State of California
The Resources Agency
Department of Boating & Waterways

Summary Report of

Man's Impact on the California Coastal Zone

STATE OF CALIFORNIA - THE RESOURCES AGENCY
DEPARTMENT OF BOATING AND WATERWAYS

SUMMARY REPORT OF

MAN'S IMPACT ON THE CALIFORNIA COASTAL ZONE

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BOATING & WATERWAYS

JUNE 1980

FOREWORD

One of the Department of Boating and Waterways' efforts to preserve and restore California's shoreline is preparing and publishing a number of documents on subjects relating to erosion of the shoreline. Some are of a technical nature for the engineer and scientist working in the coastal zone while others are more general in nature to give the general public a better understanding of this unique and valuable resource.

This particular report, prepared by Scripps Institution of Oceanography under the direction of Dr. Douglas L. Inman, describes in some detail the physical processes that occur at the shore due to wave action and applies these concepts to a number of specific sites within the State. Coastal planners, local governmental agencies and others who have responsibilities and interests in the shoreline may find similarities between these examples and their own problem areas.

Through an exchange of knowledge on coastal processes, past mistakes are less likely to be repeated and methods of preserving and enhancing California's varied shoreline can be developed. The Department of Boating and Waterways encourages those with shoreline erosion problems and those considering shoreline developments to contact the Department's staff for assistance and information at 1629 S Street, Sacramento, California 95814 (Phone (916) 445-8348.

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MAN'S IMPACT ON THE CALIFORNIA COASTAL ZONE

1. INTRODUCTION

California has approximately 1800 miles (1600 km) of ocean coastline, including two of the most remarkable natural embayments in the world, 700 miles (1100 km) of sandy beaches, and a number of estuaries and coastal lagoons. Collectively these coastal zone features constitute one of the greatest assets of the state. Together with this natural asset is a sense of responsibility toward the coastal zone reflected by the state and its people. The most recent manifestation of this responsibility has been the passage of Proposition 20 in 1972 which created the California Coastal Zone Commission and provided for a plan for the state coastal zone.

This interest in coastal zone planning and shore zone protection has brought about a recognition of the continuing need for information about the basic physical processes that are operative in the shelf and nearshore environment. Rational coastal zone planning can only be achieved from an understanding of these physical processes; and in general, plans designed to work with the forces of nature are preferred over those that attempt to overcome them. This report summarizes some of the more fundamental information necessary to understand nearshore processes, outlines some principles of coastal zone planning that are compatible with these natural processes, and suggests recommendations for correcting specific coastal problems along the California coast.

Any discussion of the coastal zone must be preceeded by a definition of the area of concern. A physical definition of the coastal zone requires the inclusion of areas at a considerable distance landward and seaward of the shoreline since many of the processes are operative beyond the surf zone. Figure 1.1 is a diagram showing coastal zone nomenclature for a coastline

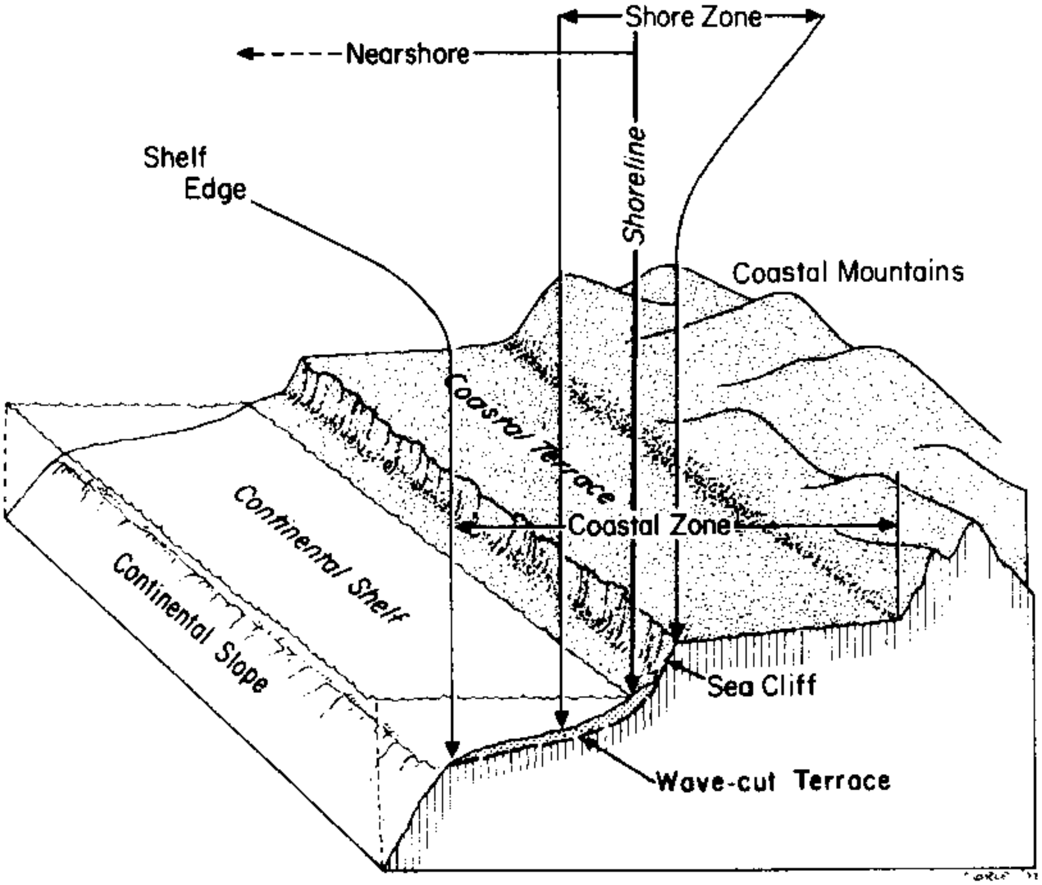


Figure 1.1. Definition sketch of coastal zone nomenclature for coasts similar to the California coast (from Inman and Brush, 1973).

similar to that along much of the State of California. This definition necessarily includes all of the offshore area to the edge of the continental shelf and all of the coastal plain since the physical processes affect these regions.

Within the coastal zone the area of land-sea contact is recognized as the shore zone. Inman and Nordstrom (1971) define the shore zone as including the beach, the surf zone and nearshore waters where wave action is effective in moving sediment. Shore zones can be defined for all bodies of water with their extent being dependent upon height of the waves, range of the tide, and size of the wave created beach features. Since the shore zone is the area of most intense interaction between the land, sea and atmosphere, it is the area of greatest concern within the coastal zone.

The significant physical processes that operate in the nearshore waters of oceans and seas are basically similar the world over and differ only in their relative intensity and scale. These differences are largely the result of the variation in the energy brought to the coast by waves and currents, the configuration of offshore bathymetry which modifies the waves and currents, and by the supply of sediment available for the waves and currents to act upon. It is becoming increasingly clear that the physical processes in nearshore waters are systematic in nature and can be characterized in terms of the basic principles of physics.

2. WAVES

Most of the energy driving nearshore processes comes from the sea. This energy is transferred to the ocean from the atmosphere by the stress of winds blowing over the ocean surface which generates waves over a broad spectrum of direction, wavelength and height. Energy also reaches the coastal zone from tides generated by the attraction of the moon and sun on the mass of the oceans. Another occasional source of energy is the catastrophic tsunamis which are caused by earthquakes or other disturbances on the sea floor. Once generated, waves can efficiently transmit energy across the ocean at their group velocity in the form of potential energy due to the displacement of the water surface, and kinetic energy which is associated with the orbital motions of the water particles under the wave form. Figure 2.1 illustrates the terminology used in the discussion of wave characteristics.

Along the California coast most of the energy is received from waves generated by storms crossing distant parts of the Pacific Ocean and by strong local winds associated with passage of storm fronts. These storms are capable of causing breakers up to 15 feet high with periods from 5 to 10 seconds in Southern California and up to 45 feet high in Northern California. Other large waves are generated by winter storms in the Gulf of Alaska which travel southward to the California coast. These waves are generally smaller in height and of longer periods due to the greater distance of travel from their source area.

Waves generated by large storm systems in either the north or south Pacific Ocean travel long distance across the ocean to reach the California coast. These waves from distant sources are lower in height and of greater periods (16-20 seconds) than the largest of those generated by local storms closer to the coast. The sea breeze is a wind blowing onshore due to the differential

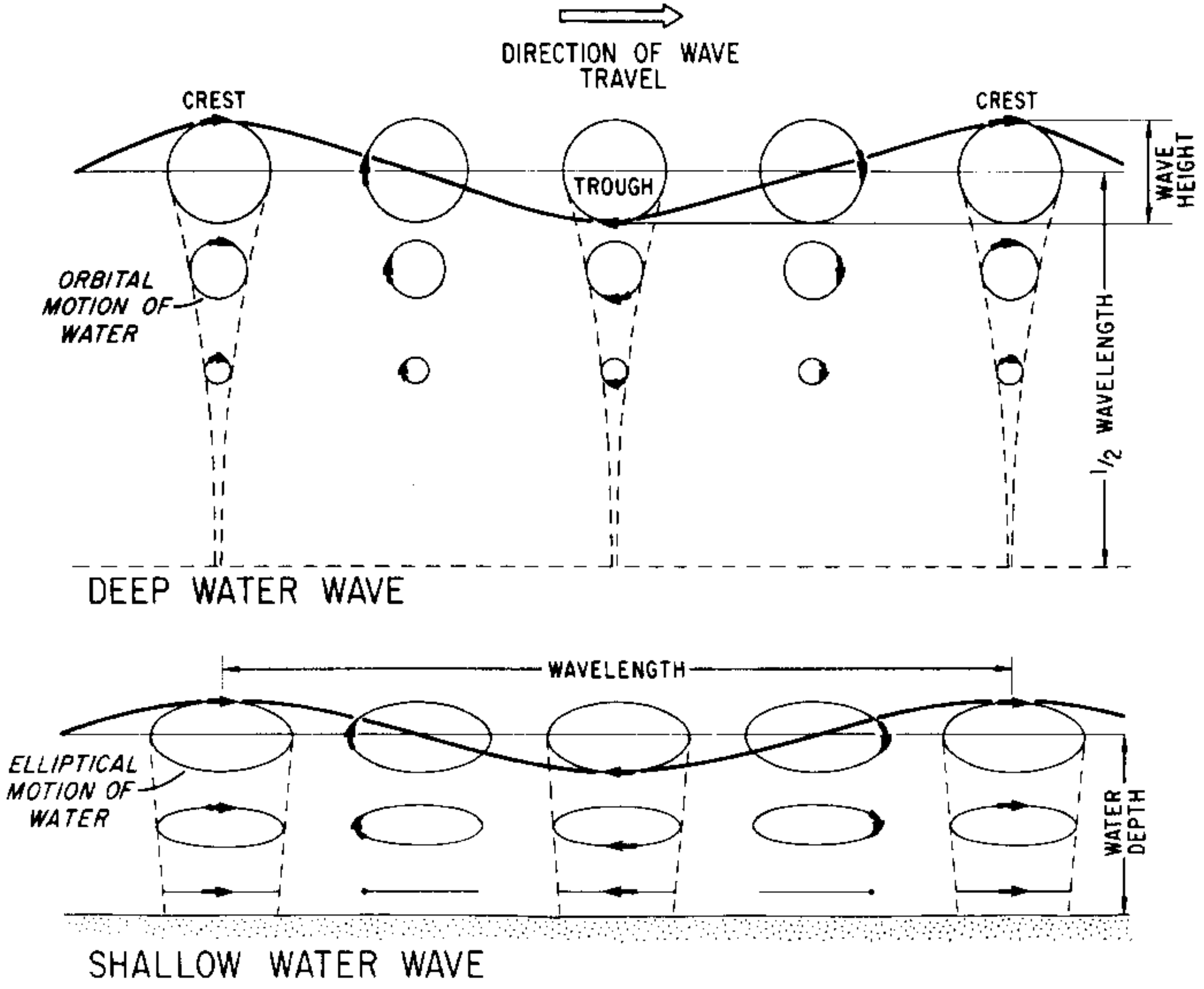


Figure 1.1. Wave parameters and water motion in deep and shallow water. In deep water, the orbital motion of the water ceases at a depth equal to 1/2 the wave length. The orbital motion of the water under waves in shallow water follows elliptical paths that become increasingly elongate as the water shoals.

heating of the land relative to the sea and usually reaches its maximum intensity during the mid-afternoon. Sea breezes are often of sufficient velocity to generate small waves of periods less than 6 seconds, but in some areas have significant effect on the coastal zone.

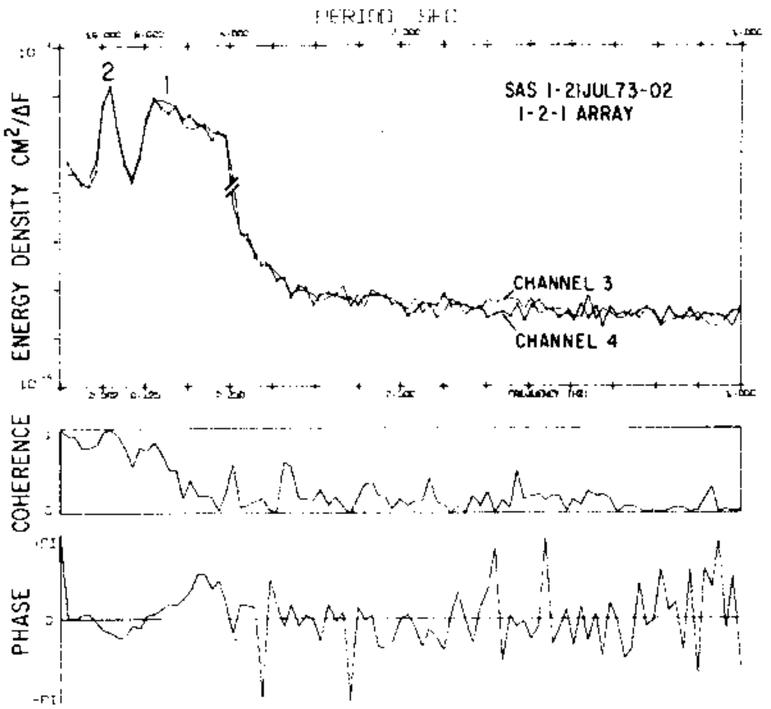
The energy contained in a single wave is proportional to the square of the height of the wave; the higher the wave, the greater the energy it contains. Waves are characterized by the parameters of <u>height</u>, <u>period</u> (or its reciprocal frequency), and <u>direction</u>. At any one time and place the sea surface is usually formed by a complex combination of many different wave trains Consequently, the measurements of ocean waves are best depicted as an energy spectrum, which is an analysis of the energy associated with particular frequencies corresponding to different wave trains. Figure 2.2 shows typical energy and directional spectra of ocean waves measured at Torrey Pines Beach, California. The peaks in the spectrum show the concentration of energy at the different wave periods or frequencies in the wave field.

Since the waves incident upon a coastline continually vary in height, period, and direction, it is necessary to make or obtain accurate measurements of waves at the site of interest to establish a <u>wave climate</u>.

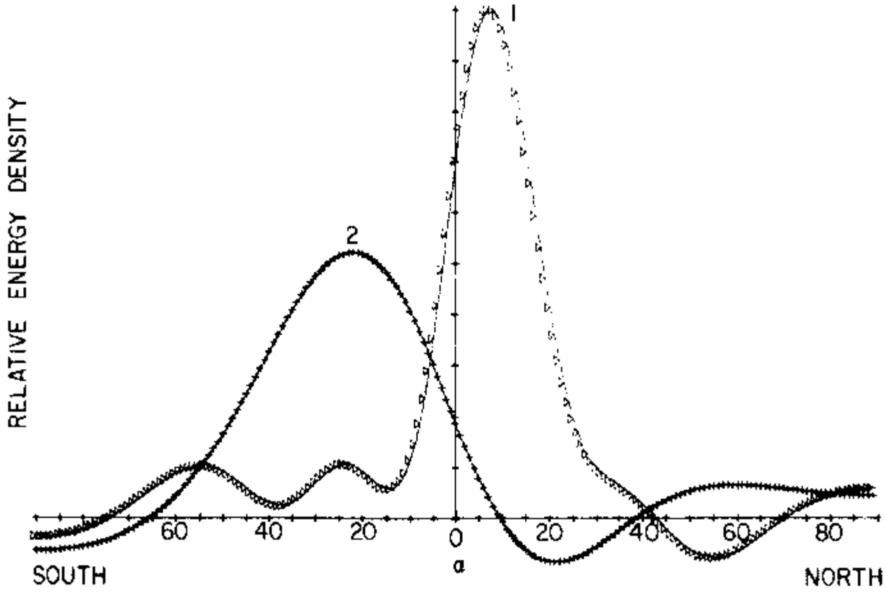
Wave "budget" or "climate" is a statistical analysis of wave data associated into frequency of occurrence by specific wave height-period-direction groups for a specific coastal or deep sea station and for each month or season. It is essential that the height-period-direction groups be correlated, otherwise the energy and momentum fluxes cannot be calculated, from the assembled data. This is the basic information that is indispensible for determining the magnitude of many of the physical processes at the shoreline.

Usually the wave climate for a specific site is the statistical representation of wave energy as a function of wave period, height, and

ENERGY SPECTRUM



DIRECTIONAL SPECTRUM



CHARACTERISTIC VALUES

PEAK	T(sec)	BW(Hz)	E_T(cm²)	E_p(cm²)	α_0
2	14.2	0.069	740	238	22°S
1	6.9	0.140		450	7°N

Figure 1.2. Energy-frequency spectrum (upper) and energy-directions spectra (lower) for waves at Torrey Pines Beach, California.

direction for an offshore station. This information is tabulated from the wave data into a wave energy budget on the basis of frequency of occurrence of waves over a period of one month from a given direction class, period class, and wave height class. The tabulation of wave energy for the offshore site must be corrected for any sheltering by islands or other obstructions. Sheltering corrections involve determining the angular sectors or "shadows" cast upon the site by the obstructions. From a knowledge of the sheltering, new estimates of the direction and amount of wave energy at the site can be determined.

Once a suitable wave energy budget has been determined for the deep water site the energy estimates must be extrapolated for shallow water at the shoreline site of interest. This is done from an understanding of the shoaling transformation that waves undergo as they enter shallow water near shore.

When waves advance toward shore over an irregular bottom or approach at an angle to the shoreline they change their direction of travel. Under these conditions portions of the same wave crest are in differing depths of water. That portion of the wave in deeper water travels faster than that portion in shallow water, thus, the wave crest tends to bend towards the shallow water paralleling the bottom contours. This process of changing direction is called wave refraction and defines how the budget of deep water wave energy can be extrapolated to the budget for waves breaking near the shoreline.

Wave refraction is a function of wave period (frequency), wave direction, and the local bathymetry. Refraction over an irregular bottom can cause localized effects such as energy convergence, divergence and large variations in breaker angle along the coast. Therefore, it is very important to make an accurate analysis of wave refraction. Suitable wave refraction diagrams can be constructed from the wave period and directional data contained in the wave budget and a bathymetric chart by either graphic or analytic methods. In either case, wave rays or lines parallel to the direction of wave travel are constructed from deep water into the depth of wave breaking. Graphic construction of wave rays can be done using the refraction template technique of Arthur, et al (1952) which utilizes a template to determine the changes in wave direction as the wave progresses through each shoaler increment of depth. Otherwise analytical techniques which employ a computer to make calculations and plot the refraction diagram can be developed using the appropriate wave equations The ratio of intensities of wave energy flux in deep to shallow water is calculated from the ratio s_∞/s_b where s_∞ is an arbitrary deep water separation of adjacent wave rays and s_b is the separation of those same rays at the breaking point of the waves (Figure 2.3).

The shoaling transformation and refraction of waves continues until the wave height is approximately equal to 0.78 to the water depth, where the waves break. At this point the orbital velocity of the water attains the velocity of the wave form so that the wave collapses. Once the wave breaks a bore is formed which is a mass of water moving unidirectionally up the beach. Much of the energy originally contained in a wave is dissipated in the breaking process and in formation of the bore. Energy contained in the bore is dissipated by turbulence in the water and by interaction of the water with the bottom causing movement of sand.

The surf zone is defined as the area between the break point of the waves and the highest run-up of water on the beach. The width of the surf zone varies as a function of the steepness of the beach and height of the incident waves. High waves breaking on gently sloping beaches produce wide

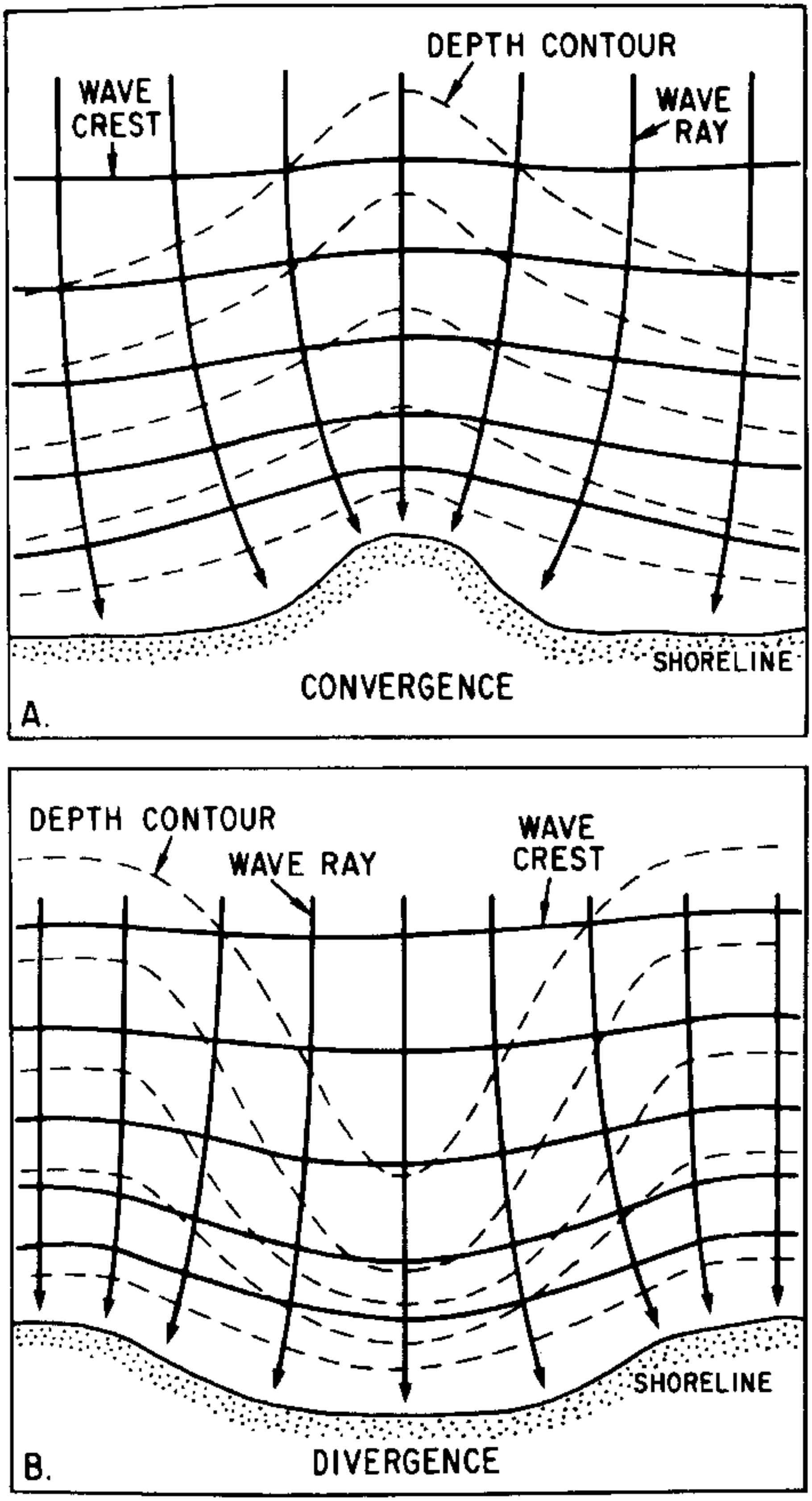


Figure 2.3. Refraction of waves over an irregular bottom. (A) shows refraction of waves over a submarine ridge; (B) shows refraction over a submarine depression (from Munk and Traylor, 1947).

surf zones; whereas, steep beaches with low waves have relatively narrow surf zones. The width of beach defining the surf zone is also a function of tidal range since the breaking point of the waves is displaced landward or seaward with the rise or fall of the tide. It is important to know the extent of the surf zone since the scale of many of the physical processes active in the nearshore environment are determined by the width of the surf zone.

Waves from several different generating areas may approach the coast simultaneously. Even though the waves are from the same generating area they will have a spread in frequencies, as shown by spectra in Figure 2.2. Waves of differing frequency "beat" together to form alternate groups of high and low waves which can be observed at almost any time by observing the relative heights of successive breakers.

There also exist other waves that are trapped against the coast and can only travel along the shore parallel to the coastline. These trapped waves are called edge waves and may obtain their energy from ocean waves incident on the coast or from other disturbances such as strong winds and traveling pressure fronts. Edge waves are generally long and may vary in scale from those forming rip currents with lengths of about 300 meters to those that generate strong currents in submarine canyons and have wavelengths of the order of the shelf width. The interaction of incident waves with edge waves cause differences in the relative breaker height along the beach. This interaction of incident and edge waves is shown schematically in Figure 2.4 where it can be seen to affect the general circulation pattern of water in the surf zone.

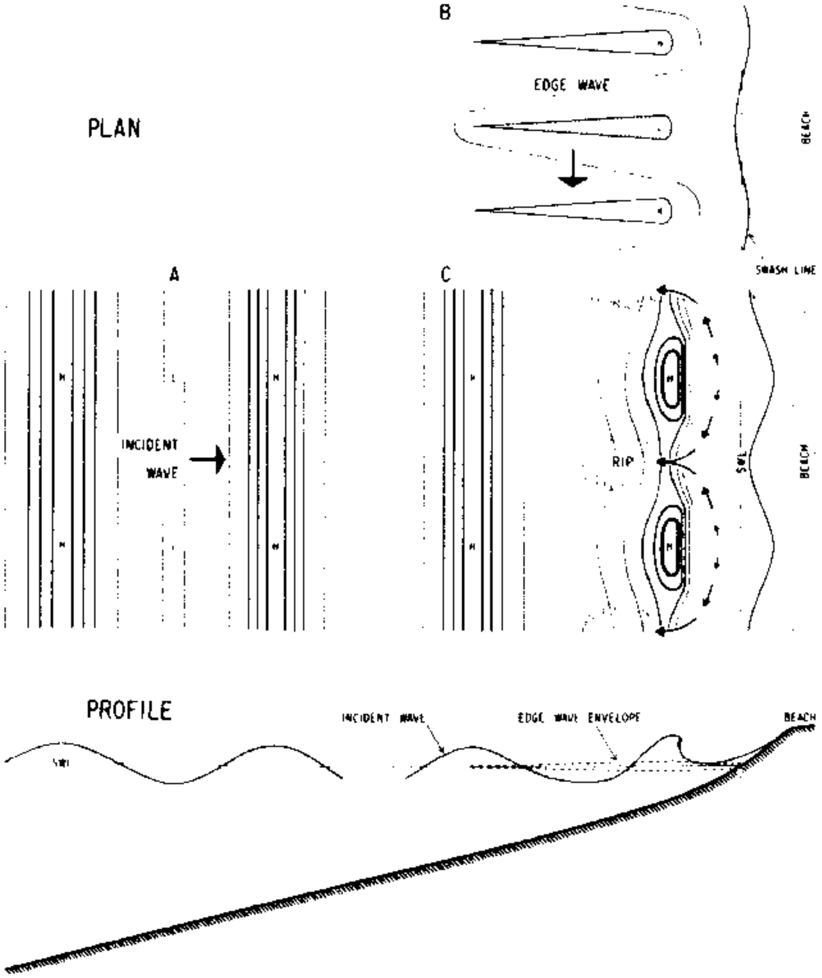


Figure 2.4. Incident wave-edge wave interaction at the break point causing the formation of high and low breakers which result in the formation of rip currents and nearshore circulation cells.

3. COASTAL CURRENTS AND MIXING

Strong coastal currents may be related to tides, local winds, or the impingement of a larger scale ocean current on the shelf. The northern and central portions of California are bordered by the southerly flowing California current, which at times may extend into shallow water. At Point Conception the Southern California coast abruptly changes trend to the east. The south flowing California current separates there and forms a large counter clockwise circulation in the form of an eddy or gyre, so that the currents along Southern California coast usually flow north from San Diego to Point Conception.

Over the shelf, other currents are generated that are smaller in scale and often considerably greater in magnitude. Some currents on the shelf consist of eddies associated with the offshore oceanic currents; whereas other currents are the result of tidal forces acting on the water mass. These currents can become quite intense when they pass through constrictions imposed by land masses.

Other shelf currents are generated by coastal winds blowing over the shelf waters. Strong offshore winds blow surface water away from the coast which is in turn replaced by water which comes onshore from greater depths. This process is called coastal upwelling and is responsible for bringing deep nutrient-rich water to the surface in the coastal zone which has profound biological effects. The opposite effect is created when strong winds blow onshore causing a movement of water toward the shoreline. This situation results in a pile-up of water against the coast. Since the accumulation of water against the coast is less over the deep water of submarine canyons than over shallow shelf areas there is a movement of water toward the canyons. Thus, water circulation over many parts of the California shelf is onshore, then alongshore to a canyon, and offshore through the canyon. Under certain conditions strong down-canyon currents are created by this offshore movement of the water (Inman, Nordstrom & Flick, 1976).

Longshore currents that are important in the transport of sand and nearshore circulation of water are generated at the shoreline by waves approaching at an angle to the coast. The longshore currents are generated by the breaking waves and flow parallel to the beach in the surf zone. The intensity of the longshore current is related to the height of the waves and the angle of approach to the beach. Water transported onshore by the waves is involved in the longshore current for some distance along the beach and then returns offshore through narrow zones as rip currents. The rip currents are higher velocity flows that extend from the surf zone through the breakers and a short distance offshore.

The onshore transport of water by waves, its lateral transport in the surf zone by longshore currents, and its return offshore by rip currents constitute the nearshore circulation cell (Figure 2.4). As can be seen, when waves break parallel to a straight beach, the flow pattern is symmetrical and return flow is divided between adjacent rip currents. However, whenever the waves approach at an angle to the shoreline the longshore current is unidirectional and a net flow occurs in one direction along the beach. A unidirectional longshore current has significant effect on the nearshore environment in that it provides a mechanism for the transport of sediment and mixing of waters.

Mixing occurs very rapidly in the surf zone due to the turbulent nature of the water. Once waves break and reform as bores there is rapid movement of water across the surf zone and along the beach. Consequently, the dilution of a substance introduced into the surf zone can be related to the nearshore circulation system (Inman, Tait and Nordstrom, 1971). Figure 3.1 shows the nearshore mixing process schematically; phase I mixing involves material which is discharged at a point and is progressively diluted as it moves along the shore by passing through each circulation cell. This type of mixing continues to be effective until the concentration of material builds-up immediately offshore where the rip heads discharge. Once the offshore area is significantly contaminated, phase 2 mixing occurs with the material being recirculated back into the surf zone to bring about rapid saturation of the nearshore waters.

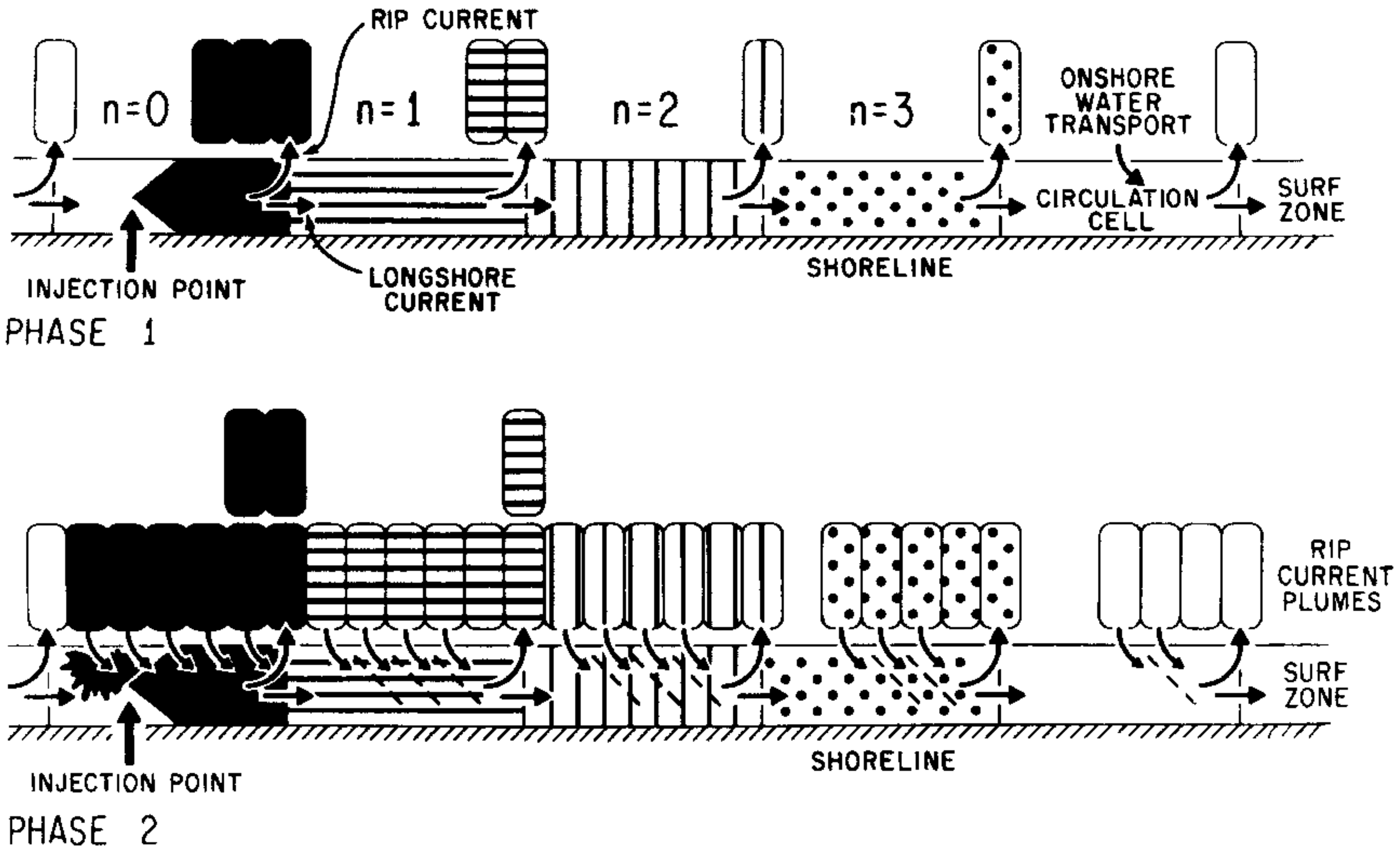


Figure 3.1. Schematic diagram of nearshore mixing. Phase 1 is the initial mixing alongshore in which the material discharged at the injection point is progressively diluted as it enters each nearshore circulation cell along the shore. Phase 2 shows what happens as the area immediately offshore of the break point becomes saturated with the material and it is recirculated into the surf zone (from Inman, Tait and Nordstrom, 1971).

4. LITTORAL SAND TRANSPORT

Since most of the specific content of this report is concerned with the problems of beach erosion and sand management in California a general discussion of the littoral sand transport process must be considered. Much of the California shoreline has a sand beach which in addition to its recreational function also serves as a barrier to the active erosion of the land. The beach being a sloping, porous, granular surface acts as an energy absorbing interface between the land and sea (Figure 4.1). Without a beach there often is rapid erosion of the land with corresponding disruptive effects on sea front property. No single cause can be attributed to beach erosion in California since it is often a result of localized wave conditions, the resistance of the bedrock, the presence of man made coastal structures, the lack of a sand supply, or a combination of these factors.

As indicated previously, waves supply most of the energy to the coastline and some fraction of this energy is used to transport sediment in the nearshore environment. Thus, one must have a knowledge of the wave climate at a specific problem site before any rational estimate can be made of littoral sand transport. From a knowledge of the wave climate the longshore sand transport can be calculated and included as an essential part of the coastal sediment budget.

4.1 Equilibrium Beach Profile

Shoaling waves affect the bottom at a depth related to their height and length which changes as the wave moves toward shore. Interaction of the orbital motion of the water with the bottom causes the generation of a net current at the bottom which flows in the direction

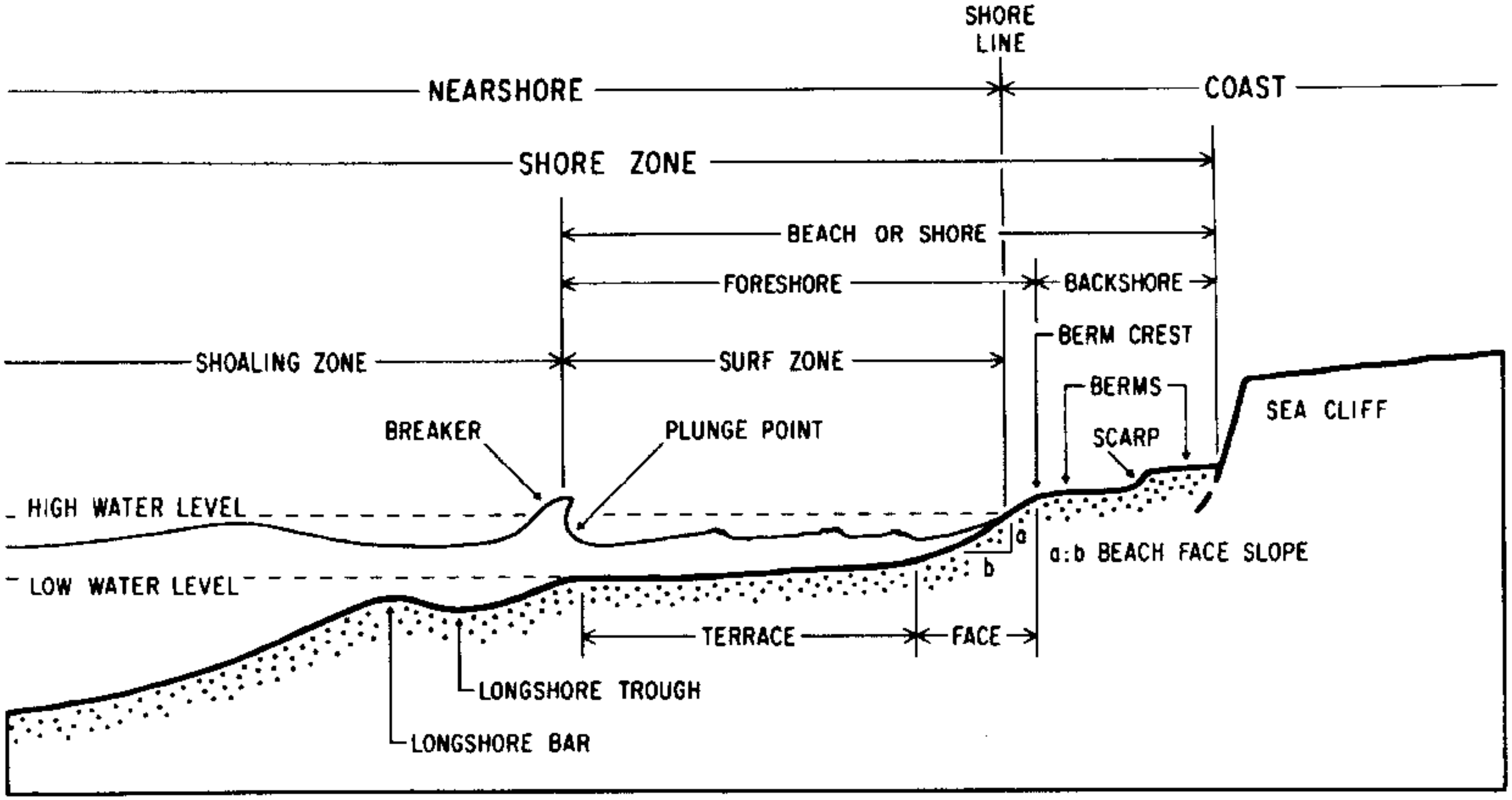


Figure 4.1. Nomenclature for a typical equilibrium beach profile (from Inman, 1971).

of wave travel. This results in a net movement of sand toward shore, hence the waves tend to contain the sand against the shore.

Waves transporting sand in the nearshore environment will produce a beach profile normal to the shoreline that is in equilibrium with the dissipation of energy as waves progress toward shore. This equilibrium profile is attained when the up-slope transport of sand toward shore by the waves is balanced by the down-slope movement of sand under the influence of gravity. A typical equilibrium beach profile is gentle in slope in deep water and gets progressively steeper toward shore in the vicinity of the break point of the waves. Where the waves break the profile flattens to form a terrace across the surf zone. At the landward margin of the surf zone the beach again steepens in slope forming the beach face. The slope of the subareal beach changes at the berm crest to form the gently sloping backshore. The steeply sloping beach face is a result of the energy dissipation in the swash and backwash of surf zone water. Since part of the wave swash is percolated into the permeable beach face the backwash is reduced causing sand deposition on the beach face.

It has long been recognized that most beaches undergo a seasonal change in configuration that is related to an annual cycle of on-offshore sand transport. This change in profile configuration involves the accretion of sand on the beach face during the summer when smaller less steep waves are present and erosion of the subareal beach by higher and steeper winter storm waves. This cycle of beach cut and fill is a result of the on-offshore transport of sand which occurs principally in depths of 15 meters or less, but may be measurable to depths of 30 or 40 meters.

Figure 4.2 shows this change in profile configuration on a Southern California beach. The summer beach configuration (23 October 74) has a well developed berm and steep beach face. A beach profile measured at the end of the winter (11 April 73) shows a quite different configuration with a gently sloping beach face and the presence of a bar at depths of 10 to 16 ft (-3 to -5 m). The removal of sand from the subareal beach by winter storm waves is often very abrupt, with considerable profile modification taking place in only a few hours. However, the onshore transport of sand to reform a summer profile takes considerably longer, with many months of wave activity being required to return the sand.

4.2 Longshore Sand Transport

When waves approach at an angle to the shoreline they transport sand along the beach. This longshore transport of sand is the combined result of the breaking waves which place the sand in suspension and the presence of a longshore current in the surf zone, which moves the sand along the beach. Field measurements of the waves incident to the beach and resultant longshore transport of sand as shown in Figure 4.3 indicate that the sand transport is directly proportional to the product of the wave phase velocity at the break point C_b and the longshore flux of momentum $M_{yx'}$, such that $C_b M_{yx'} = (ECn \sin\alpha \cos\alpha)_b$, which may be referred to as the longshore sand transport parameter; where E is the energy density, Cn is the wave group velocity, α angle of the breaking wave with the shoreline (Inman and Bagnold, 1963; Inman, Komar and Bowen, 1969; Komar and Inman, 1970; Longuet-Higgins, 1972; and Inman, et al, 1976).

The longshore sand transport parameter is related to the wave height and the angle of wave approach to the beach. Assuming constant

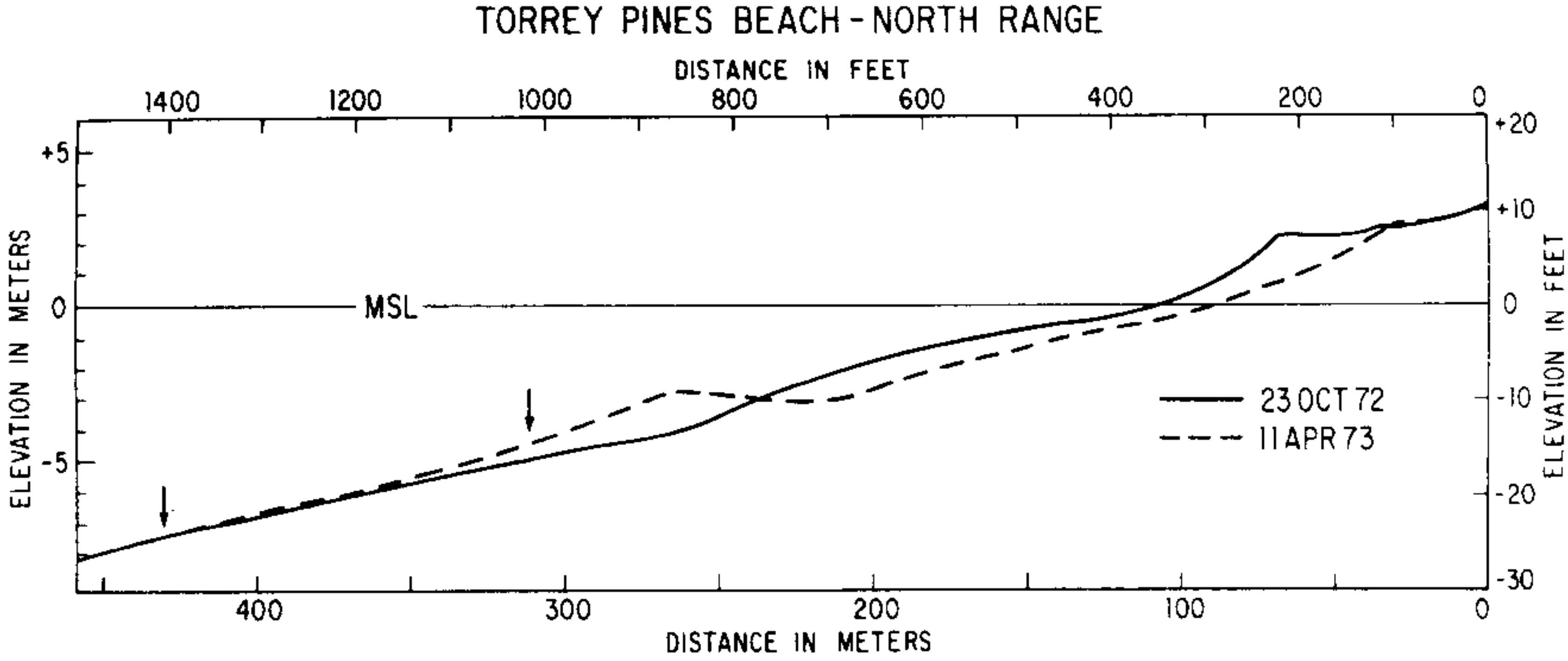


Figure 4.2. Comparison of beach profiles measured at North Range showing seasonal changes in beach configuration 1972-73. The profile measured on 23 October 1972 shows the summer beach profile configuration in 1972. The profile measured on 11 April 1973 shows the winter configuration during the winter of 1972-73 (from Nordstrom and Inman, 1975).

wave height, the value of the parameter increases as the angle of wave approach increases, reaching a maximum value for waves approaching at 45° to the coast. Since, in most cases, waves can approach from any seaward direction sand is moved both ways along the coast over any significant period of time. Thus, annual longshore sand transport is usually referred to as the annual balance of transports in both directions or the net longshore transport.

The annual net longshore transport for any specific site can be obtained either by calculating the transport from a knowledge of the wave climate or from measured rates of sand accretion and/or erosion in the vicinity of a coastal structure that intercepts the sand. If the wave climate is known then the longshore sand transport parameter at the beach can be calculated in order to determine the transport from the relation shown in Figure 4.3. The accuracy of this procedure will be dependent upon the validity of the wave data and how representative it is of the actual wave climate.

Estimates of longshore sand transport are also possible from measured rates of sand accretion or down-coast erosion near sand entrapment structures and inlet entrances. However, this type of data often underestimates the net transport because most structures allow some sand to travel around the trap.

4.3 Littoral Cells and Budget of Sediment

Sedimentation processes along the coastline of California can best be understood in terms of the littoral cell concept. A littoral cell is defined as a segment of coastline that encompasses a complete cycle of sediment supply, littoral transport, and ultimate loss of sediment from the coastal environment (Inman and Frautschy, 1966). In most

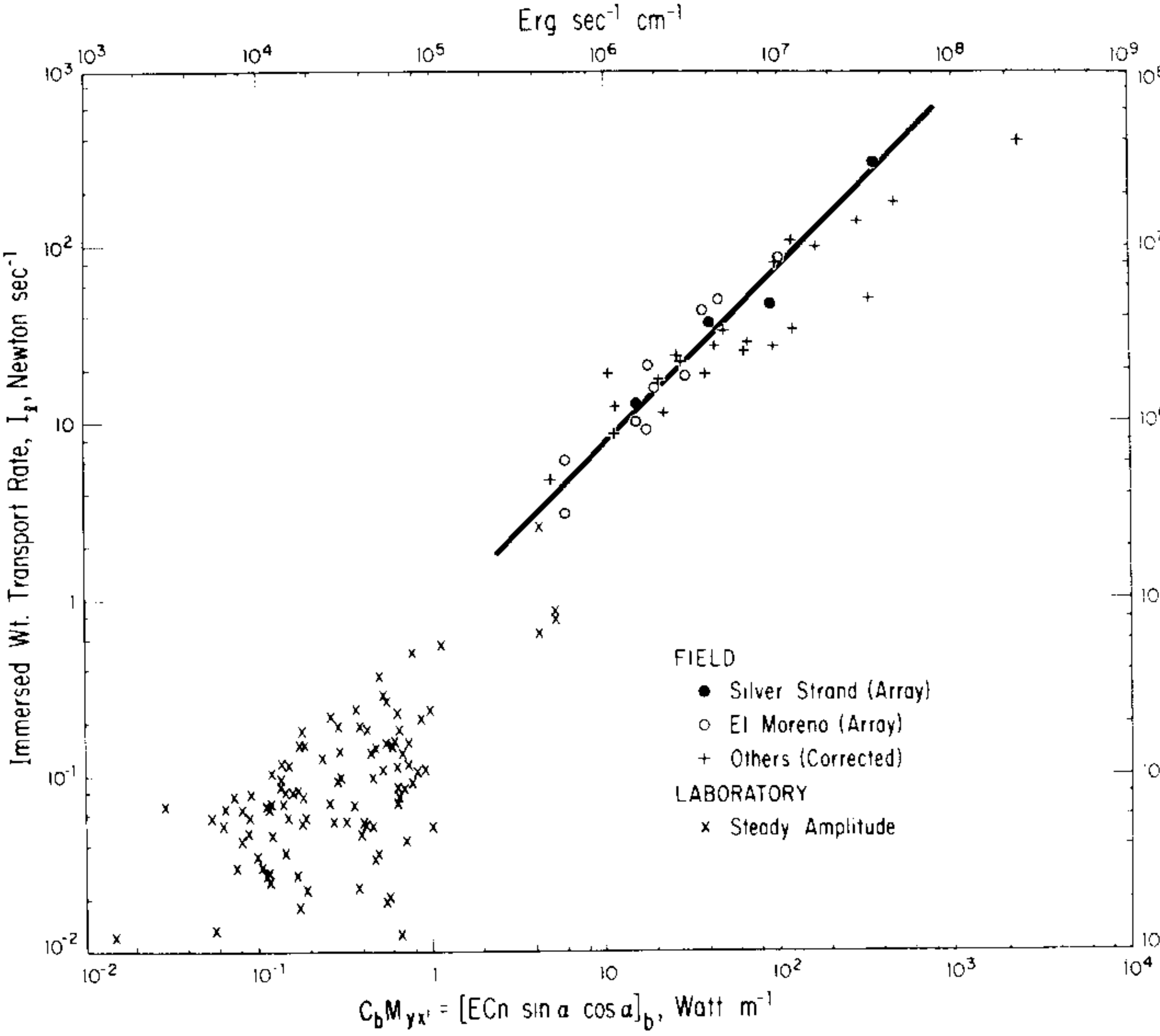


Figure 4.3. Relation between immersed weight transport rate of sand and the longshore sand transport parameter. Field data from others using significant wave height has been corrected to root-mean-square wave height in order to give the correct energy density of the waves.

cases a littoral cell is supplied with sediment by the rivers and streams that empty into the ocean within its limits. Once deposited at the coast the sandy material is sorted out by wave action and incorporated into the beach. At this point the sand becomes involved with the littoral transport along the coast. The longshore transport continues until it is intercepted by a submarine canyon or other form of sink where it is lost from the nearshore environment. Littoral cells have been defined for much of the California coastline (Bowen and Inman, 1966; Inman and Frautschy, 1966). Figure 4.4 shows the littoral cells defined for the California coast south of Point Conception.

Littoral cells are usually separate entities with their own inputs, transport rates, and losses to sinks with little interchange between cells; consequently, each cell can be characterized by its own sediment budget. The sediment budget is a determination of all the sediment inputs (credits) and losses (debits) relative to the longshore transport rates within the limits of the cell.

Most of the sediment brought to the shoreline is from the coastal streams and rivers which derive the material from erosion of their drainage basins. This is augmented in some cases by the erosion of sea cliffs, onshore transport of sand from shallow water, and the introduction of biogenous material produced by plants and animals. However, in the temperate latitudes streams and rivers supply most of the material on the beach (Inman, 1971). Thus, the most important factor in determining the sediment input to a littoral cell is estimating the annual sediment yield of the coastal streams.

The annual sediment yield of a stream is related to the annual effective precipitation in its drainage basin and the area of its drainage

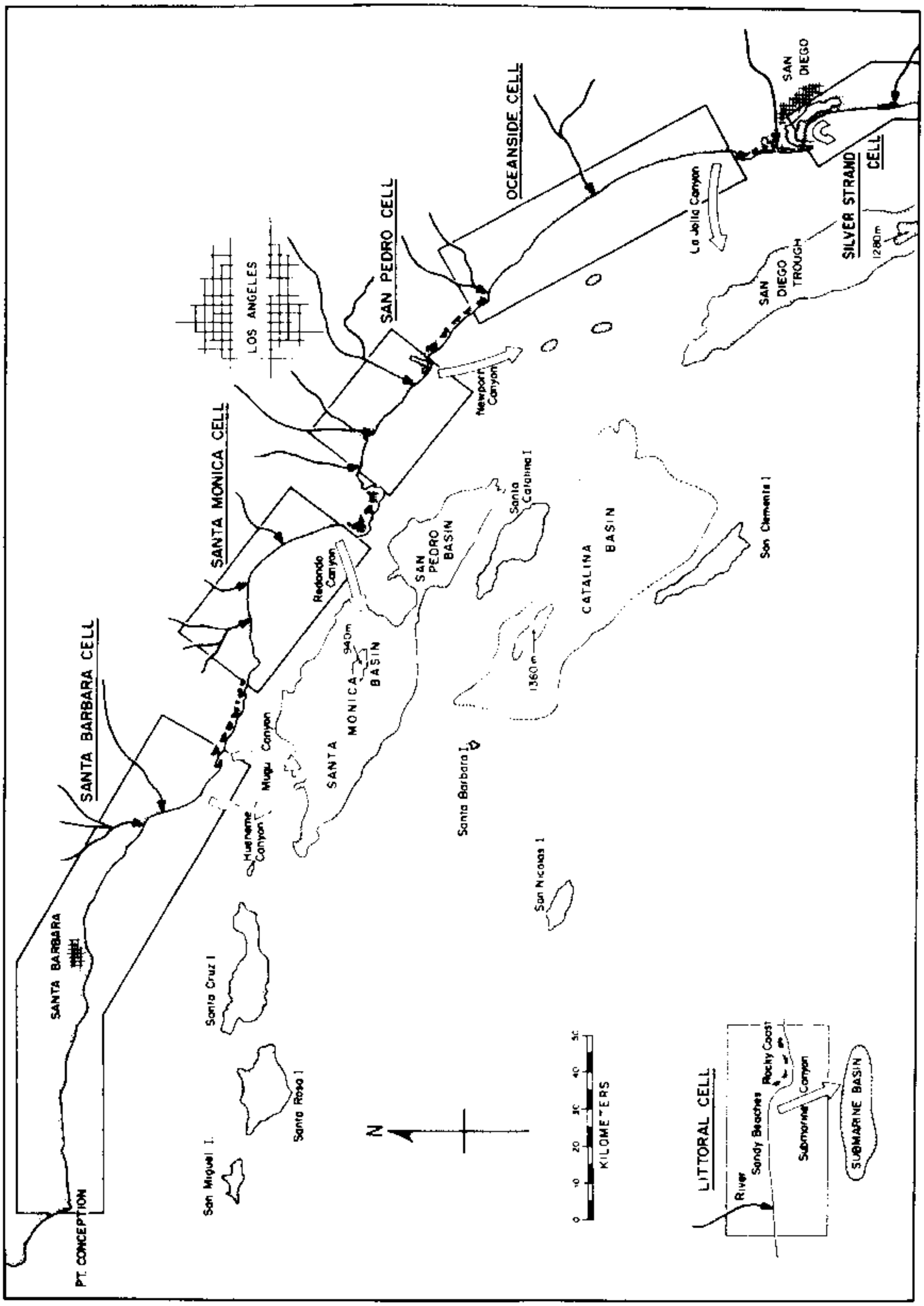


Figure 4.4. Southern California littoral cells, showing cell limits, major streams supplying sediment and sinks.

basin (Langbein and Schumm, 1958). This relation indicates that the optimum conditions for the production of sediment is between 10 and 12 inches of effective precipitation per year. Using this means of estimating sediment production or any other measurements of sediment yield the influx of sediment to the littoral cell from coastal streams can be determined by summing the contribution from each stream and river within the limits of the cell.

The annual sediment contribution is then compared to the longshore transport rate estimated for the length of coastline within the cell. This comparison gives some idea of the rate at which sand is transported through the cell and whether there is a surplus or deficit in sediment supply. The rate at which sediment is lost from the littoral cell is difficult to determine because losses occur to onshore transport by wind as dunes, offshore deposition on the shelf, transport down submarine canyon, and downcoast transport into the next littoral cell. Little is known about the quantities of sand which are involved in these losses in most of the California littoral cells because accurate measurements have not been made. However, in cases where accurate measurements exist they are found to concur with rates of sediment influx and transport through the littoral cell (Chamberlain, 1960).

The littoral cell and budget of sediment concepts will be applied to the specific areas under consideration in the remainder of this report. Attempts will be made to evaluate the sources, transport and ultimate losses of sand from these areas and to apply the information to the problems that are existent. Based on this evaluation of the natural system, from the standpoint of the physical processes, solutions will be proposed to the problems that can be implemented with a minimum of environmental disruption.

4.4 Remedial Action for Coastal Problems

The littoral cell and budget of sediment concepts presented previously lead directly to a general consideration of remedial actions for coastal problems. A useful first step in the study of such remedial actions is to classify them in terms of their relationship to the natural processes that prevail in the nearshore environment. Remedial actions that are commonly applied to coastal problems involving beach erosion and longshore transport fall into four broad categories:

1. those which seek to imitate natural processes;
2. those which attempt to modify the driving forces active in the nearshore environment;
3. those which attempt to stabilize the shoreline by disrupting longshore transport or by rendering the shoreline resistant to erosion; and,
4. those which call for a complete change in coastline use by man.

Each of these remedial actions has different implications with respect to modification of the natural environment and man's use of the coastal zone.

Remedial actions which attempt to imitate natural processes are those where man attempts to replace or improve upon a deficiency in the natural system through the use of manmade substitutes that closely resemble nature. This type of action has been employed where the problem involves the loss of a sand source to the coastline or the interruption of longshore sand transport.

Where the coastline has been deprived of a natural sediment source the dissipation of wave energy at the shoreline will cause erosion. A remedial action which seeks to imitate nature would be the periodic replenishment of the beach with sand from artificial sources at a rate which would stabilize the shoreline. In the case of an interruption of the longshore transport by a shoreline structure with its related downcoast erosion a remedial action imitating nature can be undertaken. This type of action would be to either remove the structure or to artificially move sand past the obstruction at the same rate as the natural wave induced transport thus restoring continuity to the process.

In general, any solution to a coastal problem that closely imitate the natural process should have a greater chance for success than solutions that attempt to overwhelm or counteract the process. The other types of remedial actions are greater aberrations from the natural system and in turn have a greater likelihood of creating problems associated with the proposed solutions that are equal in magnitude to that being corrected.

A second class of remedial action is that which seeks to modify the driving forces at the problem site. This type of action usually involves some form of structure designed to modify the wave energy incident to the coast. Breakwaters are the most common type of structure employed for this purpose and are designed in various configurations. Typical breakwaters are constructed to extend out from shore and enclose a nearshore area; detached from shore parallel to the shoreline, or offshore as submerged structures. In all cases the intent of the structure is to totally or partially decrease the wave energy incident upon the structure. However, when an offshore structure is constructed close to shore it casts a wave shadow at the shoreline which results in a local modification of the longshore transport (Figure 4.5). The reduced wave energy at the shoreline in the shadow causes longshore sand transport to

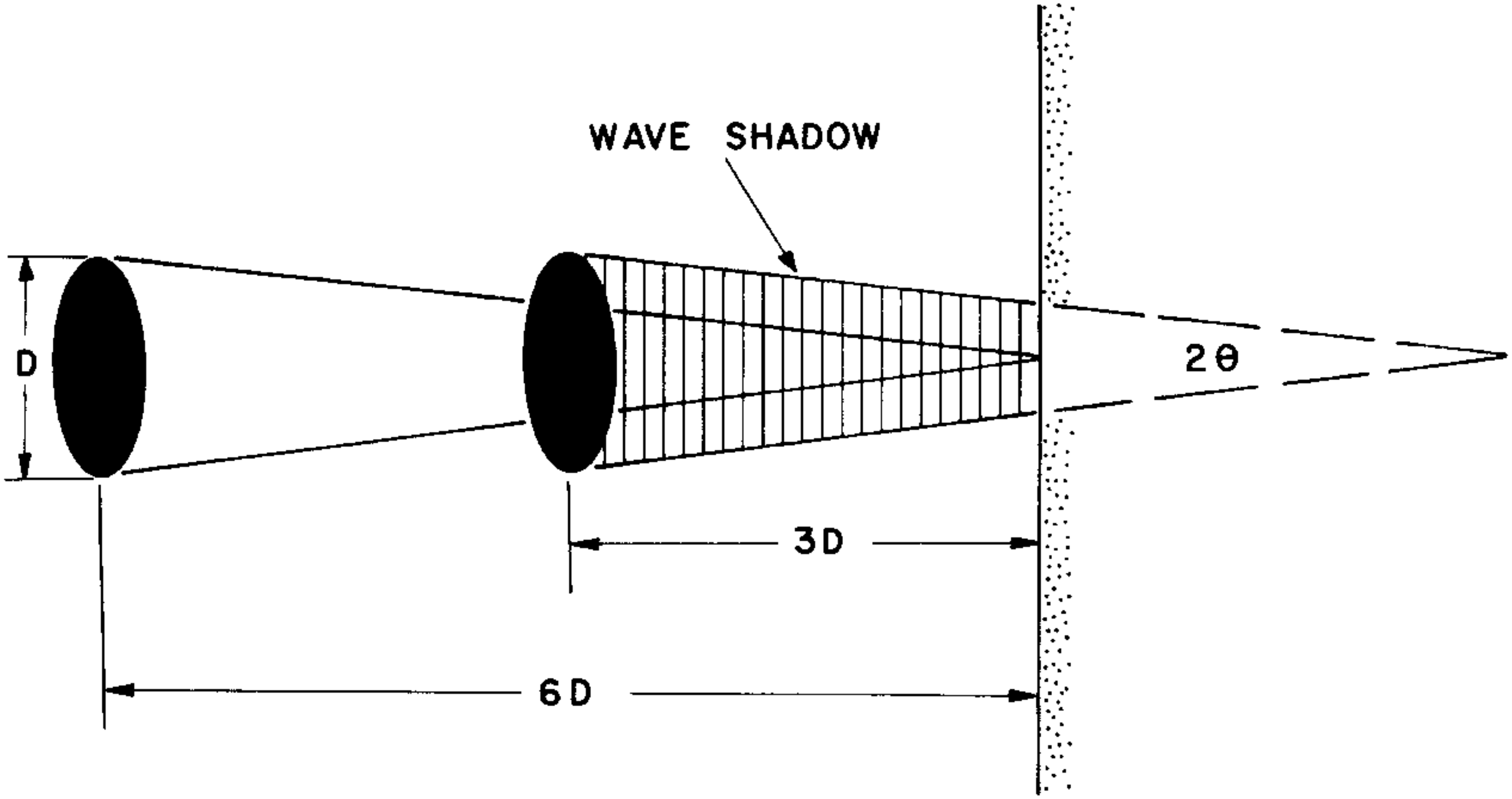


Figure 4.5. Schematic diagram showing the relationship between the length of an offshore structure (D) and the length of the resulting wave shadow (6D).

slow or stop at that point so that sand accretes behind the structure and beach erosion results downcoast. Thus, a structure which is intended to solve one coastal problem may actually cause others.

A third class of remedial action which is used to solve beach erosion problems is the construction of structures to stabilize the shoreline. These structures include those which attempt to trap beach sand and stabilize longshore transport, and those which armor the shoreline against wave attack. The most common type of structure used to entrap sand and limit longshore transport is a groin. Groins are constructed across the beach such that the structure impedes the movement of sand along the beach. However, the construction of a groin and entrapment of sand to widen a beach at a particular site causes erosion of the beach immediately downcoast. The downcoast erosion can be reduced or eliminated by filling the groin with sand from an outside source. This erosion prompts the progressive construction of groins downcoast to offset the erosion caused by the first groin (Figure 4.6). This type of remedial action to solve a problem at one site leads to the proliferation of this type of structure and the creation of a groin field in place of a continuous sand beach.

Another type of remedial action which attempts to stabilize the shoreline is through the use of structures to armor the shoreline against waves. These structures are usually seawalls or revetments of various types that are constructed at the shoreline to prevent shoreline retreat. Once this type of action is taken the natural sand beach disappears and the shoreline is defined by the revetment. Such a remedial action will probably provide a solution to the beach erosion problem at the expense of a sand beach. This action represents a situation where man attempts to overcome nature by sacrificing the natural beach to achieve his purpose.

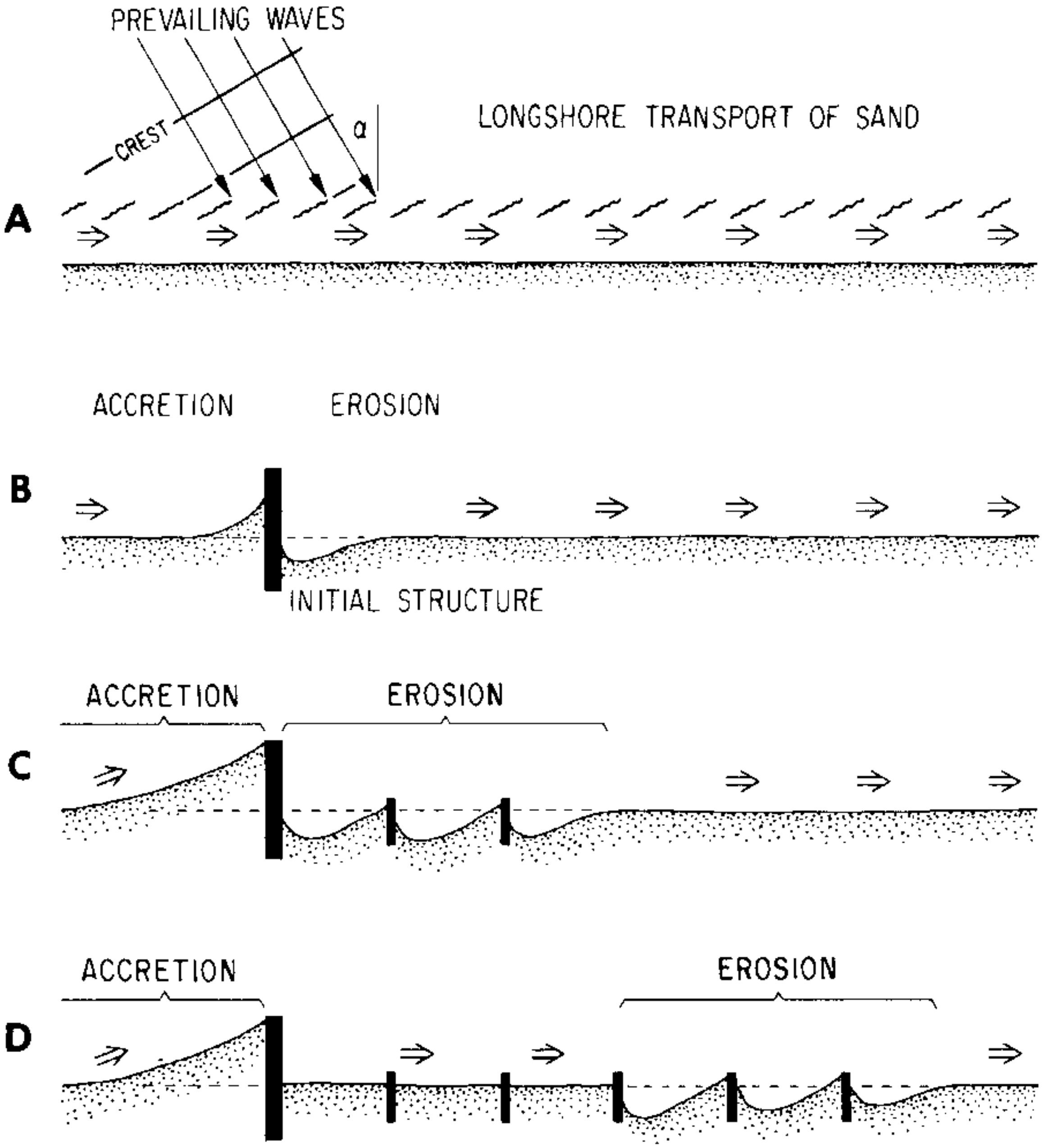


Figure 4.6. Erosional chain reaction following the installation of a single groin: (A) straight beach with prevailing waves producing longshore transport of sand; (B) accretion and erosion after initial obstruction; (C) downcoast erosion requiring two additional groins; and, (D) continuation of the downcoast erosion requiring three more groins. Note that the first three groins are now unnecessary (from Inman and Brush, 1973).

5. SILVER STRAND-IMPERIAL BEACH

5.1 Description of the Area

This specific area of concern is that segment of coastline extending from the international boundary northward to the entrance to San Diego Bay (Figure 5.1). Serious beach erosion has been a problem at various places along this coastline notably at Imperial Beach, Silver Strand State Park, and in the past at Coronado.

This segment of coastline is generally low-lying with elevations less than 20 meters near the shoreline. The southernmost part of this area is the Tijuana Lagoon which is at the mouth of the Tijuana River Valley. The north side of the lagoon is bounded by a gently sloping coastal terrace ranging in elevation from 15 to 30 m above sea level which separates San Diego Bay from the Tijuana River Valley. This slightly elevated area is occupied by the community of Imperial Beach. Silver Strand proper is a relatively narrow sand beach which extends northward from the coastal terrace and separates San Diego Bay from the Pacific Ocean. The northern end of Silver Strand joins Coronado Island thus making the Strand a tombolo. Coronado is a flat, low-lying island that was originally two separate land masses separated by a reentrant of San Diego Bay known as Spanish Bight. The northwesternmost land mass was known as North Island and was connected to Coronado by a sand beach at the ocean shoreline. Artificial fill placed in the Spanish Bight in 1944 created the present single island land mass.

The continental shelf off Silver Strand is approximately 24 km wide and gently slopes seaward to a depth of 180 m at the shelf edge. Three small islands (Los Coronados Islands) are located above seven miles

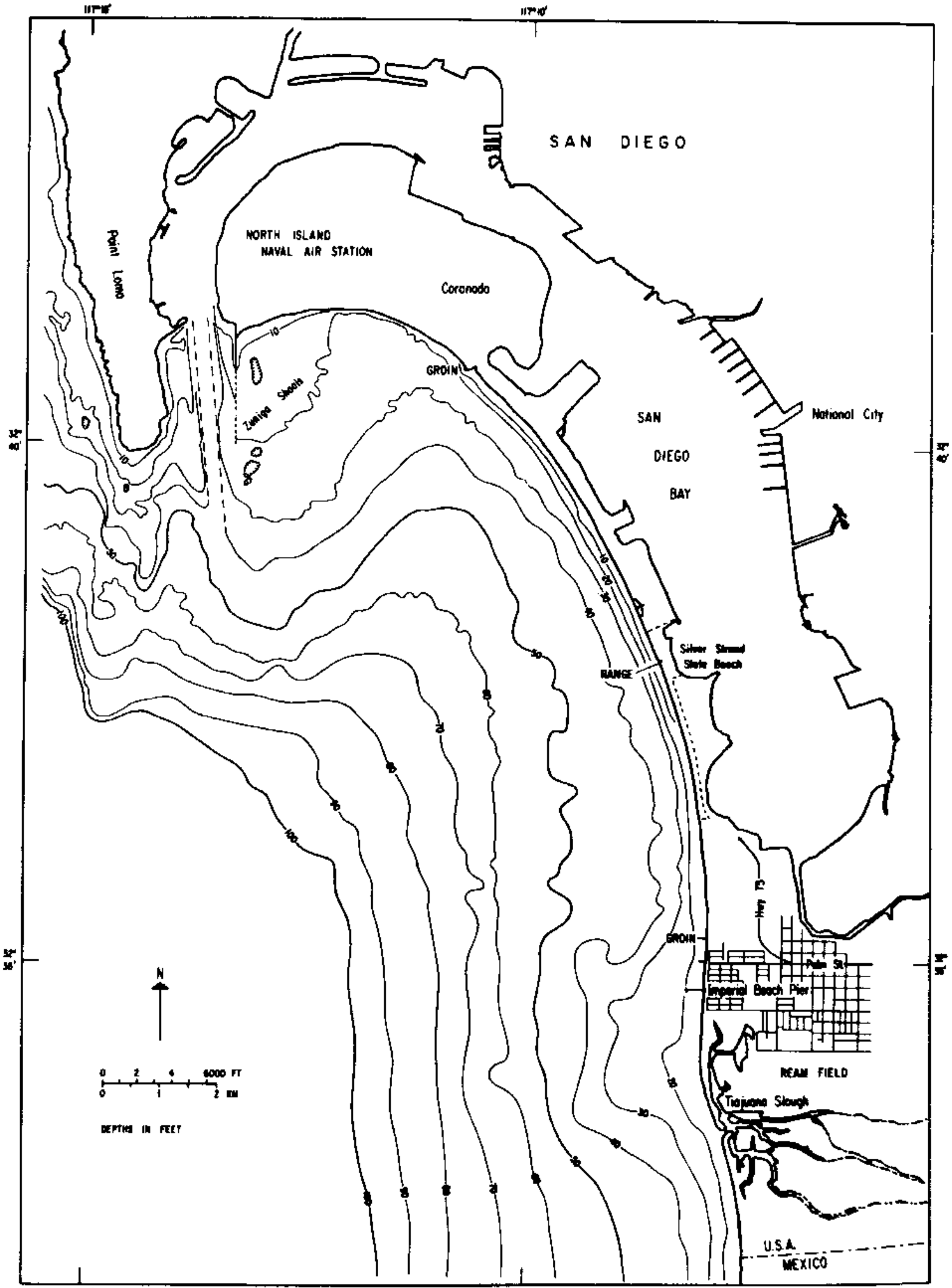


Figure 5.1. Silver Strand nearshore bathymetry. Note location of range surveyed for beach profiles shown in Figure 5.2.

offshore and just south of the international boundary. Figure 5.1 shows the bathymetry off Silver Strand indicating that the contours generally parallel the shoreline and the bottom slopes gradually seaward. Just to the north of the mouth of the Tijuana Lagoon there is a notable seaward bulge in the shallow contours which can be explained as remnants of the Tijuana River delta. The bottom in this area is covered with cobbles and boulders which are probably the residual of past flood loads of the river (Emery, et al, 1952). At the southwestern end of Coronado Island the shallow water contours bulge seaward to form Zuniga Shoals which is an extensive depositional area. The present size and configuration of this shoal area is due to Zuniga Jetty which was constructed in 1893.

The shoreline in the area of concern is a sand beach except for places near the community of Imperial Beach which have cobble shingle especially during the winter months. Figure 5.2 shows a typical beach profile from Silver Strand State Park in the central part of the Strand. Typically the beaches are characterized by a relatively flat backshore, steeper beach face, and a gentler offshore slope. Imperial Beach and Coronado Beach which have low bluffs facing the sea also have lower beach face slopes (Corps of Engineers, 1960). Figure 5.2 also shows the seasonal change in configuration of Silver Strand Beach with a comparison of profiles measured in November and December 1967. The retreat of the beach berm and accompanying accretion of sand at depths -1 to -6 m depth is a response of the beach to winter wave conditions. These profiles do not show the full magnitude of the seasonal change in configuration since the full transition requires a period of several months.

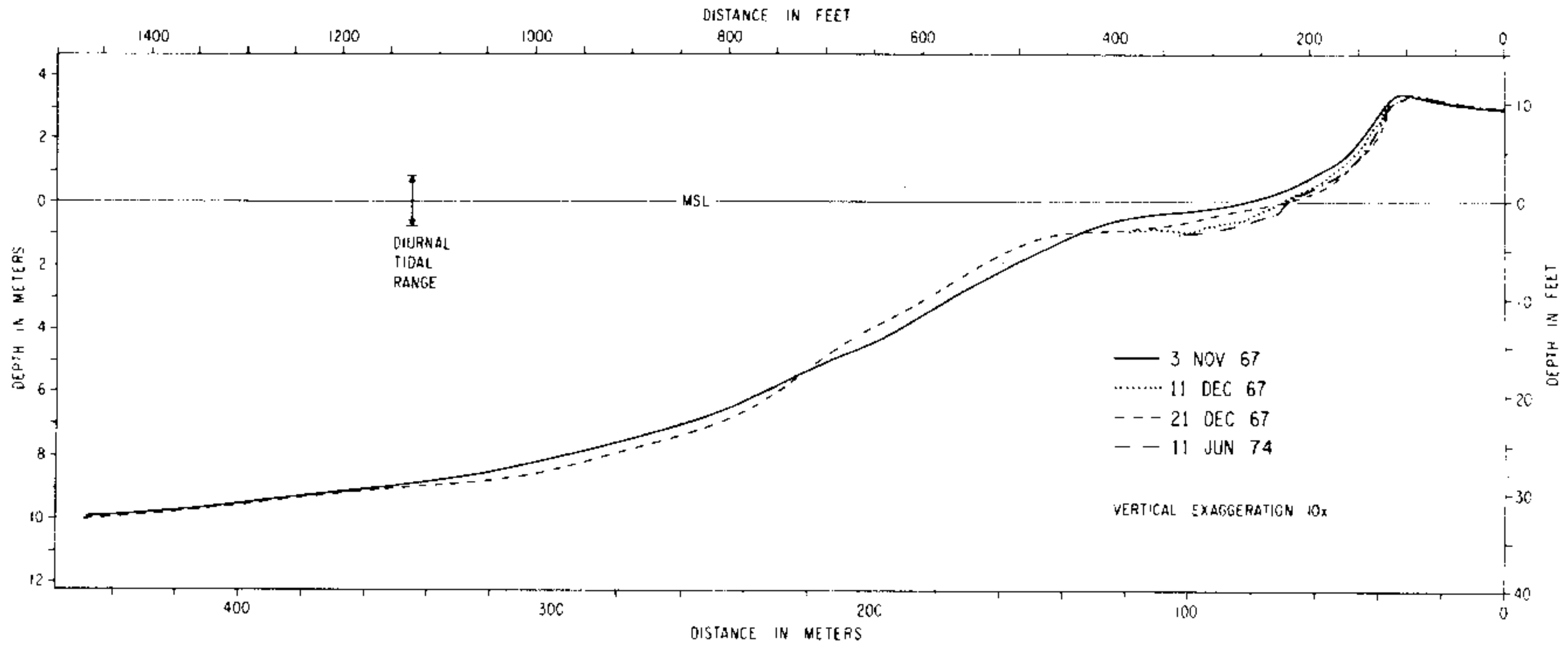


Figure 5.2. Beach profiles measured at Silver Strand State Beach along the rangeline shown in Figure 5.1.

There is a progressive decrease in the median grain size and better sorting of the beach sand northward along Silver Strand from the Tijuana River. This change in the characteristics of the sand probably reflect reworking of alluvial material from the Tijuana River as it is transported northward along the beaches (Inman, et al, 1974).

5.2 Wave Climate

An estimate of the deep water wave energy for the Silver Strand area has been compiled from a number of sources and assembled into a frequency of occurrence of waves from given directions, periods, and heights. From this information the wave climate can be classified into three groups, northern hemisphere swell, southern hemisphere swell and sea. The dominant source of wave energy is the northern hemisphere swell with periods of 6-10 sec and directions of 295-315^o. These waves are of particular importance during the winter season. Southern hemisphere swell is generally lower in height (about 1 m) but occurs frequently during the summer months.

A certain amount of the total wave energy present in the offshore waters does not reach the Silver Strand area because of sheltering by the offshore islands and Point Loma. San Clemente, San Nicolas, Santa Catalina and Point Loma obscure any wave energy approaching Silver Strand from directions greater than 300^o and shelter some energy from directions of 280^o - 300^o. Waves from southern directions are sheltered to a lesser degree by the Los Coronados Islands.

Knowing the wave climate for an offshore location it is necessary to refract the waves into the littoral zone where longshore sand transport takes place. This was done for five stations along Silver Strand (see Figure 5.1). Figure 5.3 shows a typical refraction diagram for a 12 sec wave from a direction of 222°. From these diagrams the angle that the wave ray makes with the perpendicular to the beach was determined and designated the breaker angle α_b. The breaker angle and an estimate of the intensity of the energy flux was compiled for each sector of deep water direction and wave period which was plotted on polar diagrams for each shoreline station. This information was then used for the calculations of longshore transport rate.

Figure 5.4 shows a polar diagram of α_b for station 2 in the central part of Silver Strand. The notation for α_b in this case is that a positive angle α_b indicates that the wave is approaching from a southerly direction with respect to the beach, while a negative angle α_b indicates the wave is coming from a northerly direction.

Examination of the refraction diagrams for Silver Strand shows that there is generally a divergence of wave energy at stations 1, 2, 3, and a convergence of wave energy at stations 4 and 5 (see Figure 5.1). The greatest divergence was at station 1 due to the bathymetry in the vicinity of Zuniga Shoal and the greatest convergence at station 4 where waves converge over the shoal area at the mouth of the Tijuana River.

The wave energy flux at each station was resolved into its longshore and onshore components and summed over time to give seasonal values to the longshore component of energy flux. This information was then used for calculation of longshore transport in the upcoast and downcoast direction and the determination of net longshore transport.

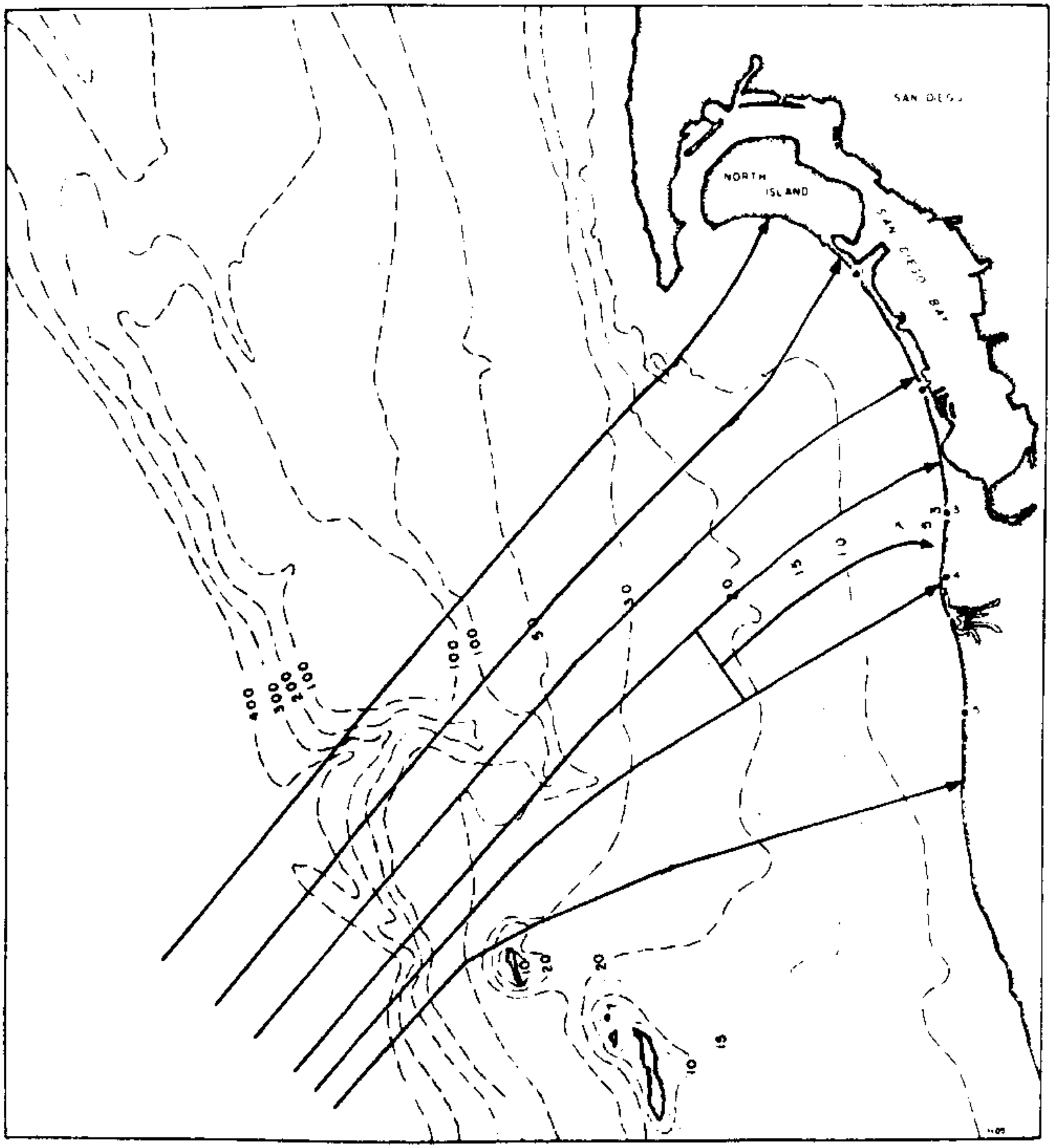


Figure 5.3. Wave refraction diagram at Silver Strand California for deep water direction 222° and wave period of 12 seconds.

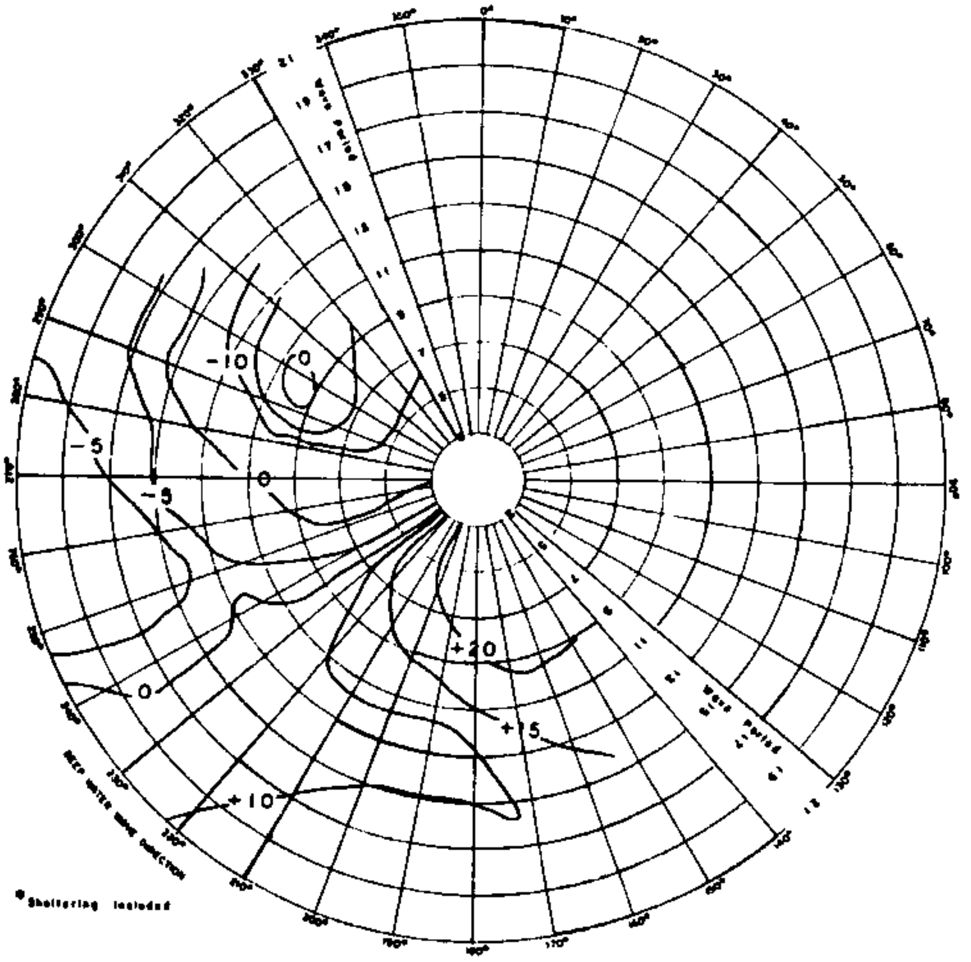


Figure 5.4. Polar plot for breaker angle α_b for station two* in Figure 5.1.

5.3 Budget of Sediment

Silver Strand is defined as a separate littoral cell with its own sediment source, transport path and sink (Figure 4.4).

The principal natural source of sediment for this cell is the Tijuana River. Sand supplied to the coast by the river is transported along the coast by waves to the entrance to San Diego Bay. The sink for this cell is the accretion of sand in Zuniga Shoal and deposition offshore by the strong ebb tidal currents which flow through the entrance channel to the bar (Figure 5.5).

The Tijuana River is an ephemeral stream formed by the confluence of Cottonwood Creek which drains the northern one-third of the drainage basin; and Rio de las Palmas which drains the southern two-thirds of the drainage basin. Topographic relief in the 1700 mi sq, 4400 sq km drainage basin of the Tijuana River varies from sea level up to elevations of 3940-5900 ft, 1200-1800 m near the crest of the coastal mountains (U.S. House of Representatives, 1957). The semi-arid climate of the area is characterized by warm, dry summers and mild winters. Most of the rainfall in the area results from winter storms that originate in the north Pacific Ocean and move southward along the Pacific Coast of North America. The amount of precipitation in the drainage basin is related to elevation with the upper part receiving more than 20 m, 500 mm per year while the coastal areas only receive about half that amount.

Run-off in the Tijuana River basin varies with the frequency and duration of the storms reaching the area. During the winter months of most years there is sufficient precipitation to cause surface flow of water. Occasionally there are years when the amount and duration of the

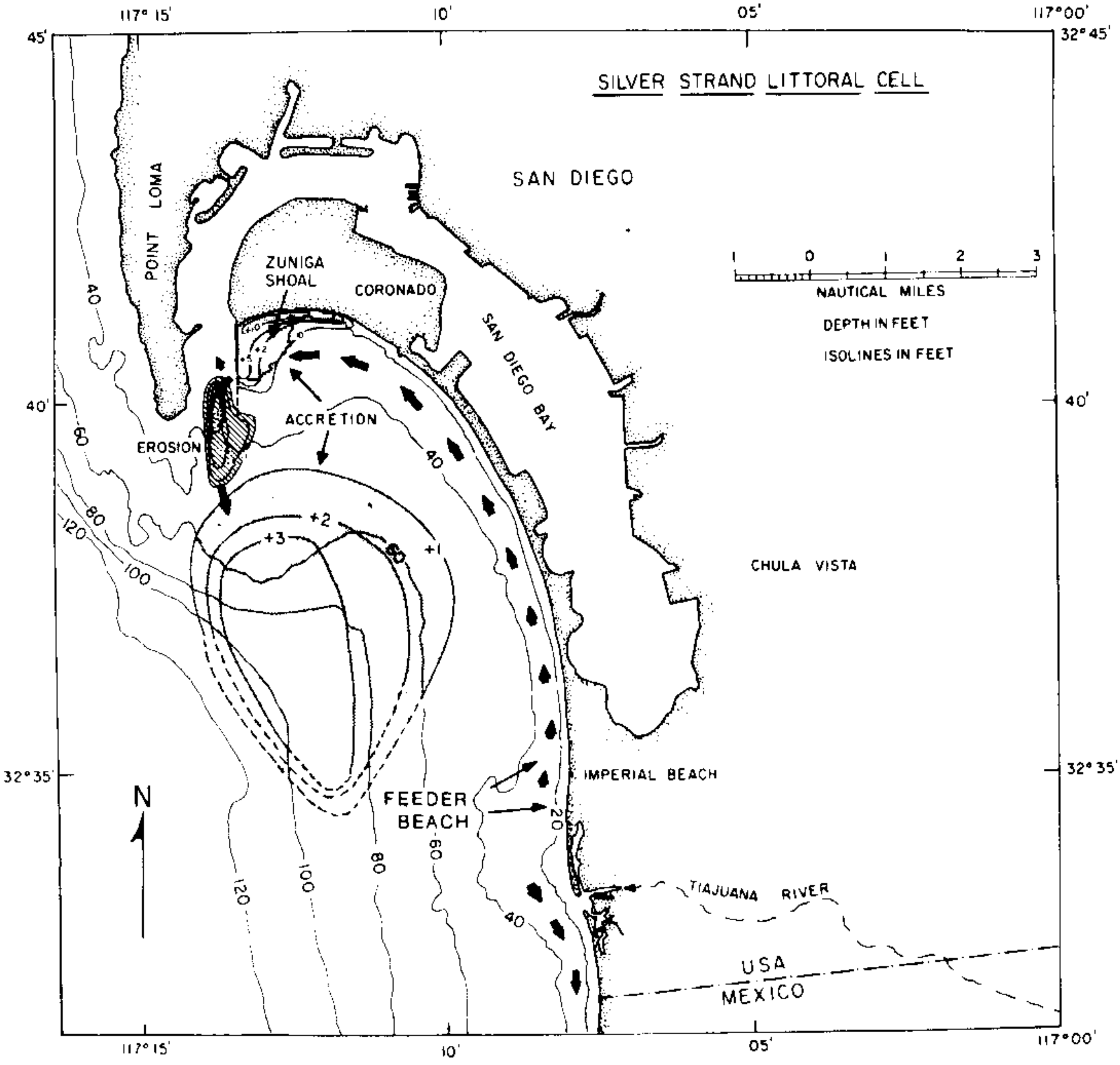


Figure 5.5 Silver Strand littoral cell showing the Tiajuana River as the former natural sand source, the littoral transport path north along Silver Strand, and the depositional area or sinks. The final sink for sand in this littoral cell is the offshore area indicated by the isolines of sand accretion determined by comparison of surveys in 1923 and 1934 (Chamberlain, et al, 1958).

rainfall is great enough to saturate the ground and further rainfall causes large volume surface flows which flood the lower portion of the drainage basin. The periodic floods are the times when most of the sediment is carried to the coast to supply the beaches of the Silver Strand littoral cell.

Table 5A shows peak discharges of the floods of the Tijuana River recorded at a stream gage near the mouth of the river and from historical documents. The largest flood of record was in 1916 which had a peak flow of over 70,600 ft sec, 200 m^3/sec. A flood discharge-frequency curve has been determined for the Tijuana River which indicates a peak discharge of about 134,200 ft^3/sec, 3800 m^3/sec every 335 years even with the present dams blocking the river channel (City of San Diego, 1973).

Unfortunately, no measurements of sediment yield under flood conditions have ever been made in the Tijuana River so that its annual yield will have to be estimated. This estimate has been made by using comparable data from other watersheds and using long-term average erosion rates. As mentioned previously one estimate can be obtained using the empirical curves relating sediment yield to effective precipitation of Langbein and Schumm (1958). Using the Langbeim and Schumm sediment yield without entrapment by dams would be about 660,500 yd/yr, 505,000 m^3/yr; whereas the total sediment yield based upon their reservoir sedimentation curve would be 1,171,000 yds/yr, 895,000 m^3/yr without entrapment (Inman, et al, 1974).

An independent estimate of sediment yield can be obtained from average long-term erosion rates of large land areas. Inman and Brush (1973) give the average long-term erosion rate for the entire United States as 1-2.5 m/1000 yrs, 3-6 cm/1000 yrs which assuming an average of 2 in/1000 yrs

Table 5A. Peak discharge data for Tijuana River

	PEAK DISCHARGE	
DATE	CUBIC FEET/SECOND	CUBIC METERS/SECOND
February 1884	50,000	1,416
December 1889	20,000	566
February 1891	20,000	566
January 1895	38,000	1,076
24 March 1906	16,000	453
21 February 1914	5,000	142
17 January 1916	75,000	2,125
12 March 1918	16,000	453
26 December 1921	15,000	425
16 February 1927	25,000	708
18 February 1932	1,500	42
Rodriguez Dam Completed Summer 1936		
7 February 1937	17,700	501
3 March 1938	6,760	191
13 March 1938	1,600	45
24 December 1940	2,700	76
22 February 1941	15,000	425
15 March 1941	8,620	244
11 April 1941	10,400	295
17 March 1942	2,770	78
23 December 1944	2,100	59
7 January 1944	2,500	71
23 February 1944	13,800	391
13 January 1949	2,600	74
16 March 1952	3,560	101
7 December 1967	2,020	57

Note: Flood data is from Nestor gaging station on the Hollister Street Bridge. No floods less than 1,500 cubic feet/sec (42 m^3/sec) are included and flood data prior to 1937 is based on historical data and information obtained from long-time residents and estimates based on data recorded from nearby streams. Table adapted from City of San Diego (1973).

for the Tijuana River drainage basin would yield about 294,000 yds^3/yr, 225,000 m^3/yr without entrapment by dams. Thus, these estimates of sediment yield vary from 294,000 yds^3/yr, 225,000 m^3/yr to 1,171,000 yds^3/yr, 895,000 m^3/yr, so that an average annual sediment yield for the Tijuana River drainage basin under natural conditions can be approximated at about 700,000 yds^3,535,000 m^3 (Inman, et al, 1974).

However, the natural flow and sediment yield of the Tijuana River has been considerably modified by the construction of dams on the main stream courses. Cottonwood Creek is impounded by Morena Dam (1911) and Barrett Dam (1921) in the United States and the Rio de las Palmas is impounded by Rodriguez Dam (1936). These three dams entrap the run-off and sediment produced in over 3100 km^2 or about 70 percent of the drainage basin (State of California, 1969). Sedimentation rates were measured in Morena Reservoir during the period 1910 to 1948 which indicate that the reservoir was trapping about 322,000 yds^3/yr, 246,000 m^3/yr of sediment from a drainage area of 116 mi^2, 300 km^2 (City of San Diego, 1953). Thus, it can be seen that these dams act as very effective sediment traps and prevent the material from reaching the coast to nourish the beaches.

Once the fluvial sediment reaches the shoreline it comes under the influence of the waves and currents which dominate the nearshore environment. These driving forces sort the sediment into specific size fractions that follow different transport paths in the coastal zone. The sediment load carried by the Tijuana River especially under flood conditions involves material ranging in size from boulders and cobbles, many cm in diameter down to silt and clay size material. Much of the coarsest material is deposited in the Tijuana Lagoon and at the mouth of the river where it has been slowly accumulating. These residual deposits consist almost entirely of cobbles and boulders too large to be moved by waves and nearshore currents so they remain as a vestigial delta at the mouth of the lagoon.

The silt and clay fraction brought to the coast by the river stays in suspension as it flows into the ocean where it is distributed over a large area by the local currents. This fine material is often carried considerable distances offshore and along shore before it finally settles to the bottom.

Sand sized material 2 mm to 0.064 mm is easily transported by the waves and becomes the source of sediment for the local beach. Upon reaching the beach the sand is then redistributed along the shoreline by the prevalent longshore currents. Sand brought to the coast by the Tijuana River is transported by waves both to the north, along Silver Strand, and to the south along Mexican beaches (Chamberlain, Horrer and Inman, 1958). The longshore transport northerly along Silver Strand has been estimated by two different techniques: (1) by following the erosion-accretion rates of artificial fill placed on the beach; and, (2) calculation of longshore transport rates from the available wave data.

In 1940-41 approximately 2.35 x 10^6 yds^3, 1.8 x 10^6 m^3 of fill was placed along the beach at North Island and during the years 1941-45 over 20 x $10^6 m^3$ of fill was placed on the central part of Silver Strand. Between the years 1940 and 1967 a total of about 29 x $10^6 yds^3$, 22 x $10^6 m^3$ of sand was placed on Silver Strand Beach which augmented its natural sand supply (Inman, 1956). Comparison of beach profile surveys along Silver Strand Beach for the years 1946 and 1954 show that much of the sand placed in the central part of the Strand was transported north to the Zuniga Shoal area at the rate of

$1.4 \times 10^6 yds^3/yr$ ($1.1 \times 10^6 m^3/yr$). This northerly movement of sand on Silver Strand has also been documented by aerial photographs of Coronado Beach which show significant widening of the beach between 1945 and 1967 (Figures 5.6a and b). Thus, the long term net movement of sand on Silver Strand Beach appears to be northerly from the vicinity of Imperial Beach to the Zuniga Shoal area.

Another estimate of the longshore transport rate through the littoral cell was made using the available wave data as described previously, and the longshore transport relations of Komar and Inman (1970). Longshore transport rates were calculated for stations 1, 2, 3, and 5 (Figure 5.1). At station 1 the annual volume transport was calculated to be $43.2 \times 10^4 yds^3/yr$ ($33.0 \times 10^3 m^3/yr$) to the north. At stations 2 and 3 the annual volume transport rates were $9.4 \times 10^3 yds^3/yr$ ($7.2 \times 10^3 m^3/yr$) to the south and $98 \times 10^3 yds^3/yr$ ($75 \times 10^3 m^3/yr$) to the south respectively. At station 5 the transport rate was $602 \times 10^3 yds^3/yr$ ($460 \times 10^3 m^3/yr$) to the south. The calculated transports for stations 1 and 5 were expected but the southerly transport at stations 2 and 3 seem anomalous in view of the net northward transport documented from the erosion-accretion data for Silver Strand. This anomaly may be the result of the fact that the available wave data is not statistically representative of the actual wave climate. The available wave data is lacking information on the southern swell which is very important in causing northerly longshore transport along Silver Strand (Inman, et al, 1974).

Figure 5.5 shows the Silver Strand littoral cell with the Tijuana River as its sediment source, a northerly longshore transport along Silver Strand, and the sediment sink at Zuniga Shoal and offshore accretion area. Early charts of San Diego Bay show that sand accreted in the vicinity of

Figure 5.6a. Aerial photograph of the north end of Silver Strand taken in January 1945. Note how narrow the beach is in the vicinity of the Hotel del Coronado groin.

Figure 5.6b. Aerial photograph of the north end of Silver Strand taken in December 1967. Comparison with the previous figure shows the effect of northerly transport of sand fill placed on Silver Strand between 1941 and 1946. Note the increase in beach width near the Hotel del Coronado groin.

Zuniga Shoal along the east side of the entrance channel to the bay. Deposition in this area was shallow enough that waves from the north that are refracted around Point Loma would transport the sand back onto the beach to resupply part of the longshore transport demand. Thus, the natural system was in balance with the Tijuana River supplying sufficient sand to maintain Silver Strand at a somewhat narrower than present width, and the recirculation of sand from Zuniga Shoal supplying Coronado Beaches with adequate sand for a relatively wide beach.

Zuniga Jetty, built in 1893, trapped the sand and caused further accretion of the shoal area immediately after its construction. The jetty also further channelized the tidal currents thus increasing the velocity of the ebb tidal current. As a result of these increased ebb currents, sand entering the channel through the porous jetty and from the end of Zuniga Jetty is carried into deeper water where it can no longer be transported back to the beach (Inman, 1973). A comparison of charts surveyed in 1923 and 1934 show that sand has been accreting in water depths of 59 to 131 ft (18 to 40 m) depth just south of Zuniga Jetty at an estimated rate of 2.1 x 10^6yds^3/yr (1.6 x 10^6m^3/yr) (Chamberlain, Horrer and Inman, 1958). This area of accretion now appears to be the final sink for the sand passing through the Silver Strand littoral cell (Figure 5.5).

5.4 Specific Problem

The specific problem in the Silver Strand littoral cell area has been the persistent beach erosion that has occurred at different locations along this coastal segment since the beginning of man's intervention. Beach erosion was first noticed on Coronado Beach in 1905 shortly after the construction of Zuniga Jetty, and progressed to a state where it was necessary to place a rock revetment wall along Ocean Avenue in Coronado. Also, beach changes have been noted in the south Imperial Beach area since the first surveys in 1856. However, since 1937 there has been a persistent retreat of the beach at Imperial Beach at the southern boundary of the community. During the early 1950's the beach erosion problems began to extend northward which prompted the Corps of Engineers to construct a rock groin at the north city limit in 1959. This groin did not prove to be effective in trapping sand so a second rock groin was constructed in 1961 south of the first groin (Figure 5.7). At present neither of these groins has been effective in controlling the beach erosion problem so that the construction of additional structures is proposed (U. S. Army Corps of Engineers, 1970).

During 1940-41 about 2.3 x 10^6yds^3 (1.8 x 10^6m^3) of sand fill was placed on the North Island Beach west of Coronado, and between 1941 and 1946 about 26 x 10^6yds^3 (20 x 10^6m^3) of sand fill was placed on central Silver Strand from the extensive dredging of San Diego Bay. This material advanced the shoreline seaward in the fill area over 985 ft (300 m) but since 1946, the shoreline in that area has steadily retreated as the sand has been transported on through the littoral cell. Unfortunately, several large condominiums have been built on this artificially created beach and are now being threatened by beach erosion requiring the construction of a revetment wall around the buildings. In general, all of the Imperial Beach-Silver Strand shoreline is presently undergoing some beach erosion and will require remedial action in the foreseeable future.

Figure 5.7. Aerial photograph taken on 29 November 1967 showing the groins at Imperial Beach. Note that these remedial structures are relatively ineffective in trapping sand.

5.5 Recommendations

The basic problem causing beach erosion in the Silver Strand littoral cell is that the natural sources of sediment for the cell have been eliminated by man's intervention into the natural system. As mentioned previously the primary source of sediment for the cell is from the Tijuana River which has about 70 percent of its drainage basin isolated from the coast by dams. Without the continuing sediment supply to the coast from the river, wave induced longshore transport has been fed by the existing beach sand. This has been most readily apparent at Imperial Beach which is at the south end of the cell nearest the source area. The central part of Silver Strand has not been severely eroded during this time because it has received large amounts of sand from the disposal of dredge spoil. This sand has also provided a source of sand for the beaches at the north end of the Strand and Coronado.

Since the beach erosion problem has developed due to the lack of a sufficient sand supply for the longshore transport demand of the waves, any rational solution will have to consider alternative sources of sand for the cell or other uses of the coastal zone which are compatible with the erosion of the shoreline. Solutions to this problem can be considered in terms of the general categories of remedial action presented previously in the report.

Since the natural source of sand for this littoral cell has been interrupted a solution which imitates nature would involve replacement of the natural source with an artificial source. This type of solution has already been applied in the past with the disposal of suitable dredge spoil from San Diego Bay on Silver Strand Beach. However, this has only been done at infrequent and irregular intervals so that it is only a short term solution and the beach erosion problem recurs once the sand is gone. In order for the artificial replenishment of sand to become a permanent solution to the beach erosion in this littoral cell the sand would have to be supplied on a regular basis which closely matches the longshore transport demand determined by the local wave climate.

The principal complications associated with the continued replenishment of beach sand artificially are: (1) locating adequate supplies of suitable sand to place on the beach; and, (2) the design, construction, and maintenance of a system for transporting the sand to the feeder beach for the littoral cell. Potential sand sources may be present in the lower Tijuana River Valley, at the downcoast end of the cell in Zuniga Shoal, and at shallow depths offshore. Each of these sand sources would require a different technology for transporting the sand from its present location to Imperial Beach for introduction to the natural transport path through the cell. As can easily be seen, this type of solution will require a considerable investment of resources and a continuing effort in order to be successful.

Perhaps the best single solution of this type would be to develop a system for recycling sand through the littoral cell. This would require a mechanical system for moving sand from Zuniga Shoal south to Imperial Beach so it can be reused in the natural transport process. This proposed solution has an advantage over others of this type in that the source sand is localized in one place and is supplied at the same rate it has to be returned to the feeder beach. Although other sand sources on land or offshore may seem to be advantageous because of their proximity to Imperial Beach, they also have the potential for being exhausted at some future date and causing other environmental complications as the sand is extracted.

The second type of approach for a solution to the beach erosion problem in the Silver Strand littoral cell would involve the construction of some type of structure to locally modify the wave climate. Typically this would be some type of detached breakwater which will decrease the wave energy incident to a segment of coastline. The structure would probably be designed to protect that part of the Silver Strand littoral cell which is presently being eroded in the Imperial Beach area. This detached breakwater could either be a surface structure which breaks the surface and would be designed to shelter the beach from virtually all wave energy or a submerged structure which will only cause partial sheltering. In either case the structure will provide some relief from wave erosion and possible trap sand in its shadow; however, the benefit of the structure is localized at the site of the structure.

Use of this type of solution also has many potential disadvantages such as: (1) the design and construction of the structure are costly; (2) improper design can result in failure of its purpose and possibly cause deleterious effects; (3) the installation of such a structure can result in a committment to a solution that is essentially irreversable; and, (4) a localized solution such as a structure is likely to simply displace the erosion problem downdrift beyond its shadow.

At Imperial Beach the application of this type of solution would involve the construction of some type of detached breakwater along the most severely eroded segment of shoreline. Success of this solution even at this site would require proper design of the structure with respect to the wave climate of the area. The important design factors would include the length, height, distance from shore, orientation with respect to shore and wave approach, etc which are difficult to determine at this site since the wave climate has a seasonal variation. Improper design could result in the structure being ineffective and perhaps even deleterious to the present situation.

Another factor in the use of this type of solution is that the construction of a breakwater represents a committment to this type of solution and once it is constructed, if poorly designed, it is virtually impossible to remove. Also the construction of a structure can cause beach erosion immediately downdrift so that the problem is simply displaced further along the sand transport path. This usually results in extension of the initial structure or construction of additional structures to stop the adjacent erosion. Finally, the application of this type of solution can result in the proliferation of structures along the coast so that the nearshore environment becomes dominated by the manmade features and loses its natural character.

Attempts to solve the beach erosion problem by stabilizing the shoreline have already been attempted at Imperial Beach. These efforts include the use of seawalls and revetments of various types and the construction of groins at Imperial Beach. The use of seawalls and revetment has been employed by individuals to protect their property. Consequently, the shore protection is discontinuous and varies in construction design. Although this type of remedial action may provide a solution for a specific piece of shoreline property it does not help restore the natural sand beach.

The construction of groins at Imperial Beach is an attempt to restore the beach by entrapping and holding sand at the eroding segment of shoreline. However, the two groins that have already been constructed are ineffective in trapping and holding sand either because of their design or simply because there is no sand available to trap. Thus, use of remedial actions which attempt to stabilize the shoreline have had only limited success in the Silver Strand littoral cell.

A final type of solution that can be applied to this coastal problem would be to modify the present use of the shoreline to accomodate beach erosion. This approach is essentially the situation in the central part of Silver Strand at the state park. The present policy of the state park is to let erosion follow its natural course and place only temporary structures which can be moved on the beach. Much of the U. S. Navy property in the area is allowed to erode because no permanent structures were constructed near the shoreline. This type of solution is most difficult to apply in the Imperial Beach and Coronado areas where poor planning has permitted the construction of expensive structures on eroding shoreline property. Application of this type of solution would imply public acquisition of privately owned shoreline property and its use reserved to the possible effects of natural erosion. However, if erosion were allowed to take its course, the narrow sections of Silver Strand could be severed thus opening the west side of San Diego Bay so it is unlikely that this solution could ever be applied to the problem.

The beach erosion problem in the Silver Strand littoral cell is presently being treated with a wide variety of remedial actions that are not coordinated with respect to each other or with the causative physical processes. Any successful solution must recognize that the problem concerns the entire littoral cell and its lack of a continuing supply of sand for longshore transport by waves. Therefore, the best solution would be a remedial action which replaces the deficient sand supply near the natural source and allows the natural processes to operate in the remainder of the littoral cell. Other remedial actions which require the construction of structures may offer temporary solutions at a specific site but cause problems further along the transport path. Since the construction of one structure often leads to others, the ultimate result may be a complete modification of the natural environment.

6. OCEANSIDE

6.1 Description of the Area

Oceanside, California is located in the central part of a littoral cell that extends from Dana Point southward to the Scripps-La Jolla Submarine Canyon (Figure 6.1). The shoreline of the Oceanside littoral cell consists of a continuous narrow beach that is bounded on the landward side by sea cliffs except at the mouths of the coastal streams. The sea cliffs are the result of wave erosion at the seaward edge of raised marine terraces and vary in height along the coast. At Oceanside the cliffs are 16-50 ft (5-15 m) in height and are composed of relatively soft materials. Loss of the protective beach at the foot of the sea cliff results in the dissipation of wave energy directly upon the cliff base and accelerated retreat of the cliff itself.

Several ephemeral rivers and streams enter the ocean within the limits of the Oceanside littoral cell. Under normal rainfall conditions the runoff from most of these streams does not reach the ocean, but accumulates in the coastal lagoon formed behind the barrier beach at its mouth. Usually these lagoons are open to the ocean only when the runoff from the stream raises the lagoon water level so that it overtops the barrier beach and cuts a channel through the beach to the ocean. These openings usually last only a short time until the beach reconstructs itself and closes the channel. However, when large floods occur, the barrier beach and lagoon are totally inundated by the volume of water passing through the stream valley into the ocean.

The shelf along the Oceanside littoral cell coastal segment gently slopes offshore to a depth of about 330 ft (100 m) at its outer edge. Width

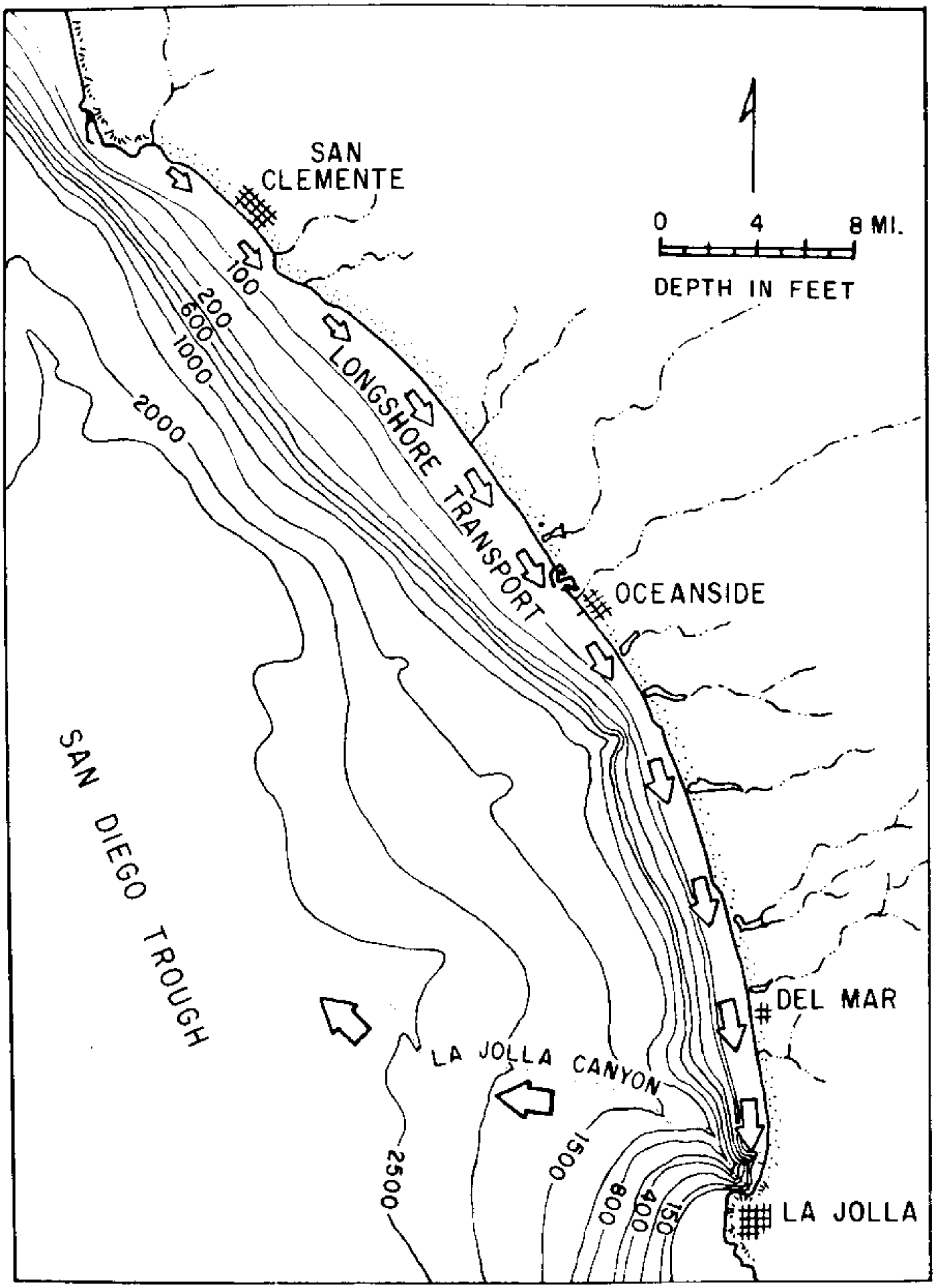


Figure 6.1. Oceanside littoral cell showing principal coastal streams as sediment sources, direction of net longshore transport, and sediment loss through the La Jolla Submarine Canyon.

of the shelf varies somewhat with it becoming progressively narrower from Dana Point south to La Jolla (Figure 6.1). North of Oceanside the average width is 4 mi (7 km) with the widest point being in the central part of Camp Pendleton. South of Oceanside the shelf narrows to an average width of 2.5 mi (4 km) off Carlsbad. The shelf narrows again south of Del Mar so that it averages only 1.6 mi (2.5 km) in width just north of La Jolla.

Seaward of the shelf edge the bottom rapidly slopes into the San Diego Trough whose lowest point is at a depth of over 4000 ft (1200 m). Two submarine canyons dissect the continental slope within the area under consideration; one located near Carlsbad is unnamed, and larger one, Scripps-La Jolla Submarine Canyon, is located at La Jolla. The smaller canyon off Carlsbad does not cross the shelf, but terminates near the shelf edge and therefore does not have significant influence on the nearshore environment. Scripps-La Jolla Canyon, on the other hand, has two branches which cut across the entire shelf and end essentially at the shoreline. This canyon has considerable influence on the nearshore processes and intercepts most of the sand being transported through the littoral cell. Sand entering the canyon is transported through the canyon to the San Diego Trough where it is deposited on the La Jolla Submarine Canyon Fan. The 2500 ft (750 m) depth contour of Figure 6.1 shows conspicuous seaward bulges at the mouths of La Jolla Submarine Canyon and the small canyon just south of Carlsbad which define the canyon fans.

The shoreline of the Oceanside littoral cell is a continuous sand beach except for short sections of beach that have exposed cobbles and pebbles. These cobble beaches vary in extent and distribution along the coast and may be related to the seasonal changes in wave characteristics.

The sand median grain size in the beach foreshore ranges from 0.19 to 0.27 mm (U. S. Army Corps of Engineers, 1960). The beaches along the Oceanside littoral cell vary considerably in profile configuration which can to some degree be related to the grain size of the beach material. Generally, these beaches do not have a well developed backshore since the landward termination of the beach is usually a sea cliff. The beach foreshore varies in steepness with the steepest foreshore slopes being coarse sand beaches and the fine sand beaches having the lowest foreshore slope.

All the beaches along the Oceanside littoral cell show seasonal changes in profile configuration that can be related to changes in the local wave climate. Accurate measurements of these sand level changes have been made at Torrey Pines Beach near southern end of the littoral cell which show that considerable amounts of sand are involved in the on-offshore transport on these beaches. Figure 6.2 from Nordstrom and Inman (1975) show seasonal changes in profile configuration at Torrey Pines Beach with the erosion of sand from the beach face and concurrent deposition offshore during the summer to winter transition. The seasonal removal of sand from the beach face often creates a problem of protection for shoreline structures during the occurrence of high winter storm waves. Shore protection problems now exist at Oceanside, Carlsbad, and Del Mar during the winter months and seem to be increasing in number and magnitude within the limits of the Oceanside littoral cell.

6.2 Wave Climate

The segment of Southern California coastline included in the Oceanside littoral cell is subject to wave energy from sources similar to

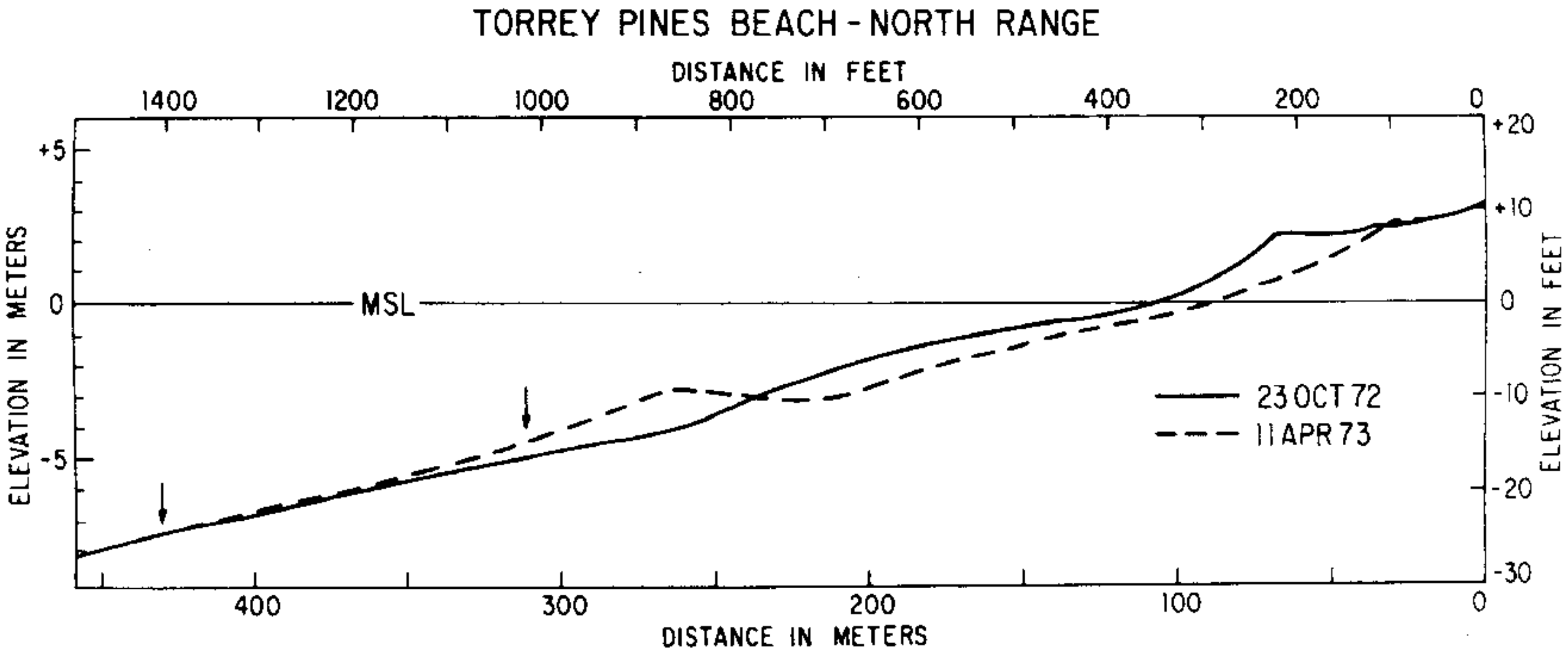


Figure 6.2. Comparison of beach profiles measured at Torrey Pines Beach showing seasonal changes in beach configuration 1972-73. The profile measured on 23 October 72 shows the summer beach configuration during the winter of 1972-73.

Silver Strand. A generalized wave climate for La Jolla was prepared by Munk and Traylor (1947). They recognized three wave types that had a seasonal occurrence that is primarily dependent on meteorological conditions in different parts of the Pacific Ocean. Winter waves are typically long period swell that is generated by cyclones moving eastward across the North Pacific Ocean; summer waves are often very long period swell approaching the coast from the south which is generated by the winter storms in the southern Pacific Ocean; and finally, there is the short period sea waves that are locally generated by storms that come into the coastal region or by winds associated with local atmospheric low pressure systems. The sea waves can occur in any season, but are most common in the winter and spring.

Pawka, et al (in press) have recently compiled a wave climate for the La Jolla area from directional measurements made with a pressure sensor array at a depth of 33 feet (10 m) located 1.2 mi (2 km) north of Scripps Institution of Oceanography. They classified the wave climate of this region into seasonal wave types based upon the characteristics of the measured wave spectra. During the summer months the wave spectra typically have a bimodal form with a low frequency peak and a higher frequency peak. The peak period of the lower frequency energy peak is between 12-17 sec, whereas the higher frequency peak is between 6-10 sec and usually contains more energy. The directional aspect of the waves indicate that the lower frequency waves come from the south and the higher frequency waves come from the north. Wave climate during the winter months differs considerably from the summer and fall. Winter wave spectra indicate that there are many components to the winter wave climate. The longer period waves generally come from the north but there also is some southern swell. Shorter period waves show a wide spread in direction with some approaching from both the northern and southern sectors. The 6 to 8 sec southern waves are usually generated by local storms that approach the coast from the west. Winds from these storms are southerly to southwesterly and are quite intense. Since most winter waves originate with local storms they are generally higher in energy than the summer waves.

During the early spring a primary source of wave energy along this coast is the north Pacific storms which generate waves of 10 to 15 sec approaching from the north. This energy from distant storms combined with that of short period waves generated by local storms combines to play an important part in the total energy budget for the year in this region. When significant wave heights are calculated for the spectral peaks from these measurements it reveals that the winter and spring waves have a higher mean significant height than the summer or fall waves.

A study was made of wave conditions at Oceanside at the time additional harbor entrance structures were designed to accomodate the recreational harbor. This study consisted of a historical compilation of the 15 most severe storms which affected the Oceanside area during the period 1900-1958 and wave hindcasts were determined from the available meteorological information (Marine Advisers, 1960). The most severe waves that occurred during the time period considered were generated by a tropical storm that hit the Southern California coast on 24-25 September 1939. These waves approached from the southeast and their breakers had a significant height greater than 24 feet (7.3 m) at Oceanside. The most severe winter storm waves during this time period approached from the west and created breakers that had a significant height of over 17 feet (5.2 m) (Marine Advisers, 1960). Consequently, it appears that the most severe wave conditions at Oceanside can be attributed to two possible sources for waves of extreme height: (1) tropical storms whose tracks extend into Southern California from the southwest; and, (2) winter storms that enter the area from the west or northwest.

Figure 6.3 is a wave exposure diagram for Oceanside which shows the extent to which wave energy entering the Southern California area is affected by the offshore islands. As can be seen, Oceanside is exposed to deep water waves from southerly and southeasterly directions but is shielded from most westerly and northwesterly approaching waves. San Clemente and Santa Catalina Islands effectively shelter Oceanside from deep water waves in most westerly directions except for the sector between azimuth 261° and 276°. However, Oceanside is exposed to locally generated sea breeze waves from all directions between azimuths 160° and 320°.

In order to apply the deep water wave information determined for the open Pacific Ocean to Oceanside some consideration must be given to the island sheltering. As waves are generated they develop a spread of travel directions upon leaving the place of origin. Statistical details of these directional spreads are not well known so the spread of each wave type in the deep water wave climate must be assigned with what information is available about the wave type. The directional spread will fit any function which smoothly decreases from a central maximum to a low value at the limits such as a gaussian distribution. For each central direction and wave period it was determined how much of this spread would be blocked by the islands. If the center of the directional spread was blocked then a

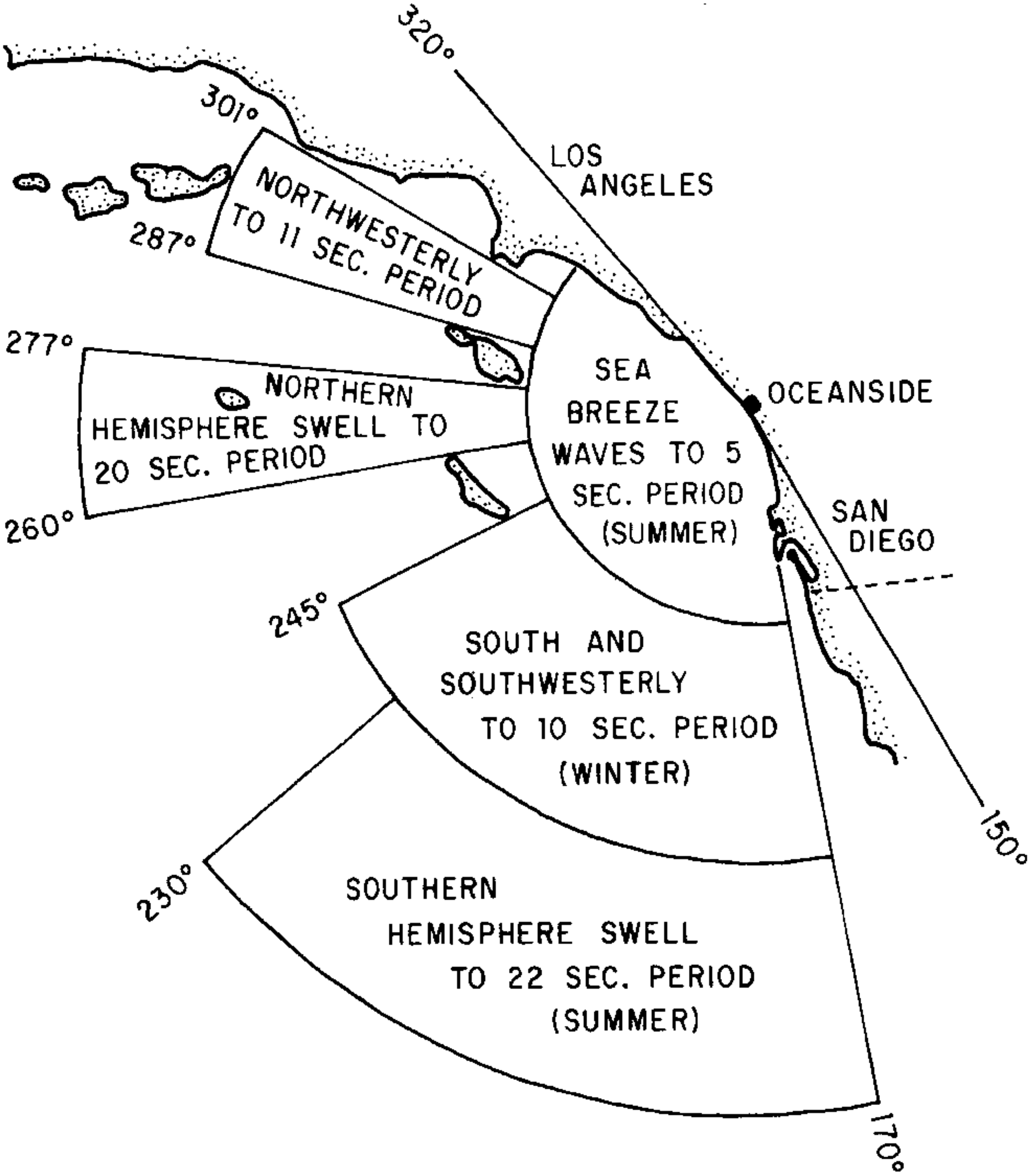


Figure 6.3. Wave exposure chart for Oceanside Harbor, California (from Marine Advisers, 1960).

new direction of dominant energy was determined. The degree of island sheltering on waves results from how effectively the island blocks the directional spread and how these waves are refracted and diffracted in the vicinity of the island.

Once the amount of open ocean wave energy has been corrected for island sheltering the wave types that pass the islands must be refracted to shore in order to determine the direction and intensity of wave energy at the shoreline. The resultant wave climate at the breaker point can then be used to determine the longshore component of wave energy and the longshore sand transport regime.

6.3 Budget of Sediment

Oceanside beach and harbor are located in the central part of a littoral cell extending from Dana Point in Orange County to Scripps-La Jolla Submarine Canyon (Figure 6.1). The Oceanside littoral cell includes a 66 mile (106 km) segment of coastline that has discrete sources, transport paths, and sink for the sediment involved in littoral transport. Consequently some consideration must be given to the entire littoral cell when attempting to understand the beach erosion problem at Oceanside.

Most of the sediment that forms the sand beach of the Oceanside littoral cell comes from the streams that enter the ocean along this coastal segment. Other contributions come from cliff erosion, downcoast longshore transport into the littoral cell, and artificial sources such as the dredging of Oceanside Harbor. The major streams contributing to this cell include San Juan Creek in Orange County, the Santa Margarita, San Luis Rey, San Dieguito Rivers, and the San Onofre, Las Pulgas, Buena Vista, Agua Hedionda, San Marcos, Escondido and Los Penasquitos Creeks.

Since all of these streams are ephemeral and only flow into the ocean under flood conditions calculation of the sediment yield to the coast on an annual basis is difficult.

This region has a semi-arid climate with most of the precipitation coming from winter storms that originate in the north Pacific Ocean. The larger drainage basins contributing to this littoral cell (Santa Margarita, San Luis Rey, and San Dieguito Rivers) drain the western slopes of the coastal mountains to higher elevations where precipitation is greater. Smaller streams contributing to the littoral cell drain only the foothills and coastal terraces.

The sediment contributions from these streams have not been accurately determined so that the total sand input can only be estimated from empirical sediment yield relationships and long-term erosion rates. Langbein and Schumm (1958) show that the annual sediment yield of a stream is related to annual effective precipitation and size of the drainage basin. Thus, an estimate of the sediment contribution from a drainage basin can be made with knowledge of these two factors. Other estimates can be determined from the world-wide flux of sediment into the ocean (Inman and Brush, 1973) and long-term erosion rates in the United States (Gilluly, et al, 1970).

Table 6A and Figure 6.4 list the principal rivers contributing to the Oceanside littoral cell and the obstructed and unobstructed areas of their drainage basins. Using this information estimates can be made of the total sediment contribution to the littoral cell under natural conditions and with the effect of dams blocking part of the drainage basin. The average annual precipitation over the coastal area and western slopes of the mountains is between 10 and 12 inches (254-305 mm). The precipitation

Table 6A. Major drainage basins contributing to the Oceanside littoral cell.

NAME OF DRAINAGE BASIN	NUMBER OF DAMS	DRAINAGE AREA SQ MILES	DRAINAGE AREA BLOCKED	PERCENTAGE OF DRAINAGE BLOCKED BY DAMS
San Juan Creek	0	274	0	0.0
San Onofre Creek	0	350	0	0.0
Santa Margarita River	3	741	319	43.0
San Luis Rey River	2	557	206	36.9
San Dieguito River	4	327	304	93.2
TOTAL	9	2249	829	36.9

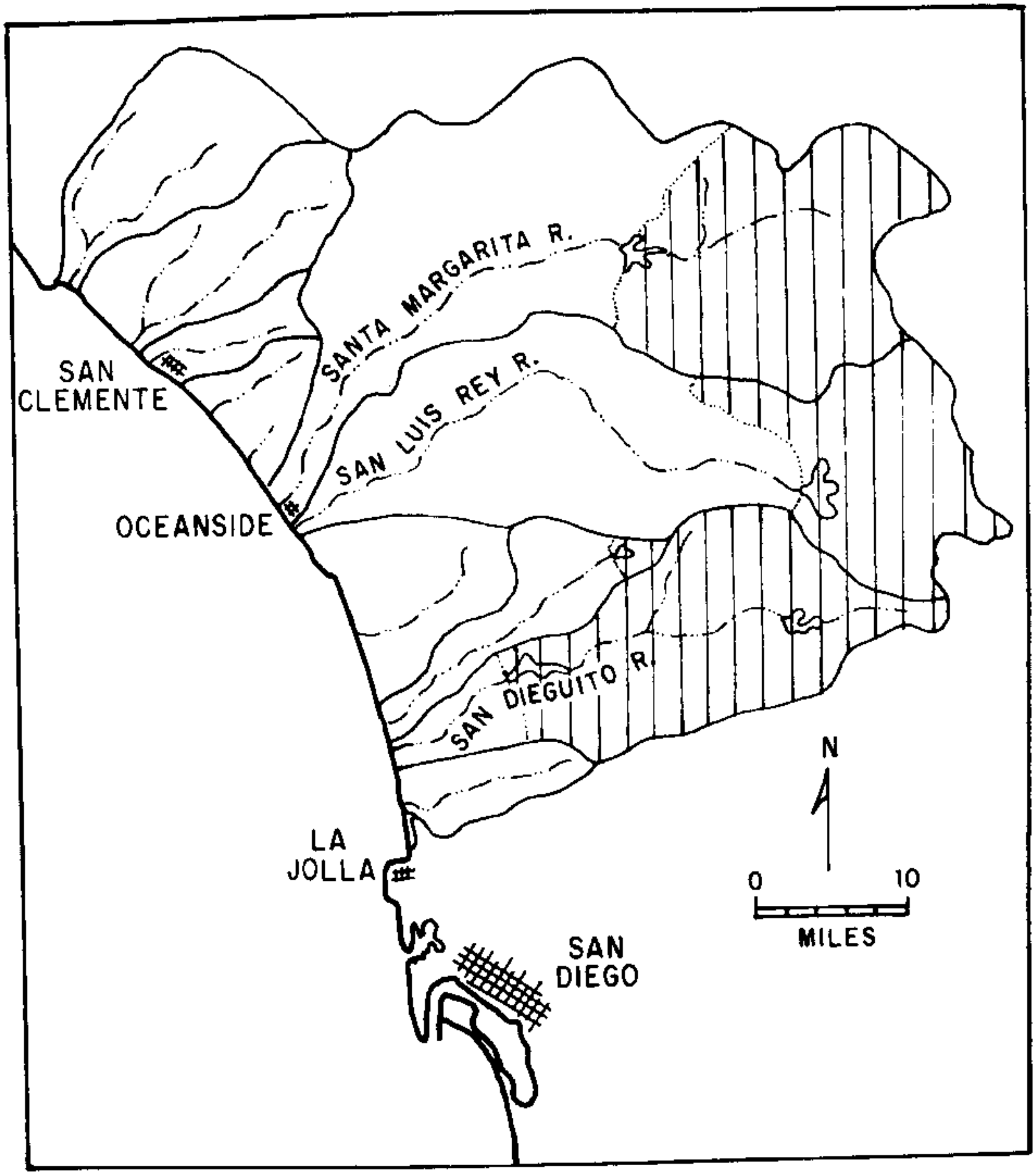


Figure 6.4. Drainage basins contributing to the Oceanside littoral cell show the blockage by dams as of 1969 (from State of California, 1969).

data together with the Langbein and Schumm (1958) relation for sediment yield provide an estimate for the sediment input to the Oceanside littoral cell from the five major drainage basins of approximately 600,000 yds^3/yr (4.5 x 10^5 m^3/yr) Chamberlain (1960). Estimates based on the flux of sediment into the ocean and long term erosion rates give sediment yields of 680,000 yds^3/yr (5.2 x 10^5 m^3/yr) and 460,000 yds^3/yr (3.5 x 10^5 m^3/yr) respectively. These estimates of sediment yield are reasonably close and have a mean value of 580,000 yds^3/yr (4.44 x 10^5 m^3/yr). The total sediment yield to the Oceanside littoral cell was also estimated by the California Department of Water Resources as 496,000 yds^3/yr (3.97 x 10^5 m^3/yr) (State of California, 1969). From all presently available information it appears that the sediment yield to the Oceanside littoral cell under natural conditions was approximately 500,000 yds^3/yr (3.82 x 10^5 m^3/yr).

Table 6A shows the number of dams present on streams contributing to the Oceanside littoral cell and the area of drainage basin they block. Assuming that the dams act as a total barrier to sediment produced upstream and that they provide efficient flood control; then it appears that about 37 percent of the natural annual sediment supply does not presently reach the coast. This reduces the naturally available sediment supply to about 315,000 yds^3/yr (2.4 x 10^5 m^3/yr).

At the coast most of these rivers terminate at a coastal lagoon which also entraps some sediment depending upon the state of discharge of the river. High discharge levels probably result in greater quantities of sediment being carried through the lagoon into the ocean; whereas, lower discharges involve greater sediment entrapment by the lagoon. Consequently, the actual sediment input into the Oceanside littoral cell is probably somewhat less than 300,000 yds^3/yr (2.3 x 10^5 m^3/yr).

Estimates of longshore transport rates through the Oceanside littoral cell have been made using available wave data and from erosion-accretion rates at Oceanside Harbor. The longshore transport rate of sand at Oceanside Harbor site was calculated from available wave data and found to be a net longshore transport to the south of 215,000 yds^3/yr (1.6×10^5 m^3/yr) (Marine Advisers, 1960). After the construction of Oceanside Harbor the accretion rate of sand in the harbor entrance was measured along with the associated loss of sand from Oceanside Beach to the south of the harbor entrance. Between 1942 and 1969 the entrance channel was dredged eleven times with an average of 250,000 yds^3/yr (1.9×10^5 m^3/yr) being moved. During that period of time the entrance was modified with the construction of a breakwater, two jetties and two groins. However, dredging has been needed on an annual basis since 1965 (Corps of Engineers, 1970). Recent dredging since Oceanside Harbor was completed indicates that the rate of sand entrapment has increased at the entrance complex to an average of 360,000 yds^3/yr (2.75×10^5 m^3/yr) (San Diego Regional Water Quality Control Board Meeting, 15 December 1970). Five miles south of Oceanside Harbor a small jetty at the entrance to Agua Hedionda Lagoon traps sand at a rate of 160,000 yds^3/yr (1.22×10^5 m^3/yr) based upon dredging records (Ritter, 1971). Thus, it appears that the net longshore transport through the Oceanside littoral cell is about 250,000 yds^3/yr (1.91×10^5 m^3/yr) to the south.

The south end of the Oceanside littoral cell is defined by the Scripps-La Jolla Submarine Canyon whose heads intercept the longshore transport and direct it seaward through the canyon to the deeper waters of the San Diego Trough. Chamberlain (1960) measured the rate of sand influx into the head of Scripps Canyon as being 260,000 yds^3/yr (2.0×10^5 m^3/yr).

Table 6B lists the sediment budget for the Oceanside littoral cell. It appears that the sediment budget for the cell is nearly in balance, with the present input being only slightly less than the annual longshore transport rate and loss from the cell. This inbalance of sand supply to demand by the available wave energy is already apparent from long term measurement of sand level on the beaches of the littoral cell. Figure 6.5 shows repeated surveys of a rangeline on Torrey Pines Beach during the past twelve years which indicate the progressively lower sand levels each winter during this time. The continuation of dry weather conditions in this region, urbanization of the coastal drainage basins, and construction of flood control structures combine to further reduce sediment supply to the cell so that this imbalance in the sediment budget will become greater. Eventually when the imbalance of input to loss becomes extreme the depletion of sand will be apparent on all the beaches of the littoral cell.

6.4 Specific Problems

The specific problem in the Oceanside littoral cell is the persistent and continuing accretion of sand in the harbor entrance and accompanying erosion of sand from Oceanside Beach immediately to the south. These problems are obviously interrelated and any solution will have to address both aspects of the problem. Before harbor construction at Oceanside there was a wide sand beach typical of most beaches in the littoral cell. However, immediately following the initial harbor construction, problems with sand accretion and beach erosion began to develop.

Table 6B. Sediment budget for Oceanside littoral cell

TOTAL SEDIMENT SUPPLY TO CELL YDS^3/yr	NET LONGSHORE TRANSPORT SOUTH YDS^3/yr	TOTAL SEDIMENT LOSS FROM CELL YDS^3/yr
250,000 *	250,000-300,000	260,000

* Sediment supply to coast with present dams trapping sediment in drainage basin and assuming about 50,000 yds^3/yr entrapment in coastal lagoons.

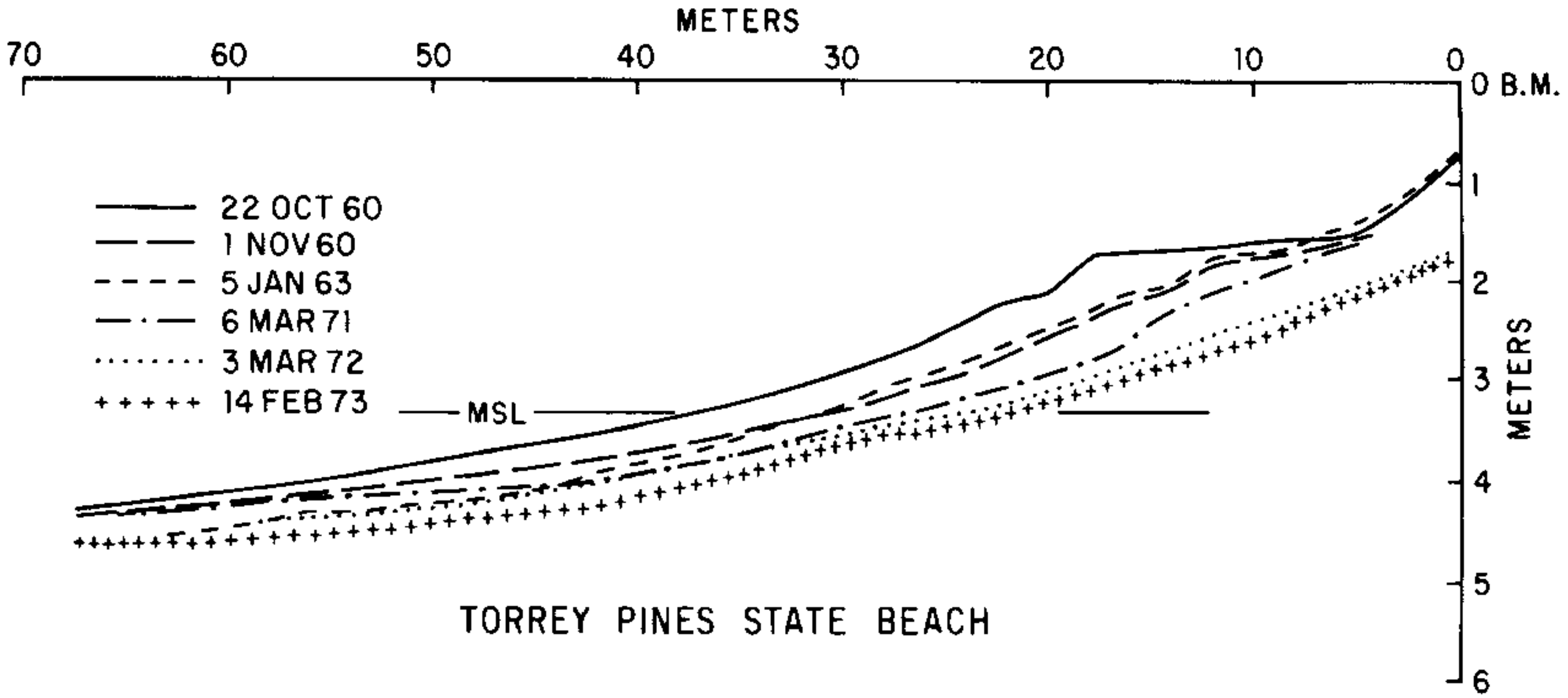


Figure 6.5. Beach profiles measured at Torrey Pines State Reserve Beach. Elevations and distances are measured relative to a monument established on beach backshore. Profiles measured from 1960 to 1973 show the progressive decrease in sand level on the beach.

In 1942 the Del Mar Boat Basin was constructed by the Department of the Navy as a war time measure to support the amphibious training program at Camp Pendleton. Initially the entrance was protected by jetties in an arrowhead configuration with the northerly jetty overlapping the southerly one. During the first ten years of its existence about 2,500,000 yds^3 (1.91 x 10^6 m^3) of sand accumulated in the vicinity of the entrance channel and closed the entrance channel. Consequently, Oceanside Beach receeded and experienced a loss of 2,700,000 yds^3 (2.06 x 10^6 m^3) as shown by U. S. Army Corps of Engineers surveys.

The Navy extended the north jetty to its present length in 1958-59 and dredged sand from the channel which was deposited on the eroded beach. However, this sand replenishment lasted only a short time and the beach continued to receed (Figure 6.6). Dredging was repeated in 1961 and the sand was placed on the depleted section of Oceanside Beach. This time a groin was constructed at the site of the present south harbor jetty in an attempt to control the sand loss from the beach.

Oceanside small craft harbor was completed in February 1963 with a total of 3,000,000 yds^3 (2.29 x 10^6 m^3) of sand and cobbles being distributed along Oceanside Beach to rebuild it to its former width. However, the harbor entrance has continued to trap sand and now requires dredging on a 12 to 18 month schedule. The modifications to the harbor entrance have caused it to trap greater amounts of sand which resulted in the erosion of Oceanside Beach to be extended further south along the coast. The continuing beach erosion has prompted the construction of a short groin at the San Luis Rey flood control channel by the City of Oceanside and several revetments by private owners to protect their property. Surveys made by the U. S. Army Corps of Engineers during the

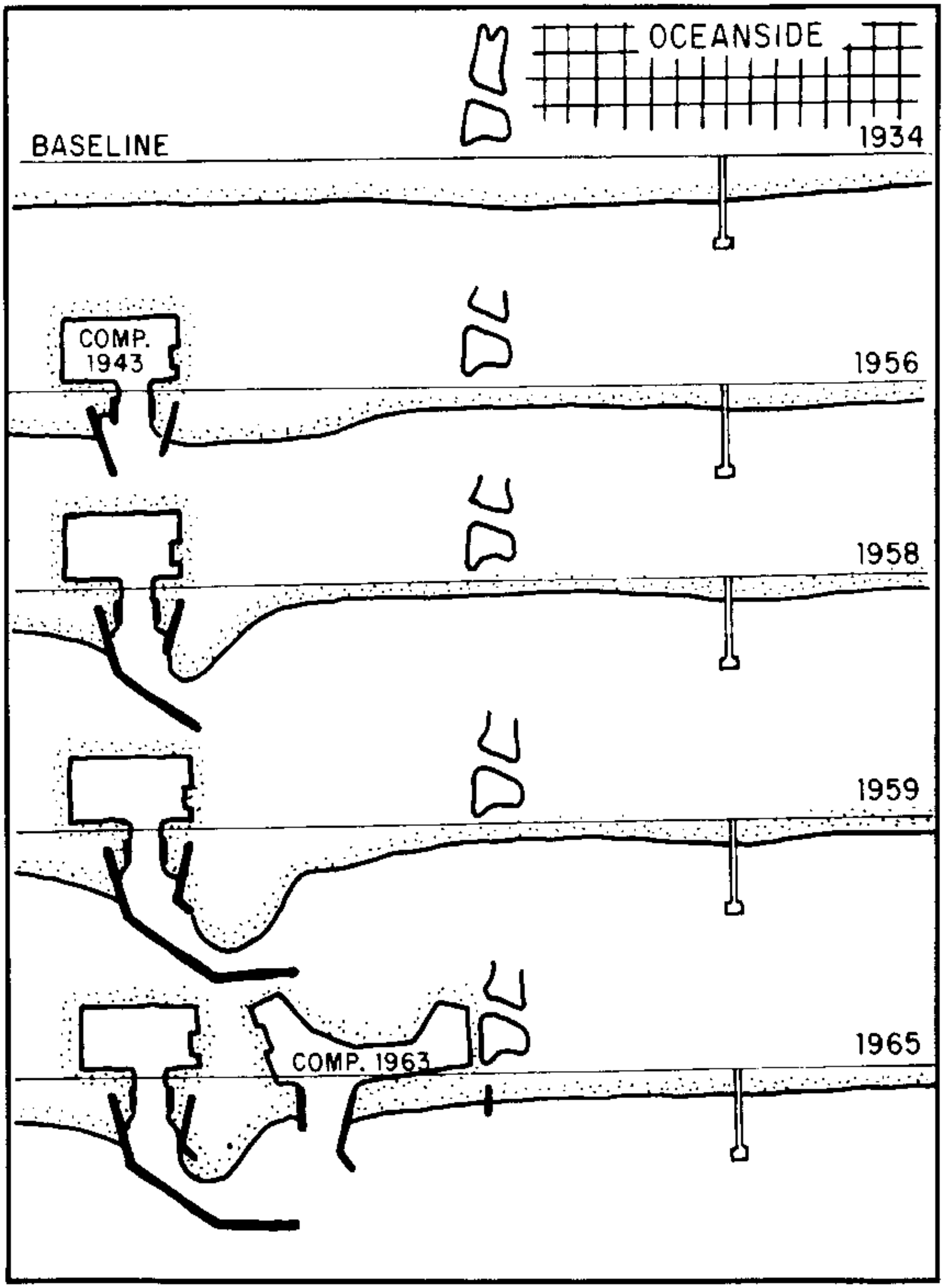


Figure 6.6. Progressive modification of shoreline at Oceanside, California between 1934 and 1965.

1960's clearly show widening of Oceanside Beach after placement of dredged sand and the subsequent retreat of the beach during the periods between dredgings (Corps of Engineers, 1970). At present Oceanside Beach is depleted of sand during much of the year so that cobbles placed on the beach are exposed offering the only protection against the waves (Figure 6.7).

6.5 Recommendations

The beach erosion problem at Oceanside can be directly attributed to the interception of the longshore transport through the littoral cell by the Oceanside Harbor entrance channel. The impoundment of this sand in the entrance channel deprives a downcoast section of beach of its sand source so that it recedes as the available sand is transported downcoast. Since the beach erosion problem at Oceanside is related to Oceanside harbor any workable solution will have to consider the entrance to the harbor and its modification of the natural system.

The Oceanside problem can be considered in terms of the remedial actions discussed in Section 4.4 in order to review recommendations for this site. Before the construction of the Del Mar Boat Basin, Oceanside Harbor complex the beach in this area was sufficiently wide to provide adequate protection to the shoreline during the most severe wave conditions. Interception of sand being transported along the shore by the entrance channel creates the interrelated problems of channel shoaling and downcoast erosion which must be treated in any remedial actions. The present approach which has been applied since the original design of the harbor is an attempt to modify the driving forces with large structures. Initial structures at Oceanside were two short jetties to intercept sand and

Figure 6.7. South Oceanside Beach showing total loss of sand from beach face due to upcoast entrapment at Oceanside Harbor.

define an entrance channel. These jetties were quickly inundated by the longshore transport of sand and further modifications were made to the entrance channel structure. The entrance channel structure now consists of large breakwaters, interior jetties, and groins in an attempt to overcome the problem by protecting the entrance from waves.

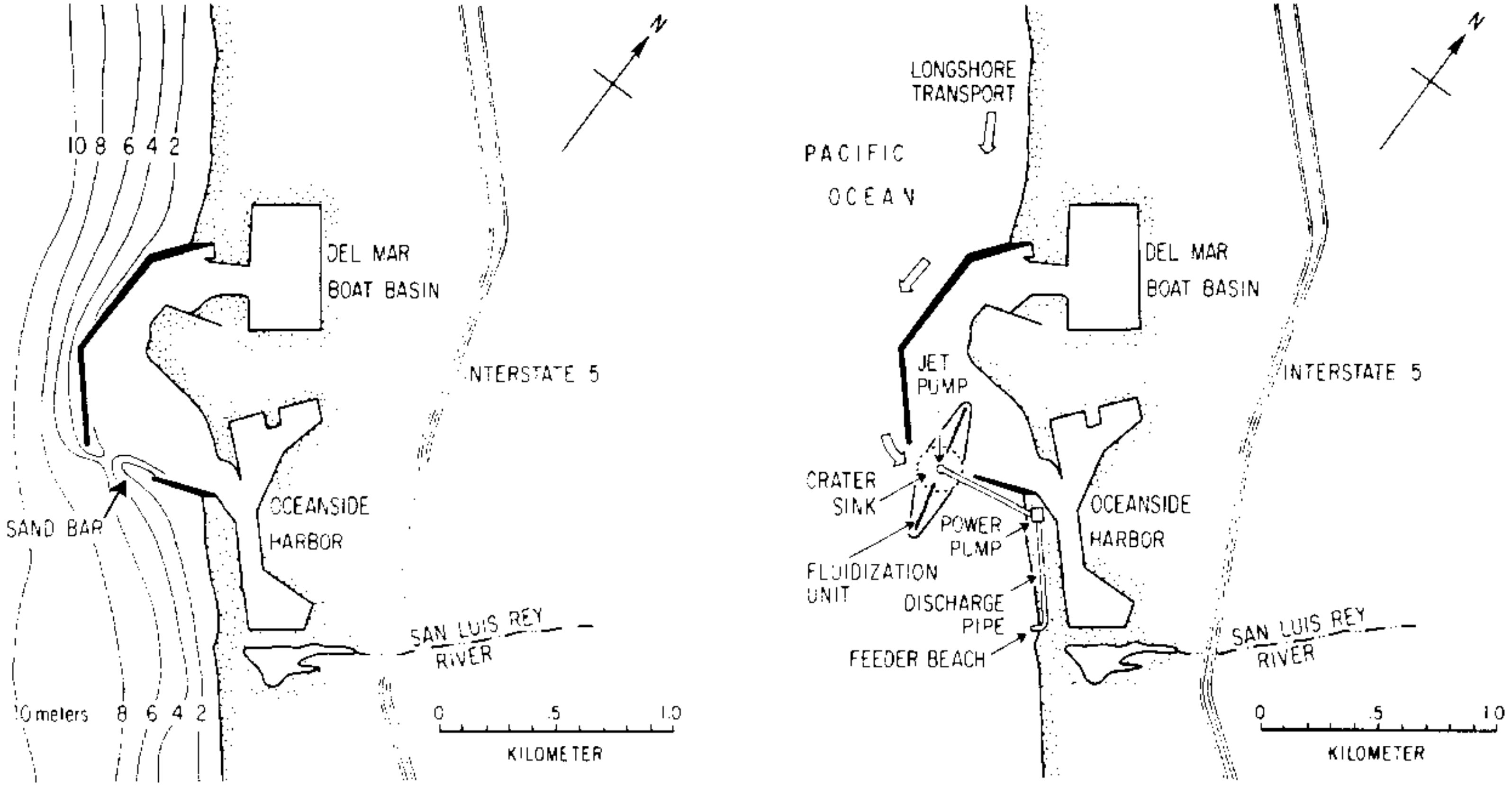
Sand continues to enter the entrance channel circumventing these large structures so that it must be removed by periodic dredging. Since the present entrance channel is not dredged frequently enough to provide continuity to the longshore transport, beach erosion occurs downcoast. In an attempt to find a solution to these problems additional coastal structures have been suggested for Oceanside, including offshore breakwaters, larger jetties and more groins. It is doubtful that this extension of the present approach will produce the desired result and a new solution should be sought.

An alternative to continuing the presently inadequate and expensive procedure for maintaining Oceanside Harbor would be to abandon it for navigation. This would permit the longshore transport of sand to continue naturally along this coastline segment. The present harbor could be converted into a lagoon for small sail boats and swimming. Although this alternative seems untenable in view of the investment in the harbor to date, it is perhaps practical when considered in terms of what will be required to continue the present dredge maintenance program in the future.

If the sand entrapment by the harbor entrance increases or the dredging schedule is lengthened, the beach erosion problem is likely to extend downcoast. This will undoubtedly result in the continued use of revetment to armor the shore and limit the destructive effect of this erosion. Eventually beach erosion could extend over several miles of coastline and revetment would replace the natural sand beach for stabilizing the shoreline. Loss of this valuable recreational beach should be balanced against the value of maintaining the harbor entrance with the present approach to remedial action.

Perhaps the best approach to a remedial action for Oceanside Harbor is to find a solution which imitates the natural sand transport process at the entrance. This can be achieved by continuously bypassing sand past the entrance channel at the natural rate of supply. Thus, the entrance channel will not shoal and the downcoast beach will receive its required sand input to prevent further erosion. A continuous bypassing system would essentially reestablish the natural longshore transport that existed before construction of the harbor entrance. Thus, with such a system in operation there would not be any accumulation in the harbor entrance to cause boating hazards and the downcoast beach would be continuously replenished with sand. Continuous sand bypassing can be achieved using a conventional floating dredge similar to the system used at Santa Barbara; however, such deployment of conventional dredges is expensive. A better solution to the problem would be the development and installation of an efficient fixed sand bypassing system such as the crater-sink system proposed by Inman and Harris (1970). This system does not require a sheltered impoundment area as is needed by a conventional dredge, but rather collects sand in a submarine crater where it is moved downcoast by a pump submerged at the bottom of the crater.

Figure 6.8 shows a crater-sink sand bypassing installation that could be used at Oceanside Harbor in which the sand is collected in a depression at the harbor entrance and then pumped south to a feeder beach at Oceanside. The development and installation costs for this system may be higher than one time dredging costs, but the continuing maintenance of the system would be relatively low. In any case, the development costs of this system at Oceanside would be considerably less than the construction of additional structures in the entrance channel.



OCEANSIDE HARBOR, CALIFORNIA 1971

PROPOSED MODIFICATION USING A CRATER-SINK AND FLUIDIZATION SYSTEM

Figure 6.8. Application of crater-sink sand bypassing system to Oceanside Harbor, California.

7. OXNARD SHORES

7.1 Description of the Area

This area of concern is the segment of Ventura County coastline between the cities of Ventura and Port Hueneme which includes the seaside communities of Oxnard Shores and Oxnard Beach. The beaches along this shoreline have been undergoing serious erosion which has resulted in significant retreat of the shoreline at Oxnard Shores. This shoreline retreat has consumed all of the set-back dedicated for shore front lots and has caused some loss of property in the community.

Oxnard Shores is located on a low-lying sandy coastal plain at the east end of the Santa Barbara Channel. The coastal plain is approximately 15 miles (24 km) wide at its widest point and varies in elevation from sea level to nearly 200 feet (61 m) at its eastern edge. This low lying coastal plain appears to have been developed from deposition by the rivers entering the ocean in this area and from littoral sand being blown onshore as coastal sand dunes. The community of Oxnard Shores was built in the central part of this dune area. At the north end of the Oxnard plain the Santa Clara and Ventura Rivers enter the ocean near the city of Ventura both of which are significant sources of sediment to this section of coastline. West of the City of Ventura the coast is typified by a narrow, elevated terrace bordering the coastal mountains.

The shelf area off the Oxnard plain is a northwest-southeast trending topographic feature approximately 24 miles (40 km) long and up to 15 miles (24 km) wide. Bathymetry of the shelf varies with five major features being defined; the Ventura Shoal, the Pitas Reentrant, the Montalvo Trough, the Montalvo Ridge, and Hueneme and Mugu Submarine Canyons (Figure 7.1). Directly west of the Oxnard shelf is the Santa Barbara Basin which

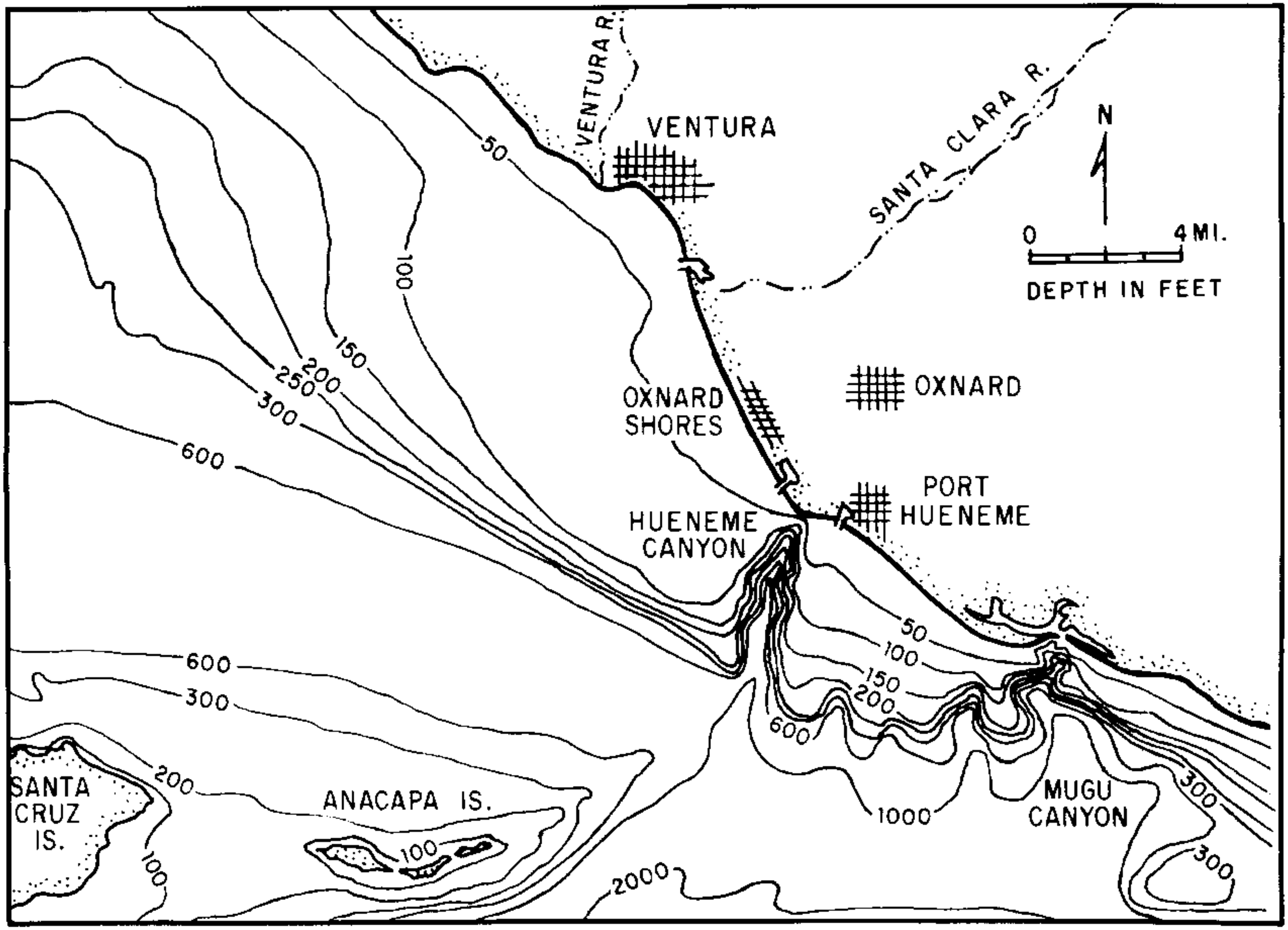


Figure 7.1. Bathymetry in vicinity of Oxnard Shores, California (adopted from Intersea Research Corp., 1973).

lies between the mainland and San Miguel, Santa Rosa, Santa Cruz, and Anacapa Islands to the south. The floor of the Santa Barbara Basin lies at a depth of over 2000 feet (610 m).

The shoreline from Point Conception to Hueneme Submarine Canyon is a sand beach except for short sections of rocky shoreline located at small headlands. The beach from Ventura to Hueneme Submarine Canyon varies from coarse-grained to fine-grained sand with the grain size reflecting the input from the Santa Clara River and the southerly longshore transport past Oxnard Shores. Figure 7.2 shows the median grain size of sand samples from the beach face along the Ventura County shore. Note the abrupt increase in median grain size at the Santa Clara River which is reflected in all samples between the river and Hueneme Submarine Canyon. South of the submarine canyon the beach sand returns to being fine-grained similar to that at Ventura. Samples collected at Oxnard shores in 1975 are significantly coarser than in 1967 which may be explained by an additional influx of coarse material from the Santa Clara flood debris of 1969.

Before the Ventura County shoreline communities were developed the backshore area was occupied by a coastal dune system. Strong winds blowing down the Santa Barbara Channel from the west transported sand from the beach inland to form dunes. This natural process provided a minor sink for some of the sand being transported along the coast. Only a small segment of the original dune field remains as a few vegetated dunes at McGrath State Beach. However, the effect of the sand blowing inland is presently evident at the Oxnard Shores development with the continual drifting of sand against the houses and in the streets of the community (Figure 7.3).

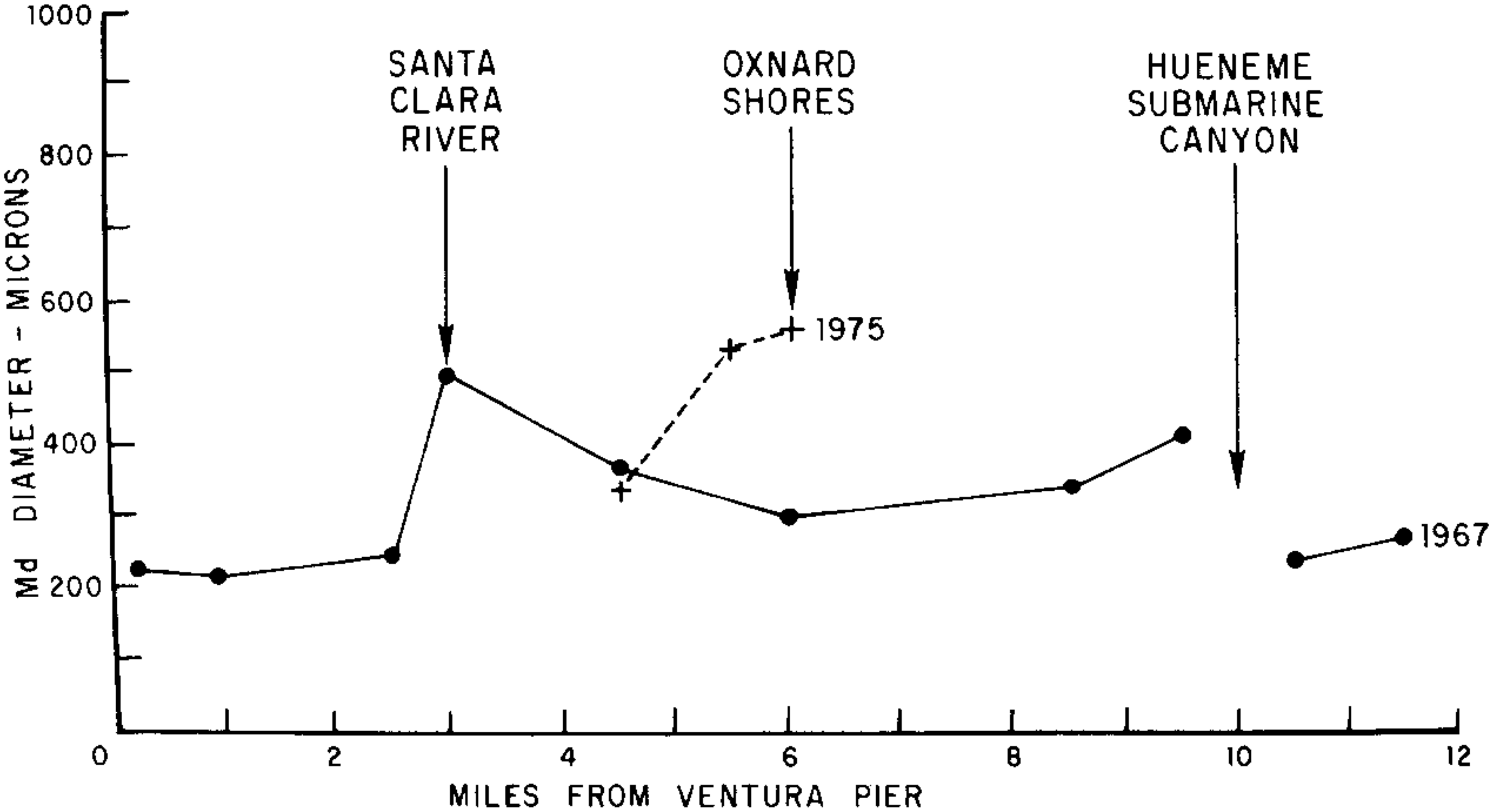


Figure 7.2. Median grain size of beach sand along Ventura County shoreline from samples collected in 1967. Note the increase in grain size at the Santa Clara River mouth and decrease in size at Hueneme Submarine Canyon.

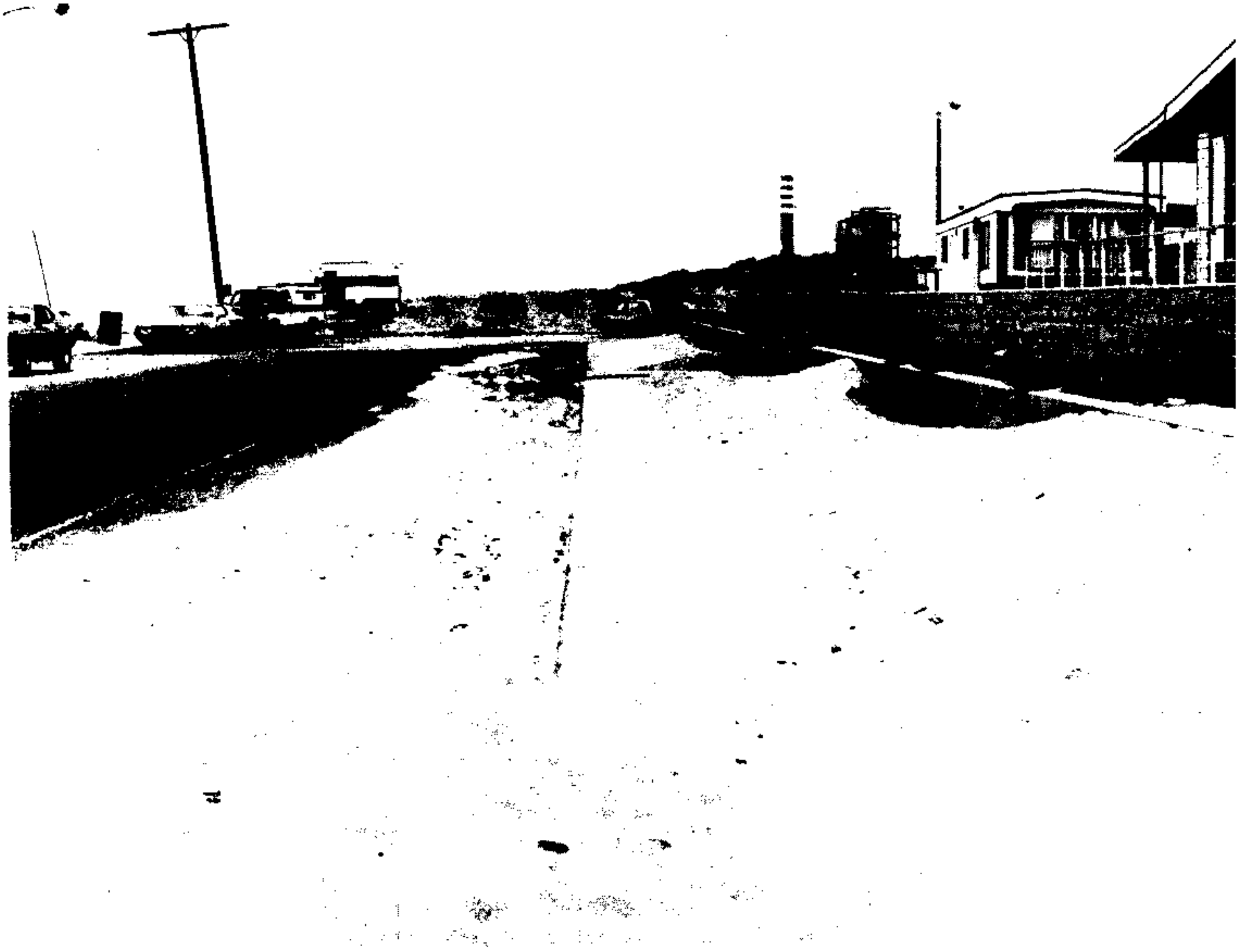


Figure 7.3. Sand being blown inland from beach at Oxnard Shores, California which was developed at the site of a former coastal dune field.

7.2 Wave Climate

The Oxnard Shores area lies at the east end of the Santa Barbara Channel so that most of the wave energy comes to the area from the west. A summary of the deep water wave energy has been made for a station outside the Channel Islands (National Marine Consultants, 1960). In the open ocean most of the wave energy comes from the northwest as locally generated waves and swell generated in the North Pacific. Northern hemisphere swell is most common during the winter months because it is generated by the strong winds associated with the seasonal cyclonic storms in the North Pacific Ocean. Swell from southerly directions can be expected 30-50% of the time from April to September (Intersea Research Corp., 1973). These waves are generated by storms in the South Pacific Ocean or by hurricanes located off the coast of Mexico. The swell generated by distant sources is of relatively long period whereas the locally generated sea is of shorter period.

Once the sea and swell enter the Santa Barbara Channel they are influenced by the sheltering effects of the islands and by refraction in the shoal areas near the islands and on the mainland shelf. Inman (1950) summarized the sheltering by the islands and mainland points in Figure 7.4 which shows the characteristic waves for the Point Mugu area. As can be seen, the greatest exposure to waves from the open ocean of the Oxnard Shores area is from the entrance to the Santa Barbara Channel directly to the west. Some wave energy also reaches the area from the south and west through small windows between the southern islands and banks. However, these waves are not as significant to the Oxnard Shores area as they are to the southwest facing beaches south of Hueneme Submarine Canyon.

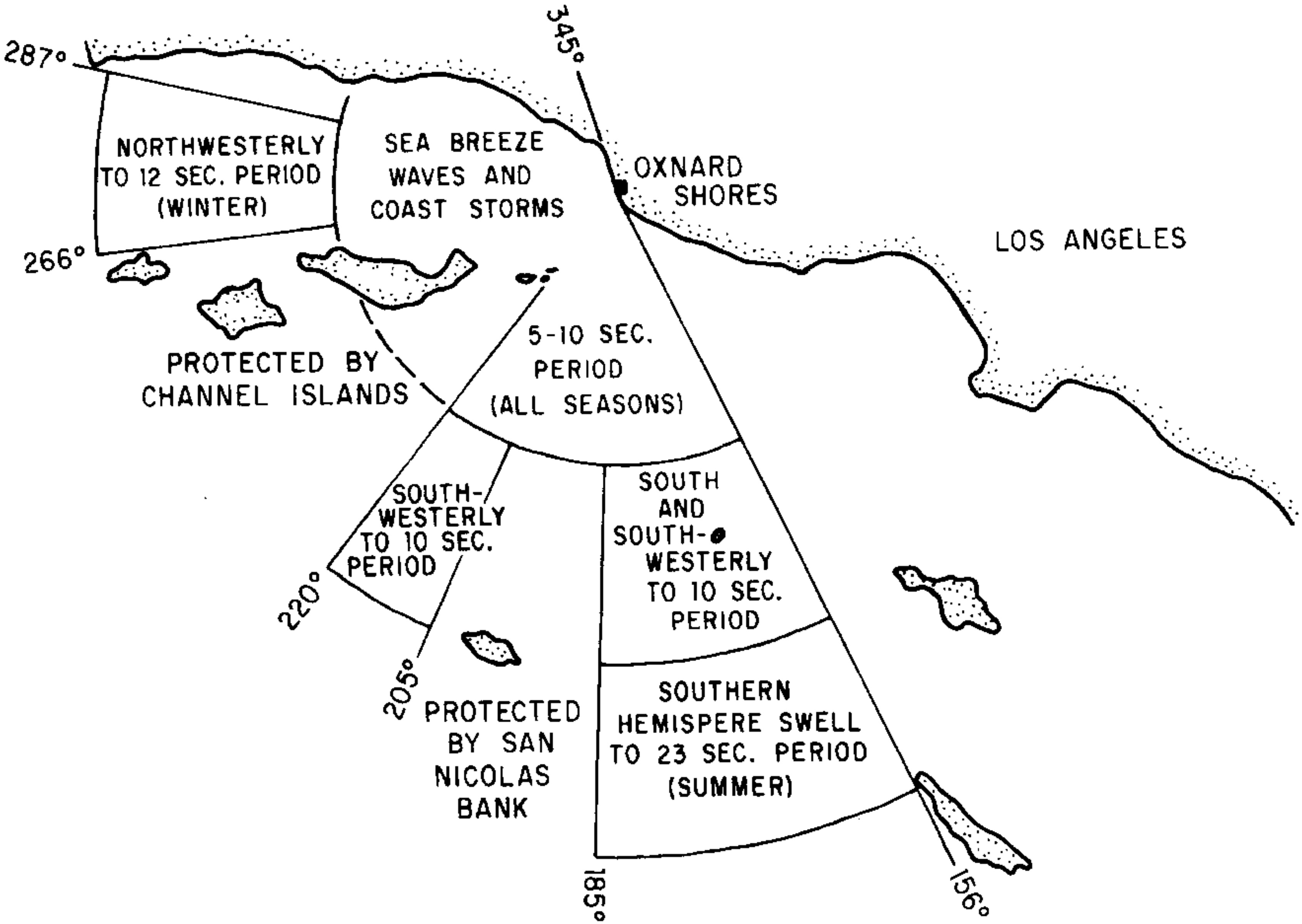


Figure 7.4. Wave characteristics and island sheltering zones for Oxnard Shores, California (from Inman, 1950).

Short period waves that are generated between the Channel Islands and the mainland can approach the Oxnard Shores area from any direction ranging from southeast to northwest. These waves are caused by storm fronts passing through the area, local storms, and localized wind systems. Aside from these local waves almost all the wave energy incident to the Oxnard Shores coastline is from the northwest through the open water of the Santa Barbara Channel.

7.3 Budget of Sediment

The Oxnard Shores shoreline is located near the southern end of the Santa Barbara littoral cell which extends from Pt. Conception to Hueneme Submarine Canyon (Inman and Frautschy, 1966). Sediment is contributed from littoral transport around Pt. Conception, coastal streams between Pt. Conception and Ventura, and the large drainage areas of the Ventura and Santa Clara Rivers. Estimates of the total amount of sediment contributed to this segment of coastline annually have been made using the previously discussed sediment yield relationship and available sediment discharge data.

Table 7A lists the major drainage systems contributing to the Santa Barbara littoral cell and the areas of the drainage basin blocked and unblocked by dams. Prior to 1948 there were no sediment restricting structures on either the Ventura or Santa Clara River drainage basins. However, since 1948 the total drainage areas of these basins have been reduced by about one-third with the construction of the Matilija, Casitas, and Santa Felicia dams.

Bowen and Inman (1966) estimate that approximately 100,000 yds^3/yr (7.65×10^4 m^3/yr) of sand enters the Santa Barbara littoral cell

Table 7A. Major drainage basin contributing to the Santa Barbara littoral cell.

NAME OF DRAINAGE BASIN	NUMBER OF DAMS	DRAINAGE AREA SQ MILES	DRAINAGE AREA BLOCKED SQ MILES	PERCENTAGE OF DRAINAGE AREA BLOCKED BY DAMS
Santa Barbara Coastal Group	3	about 421	2	0.5
Ventura River	7	226	157	69.6
Santa Clara River	3	1605	448	27.8
TOTAL	13	2252	605	26.9

by longshore transport around Pt. Conception. Contributions from the coastal streams draining the coastal slopes of the Santa Ynez Mountains from Pt. Conception to Ventura total about 466,000 yds^3/yr (3.56 x 10^5 m^3/yr) from estimates using the sediment yield relationship of Langbein and Schumm (1958). Using this method the sediment yield from the unblocked portions of the Ventura River and Santa Clara River drainage basins are 170,000 yds^3/yr (1.3 x 10^5 m^3/yr) and 493,000 yds^3/yr (3.77 x 10^5 m^3/yr) respectively. These values are comparable to the sand yields of 100,000 yds^3/yr (7.6 x 10^4 m^3/yr) for the Ventura River and 600,000 yds^3/yr (4.59 x 10^5m^3/yr) for the Santa Clara River estimated by the U. S. Army Corps of Engineers (Corps of Engineers, 1970). All of these drainage systems are ephemeral streams that flow only during the wet season. Their discharge varies considerably from year to year relative to the amount of precipitation with occasional floods of considerable magnitude that bring large amounts of sediment to the coastline.

In January and February of 1969 such a flood took place on the Santa Clara River with the highest river flow rates ever recorded on that river. The 2 month total sediment discharge for the 1969 flood was 44 x 10^6 yds^3 (34 x 10^6 m^3) of sand at the mouth of the river (Corps of Engineers, 1970). This deposition formed a delta at the river mouth which extended 2000 feet (610 m) seaward of the shoreline. The sand contributed from this flood has been estimated to be equivalent to a 22 year annual contribution from the river.

The total sediment input to the Santa Barbara littoral cell at Oxnard Shores is estimated by summing all the upcoast contributions. Based on the sediment yields presented above it appears that the total sediment supply to the cell at Oxnard Shores is approximately 1,230,000 yds^3/yr (9.41 x 10^5 m^3/yr).

The rate at which this sand is being transported through the cell can be estimated from accretion rates at sand entrapment structures located in the vicinity of Oxnard Shores. Three miles south of Oxnard Shores is the Channel Islands Harbor sand trap which is a detached breakwater and jetty designed to impound sand and prevent its loss down Hueneme Submarine Canyon. Periodically the sand is dredged from the sand trap and bypassed past the Channel Islands Harbor and Port Hueneme entrance channels to replenish Ormond Beach and Mugu Spit. Since its construction in 1960 the sand trap has been dredged on a biannual basis with the removal of about 2.5 x 10^6 yds^3/yr (1.91 x 10^6 m^3/yr) each time (Corps of Engineers, 1970). Thus, it appears that the net longshore transport rate at Oxnard Shores is about 1.25 x 10^6 yds^3/yr (9.46 x 10^5 m^3/yr) to the south.

Prior to the construction of Channel Islands Harbor and Port Hueneme sand was transported by the waves along this coastal segment to Point Mugu and Mugu Submarine Canyon. However, construction of the Port Hueneme harbor jetties caused this sand to be diverted offshore and into the head of Hueneme Submarine Canyon. This caused a sand loss down Hueneme Submarine Canyon in excess of 1 x 10^6 yds^3/yr (7.65 x 10^5 m^3/yr) based on the erosion of beaches to the south of the harbor entrance (Corps of Engineers, 1970). This loss is now prevented by the artificial impoundment and by passing of sand at Channel Islands Harbor and Port Hueneme. Once past the harbor complex sand is transported on south to Mugu Submarine Canyon and diverted offshore to its ultimate sink in the Santa Monica Basin. Annual loss from the cell now appears to be greater than 1 x 10^6 yds^3/yr (7.65 x 10^5 m^3/yr) of sand that eventually goes down Mugu Submarine Canyon.

Table 7B lists the quantities of sand involved in the sediment budget for the Oxnard Shores segment of the Santa Barbara littoral cell. As can be seen the quantitites of sand being supplied to the cell almost exactly balance the longshore transport and ultimate losses from the cell. However, in the past before man's intervention into this natural system the unblocked Ventura and Santa Clara drainage basins undoubtedly contributed more sediment than the longshore transport by waves required. The surplus of sediment supplied to this coastal segment was probably responsible for the gradual accretion of the Oxnard coastal plain and supplied the coastal dune field that was formerly present in the area.

7.4 Specific Problem

Although most of the coastal segment included in the Santa Barbara littoral cell has undergone beach erosion at one time or another the most recent area of concern is at the community of Oxnard Shores. Oxnard Shores is one of several beach communities that have been developed along the Ventura County coast in the last twenty years. The Oxnard Shores Development Company began construction of the community in 1959 by grading off the coastal dunes and subdividing the ocean front land into lots for a residential community. At the time of development initial plans provided for a 200 foot set back from the shoreline. However, since that time the shoreline has been in a continual state of regression and has consumed all of the set-back in some places (Figure 7.5).

In December 1969 high waves hit the Ventura County shoreline three times. These waves were from intense storms in the Aleutian Islands which created swell up to 20 feet high which struck the area on 4 - 7 December 1969. On 13 - 16 December 1969 another set of high

Table 7B. Sediment budget for Santa Barbara littoral cell at Oxnard Shores, California

TOTAL SEDIMENT SUPPLY TO CELL YDS^3/yr	NET LONGSHORE TRANSPORT (SOUTH) YDS^3/yr	TOTAL SEDIMENT LOSS FROM CELL YDS^3/yr
1,230,000	1,250,000	+ 1,000,000

Figure 7.5. Houses at Oxnard Shores, California located on a progressively eroding beach. Note that house in foreground has been raised on girder substructure to avoid wave damage.

waves caused swash as far as 50 feet inland from the beach front road at Silver Strand Beach. The third set of high waves came on 19 December 1969 as 10 foot high, 8 second period waves from the west. At high tide Mandalay Beach Road in Oxnard Shores was under a foot of water and considerable damage was done to the shore front homes. Private property damage and loss of beach amounted to hundreds of thousands of dollars during the three day period of high waves. Since that time the beach has never recovered and in some places continues to retreat so that property owners have had to construct protective structures in front of their houses (Figure 7.6).

The basic problem at Oxnard Shores lies in the lack of knowledge about the long term effects to the shoreline caused by man's alteration of the sediment budget for this coastline segment. Shoreline surveys of the coast between the Santa Clara River and Point Hueneme since the 1850's indicate that the shoreline moved seaward until the late 1950's and then began to retreat. The Oxnard coastal plain has undoubtedly been an accretionary area in recent geologic time since it is the depositional area for sediment brought to the coast by two significant Southern California rivers and receives sand brought along the coast by wave action. Historical records show that floods of the Santa Clara River in 1914 and 1916 produced significant seaward movement of the shoreline in this area (Corps of Engineers, 1961). Also, the presence of a coastal dune field in the Oxnard Shores area suggests an ample supply of sediment to the area. The available information suggests that under natural conditions the budget of sediment for Oxnard Shores had greater input of sediment than the capability for the waves to transport it away from the area. Thus, the Oxnard coastal plain became a local sink for this sediment

Figure 7.6. Foundation of house destroyed by waves at Oxnard Shores, California. Note the placement of revetment in front of next house to south; continued erosion of the beach is causing the revetment to collapse and scatter along the beach.

and the shoreline moved seaward as the sand accumulated.

Starting in 1948 man began to tamper with this natural system by constructing dams on the major rivers. These structures entrap sediment in the drainage basin and prevent the river from flooding so that sediment below the dams is not carried to the coast. The presence of the dams and lack of runoff during the dry years has decreased the sediment yield of these streams to perhaps only one-half their natural contribution. Consequently, the sediment budget is now closer to being in exact balance with the available wave energy at Oxnard Shores.

Since the budget of sediment is now in close balance at Oxnard Shores, the sediment that does reach the coast is just adequate to meet the wave energy demand for longshore transport without any surplus to cause accretion. Thus, when periods of increased longshore wave energy occur, such as waves from distant storms, the additional sand input requirement is from erosion of the beach. This seems to be the present situation at Oxnard Shores where the beach seems to sustain a stable position under normal wave conditions with the present sand influx to the cell, but undergoes erosion with the periodic occurrences of high waves.

7.5 Recommendations

The beach erosion problem at Oxnard Shores is related to man's intervention into the natural sediment supply for this section of coastline. Under natural conditions the Oxnard Shores area was apparently undergoing long-term accretion with some short term fluctuations in shoreline position due to variation in the rates of sediment supply and incident wave energy. Sediment supplied to this area comes from longshore transport by waves, and the Ventura and Santa Clara Rivers. Historically the sediment reaching this area has been accreting to form the Oxnard plain which is composed of relatively recent material. Deposition in this area was from the rivers, and by aeolian processes where the predominantly onshore winds created coastal dunes.

The construction of dams in the contributing drainage basins has reduced the supply of sediment to this section of coast. However, the present rate of sediment influx is sufficient to maintain the shoreline at its present position except during periods of high waves which cause erosion of the beach.

Beach erosion at Oxnard Shores appears to be the result of partial loss of the natural sand source to the littoral cell similar to Imperial Beach. Thus, the potential solutions to the problem are comparable to those suggested for that area and can be considered in terms of the remedial actions presented in Section 4.4.

A remedial action imitating nature would involve augmenting the sand supply to the littoral cell from artificial sources. If this sand were introduced to the littoral cell upcoast from Oxnard Shores it would benefit the eroding area. This supplementing of the natural sand input would have to be done at the proper time and in sufficient quantity to offset the amount being moved downcoast by the waves. This type of remedial action is dependent upon the availability of suitable sand that can be economically placed on the beach. In some cases sand has come from the construction of new marinas and the enlargement of existing harbors. Other potential sources of sand could be from offshore sand accumulations on the shelf or inland sand deposits that could be brought to the coast.

Another possibility is to recycle sand through the littoral cell by trapping it at the downcoast end and then transporting it back upcoast and returned it to the beach. This could be employed at Oxnard Shores where sand is now trapped at Channel Islands Harbor for bypassing to Point Hueneme Beach. Possibly some of this sand could be transported back upcoast to Ventura and recycled past Oxnard Shores. Use of this approach would require planning so that the beaches downcoast from Channel Islands Harbor are not deprived of needed sand.

Remedial actions which attempt to modify the driving forces in the nearshore environment could be employed at Oxnard Shores. These would be offshore structures such as detached breakwaters which reduce the wave energy incident to the problem site. This type of remedial action is site specific and very localized in its effect. A detached breakwater such as the Channel Islands Harbor sand trap absorbs and reflects all the wave energy so that sand transport stops at the beach behind it and a dredge must be used to move sand downcoast. If this type of structure were employed at Oxnard Shores the entrapment of sand at the present problem site would create severe downcoast beach erosion.

Offshore breakwaters can also be designed as partial littoral barriers by constructing them to a height less than that for wave overtopping or by placing gaps between a series of small structures. Such partial detached breakwaters permit some wave energy to reach shore and move sand downcoast at a reduced rate. Possibly a structure could be designed at Oxnard Shores which would reduce the effect of the large storm waves and not stop all longshore transport. However, the tendency is for these types of permanent structures to simply displace the problem downcoast and result in the construction of other structures along the coast.

Another concept in partial breakwaters is the dynamic or tethered float breakwater now under development. This structure consists of an array of tethered floats that interact with each other to dissipate energy as a wave passes through the float field (Seymour and Isaacs, 1974). Although this type of breakwater is now just undergoing prototype tests it could possibly be used to reduce the wave energy incident to Oxnard Shores and protect the beach from erosion under certain conditions.

The use of this type of remedial action has serious disadvantages that are inherent to the construction of large coastal structures which are necessary to modify the wave energy incident to the shoreline. The principal disadvantages are that such structures are expensive to construct and once in place they are virtually impossible to remove. Thus, if a structure is found to be ineffective or even deleterious to the problem site it is a permanent committment and very difficult to reverse.

Remedial actions which attempt to stabilize the shoreline by disrupting longshore transport or armoring the shoreline have been employed at Oxnard Shores and adjacent areas. North of the Santa Clara River at San Buenaventura State Beach a series of six groins were constructed between 1962 and 1967 which have helped stabilize that beach. The use of groins as erosion control structures has not been extended downcoast to the Oxnard Shores area.

Other attempts at shoreline stabilization have been carried out by private landowners at Oxnard Shores. Most of these remedial actions have involved the placement of revetment in front of houses threatened by beach erosion. Figure 7.6 shows two such attempts at private shore protection using pilings and revetment. As can be seen the piling structure failed under wave attack and the house was destroyed. Also it appears that the revetment in front of the next house is being scoured and the rocks are scattering from the face of the structure. These efforts have not been successful and property losses at Oxnard Shores will probably continue under severe wave conditions.

The present use of coastal structures to stabilize the shoreline at Oxnard Shores is ineffective because individually designed structures have been implemented and they do not follow any coherent plan for the area. At present many structures are raised on pilings to prevent wave damage;others are protected behind some type of wall or revetment. These discontinuous revetments and walls are easily breached by wave swash around their ends on adjacent unprotected lots. The only possibility for a workable solution using structures which armor the shoreline would be to coordinate these efforts for the entire Oxnard Shores area.

A continuous seawall or revetment of proper design along the eroding shoreline would stabilize the erosion problem; however, this type of solution could result in loss of the sand beach. The construction of a large revetment wall requires a wide base that occupies much of the sand beach; consequently, at most tidal stages the shoreline is defined by the rocks of the revetment. Since Oxnard Shores is a beach oriented community, a remedial action which sacrifices the sand beach will not be desirable.

Another category of remedial action applicable to Oxnard Shores is that which calls for a complete change in man's use of the shoreline at the problem site. When Oxnard Shores was planned and developed a setback was established for the shoreline lots. Time has proven that this setback distance was inadequate for the beach erosion at Oxnard Shores.

A solution to the beach erosion could be attained by returning to the setback concept and apply it to the present shoreline. This would involve the abandonment of present shoreline structures for a suitable distance inland to allow for future beach erosion. The setback distance could be determined by extrapolation of the most severe erosion rates for a future time period which is related to the life expectancy of potentially endangered structures. The shoreline and backshore area that has been cleared of existing structures would be committed to the beach and its fluctuating position due to natural processes.

This type of solution requires a complete change in shoreline use by man since many existing structures (houses, community buildings, etc.) now in use would have to be removed in order to bring about its implementation. Such a remedial action undoubtedly has many economic and social implications but it is perhaps the most environmentally compatible solution. In this case the remedial action allows the natural process to proceed. This type of remedial action would permit a sand beach that is essentially unaltered in configuration or appearance while those structures which are suitably setback from the shoreline would be safe from damage.

The potential remedial actions which could provide a solution to the beach erosion problem at Oxnard Shores indicate that there are a number of approaches each with its advantages and disadvantages. It is apparent that remedial actions which involve the construction of large structures are going to result in extensive modification of the present sand beach in order to protect the existing structures. Remedial actions which seek to imitate nature or to permit the natural processes to procede unhindered will preserve the beach at the expense of some of the existing structures. These alternatives will have to be considered by those agencies and people involved in the future planning of the Oxnard Shores area. However, caution should be exercised in the use of remedial actions which will extensively modify the natural processes because these solutions tend to either displace the problem to an adjacent area or create other more complicated problems.

8. SANTA CRUZ HARBOR, CALIFORNIA

8.1 Description of the Area

Santa Cruz Harbor is located at the north end of Monterey Bay about 80 miles south of San Francisco. The coastline generally runs east-west and the harbor entrance is located about 0.6 miles (1 km) east of the entrance of the San Lorenzo River and about 1.5 miles (2.4 km) west of the Soquel Point. The resort town of Capitola Beach is about 4 miles (6.4 km) east of the harbor. The coastline is generally of the rocky headland type with steep sandstone and shale cliffs and intermittent sandy beaches. The continental shelf is relatively wide with the hundred fathom isobath being about 10 miles (16 km) offshore (Figure 8.1).

Santa Cruz Beach lies at the mouth of the San Lorenzo River and extends east past the harbor. The eastern end of this beach from the harbor to Black Point is known as Twin Lakes Beach. East of Black Point there is a region of intermittent sea cliffs and cove beaches to the town of Capitola and beyond Capitola the sand beach again resumes along the east shore of Monterey Bay. The beaches in the vicinity of Santa Cruz Harbor are composed of a well-sorted fine-grained sand (Md diameter 240μ). The seasonal change in wave energy in this area results in a significant widening of the beaches during the summer and fall and the total stripping of sand from the beaches during the winter.

The San Lorenzo River has a large drainage system that floods in the winter and spring and has a low flow in the mid-summer and fall. Other smaller streams drain the coastal slopes in the vicinity

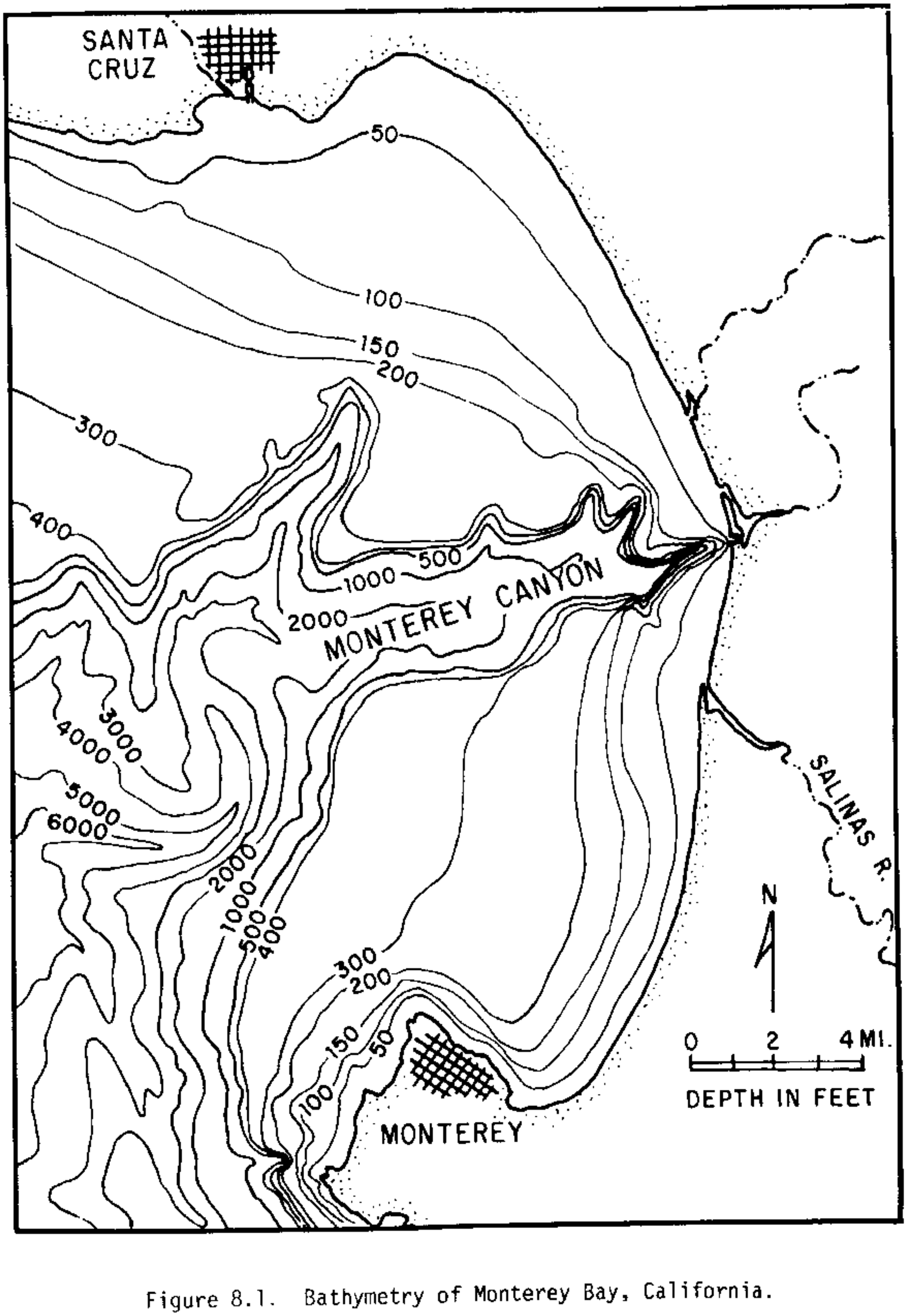


Figure 8.1. Bathymetry of Monterey Bay, California.

of Santa Cruz and empty into a series of fresh water lagoons located to the east of the river mouth. Santa Cruz Harbor occupies Woods Lagoon, a former fresh water lagoon that is the coastal terminus of Arana Gulch. This lagoon was separated from the ocean by Twin Lakes Beach before the harbor was constructed.

The diurnal range of tides in the region of Santa Cruz Harbor is 5.3 ft (1.61 m) with a mean range of 3.5 ft (1.07 m). Maximum tidal excursions are: highest high water 8.0 ft (2.44 m), lowest low water 2.5 ft (0.76 m).

8.2 Wave Climate

The prevailing direction of wave approach at Santa Cruz is from the northwest; however, deep water waves can come from any direction between due south and north-northwest. The harbor entrance is sheltered by Point Santa Cruz to the west of the city of Santa Cruz and by Point Cypress at the south end of Monterey Bay so that waves can only approach in a quadrant from 176^0 to 242^0 from true north.

Deep water waves common to the area have periods ranging from 4 to 20 seconds and significant heights between 2 feet (0.61 m) to more than 20 feet (6.1 m) (Corps of Engineers, 1974). Data from wave hindcast studies of storms indicate storm waves usually approach the area from the south southwest to west and occur during the fall and winter months. These waves are probably generated by the typical north Pacific storms that occur during the winter months. Waves from such storms which also come from the west and northwest are refracted so that they approach Santa Cruz Harbor from the southwest. Northwest waves have less energy at the shoreline than waves from other sectors because of refraction over the shelf (Corps of Engineers, 1974).

Storm waves from the southwest usually have the greatest height and duration (Corps of Engineers, 1974). Long period waves from this direction can have their origin either from distant sources in the South Pacific or tropical storms off the coast of Mexico. Short period waves from the southwest are estimated to attain a maximum deep water height of 25 feet (7.6 m) and are probably generated by storm fronts passing through the area (Corps of Engineers, 1974).

8.3 Budget of Sediment

Santa Cruz Harbor is located in a littoral cell that extends from the Golden Gate, about 65 miles (100 km) upcoast of the harbor to the head of Monterey Submarine Canyon 20 miles (32 km) downcoast from the site (Figure 8.2). Sediment contributions to this cell are transported through San Francisco Bay, from stream contributions along the coast, and from sea cliff erosion. The budget of sediment in this cell is not well known and will be given only general consideration whereas the coastal segment in the immediate vicinity of Santa Cruz will be discussed in greater detail.

Wilde (1965) examined this littoral cell in an attempt to determine the sources and amounts of sediment entering Monterey Submarine Canyon. He indicates that 6.54×10^5 yds^3/yr (5×10^5 m^3/yr) of sediment is brought downcoast from the Golden Gate to the head of Monterey Canyon. This is partially fine-grained sediment from the Great Valley that passes through San Francisco Bay and the remainder being sediment derived from coastal streams and sea cliff erosion. An additional

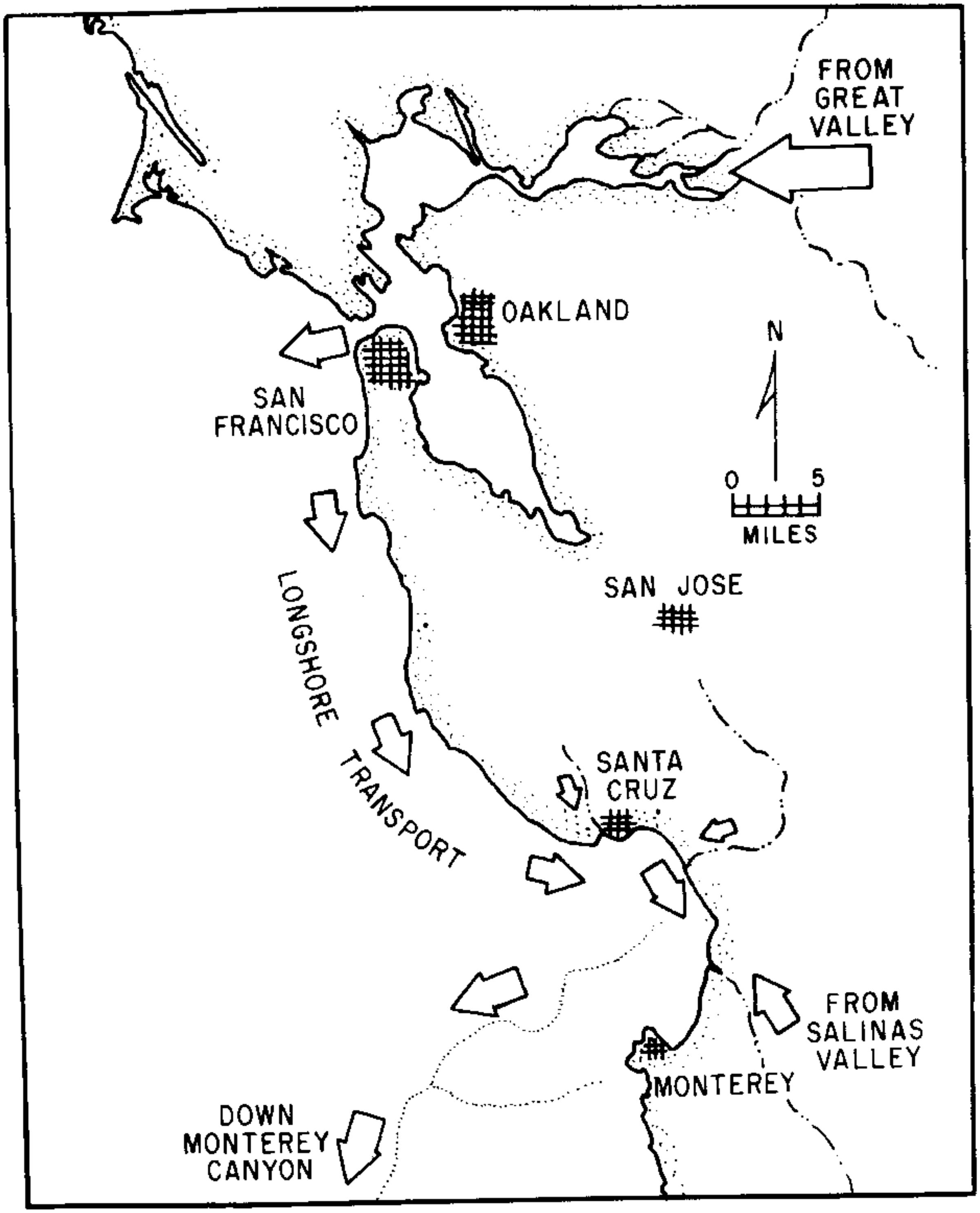


Figure 8.2. Sediment budget for the Santa Cruz littoral cell (from Wilde, 1965).

6.54×10^5 tds^3/yr (5×10^5 m^3/yr) of fine-grained sediment from the Salinas Valley enters the canyon from the southern end of Monterey Bay to make the total annual sediment loss through the canyon approximately 1.31×10^6 yds^3/yr (1×10^6 m^3/yr).

At Santa Cruz much of the sediment passing through the littoral cell is derived from upcoast sources; however, two local streams do supply additional sediment in the vicinity of the harbor. The major local sediment source is the San Lorenzo River 1.5 miles (2.4 km) west of the harbor entrance. The San Lorenzo River has a drainage area of 137 square miles (355 km^2) along the coastal slopes of the Santa Cruz Mountains. Using the sediment yield relationships of Langbein and Schumm (1958) and an annual precipitation of 30 inches the sediment yield of the San Lorenzo is about 78,500 yds^3/yr (6.0×10^4 m^3/yr). The Corps of Engineers (1974) estimate that the San Lorenzo River produces between 88,000 and 133,000 yds^3/yr ($6.7 - 10.2 \times 10^4$ m^3/yr) of which only 18,000 to 27,000 yds^3/yr (14-2.1×10^4 m^3/yr) is suitable beach sand.

Two and one-half miles downcoast from Santa Cruz Harbor, Soquel Creek enters the ocean at the community of Capitola. The sediment contributions from this source has been estimated at 8.000 yds^3/yr (6.1×10^3 m^3/yr) since it has a much smaller drainage basin (Corps of Engineers, 1974). No sediment yield data exists for the other small streams that drain the coastal slopes in the area.

The longshore transport of sand in the Santa Cruz area has been approximated from wave studies and by accretion rates at the harbor entrance. Anderson (1971) calculated the "potential drift" which is the longshore transport that would occur if an unlimited supply of sand were available. These calculations were based on deep water wave data from a report by National Marine Consultants (1960). The net easterly longshore sand transport at Santa Cruz from these calculations was about 350,000 yds^3/yr (2.68×10^5 m^3/yr).

A direct determination of the longshore transport rate at Santa Cruz was made when the harbor jetties were constructed. The jetties were completed in 1963 and in the first two years following their completion approximately 600,000 yds^3 (4.59×10^5 m^3) of sand accumulated on the west side of the entrance channel suggesting that the longshore transport is 300,000 yds^3/yr (2.3×10^5 m^3/yr) to the east (Corps of Engineers, 1974).

Thus, it appears that Santa Cruz is located near the southern end of a littoral cell that begins at the Golden Gate with an initial source of sediment from San Francisco Bay. Southerly longshore transport brings at least 200,000 yds^3/yr (1.53×10^5 m^3/yr) to the Santa Cruz from all upcoast sources. At Santa Cruz the San Lorenzo River contributes another 100,000 yds^3/yr (7.65×10^4 m^3/yr) to the ocean which must pass the harbor entrance. Under natural conditions additional sediment was added to the longshore transport by Soquel Creek, the Pajaro River, and several smaller drainage basins to attain a total of 654,000 yds^3/yr (5.0×10^5 m^3/yr) at the head of Monterey Submarine Canyon. Studies of the sediments on Monterey Canyon Sea Fan indicate that much of the fine-grained sediment is from the Great Valley and Salinas Valley whereas the coarse sand fraction comes from the coastal mountains (Wilde, 1965). Table 8A summarizes the sediment budget for the Santa Cruz littoral cell with its inputs, transport, and losses.

8.4 Specific Problem

Santa Cruz Harbor is a small craft harbor oriented toward the pleasure boat fleet with some use by commercial fishermen. It was completed in January of 1964 and since has suffered severe shoaling problems which have substantially reduced its usefulness. The entrance channel is 100 ft (30 m) wide and 900 ft (274 m) long with a design depth of 20 ft (6 m). There is an inner channel of an additional 370 ft (113 m) at a design depth of 15 ft (4.6 m) which leads to the harbor and turning basin. This channel was designed for loaded fishing vessels up to 13 ft (4 m) draft. The total surface of the harbor at high water from the entrance channel is 1.2 million square ft (1.11×10^5 m^2) (Moore, 1972). An additional 844,000 square ft (7.8×10^4 m^2) of berthing area north of the original project was completed in 1972.

The entrance channel has two rubble mound breakwaters: an east jetty which is 810 ft (247 m) long and the west dogleg jetty is 1200 ft (366 m) long. The west jetty was constructed so as to protect the harbor entrance from local wind waves and long period southern swell. The harbor layout and shoreline changes following construction are shown in Figure 8.3.

The Corps of Engineers made a preliminary investigation of the longshore transport at Santa Cruz. One was a review of earlier beach erosion studies. This showed a predominant littoral drift downcoast, i.e., west to east, for all waves except those from the south to southwest sector. A second study involved the construction of a 400 ft

Table 8A. Sediment budget for Santa Cruz littoral cell at Santa Cruz Harbor (see Figure 8.3).

TOTAL SEDIMENT SUPPLY yds^3/yr	NET LONGSHORE TRANSPORT (EAST) yds^3/yr	TOTAL LOSS FROM CELL yds^3/yr
1. From San Francisco Bay and upcoast sources 200,000	1. At Santa Cruz Harbor 300,000	1. From upcoast sources 650,000
2. San Lorenzo River 100,000	2. At Head of Monterey Canyon 650,000	
3. From downcoast sources to Monterey Canyon 350,000		
TOTAL 650,000		TOTAL 650,000

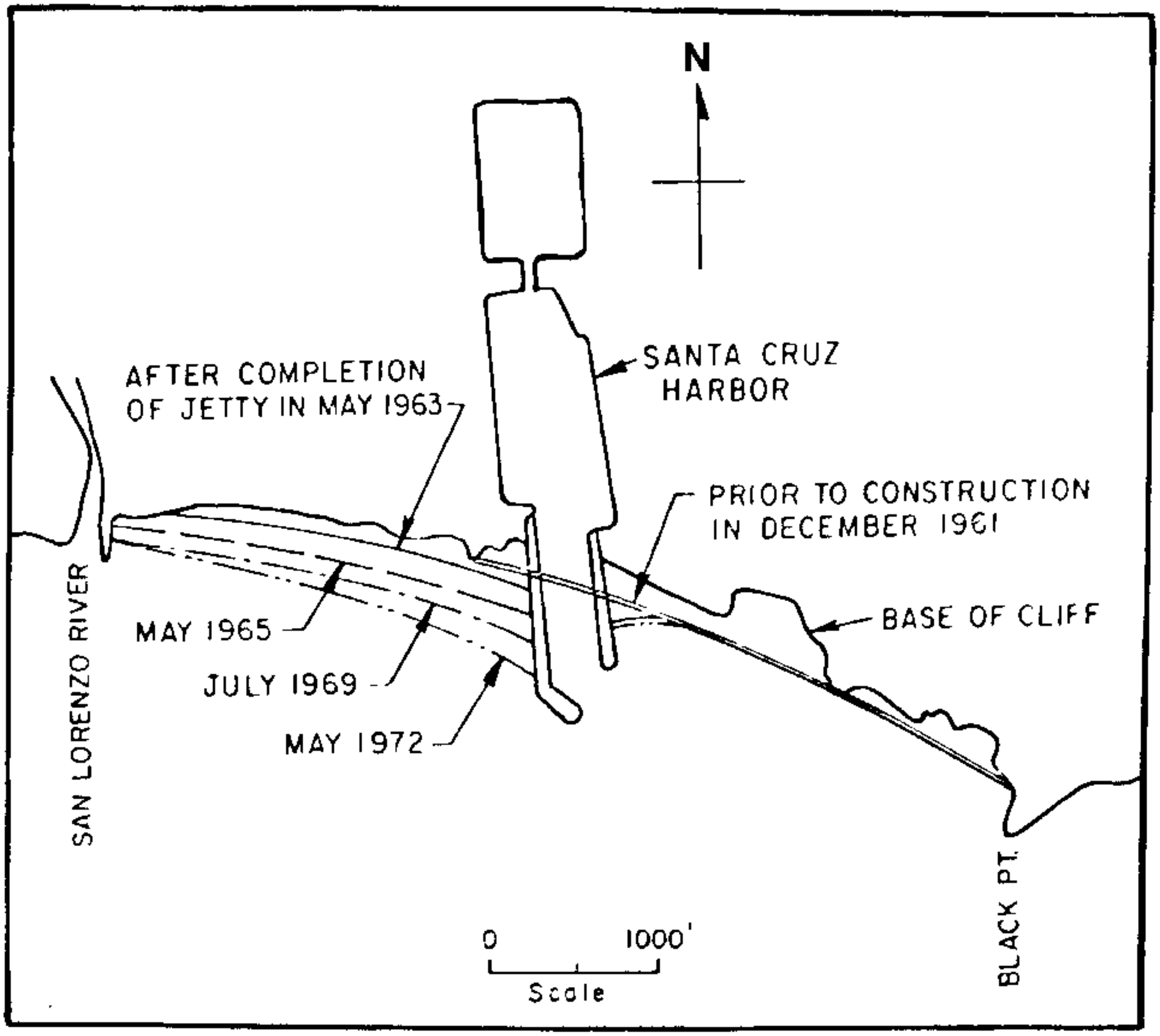


Figure 8.3. Changes in shoreline configuration following construction of Santa Cruz Harbor in 1963 (from Moore, 1972).

(122 m) long experimental groin just west of the harbor site; however, the results from the groin proved inconclusive. Finally, a gross estimate of longshore transport was assumed with a range of between 25,000 yds^3/yr (1.9×10^4 m^3/yr) and 300,000 yds^3/yr (2.3×10^5 m^3/yr).

The jetties were completed in 1963. Six hundred thousand cubic yards of sand accumulated on the upcoast beach in the first two years. Thus, the upper estimate of 300,000 cubic yards (229,000 m^3) per year appears to have been correct. Although a permanent sand bypassing system was proposed for the harbor, conventional dredging techniques have been used. It has been found that it is necessary to dredge the channel annually in order to keep it open part of the year. The amount of material removed is shown in Table 8B. The shoaling of the entrance channel occurs within a short period of time during the storm season particularly in late winter and early spring. Over dredging of the entrance channel provides for substantial sand storage; however, this storage capacity can be attained by transport during a single severe storm and subsequent storms proceed to fill the harbor entrance channel. Figure 8.4 shows typical shoaling patterns of the harbor entrance. The shoaling process appears to involve short period storm waves from the southwest that strip the beach of sand and deposit it offshore, then longer period waves from the west redistribute the sand shoreward where some is moved into the entrance to the harbor. Repeated surveys of the entrance channel show that it is consistently shoaled by sand and rendered impassable by November or December each year depending on storm activity. Apparently about 90,000 - 110,000 yds^3/yr ($6.9 - 8.4 \times 10^4$ m^3/yr) of the total 300,000 yds^3/yr (2.3×10^5 m^3/yr)

Table 8B. Material dredged from channel mouth at Santa Cruz Harbor, Santa Cruz, California

DATE	10^3 yds^3	COST ($1000)
1965	70	125
1966	34	90
1967	57	92.6
1968	60.5	104
1969	79	118
1970	11.5	151
1970 *	11.5	42
1971	108.3	179
1972	90	185
1973	109	219

* clam shell dredge to remove kelp mat

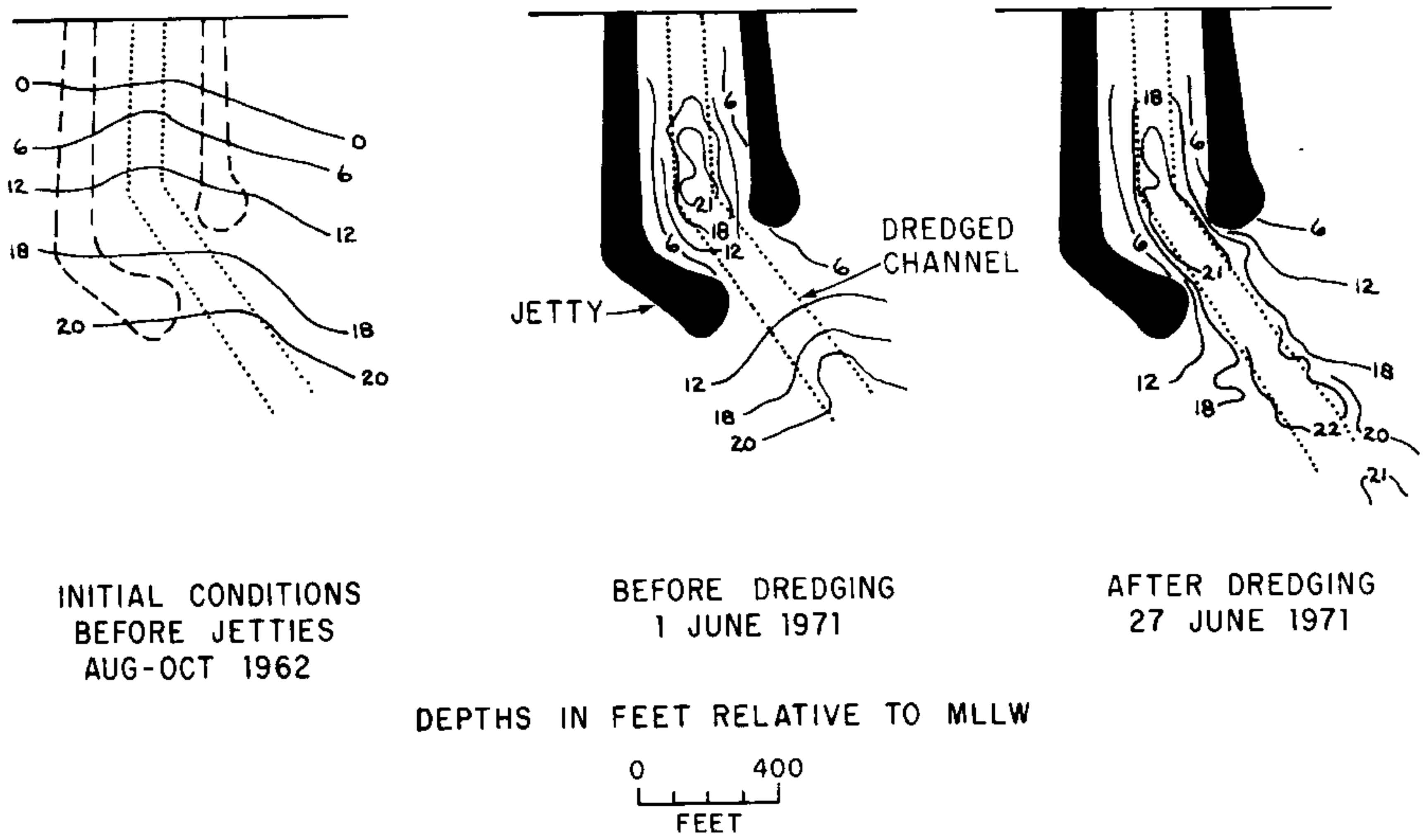


Figure 8.4. Shoaling pattern at entrance to Santa Cruz Harbor in June 1971 (from Moore, 1972).

longshore transport is trapped in the channel with the remainder bypassing the harbor (Corps of Engineers, 1974).

The entrance channel shoaling problem has become progressively worse each year since the harbor was constructed. This is because the beach upcoast of the west jetty now appears to have prograded seaward to the jetty tip and the sand moves directly into the entrance channel. Consequently, the harbor does not provide refuge for the local fishing and pleasure fleets by eliminating long runs to distant protective harbors during storms. During the period from December to May the harbor may be entered only during calm weather at high tide if at all.

Construction of the harbor and the associated sand entrapment by its jetties has apparently caused a downcoast beach erosion problem. The neighboring resort area of Capitola Beach has experienced severe beach erosion since Santa Cruz Harbor was completed. Prior to 1965 the beach at Capitola was adequate for recreational use. Since 1965 the beach has suffered extreme erosion, sometimes disappearing completely. Examination of the budget of sediment for this area indicates that the initial impoundment of 600,000 yds^3/yr ($4.59 \times 10^5\ \text{m}^3/\text{yr}$) between 1963 and 1965 could be responsible for the subsequent sand losses at Capitola. Other contributing factors could be the lack of sediment supply from Soquel Creek which empties into the ocean at Capitola. It has been noted that the peak runoff of Soquel Creek for a few years prior to 1965 was substantially below average; therefore sand was not supplied to the beach (Corps of Engineers, 1969). However, the annual sediment yield from Soquel Creek is much less than the apparent longshore transport along that coastline segment; therefore, it is difficult to the upcoast jetty impoundment area is now filled so that sand enters the channel and is trapped between the jetties. This renders the harbor unusable for much of the year and sand entrapment by the channel causes downcoast beach erosion.

The current practice at Santa Cruz is to dredge the harbor in the spring and bypass the sand to downcoast beaches. This procedure does not keep the entrance channel open for more than a few months and the bypassed sand quickly moves downcoast. Several types of remedial action have been proposed for this problem which have various advantages and disadvantages.

The most simplified remedial action for Santa Cruz is to increase the storage capacity of the existing sand entrapment structures by over dredging the entrance channel. By dredging the channel to a deeper depth than is required for navigation the channel should remain open longer and the time between dredgings lengthened. A variation of this proposal would be to create a sand trap seaward of the upcoast (west) jetty perhaps using a detached breakwater to create a more effective sand trap. This type of remedial action may solve the entrance channel shoaling problem but increasing the quantity of sand impounded at the harbor will cause beach erosion on the downcoast beaches to become more severe.

A remedial action which would imitate the natural process of longshore transport at Santa Cruz Harbor is to install a sand bypassing plant at the harbor entrance. This type of installation would approximate the natural littoral transport by intercepting the sand on the upcoast side of the entrance and transporting it to the downcoast beach. If this transfer of sand past the harbor entrance is carried out at the same rate as the natural longshore transport then the bypass system imitates the natural longshore transport at the harbor site. A workable sand bypassing system should eliminate the downcoast beach erosion.

Santa Cruz Harbor is a good site for the installation of a crater-sink sand bypassing system such as proposed by Inman and Harris (1970). Figure 8.5 shows the configuration of a crater-sink installation at Santa Cruz Harbor entrance channel. This bypassing system would consist of a crater positioned at the mouth of the entrance channel to intercept sand entering the channel from around the upcoast (west) jetty. Sand entering the crater would be pumped to a feeder beach downcoast at some distance beyond the east jetty. The area of sand influx into the crater could be increased by the use of fluidization units which would feed the crater from peripheral areas as shown in Figure 8.5. The advantages of this system are that it provides an efficient means of bypassing sand without the need for large impoundment structures and a surface dredge. The crater itself will serve the function of an impoundment structure and provide a place for sand accumulation when large longshore transports associated with storms occur.

Another approach to remedial action at Santa Cruz is to completely change man's use of the coastline at the harbor site. The present harbor was developed from a former coastal lagoon that was closed off from the ocean most of the time. Creation of the harbor entrance channel has caused the problem at this site, so if the channel were abandoned, a permanent solution would be attained. A remedial action of this type would involve conversion of the harbor to a recreational sailing basin

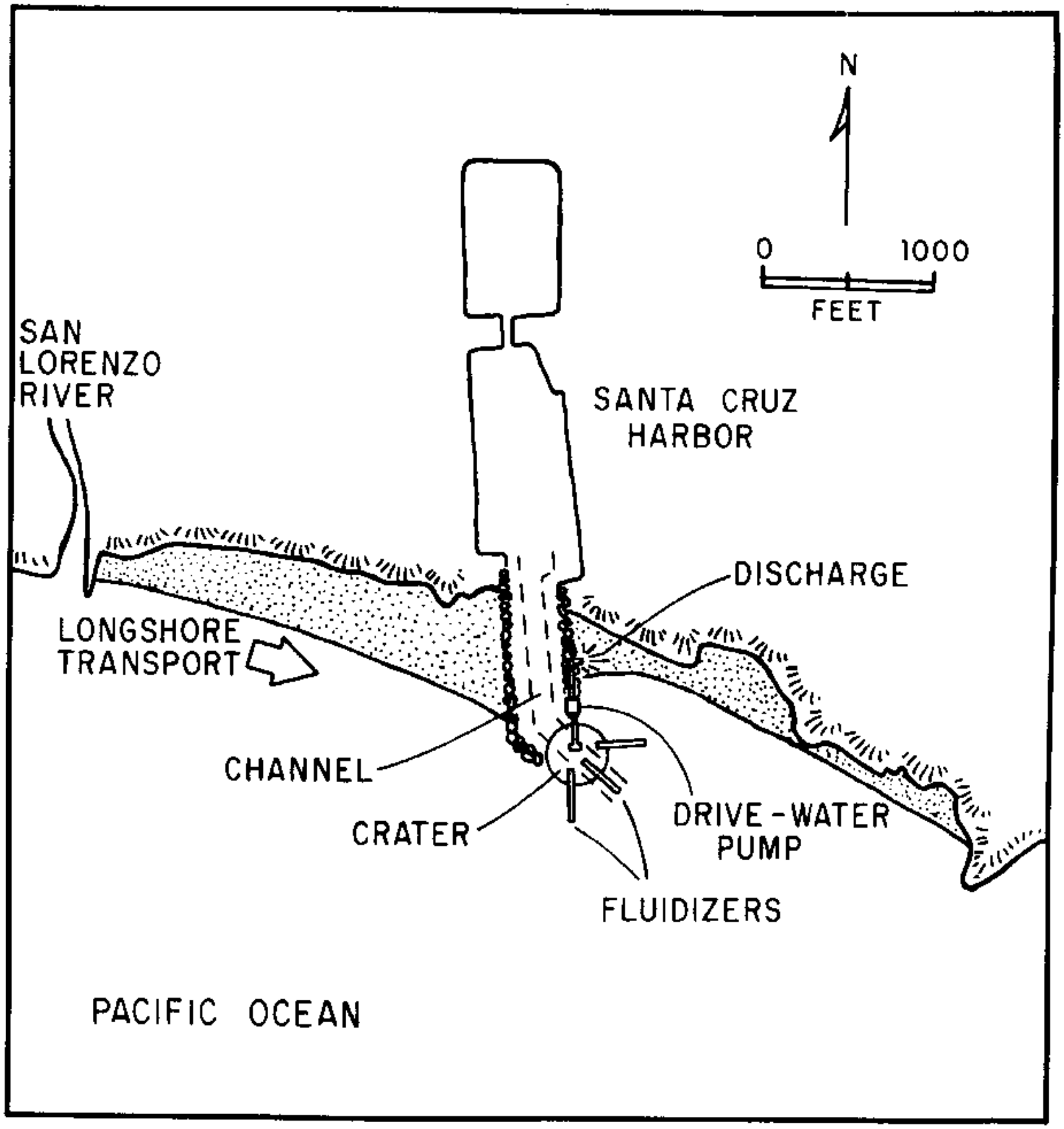


Figure 8.5. Possible application of crater-sink sand bypassing system at Santa Cruz Harbor (scale 1" = 200 ft).

or lagoon which does not require a navigable entrance channel. Implementing this type of remedial action would require allowing the entrance channel to close and the natural sand transport to proceed past the former entrance to downcoast beaches.

This type of remedial action probably has economic implications concerning revenue lost from the harbor and the expense of converting the harbor to a closed recreational basin. However, these costs should be compared to future expenses for maintaining a navigable channel by sand bypassing or periodic maintenance dredging. The conversion of the harbor to a closed basin will eliminate most of the present maintenance expense and solve the downcoast beach erosion which results in additional losses.

In summary the problems at Santa Cruz are related to the harbor entrance channel and its interception of sand. This can be solved either using a remedial action that imitates the natural sand transport by continuously bypassing sand past the entrance or an action that modifies use of the area so that the channel is not required. These totally different approaches to the problem provide the best possibility for a complete solution since they recognize that maintaining continuity to the longshore transport past the harbor entrance is essential to any workable solution.

9. BOLINAS LAGOON

9.1 Description of the Area

Bolinas Lagoon is located approximately 20 miles (32 km) north of the Golden Gate on the coast of California. The lagoon is triangular in shape and occupies a depression located along the San Andreas Fault zone. A narrow sand spit extends from Stinson Beach northwesterly toward the Bolinas headland and separates the lagoon from the Pacific Ocean. At the west end of the spit there is a channel that provides an interchange of water between the lagoon and the ocean. Streams enter the lagoon from coastal foothills on the east side of the lagoon and from the Bolinas headland on the west.

Bolinas Bay is one of several hooked embayments along the central California coast that are associated with resistant headlands (Figure 9.1). Hooked embayments are the result of the refraction of wave energy around the resistant headland which produces an equilibrium configuration to the shoreline in the lee of the headland (Johnson, 1965). At Bolinas Bay the resistant headland is formed by the exposure of Monterey Formation shale at Duxbury Point. The area of Bolinas Lagoon is about 1.5 sq miles (3.9 km^2) with much of the inner portion being tidal flats. At mean lower low water about 70 percent of the lagoon is tidal flat that is essentially in its natural state as a small estuary ecosystem (Ritter, 1969).

Bolinas Lagoon is separated from the Pacific Ocean by Stinson Spit (Seadrift) which extends from Stinson Beach toward the Bolinas headland (Figure 9.1). The median grain diameter of sand on Stinson Spit is about 230 to 260 microns (Interstate Elect. Corp., 1968). Sorting coefficients for sand

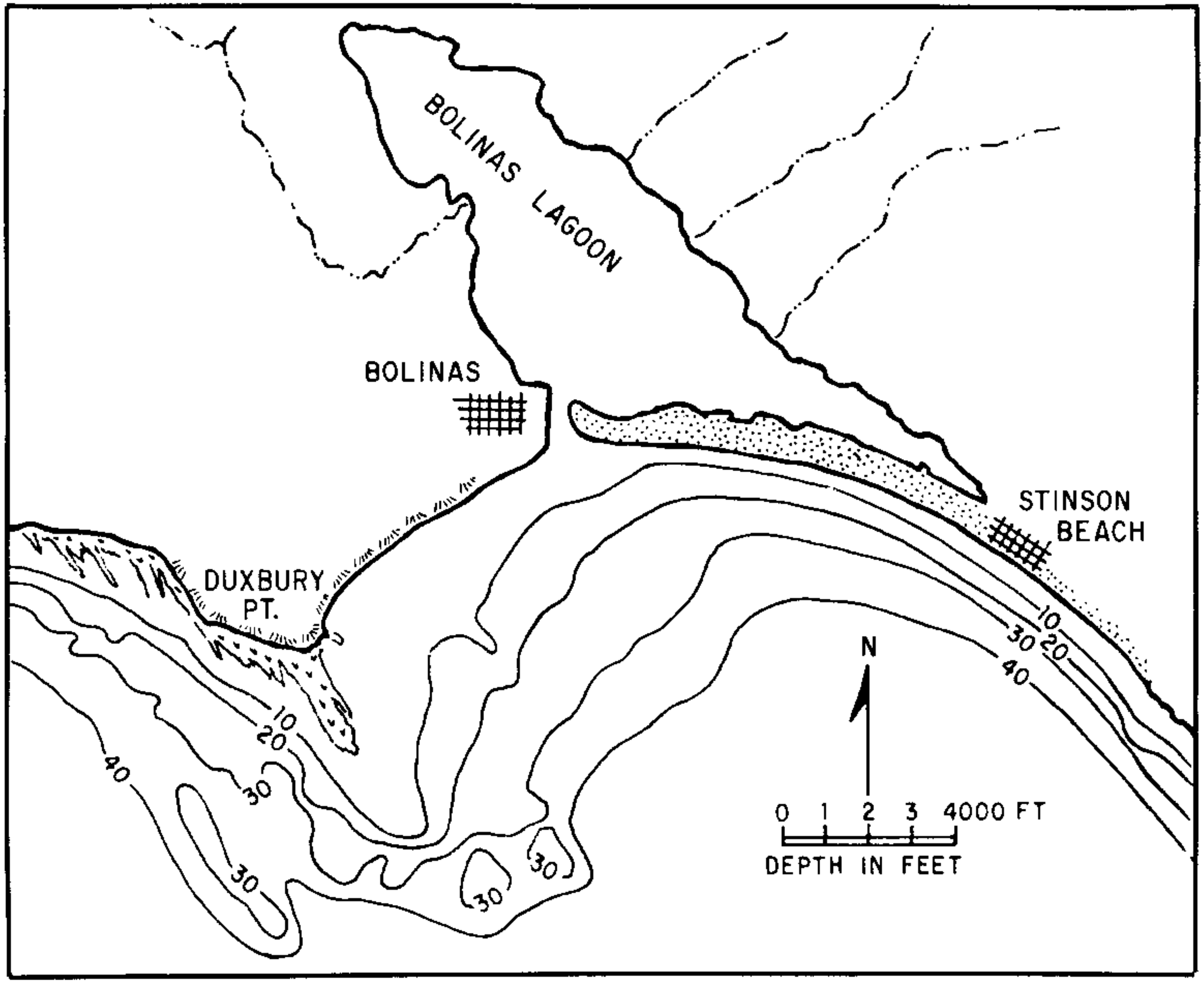


Figure 9.1. Bathymetry in vicinity of Bolinas Lagoon.

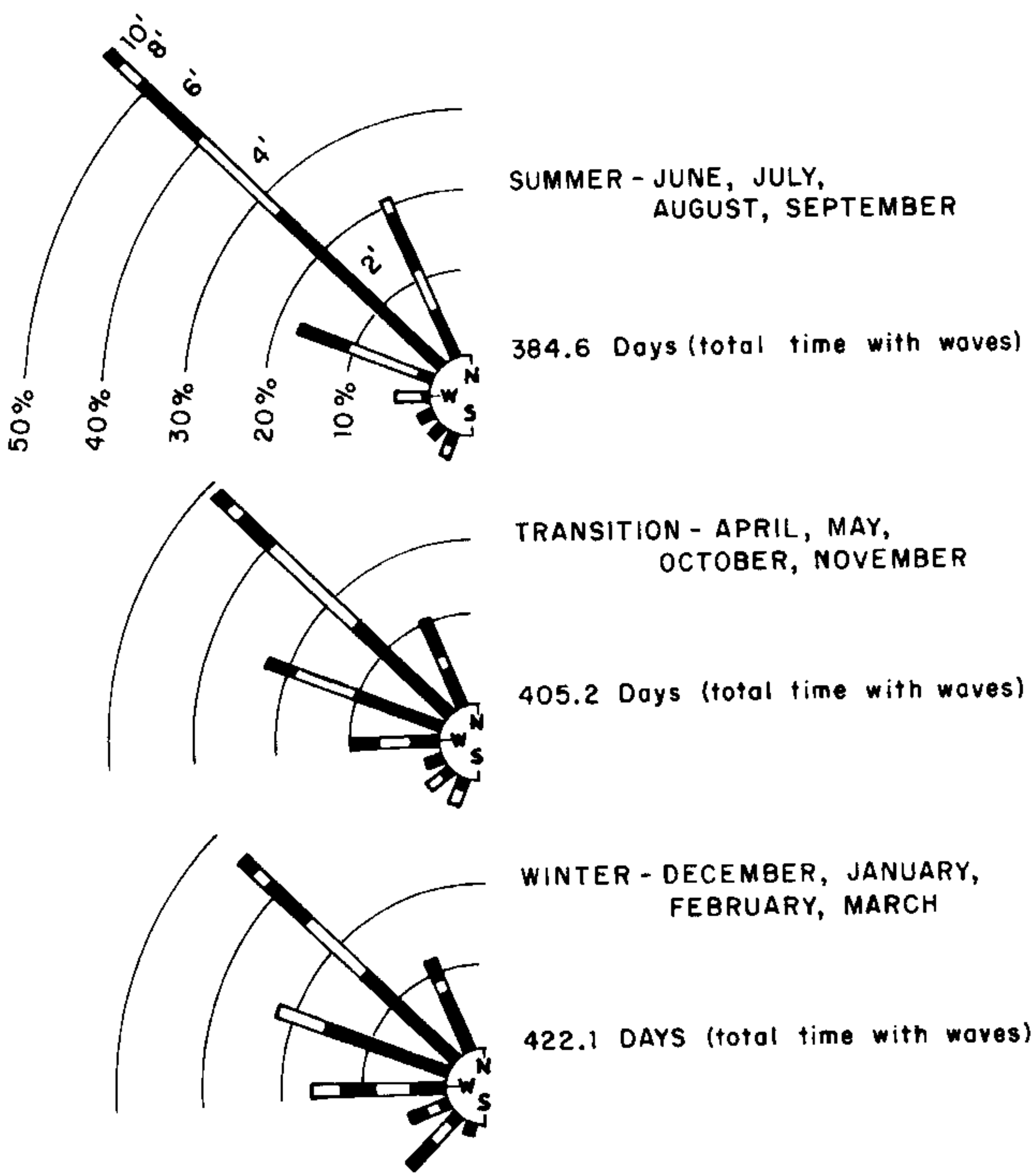
at Stinson Beach averages 1.26 with some seasonal variation. To the north of Duxbury Point and to the south of Stinson Beach the sand beach ends and the shoreline is rocky and generally devoid of sand.

The shelf off Bolinas Lagoon is approximately 30 miles (48 km) wide and is abruptly terminated at its seaward edge by the Farallon Escarpment. Locally off Bolinas the shelf is somewhat irregular, apparently due to recent activity of the San Andreas Fault where it comes ashore at Bolinas Lagoon. There are no submarine canyons which incise the shelf in the vicinity of Bolinas Lagoon that could provide a local sink for littoral sediment.

9.2 Wave Climate

The wave climate for Bolinas Bay has been developed from various sources by Johnson (1969). He obtained wave data from visual observations at the San Francisco Light Ship, Stinson Beach and Bolinas; hindcast waves from meteorological data at deep water stations for two different time periods; and recorded waves at Bolinas Bay for 6 months. The most complete wave data that could be compiled into a wave climate is the hindcast data for a deep water station west of the Golden Gate. This data was resolved into swell roses for data from the years 1936 - 1938 (Figure 9.2).

Waves from the northwest have very little effect on the entrance to Bolinas Bay since it is protected by the Bolinas headland and refraction around Duxbury Point reduces their effect on the beach south of the entrance (Figure 9.3). However, waves from the west and southwest have a direct path into Bolinas Bay. Information from the wave refraction



Diagrams give percentage of total days when wave height is less than given value.

Figure 9.2. Wave roses, vicinity San Francisco lightship for years 1936-1938 (from Johnson, 1969).

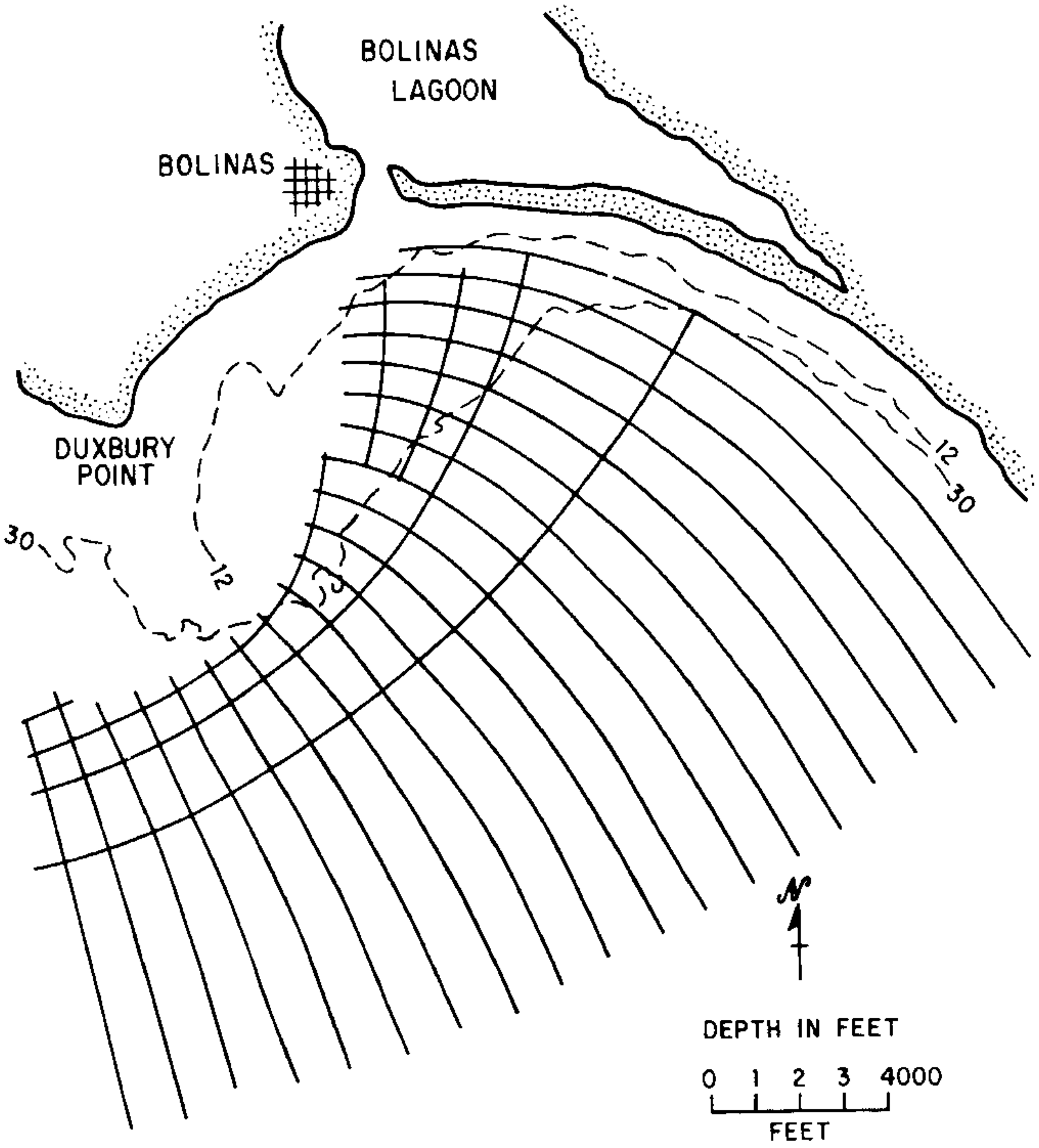


Figure 9.3. Wave refraction diagram, 12 second period wave from west (from Johnson, 1969).

diagrams can be used to assess the nature of breaking waves at the entrance to Bolinas Bay for design criteria of coastal structures and to determine the longshore transport of sand.

9.3 Budget of Sediment

Much of the coastline north of the Golden Gate including the area of Bolinas Bay is a rocky shoreline with intermittent sand beaches. The sand beaches are associated with resistant headlands such as Bodega Head, Point Reyes and Duxbury Point. Consequently, the littoral cell concept can be applied in terms of each of these sand beach segments rather than a longer section of coast including several beaches.

Johnson (1965) concluded that the rate of longshore transport along the coastline near Bolinas Bay was relatively small from an assessment of the various sediment types, their sources, and sedimentation rates in local harbors. The shoreline configuration in the vicinity of Bolinas Bay is an equilibrium beach established in the lee of a resistant headland by wave energy coming predominantly from the northwest. As can be seen in Figure 9.4 the refraction of waves from the west around the headland creates a shoreline configuration that essentially parallels the refracted wave crest. This configuration with respect to the direction of wave approach results in very little longshore transport. The stable nature of this dynamic equilibrium configuration is somewhat confirmed by the fact that the shape and position of Stinson Spit (Seadrift) and Stinson Beach have not changed since the first survey in 1854.

A study of the mineralogical composition of the sand in the vicinity of Bolinas Lagoon indicates that it is possibly derived from two sources. The presence of green hornblende suggests that some of the sand comes from granitic material which is exposed at the Pt. Reyes headland to the north or

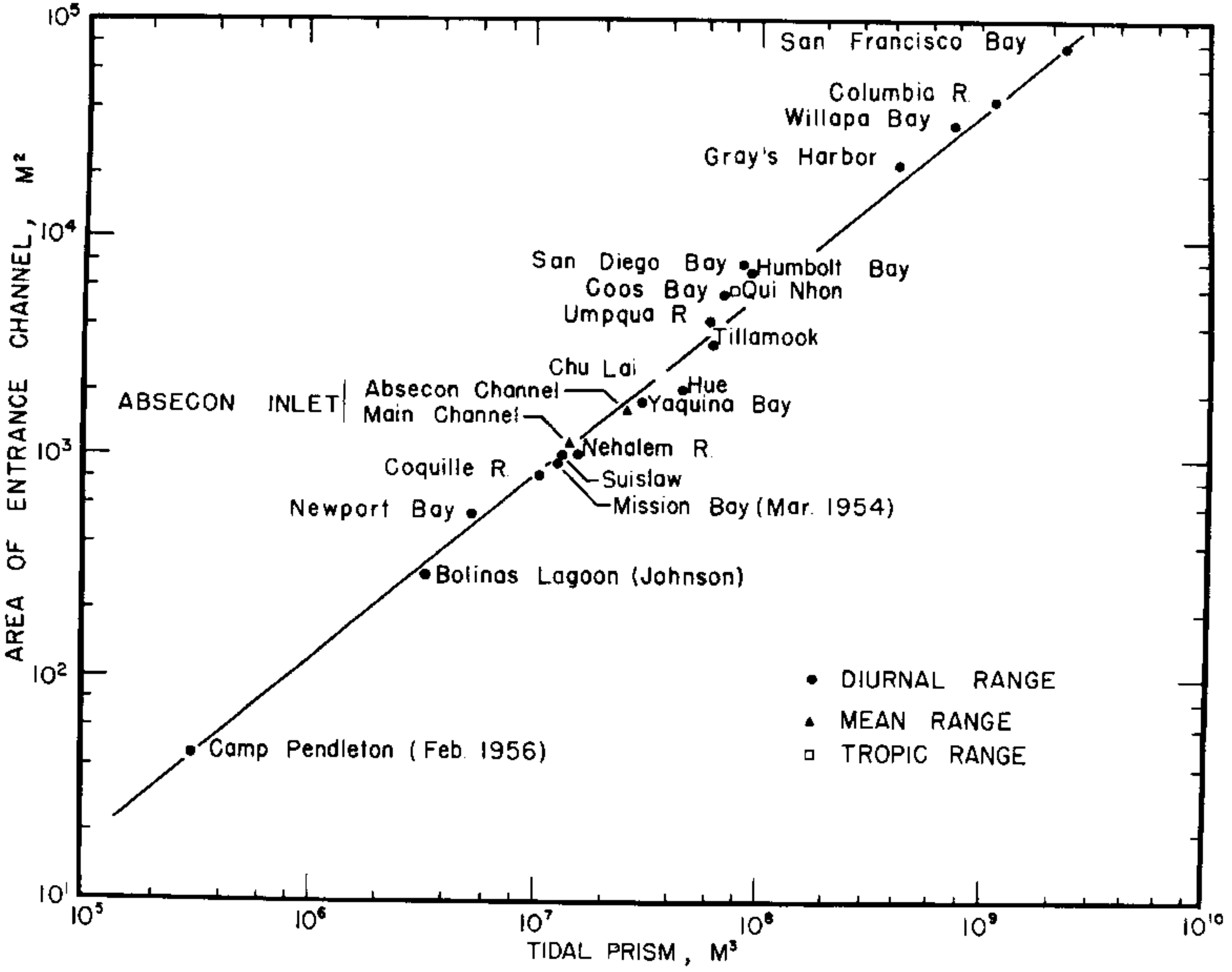


Figure 9.4. Relation between minimum cross-sectional area of entrance channel and volume of the the tidal prism for various embayments. Bolinas Lagoon is shown for the data of Johnson (1973).

it comes from the granitic terrane in the Sierra Nevada and was transported through the Golden Gate to the coast (Johnson, 1969). However, most of the minerals in the beach sands at Bolinas Bay appear to be derived from the Franciscan rocks exposed along the coast; thus, they are of a local source indicating little longshore transport along this stretch of coastline (Interstate Electronics Corp., 1968).

Beach profile measurements made along Stinson Spit since 1948 indicate that the beach undergoes seasonal changes. In general these changes in profile configuration cause the beach to be about 135 ft wider in summer than in winter due to the more severe winter wave conditions (Johnson, 1969). Beach profile data and old charts were used to determine sand volume changes along Stinson Spit. These studies indicated that there were changes in sand volume along the spit that were probably related to seasonal processes of on-offshore transport and there has been no large gain or loss of sand on the spit since 1854 (Interstate Electronics Corp., 1968).

It appears from the wave refraction conditions and the stability of Stinson Spit in historic times that there is very little longshore transport along the spit. Thus, the budget of sediment for the Bolinas Lagoon area is localized in that it involves only the Stinson Beach and spit and the adjacent area. The source of sand for this coastal segment is from local erosion of the resistant headlands and perhaps minor contributions from the San Francisco Bay bar. The sand is introduced at Stinson Beach and slowly transported northward along the spit. At the north end of Stinson Spit the sand is moved into the lagoon or offshore to form the crescent shaped bar at the lagoon mouth. Ritter

(1969, 1973) measured tidal currents at the mouth of Bolinas Lagoon and noted that the currents on the ebb tide were of higher velocity and transported most of the suspended sediment. Thus, it appears that sediment is moved to the lagoon entrance and then out offshore by the ebb tidal currents. Under storm wave conditions considerable amounts of sediment may be moved into the lagoon entrance and then subsequently removed by tidal currents under normal wave conditions (Ritter, 1969).

The sink for sediment transported through this littoral cell is the offshore shelf area seaward of the Bolinas Lagoon entrance in the lee of Duxbury Reef. No measurements have been made of the rate at which sand is accumulating in this area or of the total amount present.

9.4 Specific Problem

The specific problem at Bolinas Lagoon concerns maintaining an entrance channel for tidal circulation in order to preserve the lagoonal ecosystem. The actual existence of the lagoonal ecosystem and tidal channel are related to various natural processes that are responsible for creating the lagoon. Thus, it should be understood that the present lagoon is but a phase in an ever changing environmental situation.

The natural history of a coastal lagoon begins with an embayment being formed in the drowned mouth of a stream by rising sea level. Longshore transport of sand by waves creates a barrier bar across the mouth of the embayment so that water circulation is restricted to a narrow entrance channel. Also, sediment discharge from the stream gradually fills the lagoon to create a tidal flat confining the tidal flow to specific channels. As the filling of the lagoon continues more of its area becomes intertidal with salt marsh vegetation. This type of plant life traps additional sediment to accelerate the filling process. Finally, the tidal flow into the lagoon becomes so small that the entrance channel is closed off by longshore transport. Once circulation with the ocean ceases, the lagoon stagnates and the lagoonal ecosystem disappears. Continued sediment influx results in the total disappearance of the lagoon and eventual formation of dry land. Thus, the life span of any coastal lagoon is dependent upon the rate at which sediment fills the lagoon.

Bolinas Lagoon is at an intermediate stage in its history where lagoonal sedimentation has partially filled it to create a large tidal flat and its entrance remains open for adequate circulation with the ocean. The principal sources of sediment to the lagoon are from streams, the ocean by tidal currents and waves, and dunes moved by onshore winds. Stream inputs primarily occur during floods that are associated with storms which cause a sudden influx of material to the lagoon at the mouth of the stream. Ritter (1973) shows through a comparison of charts made over the last 100 years that there has been gradual filling of the lagoon. Most of the sediment influx has been at the mouth of Pine Creek and in the vicinity of Kent Island indicating that the stream is a principal sediment source. Logging in the vicinity of Bolinas Lagoon in the latter 1800's resulted in a greatly increased rate of sedimentation in the lagoon. This siltation affected the harbor facilities at the head of the lagoon and the discontinuation of ship building activities in the lagoon (Ritter, 1973).

Sediment also enters the lagoon by wave and tidal current transport through the entrance channel. Measurements of tidal currents and suspended sediment at the entrance channel under normal conditions suggest that tidal currents may have a net transport from the lagoon (Ritter, 1969, 1973). However, this is probably offset by a large quantity of sediment being transported into the lagoon during storm conditions. Much of the sediment that enters Bolinas Lagoon through the entrance channel apparently comes from the sea cliff between Bolinas and Duxbury Point. This cliff is composed of soft material and is eroding at a rapid rate. Littoral transport carries the sediment along the coast and to the lagoon entrance where tidal currents can carry it into the lagoon (Ritter, 1973).

Another source of sediment to Bolinas Lagoon is from aeolian transport as sand dunes on Stinson Spit (Seadrift). When a southerly wind blows across the spit, sand is blown from the beach into small dunes which migrate across the spit into the lagoon. Although this input has not been measured it probably has been a significant source of sediment to the lagoon. Stinson Spit is gradually being developed into the Seadrift residential area and the amount of aeolian transport is decreasing as the ground surface is stabilized by houses, streets and landscaping.

The entrance to Bolinas Lagoon has been located at its present position and has remained open since the earliest surveys (Ritter, 1969, Figure 3; Johnson, 1973). This would suggest that the entrance is an equilibrium channel in terms of lagoon tidal flow. An empirical study of tidal inlets on sandy coasts by O'Brien (1969) shows that there is a relationship between the cross-sectional area of the inlet and the tidal prism of the lagoon. Bolinas Lagoon has a tidal prism of 2800 acre ft (34.5×10^5 m^3) with a diurnal tidal range of 5.7 ft (1.7 m) and the cross-sectional area of the entrance channel on 24 August 1967 was 1390 ft^2 (129 m^2) (Johnson, 1969). Figure 9.4 shows the plot of the Bolinas Lagoon channel in relation to other inlet channels as defined by the O'Brien relation. As can be seen the Bolinas Lagoon channel is close to the equilibrium conditions indicated by the O'Brien relation and its area is optimal for its tidal prism.

The present channel has a crescent shaped bar located just seaward of the inlet that fluctuates in position with tidal conditions. During extreme low water conditions the bar is exposed and presents a navigational hazard (Ritter, 1969). Because the entrance channel is hazardous, proposals have been made to modify it so that it is navigable under all conditions. Most suggestions for modification include the construction of jetties to define the channel and dredging to enlarge it for safer navigation. This type of modification of the natural channel would change the cross-sectional area and cause a deviation from equilibrium. Entrance channels that are enlarged from equilibrium tend to shoal because tidal currents generated by the same tidal prism are unable to maintain the greater channel depth. Since the Bolinas Lagoon channel is presently near equilibrium deepening it for navigation without enlarging the tidal prism will result in the channel having to be maintained by periodic dredging.

9.5 Recommendations

The Marin County Parks and Recreation Department prepared a use plan for Bolinas Lagoon in 1972 with the intent of preserving the lagoon and managing it as an ecological reserve (County of Marin, 1972). This plan limits the use of the lagoon and surrounding area to those practices which are compatible with the lagoon ecosystem. Preservation of the present lagoon ecosystem requires: (1) limitation of sedimentation in the lagoon; and, (2) maintenance of an entrance channel to provide adequate tidal circulation.

The Bolinas Lagoon entrance channel appears to be in equilibrium with its present tidal prism (Figure 9.5) so that it will maintain the existing channel cross sectional area unless the tidal prism is modified However, the gradual filling of the lagoon by natural sedimentation is slowly reducing the tidal prism so that the entrance channel will eventually close. Johnson (1973) cites estimates of the rate of sedimentation in Bolinas Lagoon that suggest conversion of the lagoon will occur in the next 500 to 2000 years. Ritter (1973) compiled a sediment budget for Bolinas Lagoon and estimated from the present rate of lagoon sedimentation that it would be filled to the highest water level in 340-650 years. However, the entrance channel to the lagoon will close before the lagoon is filled to the high water level. Our understanding of the physical processes that affect the present lagoonal ecosystem indicate that certain measures could be used to prolong its existence. Some of these measures which may be practical at Bolinas Lagoon will be discussed below.

The principal cause for the progressive change from a lagoon to dry land is the filling of the lagoon by sediment; thus, if the rate

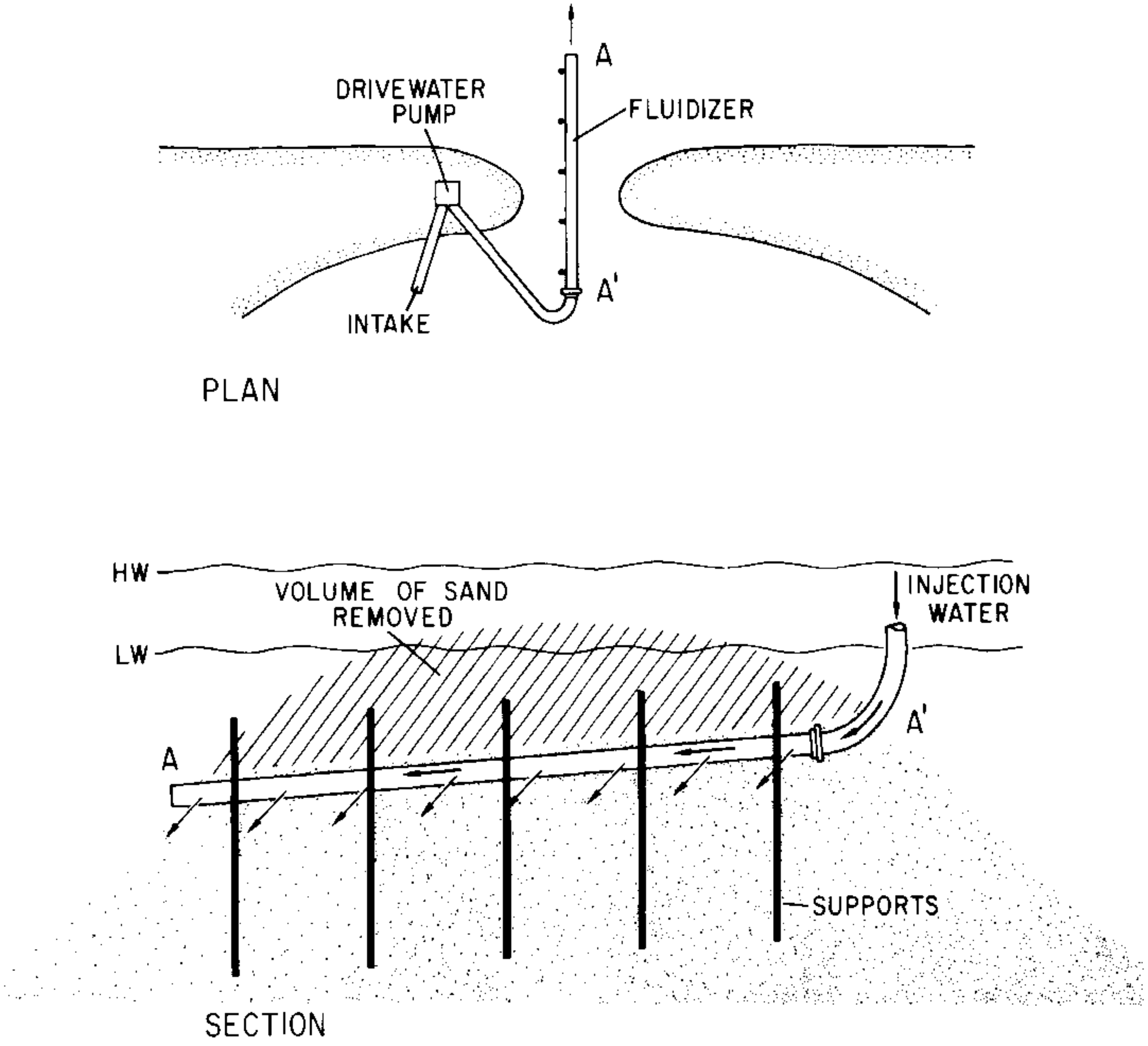


Figure 9.5. Schematic diagram of fluidizing pipe in a lagoon channel showing the artificial duct and support pipes.

of sedimentation can be reduced the life of the lagoon will be lengthened. The Marin County plan recognizes this aspect of change in the lagoon ecosystem and requires that artificial filling of the lagoon be stopped and any activity which increases erosion in the contributory watersheds be controlled to prevent acceleration of the lagoon filling. The rate of sedimentation in the lagoon can be reduced by controlling the natural influx of sediment from the contributory streams. Debris dams could be installed on Pine Creek and the other smaller drainage basins to trap the sediment upstream and prevent it from reaching the lagoon.

Sediment input from other sources can also be controlled to some degree with established procedures. Aeolian transport into the lagoon can be reduced by stabilizing the dunes on Stinson Spit with retention structures or vegetation. However, since this area is undergoing development sand transport into the lagoon is being reduced by the construction of houses over the former dune field. The influx of sediment through the entrance channel by tidal currents and waves can be controlled by monitoring changes in depth near the entrance channel and noting where accretion occurs within the lagoon. When significant filling takes place the material can be removed by periodic dredging to maintain the existing tidal prism.

Implementation of these procedures to control sedimentation in the lagoon can maintain the present tidal prism and natural entrance channel configuration. This intervention into the natural history of the lagoon will prolong the present ecosystem indefinitely unless a catastrophic environmental change occurs. It must also be recognized that these sedimentation control procedures have ecological implications that must be considered relative to the preservation of the lagoon. For instance, the problem of disposal of sediment artificially retained in the drainage basins or removed from the lagoon can be very serious. Disposal techniques and ecologically appropriate disposal sites can be very difficult to establish and may create problems more serious than the sedimentation in the lagoon.

An alternative to reducing sedimentation in the lagoon would be to permit the filling process to proceed naturally and when the tidal prism is reduced to where the entrance channel closes, then develop remedial actions for maintaining the channel. There are several possible remedial actions that could be applied to the problem of providing limited tidal circulation in Bolinas Lagoon.

When the Bolinas Lagoon entrance channel becomes too restricted in cross section to allow adequate tidal flow to the lagoon the most elementary remedial action which could provide a solution would be to periodically enlarge the channel with a dredge or bulldozer. This procedure has been used to open some Southern California lagoons with limited success. Lagoons that have been opened by mechanical means usually close in a relatively short time but the tidal exchange established while it is opened can often sustain the lagoonal ecosystem for several months. This procedure could be applied to Bolinas Lagoon which occasionally closes and needs minimal mechanical assistance to remain open.

Lagoon entrance channels can also be maintained by duct-flow fluidization which will transport sand from the channel. Duct-flow fluidization involves using high pressure drive water and a fluidizing pipe that is placed along the axis of the channel to be closed. The fluidizing pipe is closed at one end and has a series of jets along its underside. These jets are drilled into the pipe at an angle so that the water is directed along the length of the pipe. In principal, the jets of water from the pipe suspend and simultaneously transport sand as a concentrated slurry within a duct formed in the sand beneath the fluidizing pipe (Figure 9.5). As sand is removed from beneath the pipe it is replaced by sand immediately above the pipe until a trench is formed along the channel axis. Sand from this trench is moved offshore by gravity flow into deeper water. The details of operation and an analytical model of the fluidizing process are given in Bailard and Inman (1975).

Another possibility for maintaining lagoon entrance channels which could be applied to Bolinas Lagoon is by inducing anisotropic sand transport in the channel. This remedial action involves constructing a small secondary channel between the ocean and lagoon which is equipped with a tidal gate. The tidal gate on the secondary channel is opened during flood tide and closed during ebb tide in order to increase the tidal flow into the lagoon. This procedure increases the ebb tide flow through the entrance channel so that the scouring action is imbalanced in the seaward direction. Experiments with a simple model of this procedure indicate that there is a 12 percent increase in the seaward transport for a 1 percent secondary flow into the lagoon (Costa and Isaacs, 1975). Preliminary investigation of this procedure suggests that it has promise for maintaining lagoon entrance channels that may close due to reduced tidal prism.

In conclusion, the recommendations for the Bolinas Lagoon area are directed toward procedures for mechanically maintaining the lagoon entrance channel in the event the tidal prism cannot generate currents to scour a natural channel. These recommendations assume that closing of the channel will be a problem in the foreseeable future due to continued filling of the lagoon by sediment. However, prediction of when the channel will close cannot presently be made because data on the sedimentation rate in the lagoon is not available. An accurate measurement of the overall sedimentation rate in the lagoon is essential data and could lead to an estimation of when the entrance will close and remedial action will have to be implemented for preservation of the lagoonal ecosystem.

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