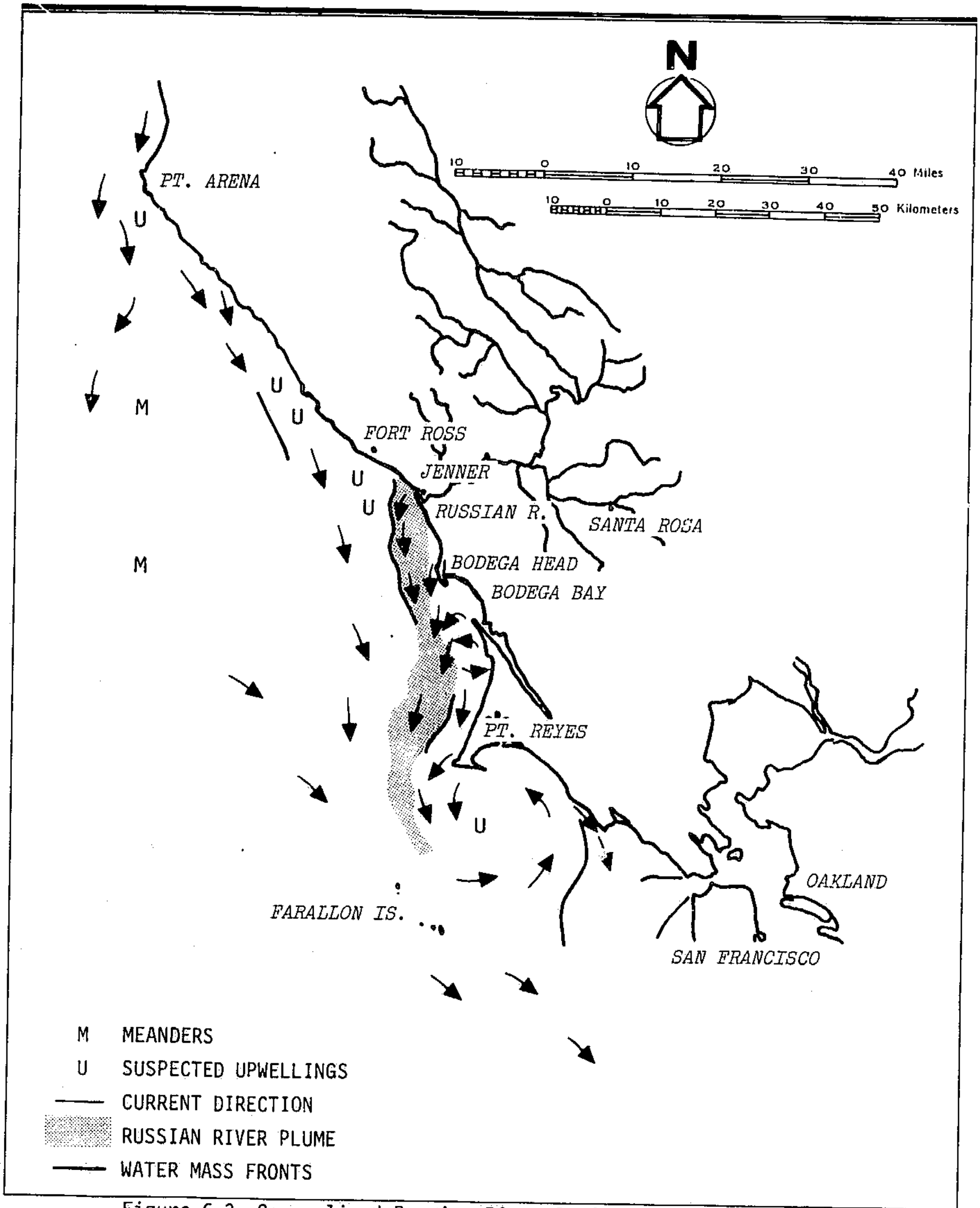

Figure 6-3 Generalized Russian River Surface Currents During Upwelling Season.

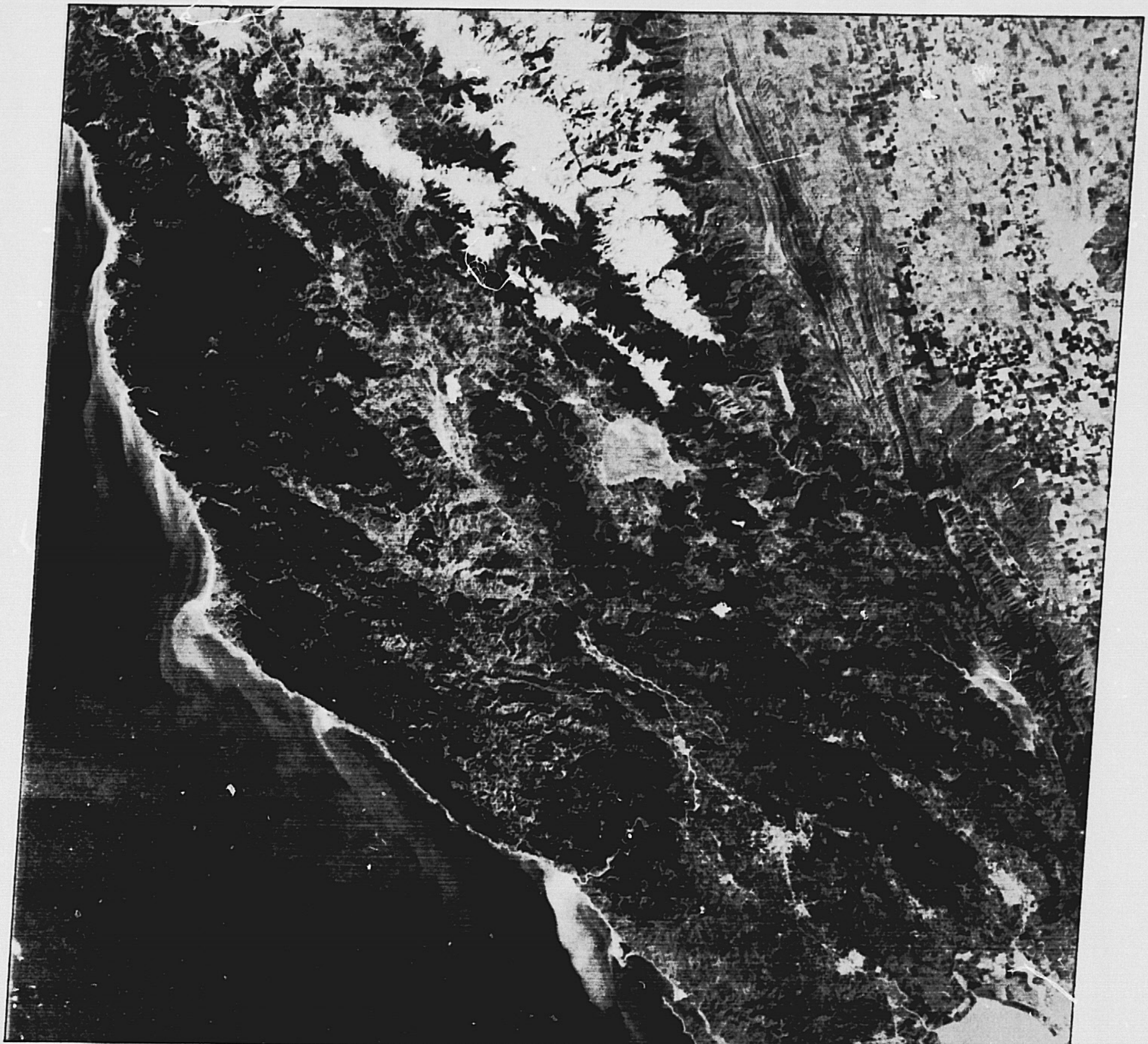

Figure 6-4 Landsat Scene 1976-18051-5, 26 March 1975

A well defined spring surface current example of the Upwelling season. Pt. Arena, California is at left center.

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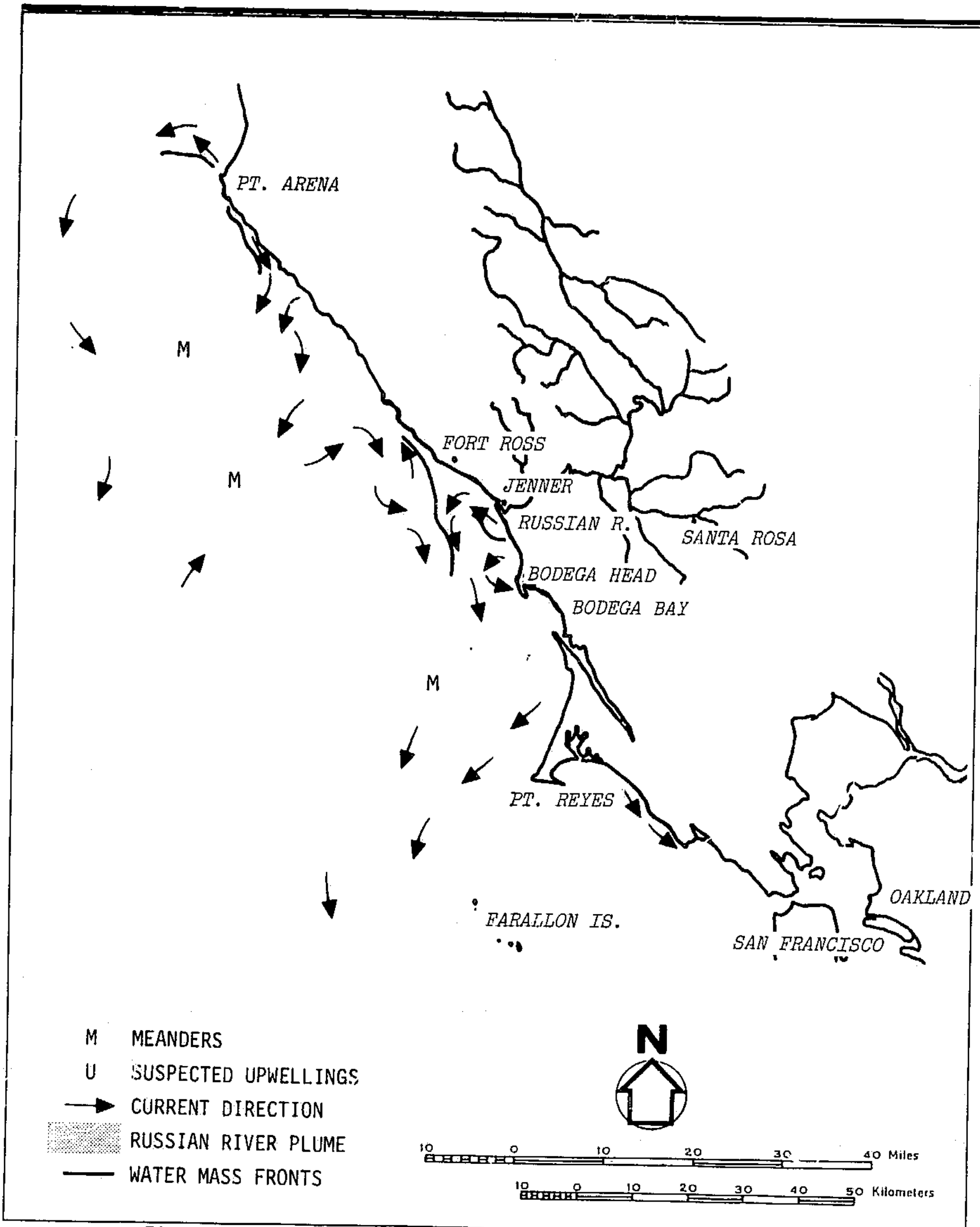

Figure 6-5 Generalized Russian River Surface Currents During Oceanic Season.

6.2 RUSSIAN RIVER MOUTH

The Russian River alternately flows freely into the Pacific Ocean or is impeded from doing so by the creation of a sand barrier at the river mouth. These actions are part of a complex natural system, including wind, waves, sand movement, riverflow and other environmental parameters which are continually at work. Beyond the natural or environmental complexities of the mouth of the Russian River, several economic and political elements must also be considered. Traditionally there has been an effort to secure continued free passage at the river mouth for various purposes. Included among these were, economic development, commercial operations, recreational boating, flood prevention and fishery access. Of perhaps the most importance were the attempts to commercially mine the gravels occuring at the river mouth, with concurrent development of recreational and commercial navigation facilities and a planned subdivision. These plans were objectionable to a significant portion of the local population and these objections were voiced strongly. Over an extended period of activity from 1964 to 1971, various private companies, citizens groups and governmental agencies were involved in the controversy. While the history of this era is too extensive to accurately present in this report, it is of value to consider the final outcome, which consisted of the ultimate denial of use permits for gravel extraction at the river mouth and return to a semi-natural inlet condition.

In the absence of any modifications, the conditions at the river mouth will continue in accordance with a natural cycle. That is, generally in the late fall the sand bar forms across the river until the first heavy winter flow, which opens the mouth through winter and into spring at which point the bar begins to once again build throughout the summer ultimately closing the entrance in the early fall. In the absence of man made changes and within this natural cycle, navigation of the entrance is dangerous at best and little economic development of the area is expected. In general, the natural resources of the area should remain intact, and continue to function in an unaltered natural cycle.

Cherry (1964), Minard (1971), Johnson (1959), and others have investigated transport phenomenon along the Pacific Coast near the mouth of the Russian River (Figure 6-6). Using available evidence in the form of technical reports, historical documents, maps, charts, photographs, field data, etc., they concluded that there is an extremely low intensity of sediment movement in the littoral zone near the Russian River. This condition is principally the result of a very small sediment supply to the coast and the refraction of prevailing waves such that littoral currents probably are relatively small. All investigators seem to agree that the rate of littoral drift along the coast is small and the quantities involved are unknown (Rice, 1974).

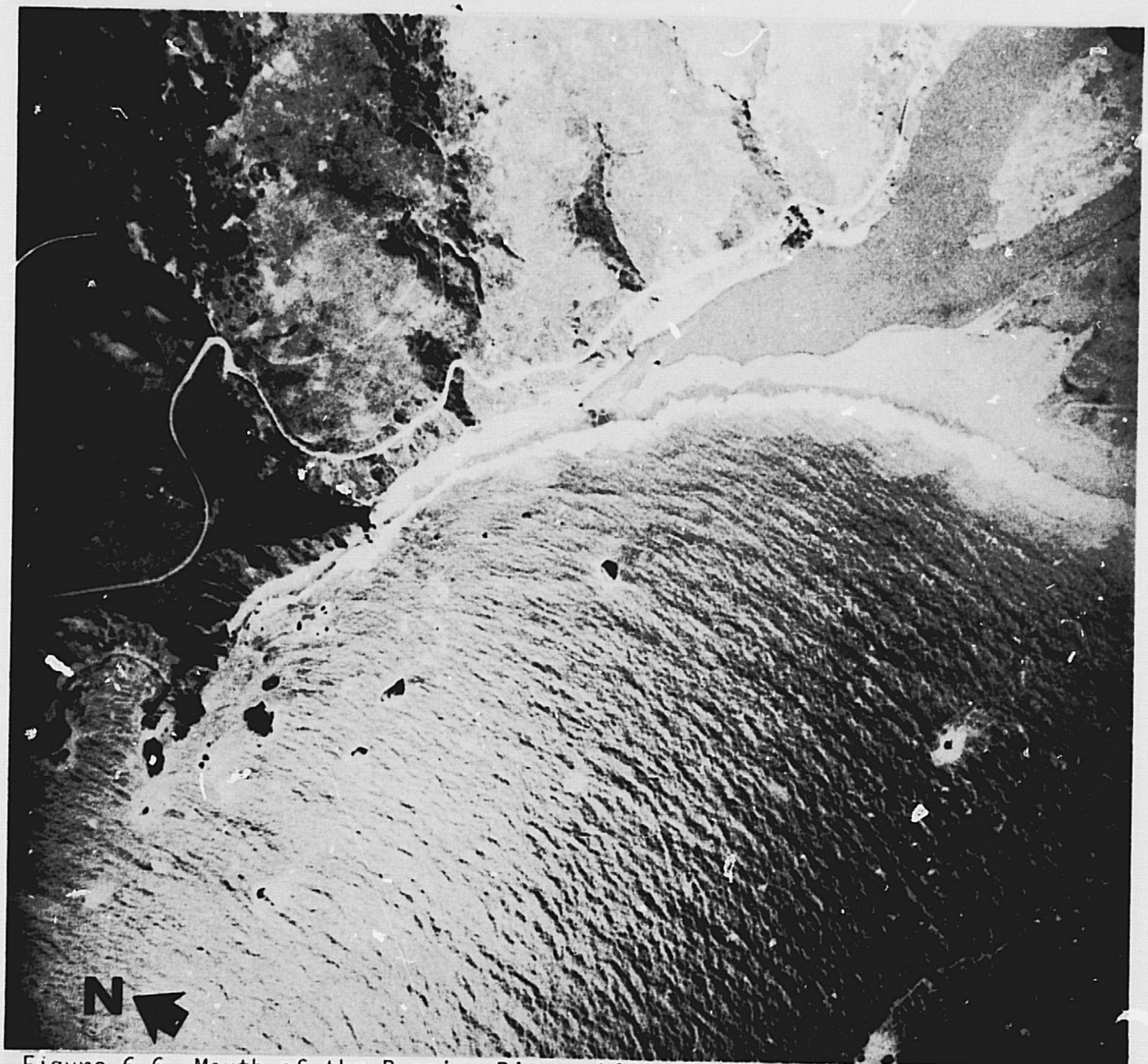

Figure 6-6 Mouth of the Russian River, NASA JSC Mission 235, 25 May 1973.

The rugged beaches northward of the Russian River mouth are more or less pocket beaches (small physiographic units) and littoral drift in the usual sense is non-existant or nearly so. Sand can be moved from north to south, in the study area, by wave action in depths out to 60 feet (18.2 meters) or more.

Over a period of years the general configuration of a shoreline appears to be relatively permanent. However, there are local changes in the surf and beach zones which result from the daily and seasonal variation in the direction and intensity of wave attack. During this study, the authors reviewed the Landsat and aircraft imagery as well as the historical charts and determined that the seasonal waterlines are quite close to those rivermouth configurations found early in this century.

The majority of the Russian River bed load sediments that contribute to the littoral drift seems to be a seasonal supply. The first heavy runoff of the year removes the entire bar north of the jetty. By doing so, the river mouth and estuary are flushed of the coarse grained sandy materials that had deposited there the year before.

When the flood season has passed and the river flow decreases, the sand bar begins to build at the northerly headland at the Russian River Cove and progresses southward. There seems to be a complete cycle of sand movement between headlands at the mouth of the river in a counterclockwise direction. During the summer months, when the normal currents and tides are not disturbed by high stream flows or high wave action, the littoral drift starts to replace the northerly bar and by early fall this accretion has been carried in a southerly direction until the top of the bar reaches a position to the lee of the jetty.

Examination of the computer program for the net annual transport volumes of littoral sands reveals no orderly annual transport relationships neither on a volume basis nor as to location along the study shoreline except that the predominant direction of net annual transport is to the south. From a careful scrutiny of the monthly transport rates (DeGraca, 1976), one begins to see a relationship in the seasonal longshore transport. During the winter months, December through February, and during the spring, March and April, the rates of transport are greatest and the transport is southerly directed over most of the shoreline. The summer-fall season, May through November, experiences theoretical lower rate of transport with many more periods of convergence and divergence of wave energy along the shoreline resulting in many areas of temporary accumulation and erosion. Unfortunately, most programmers obtain wave statistics that tend to ignore the long summer swells that arrive in the study area from the typhoon tracks off the Pacific coast of Mexico.

These swells with long wave periods tend to translate into a northerly component of littoral drift at the river mouth during the summer and early fall.

The existence of extensive beaches and well developed dune deposits in areas south of the river mouth imply that the supply of beach material exceeds the demand for longshore transport. The most readily available source of supply for these beaches is from the Russian River with some material added by nearby creeks or from cliff erosion. The lack of extensive beaches and well developed dunes in the areas north of the river mouth indicate that the demand for longshore transport exceeds the northern supply. The annual Russian River sand budget from our computer program confirms the abundant supply of beach material from the Russian River at various stations south of the mouth and the lack of any substantial quantities of beach material from the river to stations north of the river.

The finer sediment fraction (less than 0.125 mm) discharged from the Russian River is carried offshore and deposited as shelf deposits, whereas the coarser faction (greater than 0.125 mm) is distributed along the shoreline. Furthermore, 87 percent of the total sediment discharge from the Russian River occurs during December through February representing the winter season with its predominant southerly transport (DeGraca, 1976). Since much of the sediment discharged from the rivers in Northern California occurs in periods of floods, a very large volume of beach material is available for longshore transport within a very short period of time, undoubtedly exceeding the potential longshore transport within this period, especially for years with high discharges (January 1965 at the Russian River). Thus, a temporary stockpile of beach material will be deposited near the mouth of the Russian River during maximum discharges which will then feed the littoral regime during the ensuing months until these stockpiles are exhausted. The discharge beach material that is not deposited continues in transit to the south and is deposited offshore.

6.3 CONCLUSION

The use of Landsat and aircraft imagery has made it possible to qualitatively define the complex coastal processes near the mouth of the Russian River. This is most important in evaluating the inexact results from littoral drift computer studies and entrance mechanics. The surface plume seen from Landsat defines the nearshore current as well as the probable initial deposition sites for silts and clays. Initial deposition of beach type sands can be spotted with aircraft imagery with assistance derived from Landsat.

6.4 REFERENCES

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7.0 HUMBOLDT BAY AREA

Humboldt Bay is located in Humboldt County in Northern California. It is the only naturally enclosed harbor offering deep draft commercial facilities between San Francisco 416 km (225 nm) to the south and Coos Bay, Oregon 288 km (156 nm) to the north (Figure 7-1). The cities of Eureka and Arcata are located on its shores. The area is developing fast because of its allure as a "remote coastal" location and the harbor which is accessible for both recreation and commerce. The climate in the area is one of the wettest in the State of California. The Eel River empties into the Pacific Ocean 16 km (10 miles) south of Humboldt Bay. It has the highest recorded average annual suspended sediment discharge per square mile of drainage area, of any river of its size or larger in the United States (Brown and Ritter, 1971). The Mad River enters the Pacific Ocean 8 km (4.9 miles) north of Humboldt Bay and the Klamath River enters the ocean 80 km (50 miles) north of the bay. The ocean surface currents which transport discharges from these rivers result in extensive surface plumes. These plumes can be detected and mapped on Landsat imagery the year round. The result is the ability to gain a clear picture of the forces effecting offshore ocean surface utilizing Landsat data.

Because of new urban development in the Humboldt Bay area, which necessitate construction of onshore and offshore facilities, the area is well suited for Landsat investigation. Little is quantitatively known about the dynamics of the offshore region (U.S. Army Engineer District, San Francisco, 1976). This is partially due to the winter storms which are accompanied by high waves. There have been few detailed studies of the area to date. The storm waves which often reach heights of over 8 meters (26 feet) preclude extensive oceanographic shipboard surveys much of the year (Gast, 1976). The need for nearshore information plus the ability to analyze the surface dynamics using the extensive suspended sediments make the Humboldt Bay coastal area highly suitable for analysis. For the immediate Humboldt Bay offshore area, detailed oceanographic information is presently being evaluated by Winzler and Kelly's (1976) oceanographic study for the Humboldt Bay Wastewater Authority. This study is part of a site analysis for proposed wastewater facilities.

Humboldt Bay is long and narrow, shallow at the extremities with deep dredged central channels. The bay is about 23 km (14 miles) long and varies in width from less than 0.8 km (0.5 miles) wide in the middle to about 6.4 km (4 miles) wide at the north end. It is separated from the ocean by two long narrow sand spits. The bay is properly classed a coastal plain estuary formed by the drowning of one or more former river valleys. The dominant agent of transport and sorting in the bay appears to be tidal currents and wind.

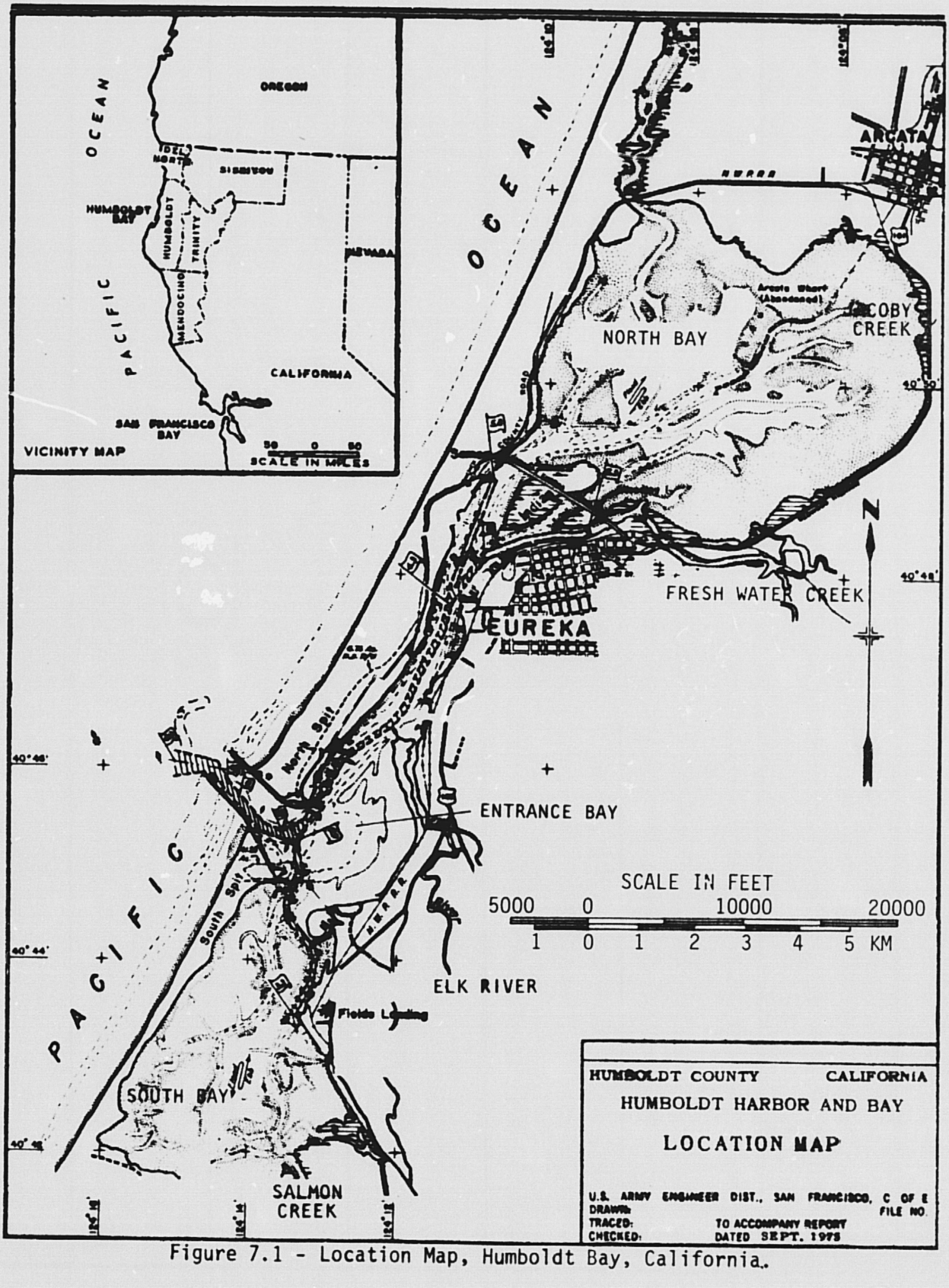

Figure 7.1 - Location Map, Humboldt Bay, California.

These currents are strong at the bay entrance and decrease away from the bay mouth. Entrance velocities reach 1.8 m/sec (3.5 knots) during maximum current periods (National Ocean Survey, 1976).

Humboldt Bay should be considered in three distinct units: the South Bay; the Entrance Bay; and the North Bay, or Arcata Bay. The South Bay is drained by two major channels, surrounded by extensive mud flats. Both South and Arcata Bays are navigable only in the main channels at low tide. The Bay is quite shallow, and channels for fishing boats and shipping vessels are maintained by dredging. Jacoby and Freshwater Creeks discharge into the north end of the bay, and Elk River and Salmon Creek discharge into the central portion and southern end of the Bay respectively. These streams and their corresponding slough are tidal from 1.6 to 3.2 km (1 to 2 miles) inland from their mouths.

Two protected jetties mark the entrance to Humboldt Bay and lead directly into the sub-bay generally known as Entrance Bay. The east portion of Entrance Bay is shallow as compared with the west where the main shipping channels occur. These channels are maintained by dredging operations and allow large vessels access to Samoa Channel, the channel which leads north to Arcata Bay. The Entrance Bay has a mean high water area of 7.5 sq km (2.9 sq miles) and this area is practically the same regardless of the tidal height (Gast, 1964). As with all the sub-bays, Entrance Bay marks the seaward end of a major stream-flow system. Elk River flows directly into Entrance Bay and accounts for approximately one-fifth of the watershed runoff entering Humboldt Bay.

The southern portion of Humboldt Bay, South Bay, extends approximately 6 km from the entrance, widening to nearly 3 km at the southernmost end. The South Bay is generally shallow with large areas of tidal flats being exposed at low water.

A fairly deep, narrow, natural channel follows the North Spit for about 5 km north from the jetties to a point defined by the junction of Samoa and Eureka Channels. The area extending north of this junction being Arcata Bay.

The Corps of Engineers has continued its harbor improvements of Humboldt Bay which began as construction of jetties at the entrance in 1889. The jetties have been improved and rebuilt a number of times. The navigation channels have been deepened and widened, following the trends of the original natural channels (Noble, 1971). Maintenance dredging continues to the present day.

At the present time, a new sanitation project is planned for the cities of Eureka and Arcata adjacent to Humboldt Bay. The objective of the project is compliance with the State Water Resources

Control Board mandate to improve the overall sewage handling processes. The reason for the extensive Winzler and Kelly (1976) study previously mentioned is to have as complete a picture of the ocean parameters at the proposed outfall site as possible. This discharge for the new facility is planned for the ocean as opposed to the bay discharge presently in use. Two major offshore discharges (Figure 7-2) are presently operating. They expell wash waters from two pulp mills on the peninsula adjacent to Humboldt Bay. This effluent is clearly visible on most of the Landsat imagery as the discharge effluent comes to the surface and disperses into the sediment laden ocean water. The diverse plans for future utilization of the waters around Humboldt Bay made it essential that a thorough investigation of the water dynamics be determined before additional facilities are added. Landsat provides information that can be essential to the overall surficial oceanographic picture and add greatly to the detailed current meter array data.

7.1 LANDSAT EVALUATION

The major variances in coastal and open ocean surface dynamics are indicated on the Landsat pictures by the sediment transport patterns which act as tracers for the currents. The Northern California coast has several major rivers including the Eel, Mad, Klamath and Mattole. Heavy rain and snow throughout much of the area, especially in the fall and winter, provides large volumes of sediment to the coastal area. Figure 7-3, taken during March 1975, is a striking example of the extensive ocean plume resulting from heavy runoff. Surface material extends out to 70 km off the coast. In the nearshore areas, gyres and eddies cause complex patterns in the dominant California Current's southern movement. Added to this are tides, upwellings, and the action of meteorological variations which further complicate the picture. A summary of the Landsat imagery from the Humboldt Bay area is seen on Table 7-1. One of the major changes noted during the study is the change in nearshore current direction. In the January - March period, north moving nearshore currents are often present and the rest of the year the pattern is generally south. This period of north moving current (Davidson Current) sometimes starts as early as November (i.e., 1975) along the Southern California coast, but at this northern latitude, such an occurence appears unusual.

This period of current reversal was called an upwelling influence by Skeesick (1963). He found significant changes in the Bay water in December 1961. The salinity increased, and there was a decrease in water temperature, the sigma-T values increased, there was a decrease in dissolved oxygen concentration, an increase in the phosphatephosphorus concentration, and an increase in the silicate-silicon concentration - samplings which appears attributable to upwelling. Skeesick found that in January all these changes again

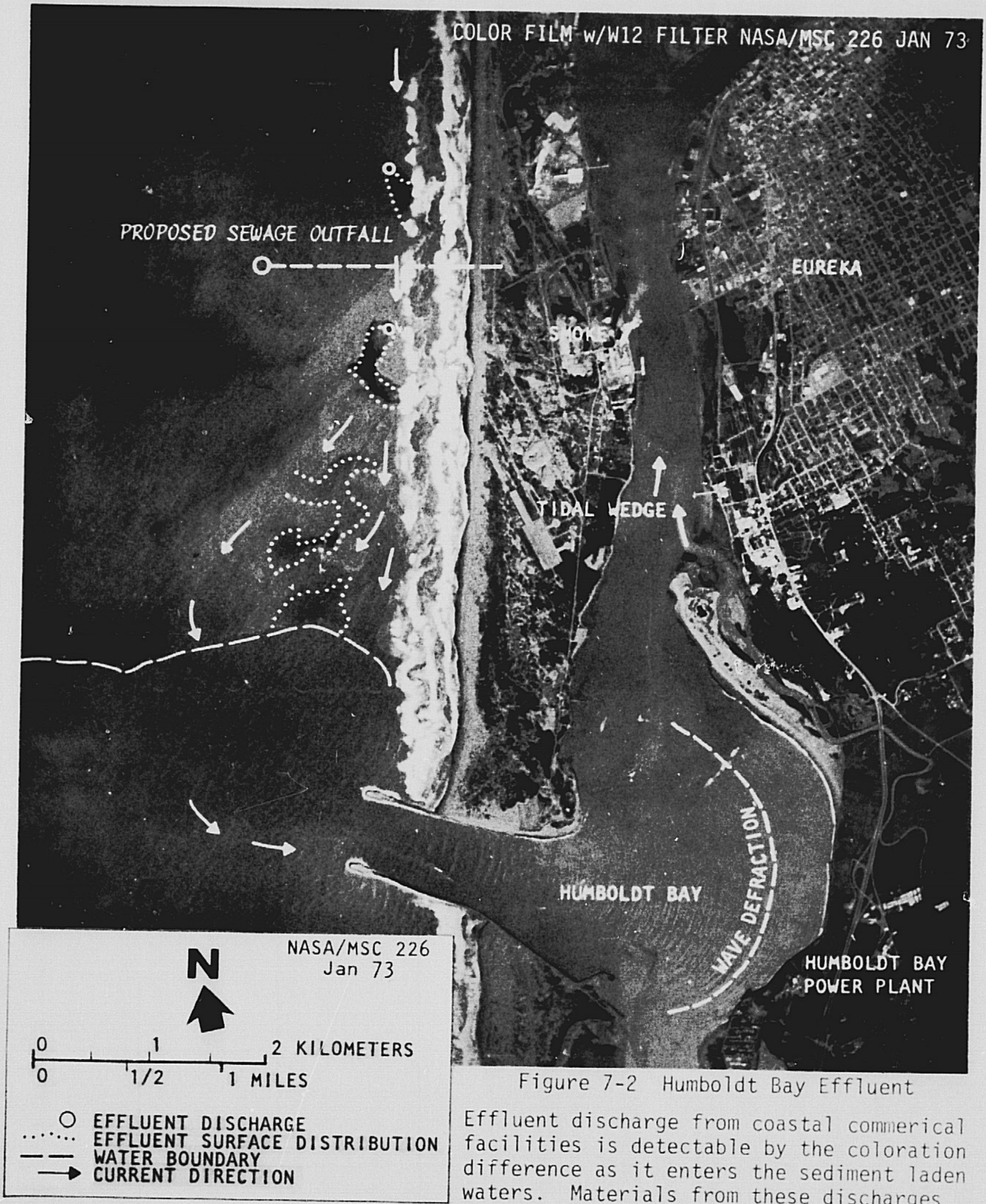

Figure 7-2 Humboldt Bay Effluent

Effluent discharge from coastal commerical facilities is detectable by the coloration difference as it enters the sediment laden waters. Materials from these discharges have been detected entering Humboldt Bay during flood tide.

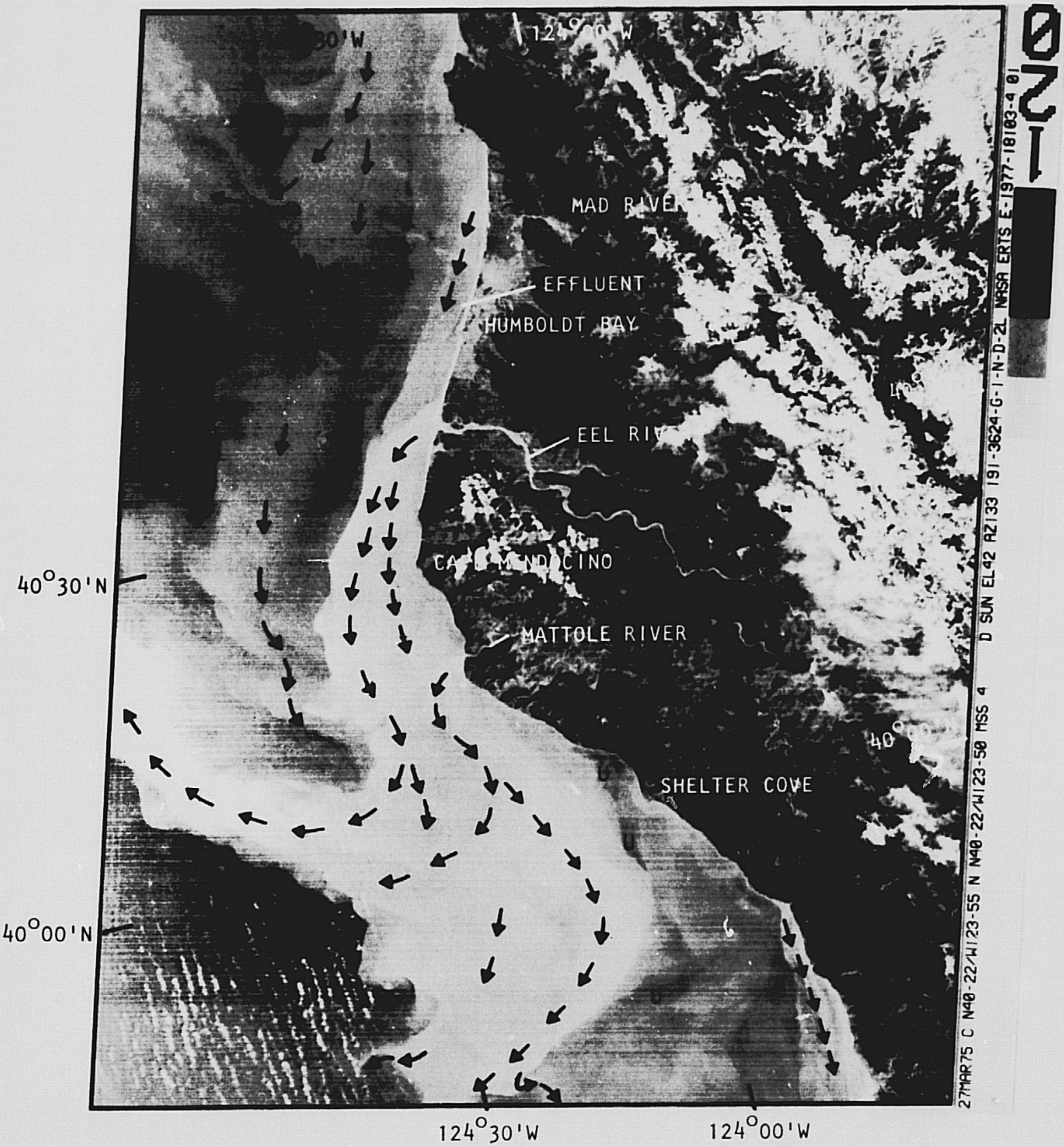

Figure 7-3 Sediment Transport - Northern California Coast.

Spring image of the northern California coast on March 27, 1975. Complex currents are outlined by the sediment transport patterns. Heavy discharge from the Mad, Eel and Mattole Rivers is clearly seen. Adjacent to Humboldt Bay effluent discharge can be seen. A number of upwellings (U) are bringing clear subsurface water into the sediment laden surface. The sediment plumes are extended to more than 100km off the coast. NASA /Landsat 1977-18103-4

TABLE 7-1

HUMBOLDT BAY
LANDSAT COVERAGE

LEGEND

CM - Cape Mendocino
HB - Humboldt Bay
PG - Punta Gorda

(C) - Clockwise
N - North
S - South

Slow / Moderate / Fast — Appearance of Current Velocity

	LANDSAT ID	DATE	REMARKS
1	1095-18283-5	26 Oct 72	3 Slow, few sediments
2	1096-18341-4	27 Oct 72	S Slow, gyre off Cape Mendocino
3	1167-18283-4	6 Jan 73	N Moderate, offshore currents heavy sediment discharge -- 6-3 km sediment strip
4	1222-18345-5	2 Mar 73	N Moderate, nearshore current
5	1258-18345-4	7 Apr 73	S Moderate, 8-10 km sediment strip
6	1275-18290-4	24 Apr 73	S Moderate, sediment, moderate upwelling, sediment strip
7	1276-18345-4	25 Apr 73	S Slow, fog narrow strip
8	1312-18343-4	31 May 73	S Slow, sediment minor, offshore pattern CM
9	1330-18342-4	18 Jun 73	S Slow, sediment minor, nearshore
10	1347-18282-4	5 Jul 73	S Slow, gyre off HB, shear off CM, and PG, upwelling
11	1348-18340-4	6 Jul 73	S Slow, gyre HB, shear breakup, upwelling, offshore
12	1365-18281-4	23 Jul 73	S Slow, gyre HB, minor sediment
13	1366-18335-4	24 Jul 73	S Slow, minor sediments
14	1401-18273-4	28 Aug 73	S Slow, minor sediments
15	1420-18330-4	16 Sep 73	S Slow, minor sediments, CM, offshore movement
16	1420-18330-4	16 Sep 73	S Slow, nearshore gyre, CM offshore movement
17	1437-18265-4	3 Oct 73	S Slow, nearshore gyre, CM offshore
18	1438-18323-4	4 Oct 73	S Slow, minor sediments
19	1528-18310-4	2 Jan 74	S Slow, Eel offshore, CM large gyre (C)
20	1546-18303-4	20 Jan 74	N Moderate, sediment 40 km offshore
21	1581-18235-4	24 Feb 74	N Moderate, nearshore N. current, offshore S. current

TABLE 7-1 (Continued)

	LANDSAT ID	DATE	REMARKS
22	1635-18225-4	19 Apr 74	S Moderate, HB effluent-visible, nearshore heavy
23	1708-18262-4	1 Jul 74	S Slow, upwelling CM
24	1744-18251-4	6 Aug 74	N Slow, HB north current anomalous
25	1815-18171-4	16 Oct 74	S Slow, minor sediments
26	1888-18201-4	28 Dec 74	S Slow, minor sediments, 32 km offshore patterns
27	1959018112-4	9 Mar 75	N Moderate, strong Davidson Current, 32 km offshore
28	1960-18170-4	10 Mar 75	N Moderate, heavy sediments, CM gyre
29	1977-18103-4	27 Mar 75	S Fast, heavy sediments, large offshore patterns 64 km
30	5013-18084-4	2 May 75	S Slow, nearshore current is loggy
31	2181-18163-4	22 Jul 75	S Slow, minor sediments
32	2307-18150-4	25 Nov 75	N Slow, heavy sediment, Davidson Current
33	2343-18143-4	31 Dec 75	S Moderate, moderate sediments, CM offshore 40 km
34	2415-18031-4	12 Mar 76	S Moderate, offshore CM 64 km
35	2469-18113-4	5 May 76	S Slow, light sediments, HB effluent
36	5391-17452-4	14 May 76	S Moderate, offshore movement, CM 40 km
37	2487-18110-4	23 May 76	S Slow, nearshore movement

reversed. Adams (1975) in his study of Humboldt Bay found that during the months of November and December 1971, the average monthly water temperatures were 2°C and 1.5°C respectively below the monthly means. In January and February 1972, he found temperatures were 1°C and 0.5°C respectively below the monthly means. By March through August, the temperatures were very close to the monthly means for 8 years.

In the Environmental Impact Statement for the new sewage facility at Humboldt Bay (Environmental Research Consultants, 1974) it was noted that virtually no information was available concerning transport and dispersion of the immense silt and clay loads entering this coastal area from the Eel and Mad Rivers. Thompson (1971) suggests that substantial quantities of silt and clay are contributed to Humboldt Bay by the Eel and Mad Rivers. However, his findings were based on sparse evidence. He implies movement of materials under the influence of littoral currents, which reverse with the season. Movement of suspended material outside the surf zone is presumably controlled by tidal and wind-driven currents. This information is put forth to re-emphasize the need for all available information - especially when designing a structure such as the planned offshore effluent outlet.

Not all of the currents along the coast fit the general pattern of south movement. In August 1974, for example, a Landsat image (Figure 7-4) shows an anomalous north moving nearshore current at the entrance to Humboldt Bay. This was in the middle of the oceanic current period when the south moving California Current usually dominates. The U.S. Geological Survey (Carlson, 1975) found some similar anomalous currents during a 1973 drift card study. During the U.S.G.S. study, northward transport from the mouth of the Eel River was noted on three occasions; June, August and October. On two of these occasions, northwest winds were blowing, making the results somewhat surprising. The tidal current must have been the dominant influencing agent. In Figure 7-4, although the material at Humboldt Bay is moving north, the suspended material near the Eel River and Cape Mendocino is moving southward. Hence, a nodal point between opposite moving current appears to have been present between the Humboldt Bay entrance and the Eel River. Although no meteorological data was collected during the Landsat overpass, a south or southwest wind was probably blowing. Such an effect was often found to be present during the oceanographic study made by Winzler and Kelly (1976).

The Winzler and Kelly study reports several occasions when high wind velocity overcomes the current flow especially when the wind blows for extended periods. They used current meter arrays with both near surface and bottom current collection stations. Typical array at or near the proposed sanitation outfall consisted of a

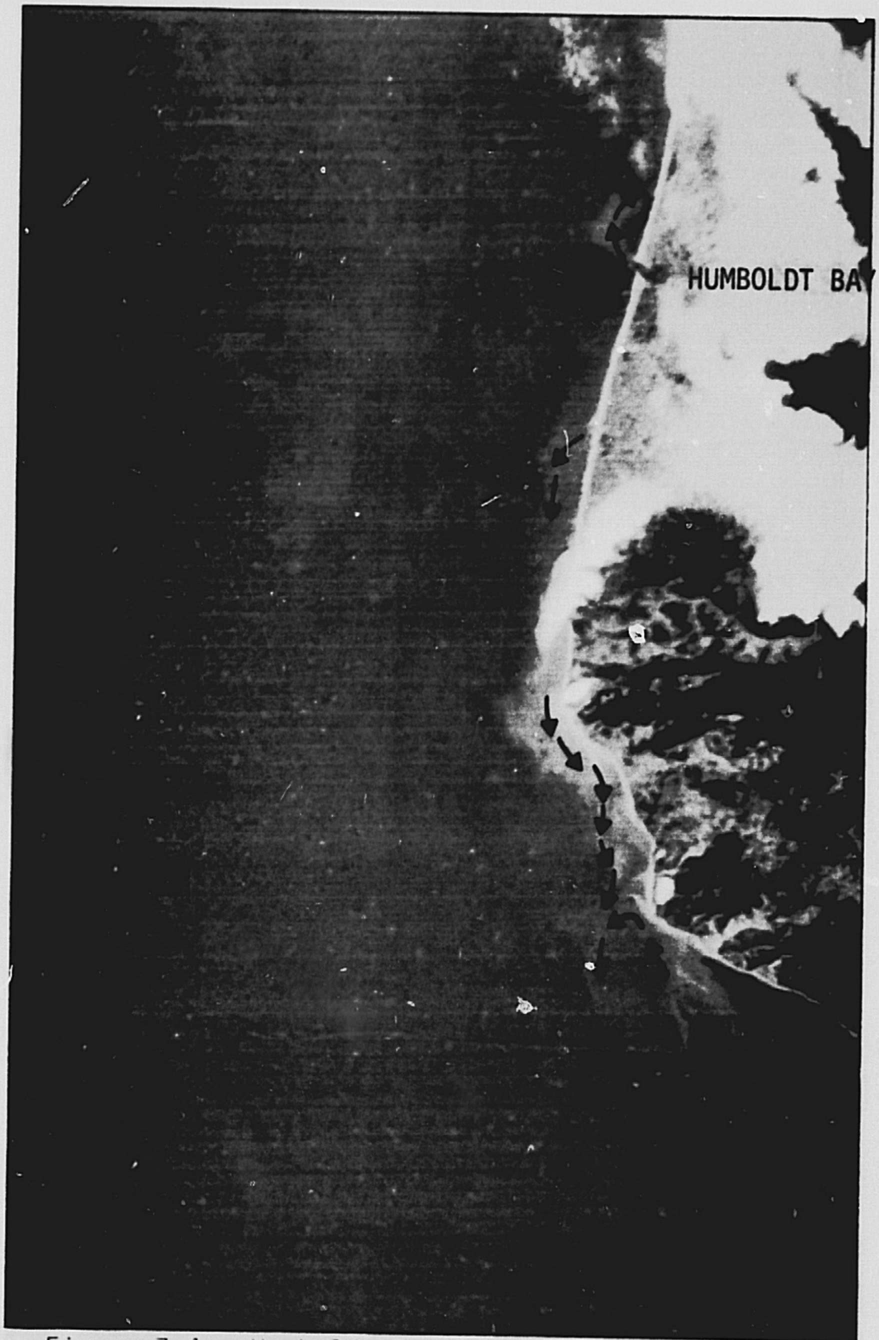

Figure 7-4 - Humboldt Bay Anomalous North Current

This August 6, 1974, Landsat image shows a north trending current at Humboldt Bay which is unusual for this period of the year. The probable cause is wind induced littoral currents. NASA/Landsat 1744-18251-4.

current meter moored 6 meters (20 feet) below the surface and 1.5 meters (5 feet) off the bottom where the water was 18 meters (59 feet) deep. In analyzing the data from such an array it was usually found that the dominant current pattern controlled the bottom meter readings, while the variable surface winds often effected the surface meter. For example, a southwest wind blowing during the period June 29 to August 2, 1976, resulted in an interruption in the dominant south moving California Current pattern. The southerly winds in 1976 were of low velocity and short duration and were not capable of establishing a northerly current but only to interrupt the southerly flowing current. The meteorological parameters which were occuring during the Landsat overpass seen in Figure 7-4 were probably somewhat similar. However, the south or southwest wind at Humboldt Bay was probably of longer duration resulting in the northern surface current illustrated by the north moving sediment plume.

7.1.1 OCEANIC CURRENT PERIOD - NORTHERN CALIFORNIA COAST

During the Oceanic Current Period (Figure 7-5) the California Current is dominant and with few exceptions current transport is southward. Suspended sediment available for transport is at a minimum but still of sufficient quantity to be detectable. The fall of 1975 was a period in which a smallest volume of suspended sediment was available because of the low rainfall. The high volume of precipitation in the Northern California area does provide for a great volume of runoff. The major problem for the investigator is obtaining cloud and fog free imagery for the area. Much of the time when the land was clear the ocean was obscured by a cloud or fog cover.

The majority of the material seen in this area comes from the Klamath, Mad, Eel and Mattole Rivers. This is true throughout the year. As the suspended sediment is transported southward during Oceanic Current Period many eddies and gyres are formed. This is especially true behind or southward of land masses which protrude into the flow. An example of this is seen repeatedly at Cape Mendocino and Point Gorda south of Humboldt Bay. The flow of the California Current is disturbed at these points and as the water moves eastward past the protruding land a counterclockwise eddy is often formed. Often the material in these eddies spin off seaward 10 to 20 km (6 to 12 miles). A number of images have been seen where the offshore pattern is the periodic north moving trend which has been local in extent and caused by south or southwest winds of short but steady duration.

7.1.2 DAVIDSON CURRENT PERIOD - NORTHERN CALIFORNIA COAST

During the Davidson Current Period (late November to February) the transport of suspended sediment is often northward or opposite

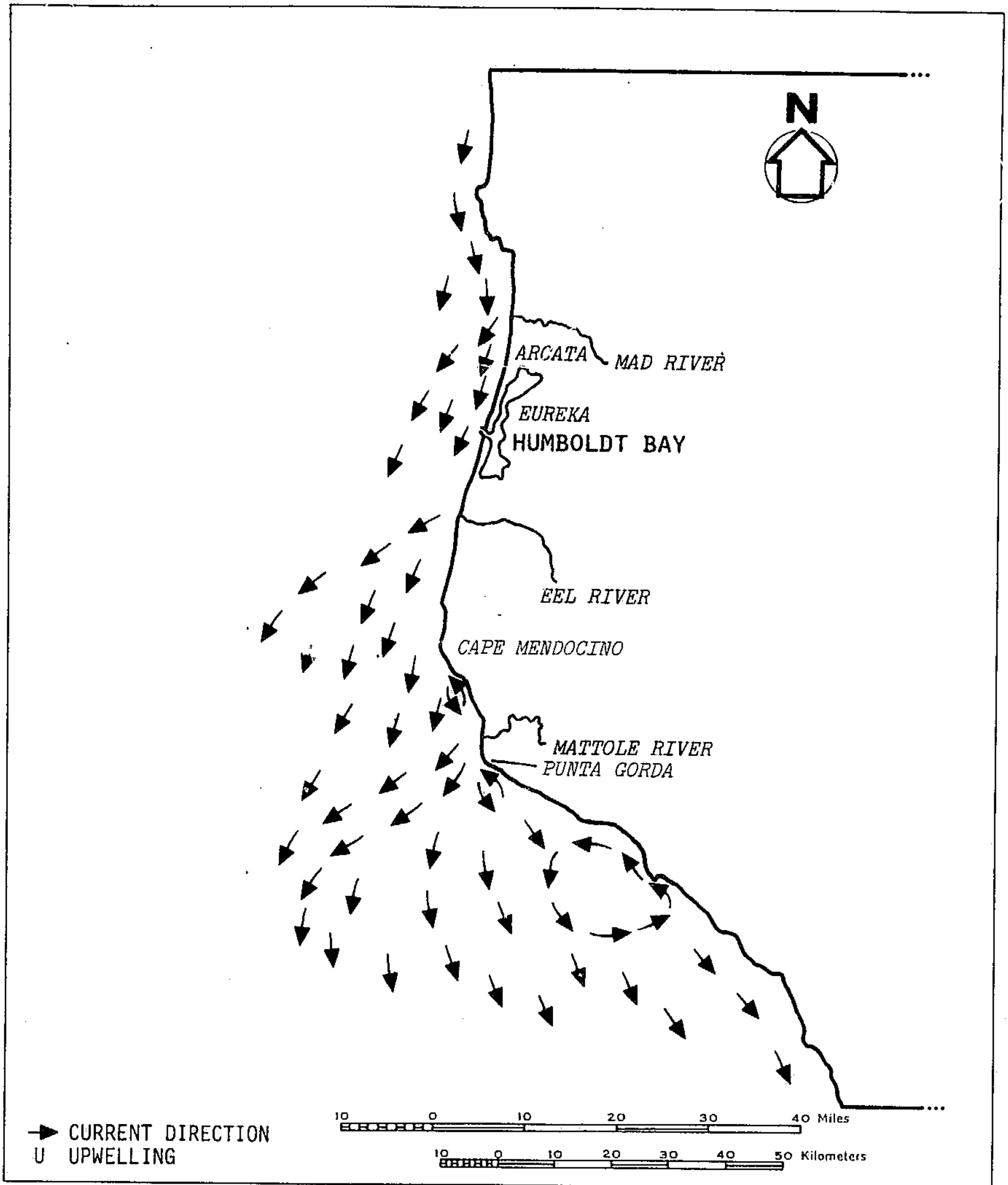

Figure 7-5 Oceanic Current Period - Northern California Composite.

to the general pattern found the rest of the year (Figure 7-6). Since this period coincides with the start of the rainy season some spectacular offshore patterns are often present. The Davidson Current forms when north winds are weak or absent and surfaces on the inshore side of the main stream of the California Current. The interesting point that is noted in viewing all the available Landsat imagery is that the northern transport near the coast is constantly interrupted by the south trending California Current offshore. The distance at which this phenomena occurs varies but it is often found at approximately 8 to 16 km (5 to 10 miles) offshore. The result is a number of counterclockwise eddies formed along the coast. The offshore component of the interrelated forces involved is often 40 or 50 km (25 or 31 miles). In other words the material from the river and streams is transported northward, then westward and then southward and is still detectable at the surface 40 or 50 km (25 or 31 miles) off the coast. Land protrusions into the northern flow disturb the pattern similar to the way they modify south moving current. Eddies form clockwise patterns that transports material shoreward. The nodal point between the north moving Davidson Current and the south moving California Current is sometimes found along the Northern California coast. In this case large offshore eddy patterns form. The Davidson Current Period extended into March 1975 so the February cut-off date must be modified sometimes.

7.1.3 UPWELLING CURRENT PERIOD - NORTHERN CALIFORNIA COAST

The Upwelling Current Period (Figure 7-7) is a result of north and northwest winds in the spring which move surface water offshore. The replacement waters are from the deep ocean and are cooler and higher in nutrients. This upwelling effect is visible on the Landsat imagery because of the lack of suspended sediment in the waters. The high reflectance pattern from the sediment laden waters is modified by the low reflectance upwelling waters brought to the surface. The dynamic patterns seen at the ocean surface are complex in nature. These upwellings often occur behind (south of) points of land. This is because as the winds blow from the north or northwest a low pressure zone is formed leeward of land masses. At the same time these winds are blowing surface waters seaward. The combination allows the subsurface water to come to the surface south of the protruding land masses.

Since the Upwelling Current Period is in the spring (late February through June) there are large volumes of runoff and sediment discharge from the river. In the relatively straight coastal areas, like the stretch from north of Humboldt Bay to Cape Mendocino, the current transport patterns trend generally southward. During this period an upwelling is often present south of Cape Mendocino, Punta Gorda and Shelter Cove.

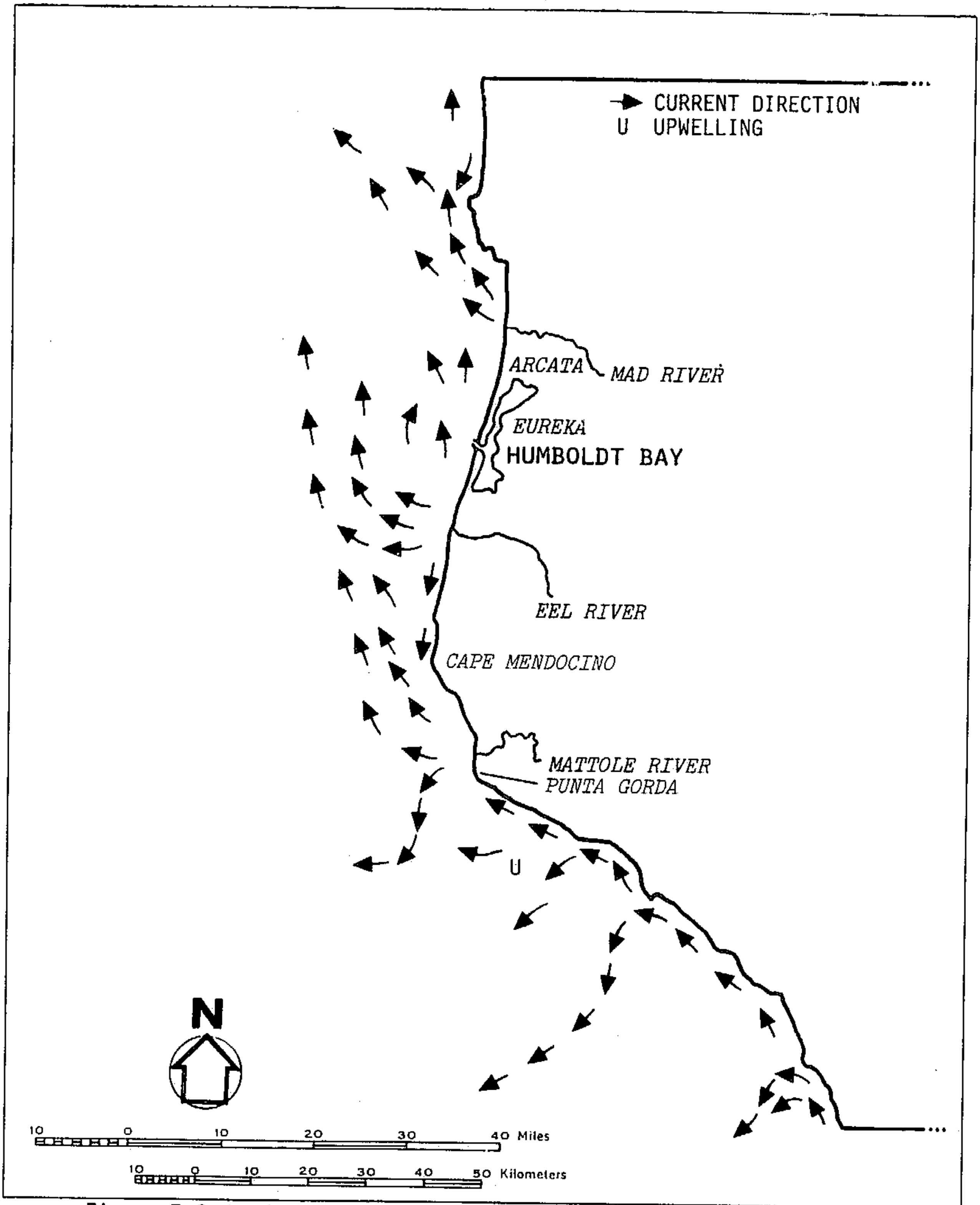

Figure 7-6 Davidson Current Period - Northern California Composite.

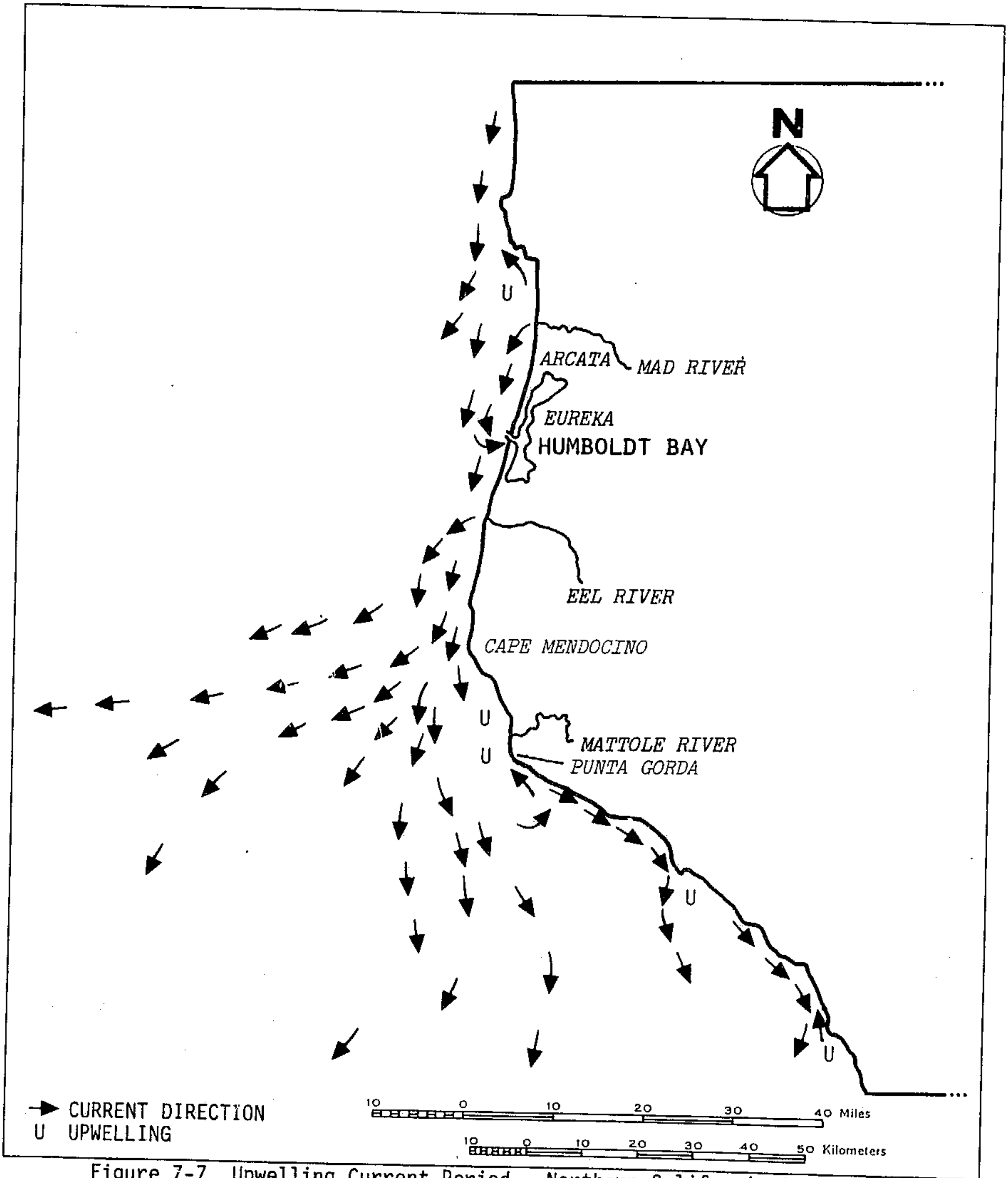

Figure 7-7 Upwelling Current Period - Northern California Composite.

At these and similar localities the south moving tangent pattern is modified. Gyres and surface eddies form and offshore movement occurs. As the material moved westward and southward past the location of the upwelling a reversal of pattern often takes place. Inshore or eastward movement combines with the always dominant southward transporting forces. As viewed on a Landsat image this process repeats itself at each land break in the south moving current.

7.2 DISCUSSION OF HUMBOLDT BAY EFFLUENT DISCHARGE FACILITIES

As a result of the 1973 break in the major sewage line at Humboldt Bay, the bacteriological quality, as determined mainly from the harvested shellfish, was reduced to a dangerously low level. After the break, only 19 of 35 water sampling stations throughout the Bay were capable of meeting the restricted growing area classification requirements (Environmental Research Consultants, 1974). This break pointed up the need for new sewage facilities. At present, the recommended plan that has the most support from several alternatives is the discharge of sewage into the ocean (see U.S. Army Engineer District, San Francisco, 1976, Public Notice No. 10603-21). The physical and political ramification of such a project are complex and varied, but the area of interest most directly related to this Landsat study is the expected effluent discharge as affected by the nearshore currents. The location of the proposed discharge as shown on Figure 7-2 is seen in section view Figure 7-8. This proposed outfall will extend 1829 meters (6,000 feet) off the Sonoma Peninsula with the last 152 meters (500 feet) being a diffuser. The end of the outfall will be in about 18 meters (60 feet) of water. The discharge at that location will be transported by the nearshore currents which can be seen and traced on the Landsat imagery. This has been especially true for the Humboldt area, because of the two major rivers, Mad (north) and Eel (south) which bracket the Bay. In viewing all the Landsat imagery for the California coast, it was noted that the northern coastal currents and sediment transport patterns can be continuously monitored.

In studying satellite and aerial photography of the Humboldt Bay entrance and the adjacent coastal areas, it becomes apparent that during certain tidal and current periods, gyres and eddies set up near the entrance breakwaters. These eddies combined with the tidal current to bring suspended materials from the nearshore area into the bay. The percentage of occurrence of this phenomena is not known and could only be determined through a continuing detailed survey of the water dynamics and physical parameter. The survey of Landsat imagery listed in Table 7-1, gives the direction and features noted for all imagery available. This, however, is just a start since, at best, it covers every nine days with many interruptions for cloudy or foggy weather.

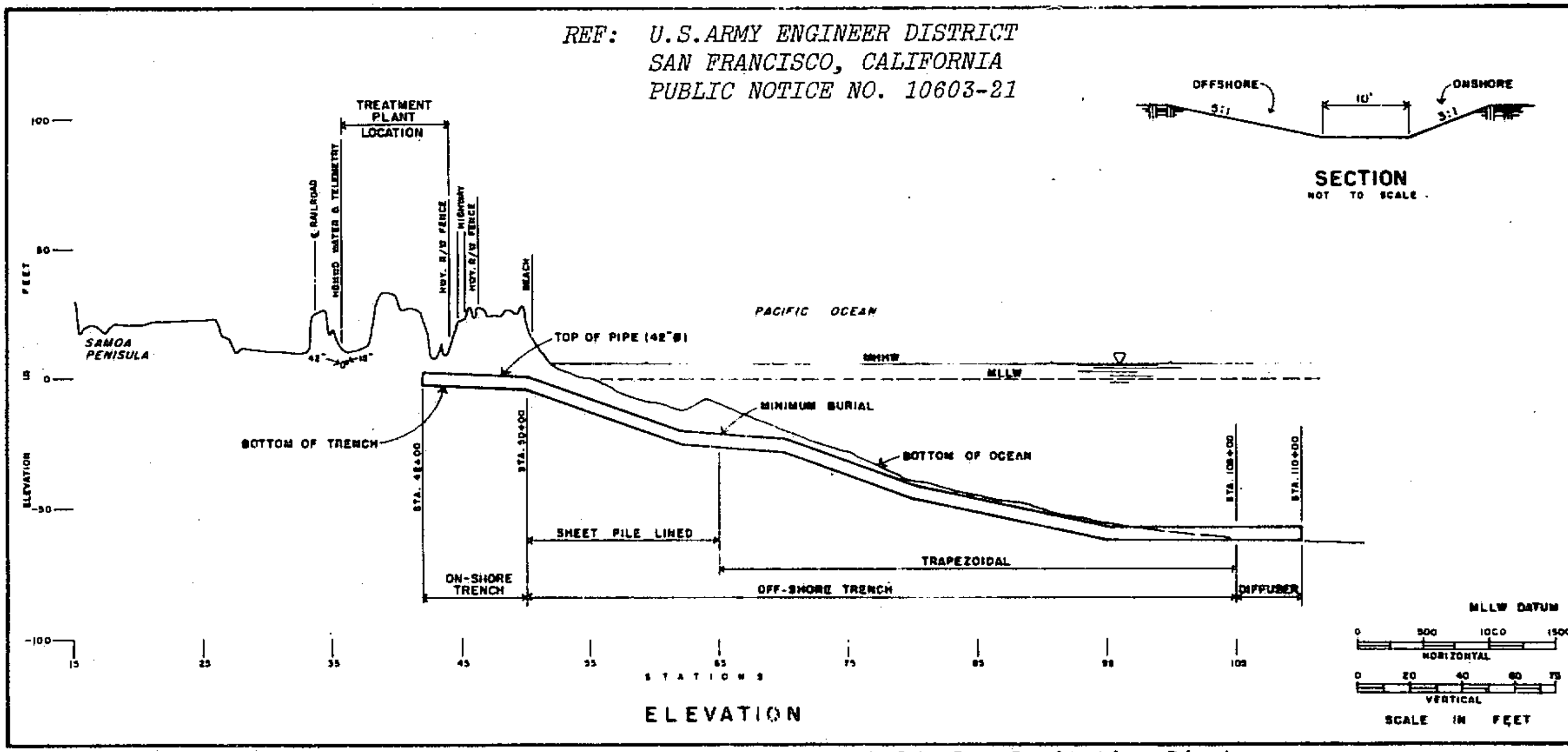

Figure 7-8 Section View of Proposed Humboldt Bay Sanitation Discharge.

7.3 HUMBOLDT BAY CONCLUSIONS

The use of information provided from Landsat imagery in coastal construction design is an on-going program at Humboldt Bay. The proposed wastewater facilities off the north spit of the bay is presently being evaluated. Landsat provides an overview of the seasonal and monthly changes in current patterns. Such information can be correlated with the detailed sea truth information being collected at the proposed wastewater outfall itself. It is too early to evaluate the scientific and cost benefits of such LANDSAT utilization but preliminary results indicate that this information is an extremely useful and economical tool. This is especially true during periods of the year when storm waves precludeshipboard oceanographic data collection.

A review of the available Landsat imagery shows discharge plumes that confirm the expected transport patterns the majority of the time (i.e., south current during the late spring, summer and fall, intermittent north current from November to March). The south currents result from the effect of the California Current - the north, the effect of the Davidson Current. Exceptions to this basic pattern have been found at various short periods especially in the late summer and fall. These variations usually are accompanied by southwest winds reinforcing the anomalous current patterns.

The effect of tidal currents can be detected on the Landsat imagery at the mouth to Humboldt Bay. Current velocities appear higher on the flooding tide and lower on the ebbing tide. Large plumes of suspended sediment from the mud flats are often present in the form of a bay mouth eddy during and after ebb tide.

Upwellings have been detected by the current meter array outside the entrance to the bay. These upwellings are often detectable on the Landsat imagery. They show up as darker patches within the lighter sediment laden coastal waters. On a smaller scale the effluent discharge from the pulp mills also appear on aircraft and satellite imagery. Upwelling occurs when the southerly winter winds are replaced by northerly winds of high velocity which tend to reinforce the southerly flowing California Current.

7.4 REFERENCES

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12. Winzler and Kelly Consulting Engineers, Oceanographic Study Humboldt Bay Wastewater Authority, 1976.

8.0 IMAGE PROCESSING

In viewing the many images available for the California coast, it is clear that for much of the year there is little that can be seen in the offshore water especially in the southern latitudes. This was definitely the case in 1974 and 1975 when rainfall were significantly lower than usual and resulted in a low runoff and low level of suspended sediment in the ocean waters. For this reason, the use of image processing techniques for enhancing the sediment patterns that were present, became a tool that was most important in the understanding of the coastal processes. A good example is illustrated by Figures 8-1 and 8-2. In this case the enhancement technique was ASTRETCH and the season of the year was fall (October 15, 1975) in southern California when the streams and rivers were dry. In the ASTRETCH enhancements, the limited digital number range which represents the suspended sediment patterns are stretched over a wide range to increase the scene contrast. This allows the investigator to interpret and analyze features not detectable on the original imagery. In the original image in this example no sediment pattern except in the immediate vicinity of the beach were detectable.

The discussion included in this section will be confined to techniques applied to the coastal process enhancements. For any detail of the computer compatible tapes, as supplied by NASA, the reader is referred to Thomas, 1975 which gives the details of the tape generation and characteristics. As received from NASA the CCT's required three steps before the film generation phase. The acronyms for the three computerized steps which are described below are: 1) TAPEIN; 2) ASTRETCH: and 3) PLOTAPE. The flow of the information is shown on Figure 8-3. Processing of the tape took place on a Data General Eclipse S200 Computer.

8.1 PROCESSING STEPS, SOFTWARE DESCRIPTION AND FILM GENERATION

STEP 1 - TAPEIN is a program to read, unpack and generate a disk resident image strip file. The image strip file contains 2256 lines of data corresponding to an image strip. Each line of data contains image data and a selected portion of the calibration information. User inputs define the tape file number, the strip number and band to be extracted.

STEP 2 - The ASTRETCH program provides the capability to perform a linear expansion of a user defined range of data to a new range of data. The data outside the range is compressed accordingly. User inputs define the input/output file names and the parameters for the stretching. This technique allows the user to perform contrast enhancements that cannot be conveniently done by ordinary photographic technique.

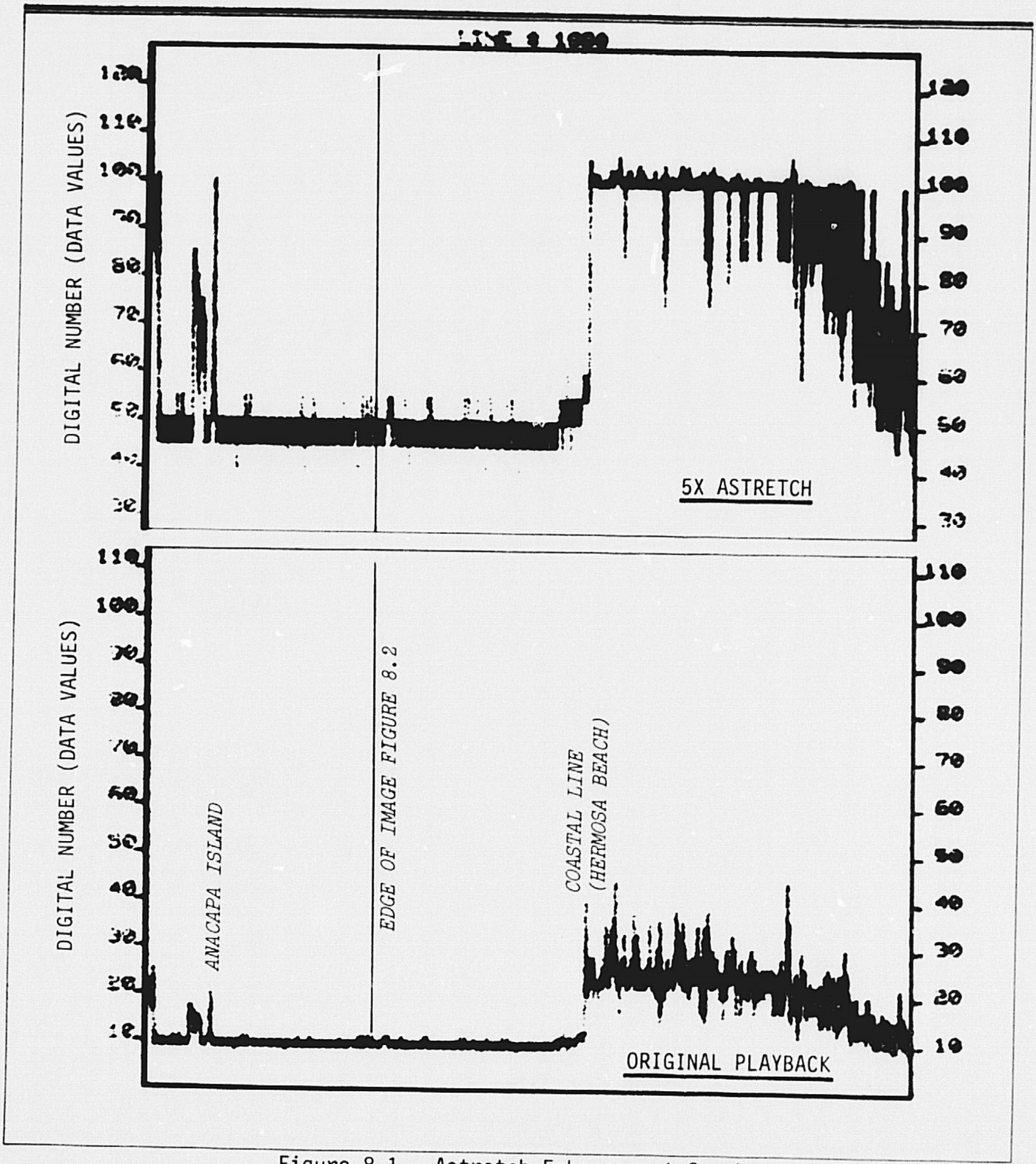

Figure 8.1 - Astretch Enhancement Graph.

Above is a 5X enhancement of the line 1990 from the image of the Santa Barbara Channel (see Figure 8.2). All water features are in the 40 to 55 range of digital numbers of the 5X Astretch. In the original the range is 8 to 12. NASA/Landsat 2266-17482-4

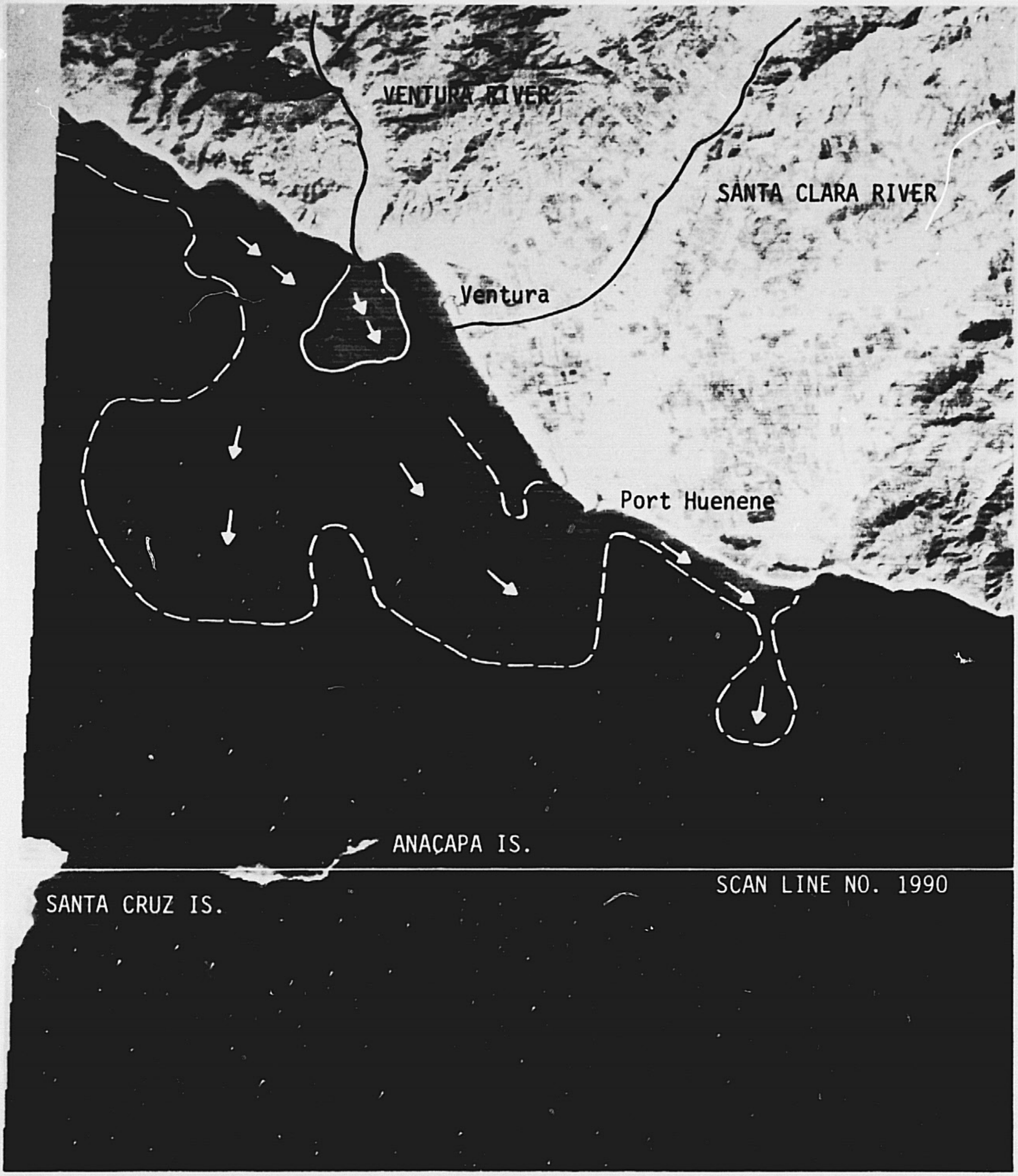

Figure 8.2 - Astretch Enhancement of Santa Barbara Channel.

This enhancement of the area between Ventura and Anacapa Island highlights sediment transport patterns present during the fall (15 October 75) when stream and river discharge is essentially non-existant. On the film product no visible patterns are present offshore. The scan line shown refers to the graphs shown in Figure 8.1. NASA/Landsat 2266-17482-4.

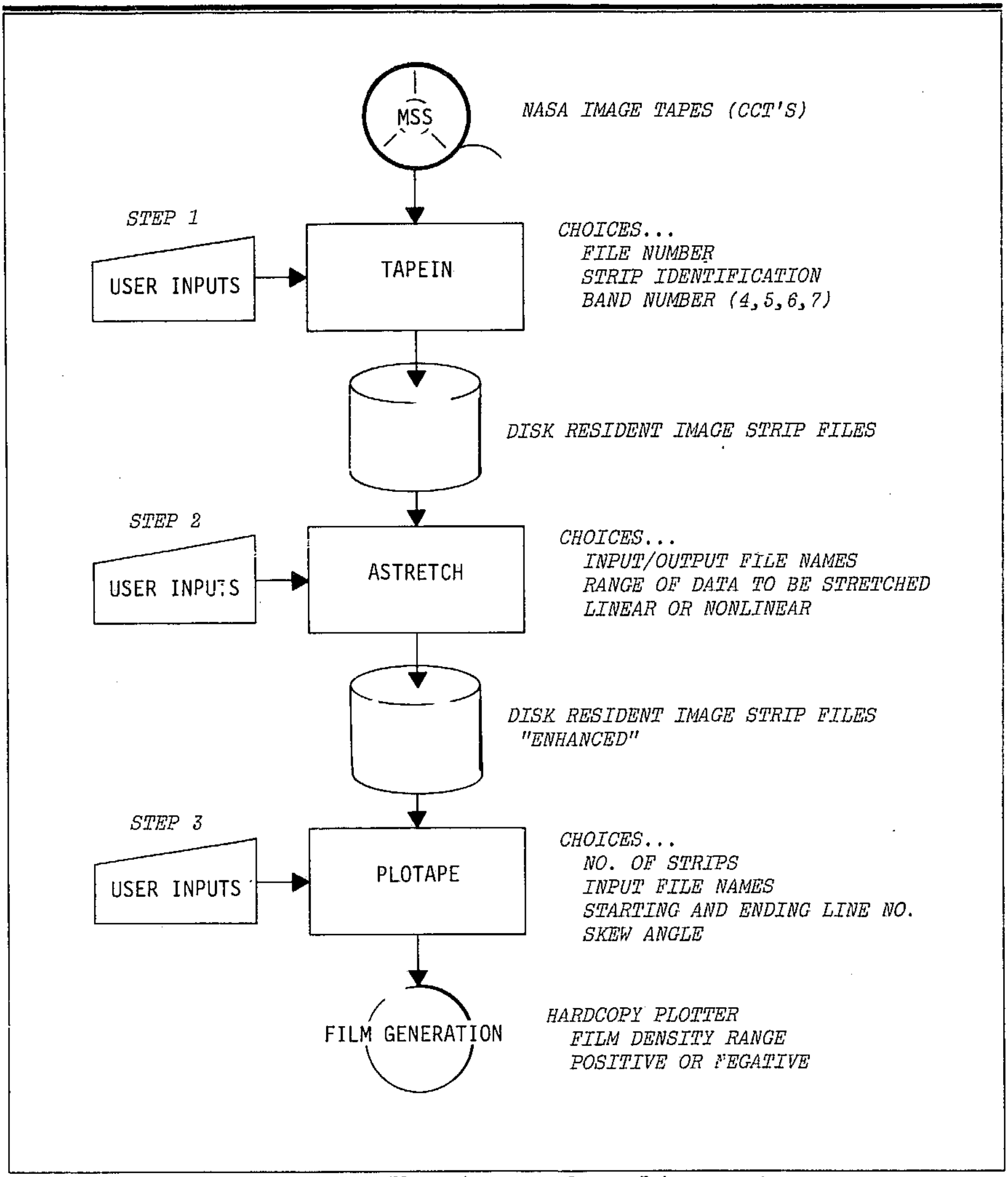

Figure 8.3 - Flow Diagram - Image Enhancement.

STEP 3 - PLOTAPE is a version of the output tape generation software especially modified to create tape compatible with a Geo Space plotter. The program can merge a user defined set of strips (up to 4 for a full image), lines and also perform skew corrections. Skew angle correction is performed by padding either the beginning or end of each line of output. A tape record consists of skew correction pixels, a merge of the image strips and any padding pixels necessary to keep each tape record a constant length. User inputs (strip numbers and scan line range) allow a selected portion of the image to be written to tape for image generation.

Film Generation - The magnetic tape is then used to drive a Geo Space plotter to create a photo film. The film is created by writing 133.33 pixels/inch and 96 line/inches which yields a good representation of the actual pixel to line spacing ratio (less than 1% error). The operator has control of the film density range and the option to produce either positive or negative images.

8.2 LANDSAT IMAGE ANNOTATION DATA RETRIEVAL SYSTEM

Data describing each Landsat image is available on two magnetic tapes and exists as 174388 records of 200 bytes each, packed 8 records to a tape block. To facilitate information retrieval a two pass tape scan system has been developed. In the first pass the two master data tapes are read sequentially and records falling within user specified geographical limits are transferred to a second tape. Only a selected portion of the input record is retained to reduce subsequent tape search time. The output tape is formatted as 16 records of 100 bytes each per tape block. The first 88 bytes of each record contain data, the rest is padded with zeros.

The second pass uses the previously created tape as input and creates a temporary disk file or records which meet user imput geographical and cloud cover limits.

The user has the option of listing the selected records or of saving the disk data and using it and/or tape data in another selection pass.

The use of CCT's are preferable over film for manipulation because accuracy is lost in recording radiometric information on film and is further degraded by duplication. Also scanning introduces additional noise into the signal. Other advantages of using the tapes for analyses include considerable analytical flexibility, reproducable results and relatively reasonable costs. Of course this cost compared to the purchase of several negatives is considerably higher but the detail and manipulation possible is necessary and preferable during certain analysis techniques. An additional example of ASTRETCH enhancement is seen in Figure 8-4. Several other enhancement techniques which are utilized are described in Table 8-1.

- DISPSCAN - Display of individual scan lines for analysis.
- ERTSRPT - ERTS scene summary and annotation.
- EXTRACT - Extract multispectral data for statistical analysis.
- GENRAD - generate slopes and offsets for banding removal and radiometric correction.
- HISTO - generate histogram of an image line.
- IMLOCATE - to determine image file location information.
- MLDR - maximum likelihood decision rule classification program.
- STATISTICS - program to generate statistical parameters for pattern recornition.

8.3 REFERENCE

1. Thomas, Valerie L., Generation and Physical Characteristics of the Landsat 1 and 2 MSS Computer Compatible Tapes, Goddard Space Flight Center, Greenbelt, MD., x-563-75-223, 1975.

Table 8-1 CCT Enhancement and Manipulation Techniques

DISPSCAN

PROGRAM TO GRAPHICALLY DISPLAY A SCAN LINE OF DATA BY DEFINING THE INPUT FILES (MAXIMUM OF FOUR) AND THE SCAN LINE NUMBER. THE PROGRAM IS ITERATIVE AND THE USER CAN ACCESS A LINE ANYWHERE IN THE FILE. ENTER LINE # 0 TERMINATES THE PROGRAM.

DORAD

PROGRAM TO PREFORM DATA CORRECTIONS BY BANDING REMOVAL BY USING SLOPES AND OFFSETS GENERATED BY GENRAD

FILTER

PROGRAM TO PERFORM A WEIGHTED AVERAGE OVER 3 PIXELS AND 3 SCAN LINE.

ERTSRPT

PROGRAM (ERTSRPT) USED TO PRODUCE SUMMARY INFORMATION FROM ERTS-B IMAGERY TAPE. THE PROGRAM MAY OPTIONALLY SCAN DATA FOR TAPE READ ERRORS.

EXTRACT

PROGRAM TO CREATE A DISK RESIDENT DATA FILE FOR A GIVEN CLASS # FOR STATISTICAL ANALYSIS

GENRAD

PROGRAM TO GENERATE SLOPES AND OFFSETS FOR BANDING REMOVAL. THE MAXIMUM AND MINIMUM CALIBRATION LEVELS ARE EXTRACTED FOR THE IMAGE STRIP FILE AND SLOPES AND OFFSET PARAMETERS ARE GENERATED FOR EACH SCAN LINE. THESE PARAMETERS ARE USED WITH AN AVERAGE SLOPE AND OFFSET FOR NORMALIZATION BY PROGRAM DORAD

HISTO

PROGRAM TO GENERATE A LINE PRINTER HISTOGRAM OF A USER DEFINED AREA IN AN IMAGE STRIP FILE.

Table 8-1 CCT Enhancement and Manipulation Techniques (Continued)

IMLOCATE

PROGRAM TO DETERMINE THE IMAGE FILE LOCATION PARAMETERS OF POINTS ON AN IMAGE BY DIGITIZING THE 4 CORNER POINTS OF AN IMAGE (LL, UL, UR, LR) X Y LOCATIONS ARE CONVERTED TO STRIP # , LINE # AND WORD #

MLDR

PROGRAM TO PERFORM MAXIMUM LIKELIHOOD DECISION RULE CLASSIFICATION ON A USER DEFINED PORTION OF AN IMAGE STRIP FILE. THE PROGRAM ALLOWS THE USER TO DEFINE THE NUMBER OF CLASSES AND THE CLASSES TO BE CONSIDER BY INPUTTING CLASS NUMBERS. OUTPUT IS TO THE LINE PRINTER.

STATISTICS

PROGRAM TO GENERATE STATISTICAL PARAMETERS FOR PATTERN RECOGNITION SOFTWARE. STATISTICAL PARAMETERS INCLUDE THE MEANS AND COVARIANCE MATRIX

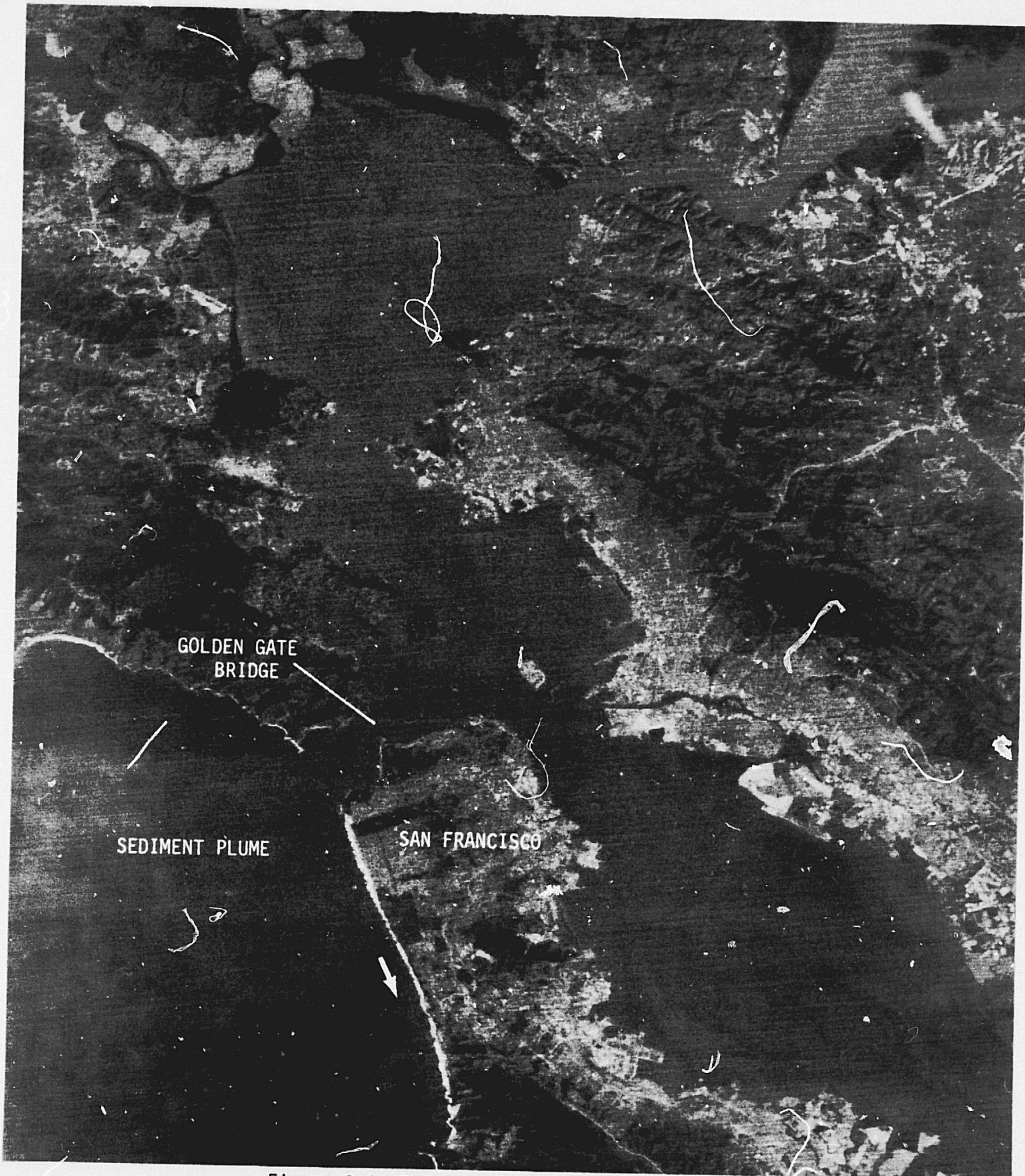

Figure 8-4 Enhanced Image of San Francisco

The plume of material discharge from San Francisco Bay is enhanced by the ASTRETCH process. The digital numbers 0-20 were stretched 3 times to 0-60. NASA/Landsat 2305-18042-5, 23 Nov 75.

9.0 CONCLUSIONS AND RECOMMENDATIONS

The littoral and nearshore processes including sediment transport, riverine discharge, nearshore currents and estuarine flushing were analyzed using the Landsat imagery. Specific studies of imagery sets from Humboldt Bay, Russian River, San Francisco Bay, Monterey Bay and the Santa Barbara Channel were emphasized. In each case the patterns formed in the water by suspended particles were interpreted. The tracer particles consisted mainly of suspended sediment, plankton, and in some cases pollutants. They were detectable on the Landsat imagery (primarily bands 4 and 5) because of the radiance level differences between the ambient waters and those waters containing the suspended material. Movement of the suspensate resulted from river discharge, tidal currents, geostrophic current, wind, waves, and upwellings. Because of the transport of the suspended material, the dynamic forces affecting the ocean surface could be analyzed. Using the Landsat imagery combined with available aircraft photography and sea truth data it was possible to formulate an accurate picture of the California nearshore processes. This includes diagrammatical charts of the three current seasons (Oceanic, Davidson and Upwelling) that continually effect the California coast.

Sea truth measurements were taken in the Santa Barbara Channel and in San Francisco Bay during this experiment. Although the sampling was limited relative to the overall study period the data provided an essential input to the study results. At the Santa Barbara Channel, oceanographic stations were occupied during three different Landsat overpasses. Total solids in surface water samples plus transparency, temperature and transmittance was measured. This information combined with simultaneously collected aircraft imagery provided a calibration of the patterns seen in the Landsat images. What appeared to be sediment lensing from the water samples was, in several instances, sediment plumes being formed into complex gyres by the currents in the area. It was possible to calibrate the image density difference according to the volume of suspended sediment measured in the sea truth samples.

The authors' investigation of the currents of Monterey Bay resulted in a set of surface current charts that are already being used by waste water managers for the assessment and review of contracted reports on alternative ocean outfall locations and impacts. The use of Landsat and aircraft imagery allowed the macro and micro investigation of regional current systems that could influence the outfall effluent mixing. Landsat data alone would not have been sufficient to allow a current definition for the small scale gyres such as those located in Monterey Bay. They are near the resolution limit of Landsat. However, Landsat was capable, on a timely basis, of defining the oceanic parameters that influenced the Monterey Bay circulation. Buttressed by high resolution U-2 and other aircraft imagery, the Landsat data began to divulge the basic current patterns needed by coastal engineers and planners. This data has already been worth at least $20,000 to the San Francisco District of the U.S. Army Corps of Engineers. The technique is unique so no price could be placed on a parallel technique for cost comparison.

In the San Francisco Bay Study data from the U.S. Army Corps of Engineers Dredge Disposal Study was used as calibration. One hundred and eleven sampling stations in the San Pablo Bay (north San Francisco Bay) were occupied monthly from March to December in 1974 and the sedimant distribution as determined from the sample evaluation was used in the Landsat interpretation. When the sampling was done close to the Landsat overpass a fairly close correlation resulted when expected sediment depositional sites were compared with the measured depositional concentrations.

The maximum utility of the Landsat data has yet to be realized by the authors' organizations or supported agencies. The Corps' study of the Russian River system, for example, is still in its infancy. However, land use of the river and various upstream regional parameters have been or are now being defined. The capability to model river flow and fishery projections based on observable flow characteristics is now thought possible. Land use modifications and resource inventories should soon be using the qualitative Landsat data source. Additional quantitative information necessary for model input will use the results of this work as a source of data suitable for locating and timing coastal and oceanographic surveys. One of the best uses of photographic aircraft and satellite data is for the definition of "where to look for answers". Where are current meters, suspended sediment, and water analysis stations positioned for the maximum return on time and effort spent? This positioning is an operational occurance utilizing Landsat data but it is presently impossible for the authors to select a monitary value.

At Humboldt Bay a new ocean sewage discharge facility is being planned. A detailed study of the oceanographic parameters that will effect the discharge site is taking place. Landsat imagery has provided an overview of the nearshore and offshore currents in the area for the last four years. Each available image has been analyzed for use in the model being applied to the oceanographic analysis. Several anomalous currents have been discovered which are being considered in the overall current season and suspensate transport picture. Although no cost can be applied to this capability it does provide information impossible to gather as economically by any other means. The nearshore processes data as determined from Landsat is especially valuable in an area such as the Northern California coast where little previous offshore information was available.

The techniques utilized for enhancing and interpreting the Landsat imagery ranged from manual photo interpretation to computerized image processing. Various photographic methods were used including enlargements and modified developing and printing techniques. The development time and printing were optimized to enhance minor changes in density that represented differing suspended sediment levels in the nearshore waters. The image processing enhancement that was the most successful was density stretching. Density levels of areas of interest as represented by digital numbers on the computer compatible tapes were first played back in graphic format. The amplitude range between ambient ocean water and water containing the maximum suspended sediment was determined. From this, a density stretch multiplier was calculated for use in the image play back mode. This technique proved to be very successful in enhancing subtle coastal features. Both image processed and straight photographic products were scrutinized utilizing densitometers. A spot densitometer was used for point source analysis and a full image Data Color densitometer was used for areal analysis.

A zoom transfer scope gave the investigators the ability for scale changing. In addition color photographs from both high and low altitude aircraft flights were evaluated as a calibration source.

In interpreting the good imagery from the last four years the authors found that the best correlation between suspended sediment and radiance level variations was in Landsat band 5 (0.6 - 0.7 micrometers). In many instances, bands 4, 5, and 6 were utilized for the interpretation. In band 4 the sediment plume showed up but it was often difficult to differentiate between surface suspended sediment and bottom features. In utilizing band 6, the contact between water and land features was possible. The wind effect on the water surface is a major influencing factor in the analysis of surface sediment.

The importance of analyzing as large a statistical sample of coastal current images as possible can t be over emphasized. The need for the larger sample is to increase confidence in the seasonal results. Ground (ocean) sampling of current parameters sould be continued and supported by a federal agency. The authors have been asked repeatedly for explicit information on currents on various sections of the California coast. Unfortunately, only seasonal tendencies could be provided. Even the seasonal tendencies were given with some lack of confidence for some portions of the coast that are often cloud or fog covered.

The work initiated under Landsat I was continued for the definition of generalized caastal currents during the Landsat II study for the entire California coast. Information from this study has already been used specifically at Humboldt Bay, San Francisco Bay, the Russian River and Monterey Bay. The dredging operations in Humboldt Bay, for example, were planned to make use of the dispersing characteristics of the nearshore currents determined from Landsat imagery. At Monterey

Bay alternative ocean outfall plans are under consideration utilizing the current and mixing patterns detectable on Landsat imagery. At the Russian River mouth Landsat combined with aircraft imagery has made it possible to qualitatively define the complex coastal processes. This is most important in evaluating the sediment budget for the beaches in the area. In San Francisco Bay new dredging and construction operations utilize the erosional and depositional patterns that Landsat combined with aircraft imagery provides. The overall seasonal California currents and their affect on nearshore processes, form the prime contribution to the study sites along the coast. No cost figure may yet be placed on the value of this current charting. Past multiple usage has saved the combined agencies a total cost many times the cost invested to support this Landsat II report. Other investigations are now underway which will use other platforms (NOAA satellites) to plot ocean currents. The results of these investigations coupled with the seasonal descriptions contained in this study will provide coastal engineers and oceanographers with specific dynamic parameters that are characteristic of the varied California coastal currents.

APPENDIX A

FLIGHT OPERATION SUMMARY

TABLE A-1 SANTA BARBARA CHANNEL

October 16, 1975

Anacapa Channel

Operator: M. Mel and R. MacKenzie
Pilot: Colby

LINE	START	TIME	FINISH	TIME	ALTITUDE	REMARKS
1	Ventura Harbor	9:45	Anacapa Island	9:55	6000	Nearshore Sediment
2	Anacapa Island	9:58	Ventura Harbor	10:08	6000	
3	Goleta	10:37	Point Dume	11:20	6000	Dredging Santa Barbara
4	Santa Monica Bay	11:40	King Harbor	11:49	6000	Effluent Discharge

EQUIPMENT

Camera #1

Type - Hasselblad
Film - Color 70mm 2448
Filter - W-12
f Stop - 4
Speed - 500

Camera #2

Type - Hasselblad
Film - Color Infrared 70mm 2443
Filter - W-12
f Stop - 4
Speed - 500

Precision
Radiation
Thermometer
PRT-5

TABLE A-2 SANTA BARBARA CHANNEL

February 18, 1976

Anacapa Channel

Operator: R. MacKenzie and
S. Gallenson
Pilot: Colby

LINE	START	TIME	FINISH	TIME	ALTITUDE	REMARKS
1	Point Dume	9:43	Ventura Harbor	10:02	6000	Oil Slick - Sediment Gyre
2	Ventura Harbor	10:10	Anacapa Island	10:20	6000	
3	Anacapa Island	10:20	Ventura Harbor	10:30	6000	
4	Ventura Harbor	10:30	Goleta	10:40	6000	Some Clouds - Oil Slick Sediment Off Santa Barbara
5	Goleta	10:41	Point Conception	10:56	6000	Some Clouds

EQUIPMENT

Camera #1

Type - Hasselblad
Film - Color 70mm 2448
Filter - W-12
f Stop - 4
Speed - 125

Camera #2

Type - Hasselblad Handheld
Film - Color Infrared 70mm 2443
Filter - W-12
f Stop - 4
Speed - 500

Precision
Radiation
Thermometer
PRT-5

TABLE A-3 HUMBOLDT BAY

June 28, 1976

Humboldt Bay

Operator: D. Steller and
R. MacKenzie
Pilot: Stickler
(Fortuna Aviation)

LINE	START	TIME	FINISH	TIME	ALTITUDE	REMARKS
1	Eel River	12:30	Eel River	12:40	3000	Offshore Sediment
2	South Bay	12:45	Eureka	12:50	3000	Thermal Effluent Discharge
3	Eureka	12:50	Arcata Bay	13:00	2000	Sanitation Discharge
4	Arcata	13:10	Mad River	13:25	2000	Gyre Offshore
5	Mad River Mouth	13:30	Humboldt Bay Breakwater	13:40	3000	Pulp Mill Discharge
6	Humboldt Bay Breakwater	13:40	Eel River	13:55	3000	

EQUIPMENT

Camera #1

Type - Pentax
Film - Ektachrome 64
Filter - W-12
f Stop - 8
Speed - 250

Camera #2

Type - Pentax
Film - Color Infrared
Filter - W-12
f Stop - 11
Speed - 125