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Bolinas Lagoon Inlet, California.

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<p>The hydraulic and sedimentary characteristics of tidal inlets on sandy coasts have long been of interest to engineers involved in harbor design and maintenance. O'Brien (1931), in a study of west coast inlets, proposed a relationship between the minimum inlet area below mean sea level and the tidal prism. Other investigators in recent years have proposed similar relationships. A reanalysis of data from inlets on U.S. coasts by O'Brien (1967), resulted in a later observation (O'Brien, 1971); he believed that the equilibrium relationship between inlet area and tidal prism as he originally proposed seemed to be a first approximation only and that the next effort should be for quantitative understanding of deviations from the approximation. If the flow area is determined by the tidal prism,</p> <p style="text-align: right;">(Continued)</p>										

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then this area is in constant process of adjustment because the tide range, and the related tidal prism, varies continually.

The Bolinas Bay-Bolinas Lagoon system is a natural laboratory in which a large amount of data has been compiled on hydrography, wave action, tidal hydraulics, sediment transport and sedimentation, and the ecosystem. However, the data are insufficient to adequately define the importance of the inlet area and tidal prism. The source, nature, and availability of data on the Bolinas Lagoon inlet are summarized as a guide to possible future studies at Bolinas, and at other inlets.

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PREFACE

CERC is publishing this report because of its interest and value to coastal engineers.

This report was prepared by J. W. Johnson, Hydraulic Engineering Laboratory, College of Engineering, University of California, Berkeley. Work was completed during the author's sabbatical-leave studies in the fall and winter quarters, 1972-73.

NOTE: Comments on this publication are invited.

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JAMES L. TRAYERS
Colonel, Corps of Engineers
Commander and Director

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BOLINAS LAGOON INLET, CALIFORNIA

by
J. W. Johnson

I. INTRODUCTION

The hydraulic and sedimentary characteristics of tidal inlets on sandy coasts have long been of interest to engineers involved in harbor design and maintenance. It was not until 1928, however, that E. I. Brown (1928) expressed the hydraulic conditions at an inlet in a rational manner and discussed in general terms some of the sedimentary problems. Later M. P. O'Brien (1931) made a study of west coast inlets and proposed a relationship between the minimum inlet area below mean-sea-level and the tidal prism. Several investigators (Brunn and Gerritsen, 1960; Wiegel, 1964; Frautschy and Inman, 1954; Inman and Frautschy, 1965), in recent years, used data from inlets on many sandy coastlines and proposed relationships between inlet area and tidal prism, but all of these relationships agree relatively closely with that of O'Brien (1931).

Recently O'Brien (1967) reanalyzed all available data from inlets on the west, east, and gulf coasts of the United States, and proposed a relationship which was accurate, between ± 10 percent in flow area and ± 15 percent in tidal prism. O'Brien (1971) later observed that the relationship seemed questionable since, (a) there appeared to be no effect of the size of sand forming the channel and adjacent shores, (b) the range of tide enters only as it affects the tidal prism, (c) the net and gross rate of transport of littoral drift is not effective, (d) both unimproved and improved inlets are included, (e) lagoons with two inlets conformed if the summation of the flow areas was used, (f) the inlets to both lagoons and estuaries followed the same relationship, and (g) there appears to be no effect of freshwater flow or of sediment transport.

O'Brien (1971) further stated that he found it difficult to visualize how it is possible that these influences would be completely ineffective in altering the throat area. He believed that the equilibrium relationship between inlet area and tidal prism as he proposed would seem to be a first approximation only, and that the next effort should be directed towards quantitative understanding of deviations from it. If the flow area is determined by the tidal prism, it would follow that this area is in a constant process of adjustment, because the tide range, and the related tidal prism, varies continually. To adequately define the importance of the variables involved in the hydraulic and sedimentary characteristics of inlets on sandy shorelines, data are necessary on such items as (a) simultaneous tides in the ocean and in the lagoon, (b) bottom changes of the inlet throughout the year, (c) friction losses, and (d) bottom sediment size distribution and sand waves. Such data are difficult, expensive, and often hazardous to obtain.

Bolinas Lagoon inlet is a natural laboratory in which a large amount of data has been collected over the years—perhaps more than for any other lagoon in existence. Even then, the data are insufficient to define adequately the importance of the variables involved in the relationships discussed above. However, the source, nature, and availability of data on the Bolinas Lagoon inlet are summarized here as a guide to possible future desirable studies at Bolinas and at other inlets.

II. NATURE AND SOURCES OF BASIC DATA

1. **General.** Bolinas Lagoon, 1,100 acres in area and located in Marin County about 15 miles northwest of San Francisco, is separated from the ocean (Bolinas Bay) by a long sand spit. (See Figures 1 and 4.) In 1956, the Bolinas Harbor District was formed to investigate the possibility of establishing a harbor of refuge in Bolinas Lagoon. In 1966, Norman T. Gilroy and Associates were engaged to coordinate, implement, and report on a multidisciplinary program of study and research into the natural environmental systems of the lagoon and its watershed, designed as the first step for planning the long-term conservation and use of the region and the lagoon. The natural environment of Bolinas Lagoon was analyzed in three fundamental segments—the watershed, the system of natural dynamics of Bolinas Lagoon and Bolinas Bay, and the ecosystem. The scope of these various studies has been published by Gilroy (1970a, 1970b).

For the watershed studies, the U.S. Geological Survey (USGS), in cooperation with the Bolinas Harbor District, began an investigation of the hydraulic and sedimentation characteristics of the lagoon to provide information on: the freshwater inflow into the lagoon, the quantity of fluvial sediment transported into the lagoon, the quantity of sediment transported into and out of the lagoon through the tidal inlet, the direction of littoral transport near the inlet, the circulation of water within the lagoon, the bottom topography, and the sediment movement within the lagoon. Some of the data from these studies have been published by Ritter (1969). Not all of these data, however, relate to the inlet itself, but where the data are pertinent to this report a summary is presented at the appropriate place below.

Of particular importance to the sedimentation problem in Bolinas Lagoon is the following comment by Ritter (1969):

“Lagoons are temporary features along a coast. A generalized history of a lagoon may begin with a river mouth drowned by a rising sea level. Littoral drift creates a spit or barrier bar across the mouth so that its access to the ocean is restricted to a narrow inlet. The lagoon begins to fill with sediment and becomes a tidal flat with channels carrying much of the tidal water. The filling continues until the lagoon becomes a salt marsh as vegetation grows on the rising tidal flats. Eventually, the lagoon becomes a flat plain that may be eroded by waves lapping against its seaward edge. The life of a lagoon depends on the rate at which sediment is entrapped in the lagoon.

Bolinas Lagoon, the seaward end of a rift valley created by the San Andreas Fault, is now probably in the stage of a tidal flat that is becoming a salt marsh.”

Figure 1. Vicinity map, central California coast. (Johnson, 1965.)

This item about Bolinas Lagoon becoming a salt marsh is ecologically important. As Ritter (1969) points out, Bolinas Lagoon is now a recreation area used for clamming, fishing, boating, nature studies, bird watching, and other *saltwater-oriented* uses. However, and probably overlooked by those most active in striving to maintain the lagoon in its present natural state, the inlet may close completely long before sedimentation has reduced the lagoon to a salt marsh, the environment will shift in a few years from a saltwater lagoon to a brackish or possibly freshwater lagoon. Examples of closed lagoons in this general area are Abbotts and Rodeo Lagoons.

To appraise the sedimentation processes at the Bolinas Lagoon inlet requires information such as: repeat bottom and beach face surveys at frequent time intervals, aerial photographs, wave data, littoral-current data, tide and tidal current data, and the physical properties of bottom and beach sediments. A summary of the nature, extent and availability of these various data follows:

1. Hydrographic surveys by the U.S. Coast and Geodetic Survey (USC&GS) were made in Bolinas Bay as follows:

Chart No.	Date	Scale
H-438	1854	1:10,000
H-456	1855	1:20,000
H-721	1858-60	1:100,000
H-4975	1919	1:20,000

2. Hydrographic surveys along the northern part of Bolinas Bay near the mouth of Bolinas Lagoon were made by R. M. Towill Corp. for the Bolinas Harbor District at a scale of 1 inch = 200 feet on the following dates (Gilroy, 1970a, App. No. 3): 17 May, 21 Aug., 19 Dec. 1968; 15 Apr., and 16 May 1969.

3. Beach profiles along three ranges on the Stinson spit were surveyed on several occasions by Trask (1959), and Trask and Snow (1961) of the University of California. (See Figure 4.)

4. Beach profiles along five ranges on the Stinson spit were surveyed by the Corps of Engineers (1965) in March and August 1961. The same well-referenced ranges were resurveyed in March and April 1969 by the California State Lands Division (1970).

5. A range across the Stinson spit was established by the State Lands Division near the Corps of Engineers' Range BB-3 early in 1969, and was measured daily for about 6 months by Stinson State Park personnel at 16 points along the range. (Thompson, 1970.)

6. In the vicinity of the range (5) above, the State Lands Division established the position of mean high tide line for a distance of about 500 feet along the beach face on 11 occasions from October 1948 through December 1969. These data are available from State Lands Division (1970) in Sacramento.

7. Bottom topography within Bolinas Lagoon was obtained from soundings made in July and August 1939 by the San Francisco District, Corps of Engineers, (1939 and 1956).

8. Bottom topography within Bolinas Lagoon was obtained from aerial photography by R. M. Towill, Corp. for the Bolinas Harbor District, (Gilroy, 1970a), and by the USGS in 1967 from profiles of the bottom along 25 ranges. (Ritter, 1969.)

9. Soundings in the Bolinas Lagoon entrance channel were made in October 1956 by the San Francisco District, Corps of Engineers (1956).

10. Three cross sections at the throat of the Bolinas Lagoon inlet were obtained when the USGS measured the quantity of sediment moving in and out of the inlet, 22 June, 24-25 October 1967, and 16-17 May 1968. (Ritter, 1969.)

2. Wave Data. The most important factors in coastal sediment processes in the nearshore area are wave action and tidal currents. Wave data representative of the general area of Bolinas Bay have been compiled from visual observations, the hindcasting technique, and a recording wave meter. The nature and period of record of these various data follow:

a. San Francisco Light Ship. These data were obtained by visual observation every 6 hours (0430, 1030, 1630, and 2230 PST) and transmitted to the U.S. Weather Bureau in San Francisco where the wave height, period, and direction were entered in code on the weather charts issued for each of these 6-hour periods. The weather charts for the 3-year period from 1 September 1949 through 31 August 1952 were procured, and the wave data summarized by wave roses. (Johnson, 1953.) These roses show the percent of time that various wave heights and periods occurred during the various months of the year averaged from the 3 years of record. Such data are relatively crude compared with the other data listed below.

b. Hindcast for Deepwater Station (37.5°N, 123.0°W). Wave roses were prepared for a deepwater station by hindcasting from weather maps for the 3-year period 1936–1938. (Scripps Institution of Oceanography, 1947.) The 3-year period was considered to give a good representation of the average wave conditions, but did not necessarily include the most extreme conditions which could occur. Data on southern swell also were not included. The roses show the percent of time that waves of various heights occur during three periods throughout the year—summer, winter, and a transition period.

c. Hindcast for Deepwater Station (37.6°N, 123.5°W). Deepwater wave statistics for 10 stations along the California, Oregon, and Washington coasts were compiled by hindcasting techniques using meteorological records and charts for the years 1956, 1957, and 1958. (National Marine Consultants, 1960a, 1961.) The statistics include wave height, wave direction, and wave period of both sea and swell, and are presented as monthly and annual averages in both tabular form and roses. As in item *b* above, data on southern swell are not included. Station 3 for the California coast (National Marine Consultants, 1960a) located at Lat. 37.6°N and Long. 123.5°W provides wave data which are representative of conditions offshore from Bolinas Bay.

d. *Hindcast of Severe Storms.* Wave statistics were compiled by hindcasting techniques for the 10 most severe storms for three selected stations off the Northern California coast during the period 1951–1960. (National Marine Consultants, 1960b.) Station 3 (37.6°N, 123.5°W) is representative of severe wave conditions offshore in deep water from the Golden Gate. For each storm the significant heights and periods and direction of waves are tabulated for four times each day for the duration of the storm.

e. *Bolinas Bay Wave Recorder.* A pressure-type wave recorder was installed in 18 feet of water in Bolinas Bay by the Bolinas Harbor District in February 1969. Except for a few days, when the recorder was inoperative due to power or other failures, continuous records were obtained from 20 February to 23 August 1969. Significant heights and dominant periods at the wave gage were compiled and plotted against time. (Gilroy, 1970a, App. No. 3.) No data were available on wave direction.

f. *Stinson Beach State Park and Bolinas, California.* Surf observations at Stinson Beach by State Park personnel and at Bolinas by personnel of the Bolinas Harbor District were instituted in May 1968 following procedures prescribed by the Coastal Engineering Research Center (CERC). (Darling, 1968; Berg, 1968.) Visual observations (twice daily) were made and recorded on wave period, height, and direction; breaker type; wind speed and direction; littoral current speed and direction; berm height; and beach slope. A report on the observations at Bolinas and Stinson Beach State Park for the period February–December 1968 has been published by CERC. (Szuwalski, 1970.) Computer readouts for the entire period of record are available upon request from CERC.

3. *Wave Refraction.* Wave data from the San Francisco Light Ship and the three hindcast summaries (items *a*, *b*, *c*, and *d* in the above section) refer to deepwater conditions. When waves move from deep water into shallow water, changes in the wave heights usually occur as a result of refraction and diffraction. The characteristics of the bottom topography, the wave period, and the direction in deep water determine the pattern of the wave crests, and consequently the wave heights, in shallow water.

Refraction diagrams prepared by the San Francisco District, Corps of Engineers (Table 1) show how the waves from deep water transform while approaching the central California coastline.

Table 1. Corps of Engineers Refraction Diagrams for the Central California Coast

Location	Wave (sec)	Wave Direction	Scale
Point Reyes to Santa Cruz	8	NW	1:210,000
Golden Gate north to Fort Ross	8	W	1:210,000
	8	SW	1:210,000
	12	WNW	not given
	12	W	1:210,000
	12	SW	1:210,000
	16	NW	not given
	16	WNW	not given
	16	W	1:210,000
	16	SW	not given

The refraction diagrams listed in Table 1 are on so small a scale that the orthogonals terminate at about the 10-fathom contour; hence, no information is given on the refraction of the waves as they move into the shallow water of Bolinas Bay. To provide such information, a few refraction diagrams at a large scale have been prepared for waves of the average period of 12 seconds approaching from the critical directions of west-northwest, west, and south-southwest. (Gilroy, 1970a, App. No. 3.)

4. Wave Power. In certain coastal sedimentation processes, such as the possible closure of tidal inlets, the wave power at the shoreline appears to be important. Wave data compiled by the hindcast technique for 10 deepwater stations along the California, Oregon, and Washington coasts (National Marine Consultants, 1960a, 1961) have been used in the preparation of a summary of annual wave power for these 10 Pacific Coast stations. (Johnson, Moore, and Orrett, 1971.) This summary also contains wave power data by months for Station 3 off the California coast at Lat. 37.6°N and Long. 123.5°W. The wave power, P , in deep water is given as follows:

$$P = \frac{E}{2T}$$

where

$$E = \text{Energy per unit width of crest} = \frac{\gamma H_o^2 L_o}{8}$$

$$H_o = \text{Deepwater wave height}$$

$$L_o = \text{Deepwater wave length}$$

$$T = \text{Wave period}$$

$$\gamma = \text{Unit weight of water}$$

or the power in ft-lbs per sec per unit width of crest is

$$P \propto H_o^2 T$$

The total power for a month would equal the product of the average power per second for that month times the number of seconds in the month. Since the compilation of statistical data (National Marine Consultants, 1960a) gives the percentage of time that waves of various heights and period occur, the total power for each month has been computed for both sea and swell, and is discussed in Section III.

5. Longshore Currents. When waves break at an angle to the shore, a longshore current is induced, and is effective in moving water and sediment along the shore. Observations of the

strength and direction of longshore currents at the Stinson Beach State Park and at Bolinas were started in May 1968, and continued for about 2 years at Stinson Beach and 1 year at Bolinas. The observations for 1968 have been published by CERC. (Szuwalski, 1970.) Printouts of the complete records are available upon request.

6. Littoral Transport. Littoral transport is defined as the movement of material in the littoral zone by the wave-generated littoral currents. In 1965, an 80-mile reach of the central California coast, extending from the mouth of the Russian River in the north to Half Moon Bay in the south (Fig. 1), was studied for the characteristics of sediment movement in the nearshore zone. From the results of many beach and offshore sediment samples and other information, several techniques were utilized in appraising the nature of sediment movement along this coastline. The following were studied: (a) the physical nature of the coastline from a consideration of the prevailing wave energy, (b) the distribution of light and heavy minerals and their sources, (c) the use as tracers of certain naturally radioactive minerals, and (d) the sedimentation experience at harbors where both natural and stabilized entrances exist. It was concluded from these studies that the transport of nearshore sediments in this region (which includes Bolinas Bay) is relatively small. (Johnson, 1965.)

The only actual measurements of sediment movement in Bolinas Bay were a limited number of observations on littoral drift made by the USGS using fluorescent-dyed sand at three beach sites in the Bay. (Ritter, 1969.) Other data providing information on the general movement of sediment in the entire Bolinas Bay resulted from the use of heavy minerals as tracers. (Wilde, et al., 1969; Wilde and Yancey, 1970.)

7. Bottom Sediments. The mechanical and mineralogical characteristics of beach and offshore sediments in Bolinas Bay have been under investigation for several years by the University of California on a project sponsored by CERC. (Moore, 1965; Isselhardt, et al., 1968 and 1969; Wilde, et al., 1969.)

8. Tidal Relationships. The reference tide station for central California is the National Ocean Survey (NOS) (formerly USC&GS) gage located at The Presidio, San Francisco. Lower low water datum at this station is based on miscellaneous observations prior to 1907, and adopted as standard in March, 1907. Elevations of other tide planes referred to this datum are based on the 19 years of records, 1941-59. The USC&GS operated a tide gage for a short period at Bolinas (probably immediately inside the Lagoon entrance) and apparently used these data in calculating the difference in the time and height of tides at Bolinas Bay and Bolinas Lagoon with respect to The Presidio, San Francisco. The 1972 NOS Tide Tables for the west coast of North and South America give the tidal differences shown in Table 2. Additional statistical data on tidal planes at San Francisco, Bolinas Bay, and Bolinas Lagoon are presented in Table 3.

9. Surveys of Beaches and Bottom. As previously mentioned, several beach and bottom surveys were conducted over the last few years by various agencies to determine the hydrography in both Bolinas Bay and Bolinas Lagoon, and to evaluate seasonal changes of the shoreline in this area. Details of these surveys follow:

Table 2. Tidal Differences—Bolas Bay and Bolas Lagoon

Place	Differences				Ranges	
	Time (hrs—min)		Height (ft)		Mean (ft)	Diurnal (ft)
	High Water	Low Water	High Water	Low Water		
Bolas Bay	−0.29	−0.17	0.0	0.0	4.0	5.7
Bolas Lagoon	−0.20*	+0.31	0.74†	0.73†	3.0	4.4
San Francisco (Golden Gate) — Daily predictions					4.0	5.7

*A plus (+) sign indicates that the tide at the subordinate station is later than at the reference station, San Francisco, and the difference should be added, a minus (−) sign, that it is earlier and should be subtracted.

†Ratio of height at subordinate station to the height at San Francisco.

Table 3. Tidal Data

Tidal Plane	San Francisco (feet)	Bolas Bay (feet)	Bolas Lagoon (feet)
Highest Tide, 24 Dec. 1940	8.0	—	—
Higher High Water	5.7	5.7	4.4
High Water Springs	5.5	5.5	4.1
Mean High Water	5.1	5.1	3.8
High Water Neaps	4.7	4.7	3.5
Mean Tide Level	3.1	3.1	2.3
Sea Level Datum (1929)*	—	2.8	1.9
Low Water Neaps	1.5	1.5	1.1
Mean Low Water	1.1	1.1	0.8
Low Water Springs	0.7	0.7	0.5
Mean Lower Low Water	0.0	0.0	0.0
Lower Low Water	−0.2	—	—
Lowest Tide, 26 Dec. 1932 and 17 Dec. 1933	−2.70	—	—
Tidal Range			
Diurnal	5.7	5.7	4.4
Mean	4.0	4.0	3.0
Spring	4.8	4.8	3.6
Neap	3.2	3.2	2.4

*The U.S. Geological Survey mean sea level is identical with the 1929 U.S. Coast and Geodetic Survey sea-level datum.

a. *Corps of Engineers.* Bottom surveys in Bolinas Lagoon were made between 26 July, and 8 August 1939 and in October 1956. Five ranges along the bay side of Stinson Beach spit were surveyed in March and August, 1971. Depths and elevations in all of these surveys were referred to local MLLW. At the time of these surveys, MLLW was listed by the USC&GS as being 2.07 feet below the 1929 sea-level datum (SLD). On 6 May 1965, the USC&GS revised these values such that now MLLW in Bolinas Lagoon is listed as being 1.9 feet below the 1929 SLD. The five Corps of Engineer ranges were resurveyed (on the beach face only) by the State Lands Division, 3-4 March, and 3 April 1969. The Corps' bench marks, previously established in their 1961 surveys, were used for the vertical control; mean lower low water was assumed as 2.07 feet below the 1929 USC&GS sea-level datum.

b. *Bolinas Harbor District.* In 1968 and 1969, the Harbor District contracted with R. M. Towill Corp. of San Francisco to conduct the five bottom surveys offshore in Bolinas Bay as previously mentioned. Surveys of Bolinas Lagoon were also made by R. M. Towill Corp. from aerial photographs taken at low tide on 16 May 1968. All of the above surveys give soundings below the 1929 USC&GS sea-level datum.

c. *U.S. Geological Survey.* In August and September 1967 profiles of the bottom of Bolinas Lagoon were surveyed along 26 referenced ranges to document the location and configuration of channels. Elevations and depths were referred to the 1929 USC&GS sea-level datum.

d. *State Lands Division.* From 1948 to 1968, the State Lands Division determined the alinement of mean high tide for a distance of about 500 feet along the beach face on Stinson Beach Spit. Mean high tide was assumed to be 3.8 feet above the mean lower low water for Bolinas Lagoon (Table 3) or 1.9 feet above the 1929 sea-level datum.

10. *Tidal Prism.* O'Brien (1967) established a unique relationship between the minimum flow cross section of a tidal inlet and tidal prism (the volume of water that flows into and out of the lagoon during a tidal cycle). From the R. M. Towill bottom surveys of Bolinas Lagoon, the USGS (J. R. Ritter, 9 July 1971, private communication), prepared a contour map of the lagoon and calculated the volume of water in the lagoon at several tide stages as follows:

Tide Stage (MSL Datum) (feet)	Volume (million cu ft)
-6	0.0
-4	3.0
0	79.2
+2	161.0
+4	257.0
+6	360.0

From a plot of these data the tidal prism between MLW (+0.8 MLLW) and MHW (+3.8 MLLW) was determined to be 109 million cubic feet.

11. Tidal Currents. Data on currents resulting from tidal action within Bolinas Bay are relatively sparse. Known data follow:

1. Measurement of water and sediment flow through a section of the entrance to Bolinas Lagoon was made over a tidal day by the USGS on three occasions, 22 June, 24-25 October 1967, and 16-17 May 1968. (Ritter, 1969.)

2. A limited number of current measurements by the use of current drogues, dye, and bottle caps were made in Bolinas Bay and vicinity in connection with a sewerage study for Marin County. (Brown and Caldwell, 1967.)

12. Sediment Transport in Bolinas Lagoon Inlet. Suspended-sediment discharge in or near the inlet was measured during the tidal current measurements mentioned above. (Ritter, 1969 and 1972.)

13. The Ecosystem. Although not of primary importance in relation to the inlet to Bolinas Lagoon, an extensive series of studies of the ecosystem of the lagoon was completed by a team led by Joel Gustafson of Resources and Ecology Projects, Inc. Reports on this phase of the total investigation of Bolinas Lagoon are included in the report by Gilroy (1970a, App. No. 6).

III. SUMMARY OF DATA RELEVANT TO THE INLET

The investigations pertaining to various natural processes occurring in the Bolinas Bay-Bolinas Lagoon-system were briefly described in Section II. Data for those aspects of the system which specifically influence the dynamics of the Bolinas Lagoon inlet are summarized as follows:

1. Wave Data. The most reliable data on wave climate and severe storm conditions for the central California coast are those compiled by National Marine Consultants (1960a, 1960b) for Station 3 at Lat. 37.6°N , Long. 123.5°W . (See Figure 1.) Figure 2 presents the average annual sea and swell data for Station 3. These data are for deep water, and to project such information to the vicinity of the Bolinas Lagoon inlet requires the use of wave refraction diagrams for a large range of wave periods and directions. An illustration of wave refraction into Bolinas Bay is shown in Figure 3 for a 12-second wave from the west.

As previously mentioned in Section II, some visual observations of wave conditions were made in 1968-69 at Stinson Beach State Park and at Bolinas. Also, a wave gage was operated offshore between the two beach stations. The locations of these observation sites are shown in Figure 4. It is of interest to note that the wave direction observed at the Bolinas station by a special sighting device showed that for the entire period of observation waves approached the Bolinas Lagoon inlet within a narrow sector between 10° and 20° east of south. (Gilroy, 1970a, App. No. 3.) Summaries of data on wave power and littoral currents derived from observed and hindcast wave data are presented below.

2. Wave Power. As mentioned in Section II, computations of wave power (both sea and swell) were made for Station 3 offshore from the Golden Gate. (Johnson et al., 1971.) A plot of the monthly wave power ($H_0^2 T$) for all directions of both sea and swell is shown in Figure 5. The power in swell is relatively small in this region during June, July, and August.

Figure 2. Sea and swell roses, west of Golden Gate. (National Marine Consultants 1960a, 1960b.)

Figure 3. Wave refraction diagram. Twelve-second period wave from west.
(Gilroy, 1970a.)

Figure 4. Location of bottom surveys, beach ranges, beach observation sites, and wave gage in Bolinas Bay. (Johnson, 1970.)

Figure 5. Deepwater wave power (sea and swell) for various months at Station No. 3, California coast. (Johnson, et al., 1971.)

The power in sea, on the other hand, increases gradually from January to July, and then decreases during the remainder of the year. The sum of sea and swell also is shown in Figure 5. This latter curve shows that total wave power is least during July, August, and September.

To transpose deepwater wave power shown in Figure 5 to nearshore points in Bolinas Bay requires the use of refraction and diffraction diagrams for a large range of wave periods and directions. Unfortunately such diagrams are not available. However, to obtain some measure of relative intensity of wave power in Bolinas Bay, the visual wave observations (at Bolinas and Stinson Beach State Park) and the data from the wave gage in the bay were used. Wave data for these three locations (Fig. 4) were available for the following periods:

Bolinas, 1 May 1968 to 23 February 1969

Stinson Beach, 1 May 1968 to 30 November 1969

Bolinas Bay wave gage, 20 February 1969 to 23 August 1969

For each of these stations the wave height and period were tabulated for each day of record. The data from the Bolinas and Stinson Beach Stations were breaker heights (Szuwalski, 1970); data from the wave gage were the heights recorded offshore over the underwater pressure unit. Values of H^2T were computed for each day for each location. To smooth the data and provide a visual comparison of the relative magnitude of wave power at the three localities, 5-day moving averages were computed, tabulated, and then plotted in Figure 6. The effect of wave exposure is seen by comparing the plots from Stinson Beach State Park and Bolinas. The Stinson Beach station is more exposed to the prevailing waves from the west-northwest sector than the Bolinas station which is near the Bolinas Lagoon inlet, and consequently receives protection from Duxbury Reef. (See Figure 3.) Unfortunately the Bolinas observation program was terminated before the installation of the Bolinas wave gage; therefore, a comparison of wave power at the gage can be made only with the Stinson Beach data. The wave gage is more protected from wave action by refraction effects than is Stinson Beach.

A further comparison of relative magnitude of wave power is shown in Figure 7. In this figure the monthly wave power (sum of sea and swell) for the offshore station (Station 3) summarized in Figure 5 is plotted along with the monthly wave power as computed from the wave data observed at Bolinas and Stinson Beach. The figures show wave power is least at Bolinas, somewhat higher at Stinson Beach, and both are significantly less than the exposed deepwater station.

3. Longshore Currents. The strength and direction of longshore currents generated by waves breaking at an angle to the shoreline are necessary data in evaluating such shoreline processes as littoral transport and seasonal beach and bottom changes in Bolinas Bay. The only known measurements of longshore currents in Bolinas Bay were the surf observations made at Stinson Beach State Park and at Bolinas. Printout data for these stations were obtained from CERC. Plots of the observations on longshore currents (strength and

Figure 6. Wave power for Station No. 3 (California coast) compared with beach observations at Stinson Beach and Bolinas Bay.

Figure 7. Five-day moving averages of wave power from observations at Stinson Beach, Bolinas Bay, and the Bolinas wave gage.

direction) and wave period from these printouts are shown in Figure 8. The data for the two stations show that there are extended periods when the longshore current prevailed in one direction. For example, from February to June 1969, the longshore current at Stinson Beach was generally in a southeast direction with a reversal occurring on only about 15 days during the 5 months of record. (Johnson, 1970.)

4. Sedimentation Processes—Bolinās Bay. Sedimentation processes in Bolinas Bay cause both short- and long-term effects. The long-term effects are the slow natural changes which may be detected only by a close comparison of bottom and beach surveys which have been repeated over the years. The only sources of reliable information on bottom changes are the USC&GS hydrographic surveys which have been repeated at several intervals since 1854. A comparison of these surveys was made, and it was concluded that the Stinson Beach spit has been stable in geometric configuration since the first survey in 1854; that is, the shoreline of Bolinas Bay is in dynamic equilibrium. (Gilroy, 1970a, App. No. 3.)

a. Bottom Changes. To obtain a measure of the seasonal bottom changes in the area offshore from the inlet, each of the five surveys made between 17 May 1968 and 16 May 1969 for the Bolinas Harbor District was compared with the next following survey. The depth of scour or fill was noted on an overlay. (See Figure 4 for general area covered by the bottom surveys.) These overlays were then contoured to give areas and depth of scour and fill occurring between the two dates. Thus, four comparison maps resulted, and a comparison map for 1 year from the initial survey on 17 May 1968 to the final survey on 16 May 1969. (Gilroy, 1970a, App. No. 3; Johnson, 1970.) An example of these maps is presented in Figure 9 which shows a comparison between the survey of 21 August 1968 and that of 19 December 1968. An area of scour occurred near the entrance of Bolinas Lagoon, but a general fill occurred over the remainder of the area surveyed. The largest fill occurred near the surf zone—probably such material was removed from the beach face and deposited immediately offshore by early winter storms. As a result of this general fill the position of the 30-foot depth contour in December was further offshore than in August.

That sand may be shifted laterally within Bolinas Bay is shown in Figure 10 which compares positions of several depth contours as they existed on 17 May 1968 and on 16 May 1969. This figure shows that the area opposite the entrance to Bolinas Lagoon in May 1969 had been generally filled compared with May 1968; that is, over most of the area the May 1969 contours are seaward of the 1968 contours. On the other hand, at the east side of Figure 10, a region of scour has occurred; that is, the 1969 contours are generally shoreward of the 1968 positions.

This indicates that, between the 1968 and 1969 surveys, sand appears to have been shifted northward from Stinson Beach into the north end of Bolinas Bay. Wave conditions and tidal currents in the following year could possibly be such that the material would be shifted back in an east and southerly direction. In the comparison maps discussed above, the actual depths of scour and fill are subject to some sounding error, but the areas of scour and fill show no randomness and are consistent with seasonal changes generally observed elsewhere.

Figure 8. Wave period and longshore currents, Stinson Beach State Park and Bolinas, California, 1968-69. (Johnson, 1970.)

Figure 9. Areas of scour and fill between 21 August 1968 and 19 December 1968. Values are in feet. (Johnson, 1970.)

Figure 10. Comparison of Bolinas Bay bottom contour maps of 17 May 1968 and 16 May 1969. Contours in feet. (Johnson, 1970.)

Other data that provide information on the general movement of sediment in the entire Bolinas Bay are presented by Wilde and Yancey (1970) who utilized heavy minerals as tracers. Other supplementary data on sediment movement in Bolinas Bay resulted from sand tracing studies along the beach face by the USGS during investigations of sedimentation and hydrology in Bolinas Lagoon. (Gilroy, 1970a, App. No. 5.) This study used the placement of fluorescent-dyed sand on the beach at both the town of Bolinas (Brighton Avenue) and the Stinson Beach State Park with periodic detection of the direction of movement away from the source by use of an ultraviolet lamp. Sand, at both localities, was placed on 23-24 July 1968, and then periodically sampled until late October 1968 when the dyed material either was completely scattered and buried or the dye strength had been greatly reduced.

The results of these limited and qualitative tests by the USGS showed that at Bolinas the movement of sand was always eastward toward the entrance of Bolinas Lagoon, but no material ever crossed the lagoon entrance to the Stinson spit. Although the surf observations summarized by CERC showed a general westerly longshore current in this same locality during the period of the sand tracing studies (Fig. 8), it is possible that tidal currents into Bolinas Lagoon rather than wave-generated longshore currents moved sand generally eastward along the beach.

In the Stinson Beach State Park studies, the dyed sand moved in both the southeasterly and northwesterly directions; some material was detected about 1.5 miles northwesterly up the beach 2 months after initial placement. This might be expected upon examination of Figure 8 which shows that a northwesterly longshore current prevailed over most of the period, (August and September), following the start of the tracer tests.

b. Beach Changes. Beaches exposed to wave action undergo profile changes throughout the year, because of seasonal changes in wave characteristics. One of the most important factors in determining the character of a beach profile is the ratio of wave height to wave length—defined as wave steepness. During extended periods of low wave steepness, low berms usually are built beyond the foreshore with very steep profiles on the beach face, and bars immediately offshore tend to disappear or become discontinuous. During periods of high wave steepness (storm or winter conditions) the beach face becomes less steep and the offshore bars become more pronounced.

On the beaches along Bolinas Bay, the seasonal changes in characteristics are less well defined than the changes in the offshore area. This lack of definition is primarily in the surf zone, and is the result of the difficulties and hazards of making accurate bottom surveys in the surf zone—especially during winter storms. The hydrographic surveys used in preparing the comparison maps (Fig. 9) were made no closer to shore than about the 8-foot depth contour. The data on seasonal beach changes are therefore confined to the beach profiles made by; (a) Trask (1959), and Trask and Snow (1961), and (b) the Corps of Engineers (1965) and repeat surveys of these ranges by the California State Lands Division in 1969. The location of the Corps' ranges is shown in Figure 4. Surveys by the State Lands Division to determine the position of the mean high tide lines over a limited length of the Stinson spit for the period 1948 to 1970 are important in evaluating beach changes in Bolinas Bay.

To provide an accurate measure of the seasonal fluctuations of the width of the beach at Stinson spit, the data on the position of the mean high tide line, as determined by the State Lands Division and other sources on 27 occasions from 1948 to 1970, are of value. To obtain information on the position of the mean high tide line, the distance from a base line to the high tide line was measured and plotted as shown in Figure 11 for the appropriate day of the month. (Johnson, 1971.) There is an obvious cyclic pattern of position of the high tide line with the seasons, but no precise relationship exists because of the variation of intensity of wave attack that undoubtedly occurred from year to year. An upper and lower envelope has been drawn in Figure 11 to enclose the plotted points. This plot shows that the position of the mean high tide lines is more variable from year to year during the spring months than during late summer and fall. The distance between envelopes during the spring may amount to as much as 50 feet, and the beach at the mean high tide line is about 150 feet wider in summer than in winter. The surveys of the five Corps of Engineers ranges showed an average difference in width of about 100 feet between winter and summer conditions of the mean high tide level. (Corps of Engineers, 1965.)

Figure 11. Seasonal variation of the position of the mean high tide line, Stinson Beach spit, 1948–1970. (Johnson, 1971.)

Data which give more detail on the day-to-day changes in a profile on the Stinson Beach spit are those of Thompson (1970) which are plotted in Figure 12. The plots resulted from a field study conducted from 4 January through 2 May 1969 on a profile near the Corps of Engineer's Range 3. (See Figure 4.) This profile was measured daily; the waves incident upon the profile were obtained from the Bolinas Harbor District wave gage. The daily position of the mean low water line, mean tide line, and mean high water line are indicated along with other elevations with respect to the 1929 sea level datum. The wide variation in the position of those lines (with time) in the zone of wave action is strikingly evident.

5. Inlet Characteristics. At most lagoon inlets, two opposing forces control the location and size of the opening. These forces are the ebb currents and the wave forces. The ebb currents provide a flushing action of the entrance and move sand offshore; wave action moves sand shoreward to fill the entrance. Often, the strength of the wave forces exceed those of the ebb currents, and the inlet remains completely closed (except possibly in times of flood, if appreciable stream flow enters a lagoon from a watershed). At bays or lagoons where wave refraction varies the wave height along the barrier beach between the lagoon and the ocean, the tidal inlet will be located where the forces of the ebb currents and the wave forces are approximately in balance. This is the condition at Bolinas Lagoon where charts and photographs show the entrance historically to be always adjacent to the Bolinas headland where refraction effects (Fig. 3) cause the least wave height of any location along the Stinson Beach spit.

Figure 12. Day-to-day variation over a 4-month period of the horizontal distance from a reference point on shore to various beach contours, Stinson Beach spit, California. (Thompson, 1970.)—Part 1

Figure 12. Day-to-day variation over a 4-month period of the horizontal distance from a reference point on shore to various beach contours, Stinson Beach spit, California. (Thompson, 1970).—Part 2

Although the inlet has always been in the same general location, it is probably in a continuous state of change in both cross-section area and planform because of the seasonal variation in the intensity of wave attack and strength of tidal currents. This is readily apparent in the aerial photographs shown in Figures 13 through 20, which cover a 25-year period from 1945 to 1969. These photographs are all reproduced to about the same scale for comparative purposes. Because the photographs were taken at various tide stages, some differences in appearance are obvious; shoal areas are uncovered at low tide, but covered at high tide. Hence, the appearance of the channel across the offshore bar may vary considerably between low and high tide. The aerial photographs (Figs. 13–20) also show that the waves generally break on the offshore bar so that little wave action appears at the gorge or narrowest section of the inlet—except possibly during periods of extreme high tides.

Although the aerial photographs of the Bolinas Lagoon inlet (Figs. 13–20), indicate that changes in the configuration of the channel must be occurring frequently, few bottom surveys of the inlet and adjacent area are available to document the nature and extent of such changes, probably because of the difficulties and hazards in making accurate surveys especially during heavy wave action and strong tidal currents. Some limited information on the changes that occur at the throat section is available from the three USGS discharge measurements in 1967-68. Plots of these cross sections are shown in Figure 21. (J. R. Ritter, 10 May 1971, private communication.) Cross-section areas of these sections below mean-sea-level follow:

A_c = 1330 square feet on 22 June 1967

A_c = 1198 square feet on 24 Oct. 1967

A_c = 1378 square feet on 17 May 1968

Some quantitative information on changes at the Bolinas Lagoon inlet was obtained by the USGS (Beck, 1971) by time-lapse photography during the period from January 1968 until July 1969. A camera, located on the Bolinas bluff, was focused on the mouth of Bolinas Lagoon and the end of Stinson Beach spit to observe the high and low tides.

6. Sediment Transport by Tidal Currents. Suspended-sediment discharge in or near the Bolinas Lagoon inlet was measured during seven ebbs and six floods in June and October 1967. (Ritter, 1969.) The measured suspended load for the ebbs ranges from 3 to 1,150 tons and for the floods from 49 to 152 tons. The suspended load discharge was directly related to average velocity. (Ritter, 1972.) Most of the transported sediment was sand, the concentration of which had considerable temporal, lateral, and vertical variation. The concentration of suspended sediment finer than sand remained relatively constant.

No data are available on the net amount of sand (moved inward and outward at the inlet with each change of tide) that either remains permanently in the lagoon or is carried out of the lagoon system to deposit offshore. Most of the sediments of sand size which are carried into the lagoon by streams from the watershed probably remain in the lagoon and

Figure 13. Aerial vertical photo of Bolinas Lagoon inlet on 1 April 1945. High tide stage is 3.9 feet MLLW. (Hydraulic Laboratory photograph, University of California.)

Figure 14. Aerial vertical photo of Bolinas Lagoon inlet on 31 August 1948; probably taken at high tide. (Hydraulic Laboratory photograph, University of California.)

Figure 15. Aerial vertical photo of Bolinas Lagoon inlet on 25 September 1959. Flood tide stage is 3.8 feet MLLW. (Courtesy of N. T. Gilroy.)

Figure 16. Aerial vertical photo of Bolinas Lagoon inlet on 10 November 1959. Low tide stage is 1.2 feet MLLW. (Courtesy of N. T. Gilroy.)

Figure 17. Aerial vertical photo of Bolinas Lagoon inlet on 24 May 1961; probably taken at low tide. (Photograph, California Department of Fish and Game.)

Figure 18. Aerial vertical photo of Bolinas Lagoon inlet on 19 June 1962; probably taken near low tide. (Courtesy of N. T. Gilroy.)

Figure 19. Aerial vertical photo of Bolinas Lagoon inlet on 27 May 1968; probably taken at high tide. (Photograph, R. M. Towill, Corporation.)

Figure 20. Aerial vertical photo of Bolinas Lagoon inlet on 9 November 1969. Ebb tide stage is 4.4 feet MLLW. (Courtesy of Marin County Planning Department.)

Figure 21. Throat sections at Bolinas Lagoon inlet from U.S. Geological Survey tidal measurements. (J. R. Ritter, 1971.)

contribute to its filling. A large part of the stream-born sediments finer than sand entering the lagoon also probably remains in the lagoon. The USGS studies show that the lagoon's circulatory pattern is nearly inoperative as a self-flushing, self-maintaining, dynamic system. (Gilroy, 1970b.)

Although the Marin County Parks and Recreation Department (1971) recognizes that there are areas in Bolinas Lagoon of pollution, poor circulation, and increased sedimentation, no recommendation has been made to correct a situation which can only lead to an increase in the sedimentation rate in the lagoon and consequent deterioration of the system. To correct this undesirable condition, it would appear to be ideal to apply the principal proposed by O'Brien (1971) to improve the interior channels as follows:

"Dredging shoals between LW and HW in the shallow upper reaches of a lagoon or estuary will not only aid in the maintenance of navigation channels, but will also improve the water exchange and flushing of the lagoon or estuary."

Fine sediments resulting from cliff erosion on the outer coast enter the lagoon on the flood tide. Some of these sediments are carried well into the lagoon, and contribute to its silting.

As emphasized by Ritter (1969) and Gilroy (1970b), nature, with some assistance from man's operation on the watershed, will transform Bolinas Lagoon by sedimentation into a muddy meadow. As mentioned in the General Comments in Section II, a tidal lagoon inlet may be closed completely by the forces of wave action long before the tidal prism is reduced to zero by sedimentation processes in the lagoon. J. R. Ritter, (19 Sept. 1972, private communication), estimates that Bolinas Lagoon will become filled to highest high water in about 500 years, if the present rate of filling (16 acre-feet per year) continues. This rate is based on the rate of deposition over the 29-year period between the bottom surveys by the Corps of Engineers, 1939 and the Bolinas Harbor District, 1968. C. Wahrhaftig (Conservation Foundation, 1971) estimates that the lagoon will be converted to dry land in 500 to 2,000 years if the past average rate of sedimentation were to continue. Actually, the lagoon entrance will probably close completely long before the lagoon is filled with sediment to the highest high water level. The time to closure, however, cannot be estimated because the closure criterion (the ratio of wave power to tidal power) for natural lagoons has not been established. Of interest, however, are the following lagoons along the northern California coast which appear to be always closed.

Lagoon	Surface Area (ft ²)
Lake Earl	10 × 10 ⁷
Freshwater Lagoon	1 × 10 ⁷
Stone Lagoon	2.6 × 10 ⁷
Big Lagoon	6.8 × 10 ⁷
Abbotts Lagoon	0.9 × 10 ⁷

All of these lagoons are fully exposed to the severe prevailing W to NW waves; whereas, Bolinas Lagoon (with a high-water surface of $4.6 \times 10^7 \text{ ft}^2$) is well protected by refraction effects from such wave exposure. Since the surface area of the lagoon is a measure of the potential tidal prism, it appears that Bolinas Lagoon inlet would be completely closed if it were subjected to the same wave exposure as the above listed lagoons.

IV. CONCLUSIONS AND RECOMMENDATIONS

The Bolinas Bay- Bolinas Lagoon-system is a natural laboratory—unique because perhaps more basic data cover almost every aspect of hydrography, wave action, tidal hydraulics, sediment transport, and the ecosystem than for any other lagoon. There are problems, however, in which further studies are highly desirable to provide knowledge on the natural dynamics of a lagoon system which has been undisturbed by man except for some logging operations in the 1870's. From a consideration of the limited flushing action by tidal currents and the rate of sedimentation in Bolinas Lagoon it appears that the inlet will close completely long before the lagoon fills by sedimentation from the watershed, thus converting the lagoon from a saltwater to a freshwater environment. Those additional studies which are desirable and which would in no way influence the present environment of the Bay-Lagoon system or be unsightly in their operation, but which would be applicable to a better understanding of the natural processes occurring in tidal lagoons in general, follow:

1. Install tide gages in the ocean and in the lagoon to obtain data on such tidal hydraulic phenomena as ratio of tidal range in the ocean and lagoon, tidal lag, superelevation, channel friction, and wave setup.
2. Periodically survey the bottom of the inlet channel to document seasonal changes of the inlet resulting from variations in tide and wave action during the year.
3. Operate a wave gage offshore from the lagoon inlet to obtain a record of wave height and period. Supplement the wave gage observations with daily estimates of wave direction.
4. In view of the ecologically depleted condition of parts of the lagoon (pollution, poor circulation, and high sedimentation rates), it appears desirable to investigate further the simple means of correcting this undesirable situation by increasing the tidal prism in the upper reaches of the lagoon. An increase in tidal prism and reduction in sedimentation rates will also delay the time when complete closure of the inlet will occur and convert the lagoon from a salt- to a fresh-water body of water.

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