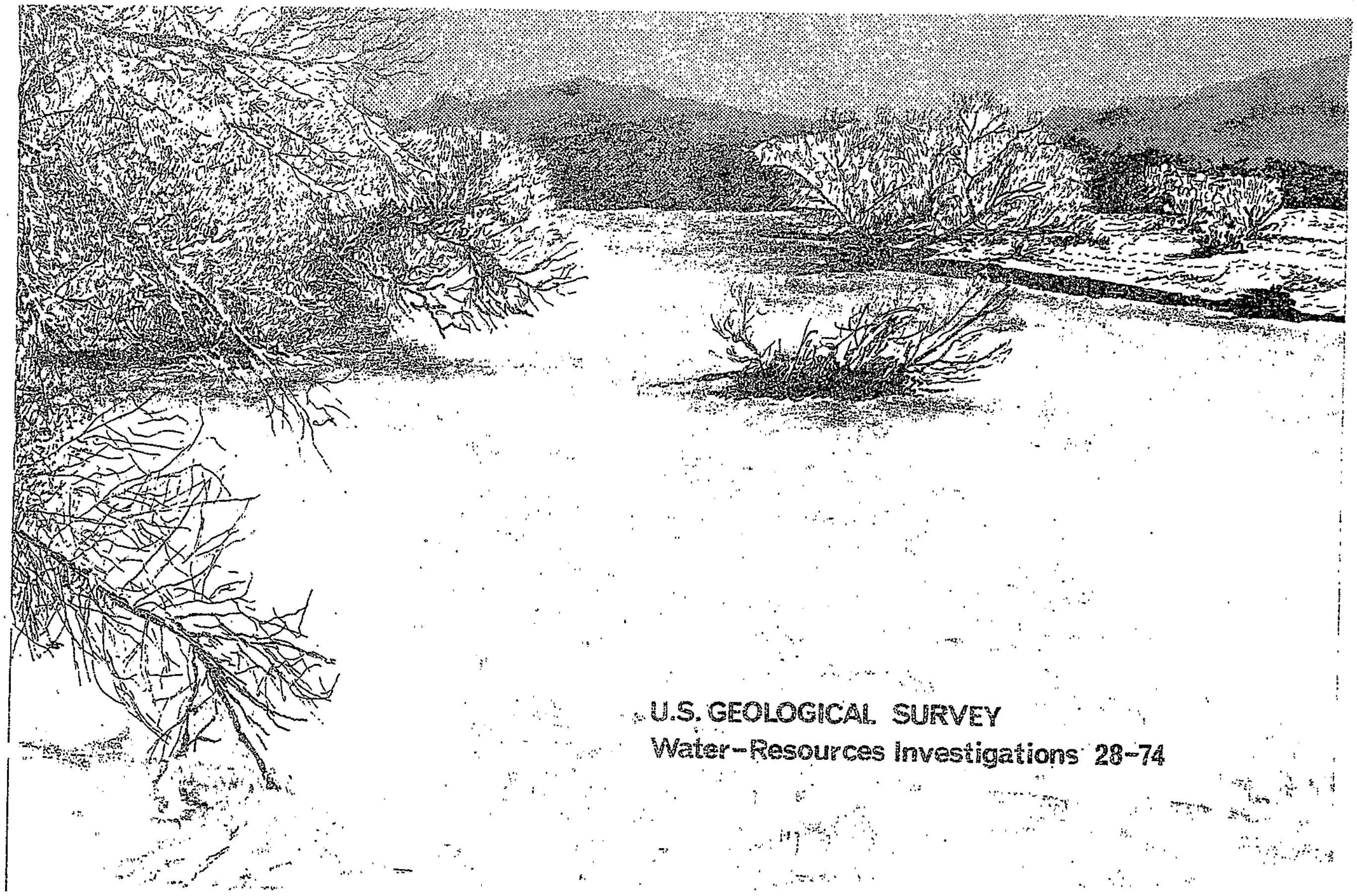
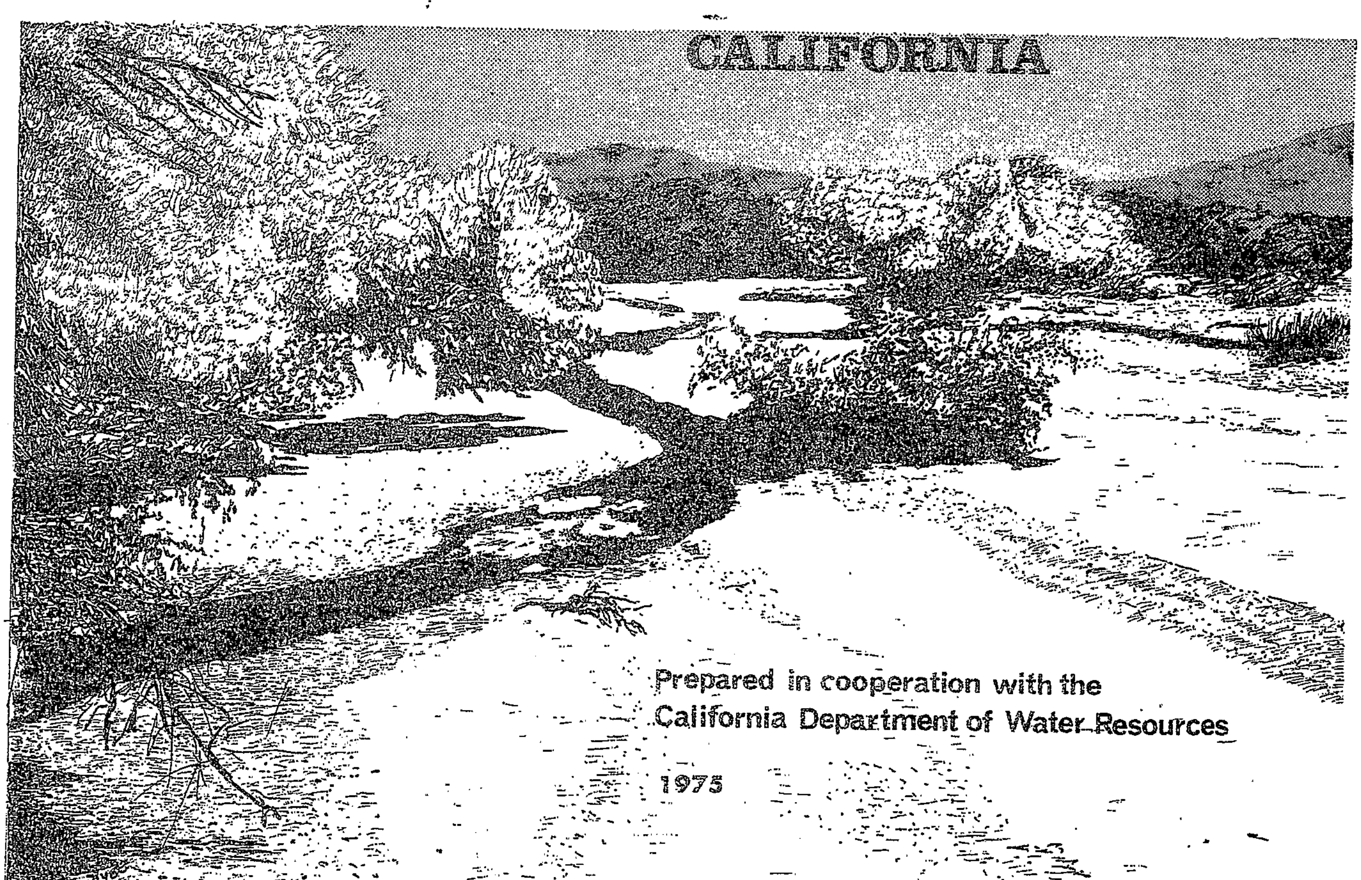


U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 28-74

# EVALUATION of the CAUSES of LEVEE EROSION in the SACRAMENTO-SAN JOAQUIN DELTA CALIFORNIA



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A method for applying findings from the observation channels to other delta channels is proposed.

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By John T. Limerinos and Winchell Smith

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UNITED STATES DEPARTMENT OF THE INTERIOR

Rogers C. B. Morton, Secretary

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## CONVERSION FACTORS

Factors for converting English units to the International System of Units (SI) are given below. In the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English Units.

| *English* | *Multiply by* | *Metric (SI)* |
|---|---|---|
| inches (in.) | 25.4 | millimetres (mm) |
| feet (ft) | .3048 | metres (m) |
| miles (mi) | 1.609 | kilometres (km) |
| square miles (mi$^2$) | 2.590 | square kilometres (km$^2$) |
| feet per second (ft/s) | .3048 | metres per second (m/s) |
| cubic feet per second (ft$^3$/s) | .02832 | cubic metres per second (m$^3$/s) |
| foot-pounds (ft-lbs) | 1.3558 | Joules (J) |
| foot-pounds per foot (ft-lbs/ft) | 4.4482 | Joules per metre (J/m) |

# EVALUATION OF THE CAUSES OF LEVEE EROSION IN THE SACRAMENTO–SAN JOAQUIN DELTA, CALIFORNIA

By John T. Limerinos and Winchell Smith

ABSTRACT

Studies were made in two typical channels in the Sacramento–San Joaquin Delta, California, to determine the relative amount of levee erosion caused by natural forces and waves generated by boats. These studies showed that during the study period (1972–73) in a typical narrow channel, subject to winter floodflows and heavy boat traffic, about 20 percent of the annual energy dissipated against the levees could be attributed to boat-generated waves, about 10 percent to wind-generated waves, and 70 percent to tractive shear stress. In a channel relatively unaffected by winter floodflows, energy dissipation from boat-generated waves was shown to range from about 45 to 80 percent of the total, depending upon wind-movement assumptions made in the computations.

A method of applying findings from the observation channels to other delta channels is proposed.

## INTRODUCTION

The Sacramento–San Joaquin delta is a complex system of islands and interconnected waterways formed at the confluence of the two major rivers which drain the Central Valley of California, a drainage basin of about 43,000 mi$^2$ (110,000 km$^2$). An aerial photograph of part of this delta is shown in figure 1. It consists of about 60 tracts or islands covering an area of about 1,100 mi$^2$ (2,800 km$^2$). There are 700 mi (1,100 km) of waterways and 1,100 mi (1,800 km) of levees built to protect the adjacent lands from flooding. Many of the islands lie at or below sea level, some by as much as 20 ft (6 m).

Soils in the area are predominantly silt, sand, and peat, providing an excellent base for the intensive agriculture which dominates the economy of the region. Location of the area (fig. 2), bounded on the north by the Sacramento River, on the east by the city of Stockton, and on the south by the city of Tracy, is of prime economic significance. There is ready access by surface and water transportation to markets in the cities of Stockton and Sacramento and metropolitan centers around the San Francisco Bay.

Although the delta streams were previously used only for irrigation and surface transportation, and agriculture is still dominant, the delta now has an important recreational function. The marinas and boat-launch facilities scattered throughout the area help meet the recreational needs of millions of people each year. A significant sport fishery has developed, together with expanded use of the waterways for all forms of recreational boating. This change in usage has brought new problems. Now there is widespread concern that wave action resulting from the increased boat traffic will aggravate the serious problems of levee erosion and failure and increase cost of levee maintenance.

### LEVEE SYSTEM

#### LEVEE DEVELOPMENT

A brief review of the development of the levee system will help to bring erosion and levee failure problems in focus. Prior to the gold rush the delta was a tule marshland. The Sacramento and San Joaquin Rivers and the interconnecting sloughs meandered back and forth across the tidelands, frequently overflowing their banks. The area was undeveloped and little used. Then it changed rather rapidly with the influx of gold seekers. The increased demand for food was the incentive needed to start developing the agricultural potential of the delta marshlands.

The first levees were constructed by hand labor to a height of about 5 ft (1.5 m). They proved inadequate, being destroyed each year by floods. Later, dredges were used to build higher levees with material excavated from the channel bottoms. These weak materials, sands, silts, and peat,

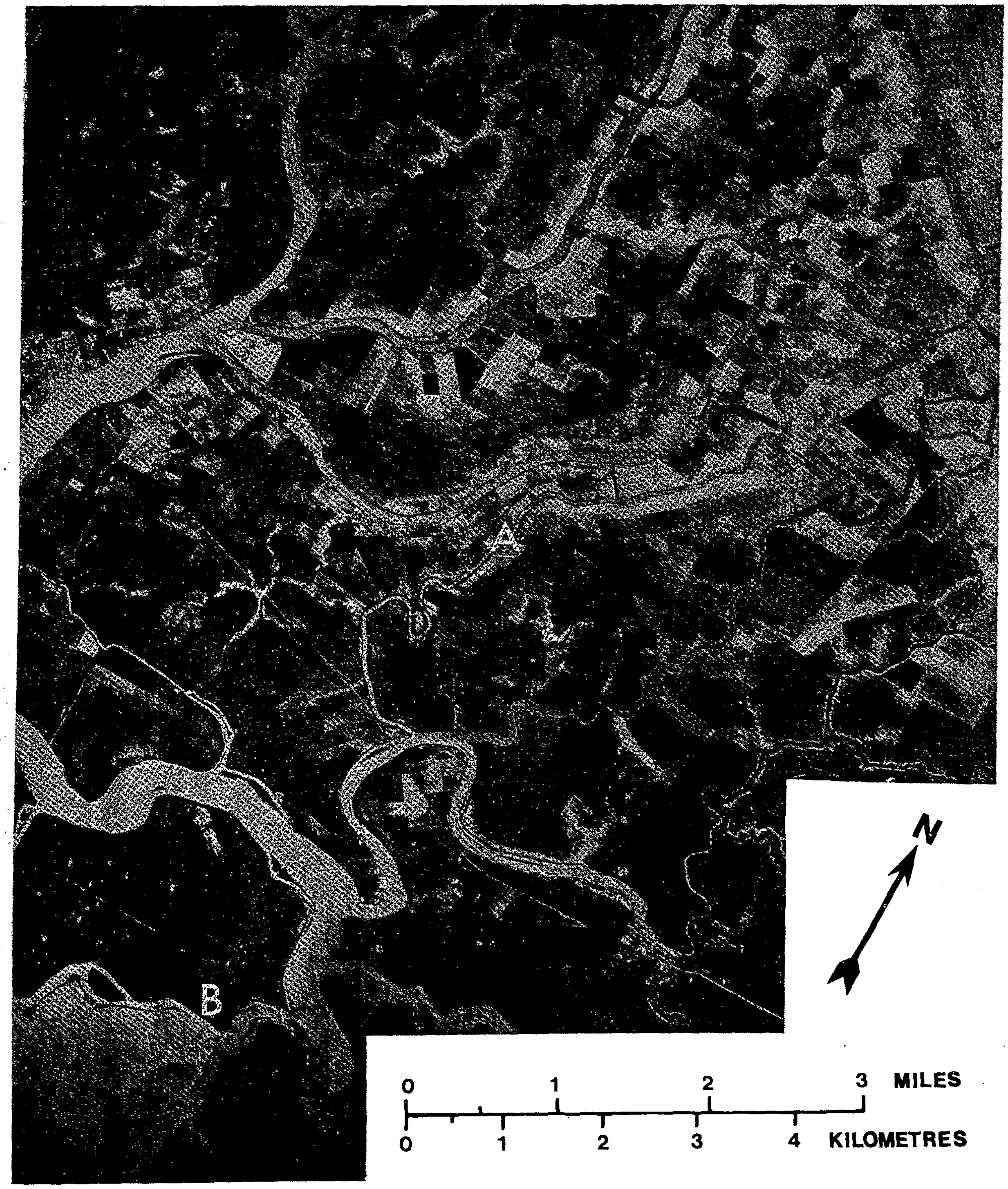


FIGURE 1.—Aerial photograph of part of the Sacramento–San Joaquin Delta showing principal study areas. *A*, Georgiana Slough near center of photograph; and *B*, False River, lower left. (Photograph courtesy National Aeronautics and Space Administration Manned Spacecraft Center.)

were used to construct the levees surrounding some 50 islands by the turn of the century. Since then, construction practices, except for major improvements made in a few channels, have changed little.

### LEVEE MAINTENANCE PROBLEMS

The principal levee problems faced today derive from the following:

1. The foundation for most levees is a 20- to 30-ft (6 to 9 m) thick layer of decayed vegetation or peat. A few levees have peat foundations as much as 60 ft (18 m) thick. Peat is a spongy, partially carbonized vegetable material that compresses under the load of the levee, and new material must be added continually to compensate for consolidation.
2. The native materials used in construction, sand, silt, and peat, possess minimal resistance to shear and are easily eroded.
3. Farm lands adjacent to the levees are subsiding about 3 in (76 mm) per year. These lands were once above or near sea level, but the combined actions of wind erosion, oxidation of the peat soil, and farming operations including burning and compaction have lowered the land surface by as much as 25 ft (7.6 m) in some areas. Minor subsidence in parts of the delta region is attributed to gas and water extraction from local gas fields. Each year, as the hydrostatic pressure against the levees increases as a result of subsidence, the conditions favoring levee failure increase.

### MAINTENANCE RESPONSIBILITY

The local reclamation districts and levee maintenance districts are responsible for maintaining delta levees. About 25 percent of the levees are maintained to standards prescribed by the Federal Government. These standards cover the flood channels of the Sacramento and San Joaquin Rivers and the principal navigation channels. The other 75 percent of the levees are maintained to no specific standards.

The California Department of Water Resources has been charged, under Section 12878 of the California Water Code (1957 statutes), with regulating the activities of local agencies in complying with Federal regulations concerning operation and maintenance of flood-control project levees.

Furthermore, the State Reclamation Board has been charged under SB541 (Section 12980 of the Water Code) with program development for the purpose of improving nonproject levees consistent with the best interests of public health and safety and the resources of the delta.

## PURPOSE AND SCOPE OF STUDY

The purpose of the study was to assess the relative magnitude of levee erosion caused by natural phenomena and boats, and to devise a technique or procedure for applying these findings to other delta channels. The California Department of Water Resources needs information on levee damage that can be used, along with other considerations, in developing a cost-sharing formula for the rehabilitation and maintenance of all the levees in the delta region.

Scope of the project has been limited to the study of erosion and erosive forces in two typical heavily used delta channels, Georgiana Slough and False River (fig. 3). Georgiana Slough is a 12-mi long (19 km) major northeast-southwest oriented distributary; it branches off from the Sacramento River near Walnut Grove and separates Andrus Island on the west from Tyler Island on the east. The channel carries significant floodflows and heavy pleasure boat traffic. The levees of this waterway show signs of active erosion. The False River study reach is a 3-mi (5 km) long, east-west oriented channel located just north of Franks Tract. Flow in this channel is dominated by tidal action, and boat traffic in False River is greater than that in Georgiana Slough. Field observations and analyses are focused on evaluation of the relative significance to levee erosion of shear stresses imposed by movement of water through the channels and stresses imposed by wind-generated waves and boat-generated waves.

These three dynamic energy sources are generally conceded to be the principal factors in the erosion process. Other problems, including levee subsidence, damage from rodents, seepage forces, direct wind erosion, and vegetation changes are not evaluated in this study. The economic and time constraints limited data collection to a period of 12 months of Georgiana Slough and 4 months on False River.

## ACKNOWLEDGMENTS

The study was made by the U.S. Geological Survey in cooperation with the California Department of Water Resources. Assistance and suggestions by Arthur L. Winslow, Jr., and John F. Wright, Jr., California Department of Water Resources, the levee maintenance data provided by the U.S. Army Engineer District, Sacramento, Corps of Engineers, and the detailed accounting of

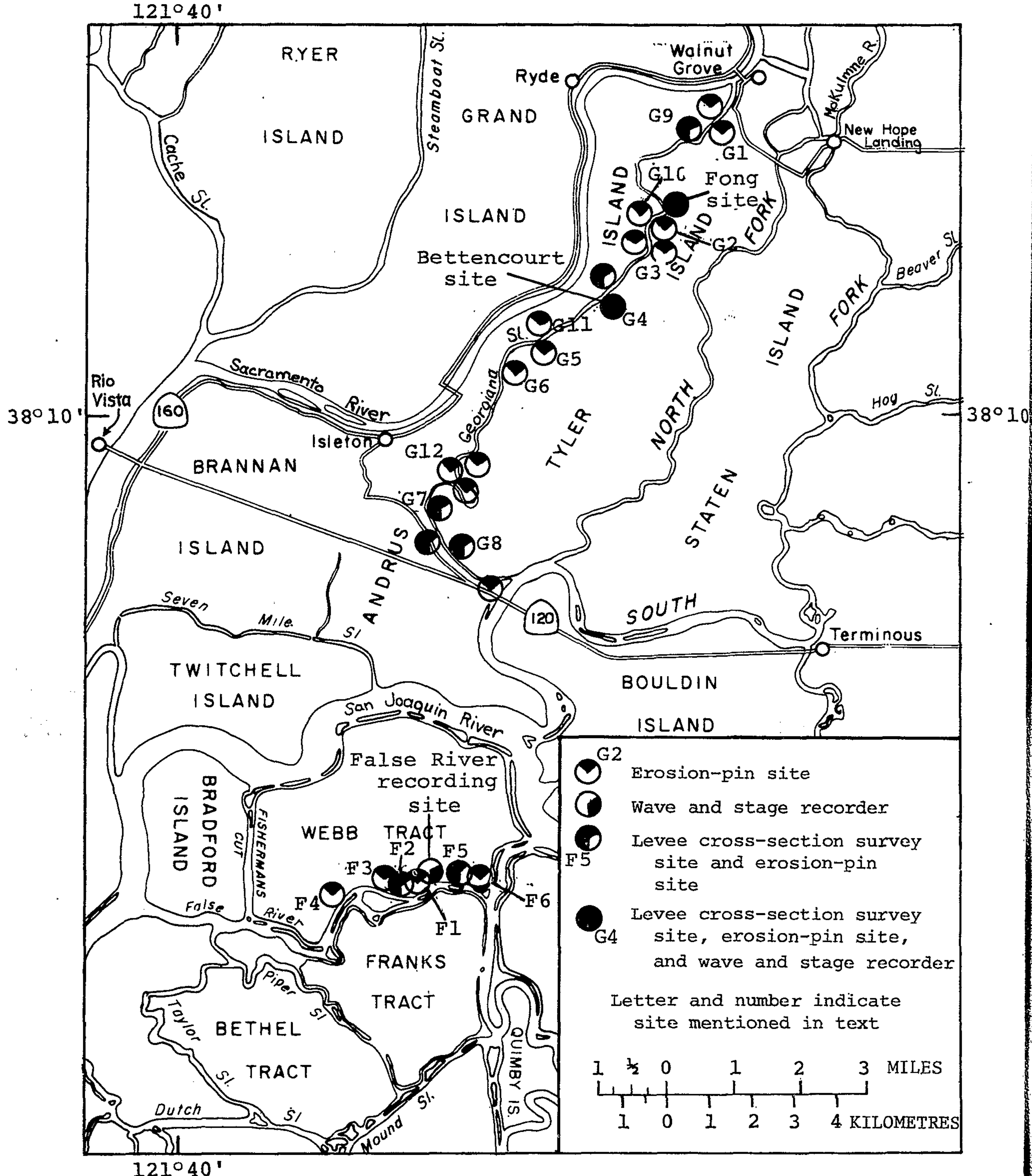


FIGURE 3.—Location of cross-section surveys, erosion-pin sites, and instrumentation on Georgiana Slough and False River. (Base from California Department of Water Resources, Central District, Sacramento.)

boat traffic supplied by the Sacramento County bridge tender at the Tyler Island bridge were invaluable in the study. The energetic assistance furnished by James M. Bergmann, Paul E. Lugo, and Larry F. Trujillo in the collection and analysis of data and the technical support and guidance furnished by David R. Dawdy, of the U.S. Geological Survey, is gratefully acknowledged.

## METHOD OF APPROACH

The basic assumption made at the beginning of the study was that levee erosion could be related directly to the energy dissipated on the banks. The energy sources were assumed to be tractive shear stresses caused by the velocity of flow in the channels, waves generated by winds, and waves generated by boats. In order to evaluate the relative effects of these three major dynamic factors, the following studies were initiated:

1. Evaluation of long-term (previous 20 years) levee maintenance records to determine if there were discernable relations, first, between erosion rates and the increased use of the channels for recreational boating, and, second, between the orientation of areas of active levee erosion and the orientation of dominant wind movement in the area. These evaluations were made solely to obtain an overview of the erosion problem. They could not produce definitive results because each evaluation was concerned with a single causative factor and does not isolate that factor from other factors that also cause erosion.
2. Direct measurement of erosion rates at selected points along the channel and documentation of flow regime, wind-caused waves, and boat-caused wave action.
3. Theoretical analysis of the relative energies dissipated against the banks by tractive shear stress, wind-generated waves, and boat-generated waves.
4. Comparison of computed energy dissipation with observed erosion in selected channels.

## EVALUATION OF LONG-TERM LEVEE MAINTENANCE RECORDS

### LONG-TERM TRENDS IN MAINTENANCE REQUIREMENTS

The thesis of this part of the study was that if levee erosion rates were significantly affected by boat-generated waves, there should be a positive correlation between changes in levee maintenance requirements and changes in boat traffic, assuming there had been little change over the years in the amount of erosion attributable to wind action, high streamflow, or floods.

There has been a significant increase in boat traffic in the past two decades. Contacts with levee maintenance districts throughout the delta produced only one set of usable levee rehabilitation data for those decades. On Georgiana Slough 0.09 mi (0.14 km) of revetment work was done between 1950 and 1960, 0.58 mi (0.93 km) was revetted between 1961 and 1970, and 0.62 mi (1.0 km) was revetted in the 2-year period 1972 through 1973. It is of interest that both boat traffic and levee maintenance requirements increased in the past 24 years. However, data are not available to isolate quantitatively the effects of streamflow, wind movement, and boat traffic over that period. Consequently, no meaningful conclusions can be drawn from this cursory examination of limited available information.

### COMPARISON OF LEVEE MAINTENANCE REQUIREMENTS TO DOMINANT WIND MOVEMENT

The purpose of this phase of the study was to determine if the orientation of areas of active levee erosion could be related to the orientation of recorded wind movement across the delta. Wind-generated waves travel in the direction of the prevailing wind movement. Most of the wave energy that is developed is dissipated at the outside of bends where waves have a direct-attack opportunity. (This is discussed in more detail in the section "Wind-Generated Wave Energy.") Where weak bank materials exist, as is the case with most delta levees, wave energy dissipation results in erosion. Hence, the long-term effect of this process might be expected to produce levee damage proportional to the direction and intensity of wind movement. Bends at the ends of reaches of the channels oriented parallel to the dominant wind movement would be expected to incur more damage than bends at the ends of channels oriented normal to the dominant wind movement.

Levee erosion in Georgiana Slough has been surveyed periodically over the past 20 years in conjunction with levee repair projects sponsored by the U.S. Army Engineer District, Corps of Engineers, and the State of California. Data from these surveys, available in the Sacramento district office of the Corps of Engineers, show, on large scale maps, the location and lengths of dam-

TABLE 1.—*Levee erosion statistics for Georgiana Slough*

| Channel and levee parameters | Orientation of channel | | | |
|---|---|---|---|---|
| | North-south | Northeast-southwest | East-west | Southeast-northwest |
| Channel length, in feet | 10,750 | 26,750 | 11,900 | 15,300 |
| Levee length, in feet | 21,500 | 53,500 | 23,800 | 30,600 |
| Levee erosion, in percent of length | 18.6 | 22.2 | 24.2 | 13.2 |
| Levee rehabilitation, in percent of length | 3.5 | 4.8 | 19.9 | 2.5 |

aged areas and repaired segments. It was presumed that erosion was the primary factor contributing to the recorded levee damage and that these statistics could be used as a measure of relative erosion along the levees. For this part of the study these maps were used to determine the lineal extent of damage along the levees with respect to the orientation of channel segments. The data are summarized in table 1. It can be assumed that rehabilitation work, given in the last line of table 1, is associated with the more heavily damaged areas found in the surveys. Table 1 shows the same rank order of distribution of percentage of damage observed and the percentage of rehabilitation work done. The east-west channel segments experienced the heaviest erosion (24.2 percent of levees oriented east-west were damaged), and those channels also required the largest amount of rehabilitation, 19.9 percent of the total length in that orientation.

There are no long-term wind records at sites within the delta. The nearest ones are at Stockton, Pittsburg, Travis Air Force Base, and Mather Air Force Base in Sacramento. A record was obtained as a part of this study at the Bettencourt ranch on Georgiana Slough for the period October 1972 through September 1973. Location of these wind-recording stations is shown in figure 2. Wind distribution for these stations, expressed as the percentage of total wind movement for the period of record, is given in table 2.

The wind-movement records were initially re-

TABLE 2.—*Delta region wind orientation*

| Station | Period of record | Distance from Georgiana Slough (mi) | Distribution of wind in percentage of total movement | | | |
|---|---|---|---|---|---|---|
| | | | North-south | Northeast-southwest | East-west | Southeast-northwest |
| Bettencourt ranch | Oct. 1972–Sept. 1973 | - | 16.6 | 23.9 | 29.9 | 29.6 |
| Mather Air Force Base | Not known | 30 | 36.7 | 24.1 | 12.9 | 26.3 |
| Pittsburg | 1956–65 | 19 | 12.5 | 17.3 | 36.3 | 33.9 |
| Stockton | Not known | 23 | 17.3 | 16.7 | 32.7 | 33.3 |
| Travis Air Force Base | 1943–65 | 21 | 24.0 | 39.5 | 28.9 | 7.6 |
| Average | | | 21.4 | 24.3 | 28.1 | 26.1 |

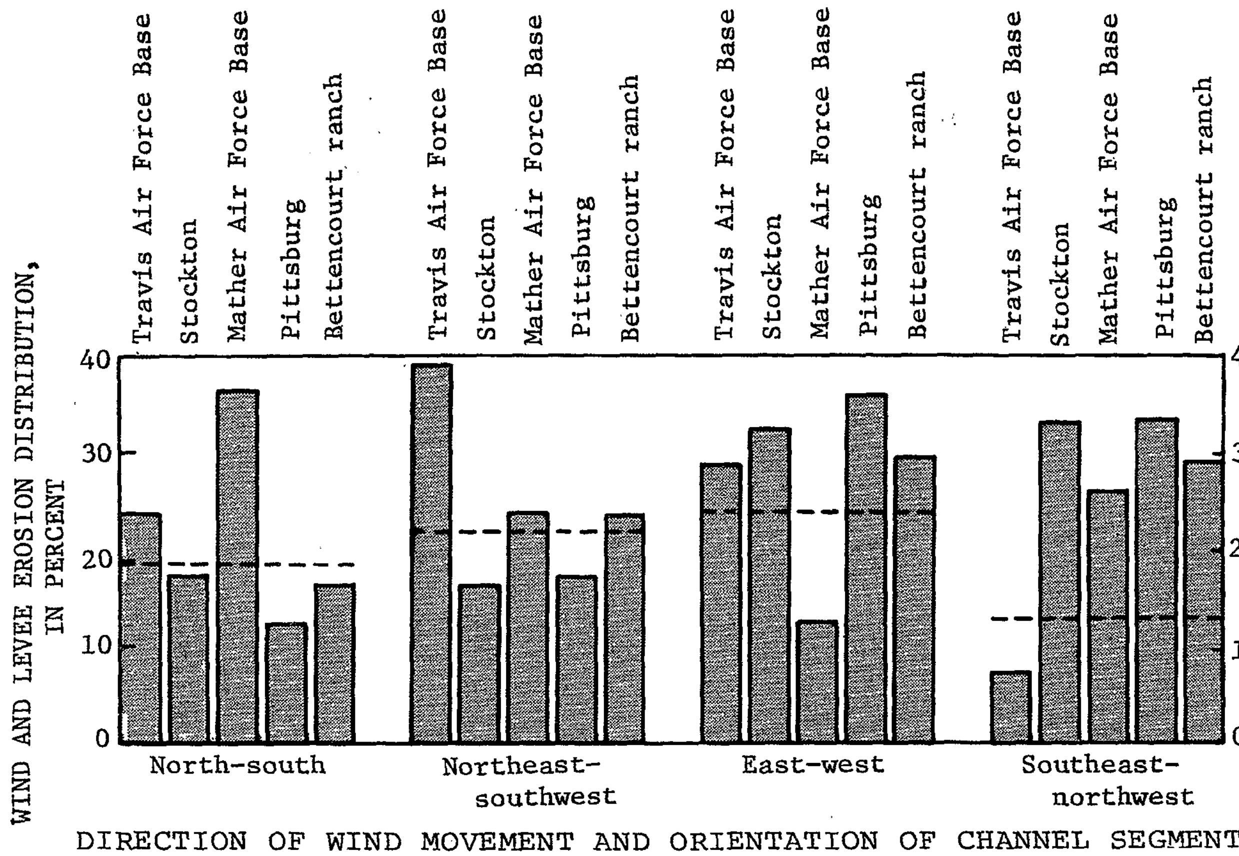


FIGURE 4.—Levee erosion distribution in Georgiana Slough (dashed line) and wind distribution at nearby wind recording gages.

duced to show the distribution in eight compass directions. Then, because stream velocities in the delta are low and wind from either of two diametrically opposite directions will generate waves that have nearly the same angle of attack on the banks of a given channel, the distribution was further reduced by combining wind movements in diametrically opposite directions. Thus, for example, wind movement from the north and from the south was combined and is shown as "north-south" in the tabulation. Wind movement tabulated for each of the resulting four compass positions also includes components of wind movement from winds coming from angles up to 45° on either side. This follows the rationale of Saville (1954) who reported that the wave-generating effectiveness of winds varies with the cosine of angles up to 45° but is not effective for greater angles.

Graphic comparison of erosion and wind data is shown in figure 4. Analysis of figure 4 yields very little information, but comparison of the data by rank correlation (Spearman, 1904), shown in table 3, indicates moderate to good correlation between erosion and the long-term wind movement statistics for the stations at Pittsburg and Travis Air Force Base. Negative correlations are suggested by the rank correlations of the erosion with records at Stockton and Mather Air Force Base.

Unfortunately, detailed analysis of the four long-term wind records, with respect to the period October 1972 through September 1973 when the Bettencourt wind gage was in operation, is not available at this time (1974). Hence, correlation of the short-term wind statistics obtained at the Bettencourt site on Georgiana Slough with the corresponding time-based statistics from the long-term record sites cannot yet be made. The rank correlations (table 3) show no correlation between the Bettencourt wind record and the long-term Travis Air Force Base record, a strong positive correlation with the Pittsburg record, a negative correlation with the Mather Air Force Base record, and a positive trend in relation to the Stockton record. The fact that the long-term Pittsburg record shows identical rank comparison with the Bettencourt record suggests that the 1972–73

TABLE 3.—*Rank order correlation of wind movement with levee erosion in Georgiana Slough*

| Parameter | Rank order at given orientation | | | | Rank order correlation, Spearman coefficient | |
|---|---|---|---|---|---|---|
| | North-south | Northeast-southwest | East-west | Southeast-northwest | With Bettencourt ranch record | With erosion |
| Percent levee erosion | 3 | 2 | 1 | 4 | - | - |
| Pittsburg wind | 4 | 3 | 1 | 2 | +1.0 | +0.4 |
| Travis Air Force Base wind | 3 | 1 | 2 | 4 | 0 | +.8 |
| Mather Air Force Base wind | 1 | 3 | 4 | 2 | -.8 | -.8 |
| Stockton wind | 3 | 4 | 2 | 1 | +.6 | -.4 |
| Bettencourt ranch wind | 4 | 3 | 1 | 2 | - | +.4 |
| Average percentage wind movement | 4 | 3 | 1 | 2 | +1.0 | +.4 |

$$\text{Spearman coefficient} = 1 - \frac{6\Sigma(d^2)}{n(n^2-1)}$$

where $d$ is rank difference and
$n$ is number of samples (four in this case)
Spearman coefficient = +1.0 represents perfect direct correlation
Spearman coefficient = 0 represents no correlation
Spearman coefficient = -1.0 represents perfect inverse correlation

period, covered by this gage, may be typical. However, the variability shown between available records demonstrates that winds across the delta cannot be considered uniform in direction and magnitude, and further, that no one of the available wind records can be considered representative of the area. Despite these variations, the average percentage wind movement of all the stations has perfect rank correlation with the Bettencourt ranch gage.

The analysis made does show a moderate correlation between occurrence of erosion and selected wind movement statistics, but no quantitative clues are provided on the significance of the wind movement factor in relation to the other dynamic stresses imposed on the levee system.

If long-term records providing wind velocity, duration, and direction at points within the delta were available, then rational analysis of this energy source could conceivably be made. However, the assumptions necessary to transpose such data to the protected narrow channels of the delta would cast considerable doubt on the validity of quantitative calculations.

These brief studies showed that quantitative measures of causes of levee erosion could not be obtained from existing maintenance and wind records and that solutions to the problem would have to be sought by other techniques. Emphasis was accordingly placed on short-term observation of actively eroding areas and on the evaluation of relative stresses imposed on the levees by the natural forces of flood and tidal flows, wind-generated waves, and boat-generated waves.

## FIELD INVESTIGATIONS

The initial project proposal outlined the need for data-collection efforts to document the active erosion and corresponding erosive forces in a selected delta channel. Georgiana Slough was selected for study, and data collection was started in October 1972 to measure progressive erosion during the following 12-month period and to collect wind records, wave records, and boat-traffic records. Similar data, excepting wind records, were collected on False River from June through September 1973.

### EROSION SURVEYS

Test sites at several locations on Georgiana Slough and False River were selected for observation. On Georgiana Slough these sites were distributed to include actively eroding areas on each bank, levees constructed of apparently different material, channels of varying orientation, and straight reaches as well as the inside and outside of bends in the channel. On the east-west oriented False River channel, test sites were located on levees composed of generally uniform material. The locations of the test sites are shown in figure 3. Description of the methods used in recording levee profile changes and the results of analyses are given in the section "Analysis of Erosion Data."

### WIND RECORD

A standard, commercially produced recording anemometer and wind-direction instrument was installed near Georgiana Slough at the Bettencourt Ranch in October 1972 (fig. 2). The instrument was placed about 30 ft (9.1 m) above local ground surface and about 15 ft (4.6 m) above the levee top. Continuous records of wind speed and direction were collected from October 1, 1972, through September 30, 1973. This wind record is referred to in other sections of this report as the Bettencourt record.

### TIDE AND WAVE-HEIGHT RECORD

Initially vandalism was expected to be a problem in the delta region which attracts so many people for recreational activities. Therefore, a commercial wave-gage system employing a submerged pressure sensor was selected and installed at the Bettencourt site on Georgiana Slough on August 30, 1972, and operated until September 17, 1972. Records obtained with this equipment over the Labor Day weekend, when boat traffic was heavy, demonstrated that this type of hardware would not record data of the accuracy needed for this study. Wave amplitudes were low, wave periods were short (0.5–2 s), and variations in depth above the sensor caused by tidal fluctuations were large relative to the wave height. The combination of these factors produced records which could be interpreted economically only by computer, suggesting the need for recording on magnetic tape or other machine-readable output.

Acquisition of the hardware necessary for implementation of a sophisticated approach to the problem would have postponed data collection by several months so a decision was made to ignore, if possible, anticipated vandalism problems and to attempt to record tidal variations, wind-generated waves, and boat-generated waves with a simple float-operated strip-chart recorder. This exposed equipment, installed at three different sites, was not tampered with at any time during the project period.

A schematic diagram of the equipment is shown in figure 5. To minimize dampening of wave action, a 10-in. (254 mm) diameter float was suspended in the open water between guidelines that threaded through sleeves on either sides of the float. These guidelines were secured at the top and separated at the bottom with a weighted spreader bar as illustrated. Two strip-chart recorders were ganged together so that traces could be simultaneously recorded at different chart speeds. One recorder operated continuously at a chart speed that could be set for either 0.05 in.(1.27 mm) or 0.1 in. (2.54 mm) per minute. This trace provided a record of tidal fluctuations on which was superimposed a record of the magnitude and duration of wind-generated waves and the magnitude and number of waves generated by boats. The second recorder, controlled by a time clock, operated periodically at a much faster chart speed, 6 in (152 mm) per minute, to produce a detailed trace of wind or boat waves suitable for spectral analysis.

Recording equipment of the configuration described was installed at the Bettencourt site on September 2, 1972, at a site on the northwest-southeast oriented channel of Georgiana Slough (Fong site) on October 23, 1972, and on False River on June 4, 1973. These locations are shown in figure 3. The tide and wave records from the Bettencourt and Fong sites were used in the analysis of energy dissipation in Georgiana Slough. Records at the False River site provided data for similar analysis in that channel.

### BOAT-TRAVEL STATISTICS

Records of boat traffic in Georgiana Slough were compiled on the basis of the log kept by the bridge tender at the Tyler Island drawbridge and from analysis of wave-gage traces obtained from the equipment discussed in the previous section "Tide and Wave-Height Record." The historical log kept by the bridge tender lists information on the passage of large boats that required opening of the drawbridge. Information on small boat traffic was logged by the bridge tender from August 23, 1972, through September 30, 1973. Thus, the record of the number and sizes of all boats traversing Georgiana Slough from October 1972 through September 1973 can be considered fairly accurate. These statistics and estimates of annual boat traffic in Georgiana Slough from October 1967 through September 1972 are shown in table 4. The

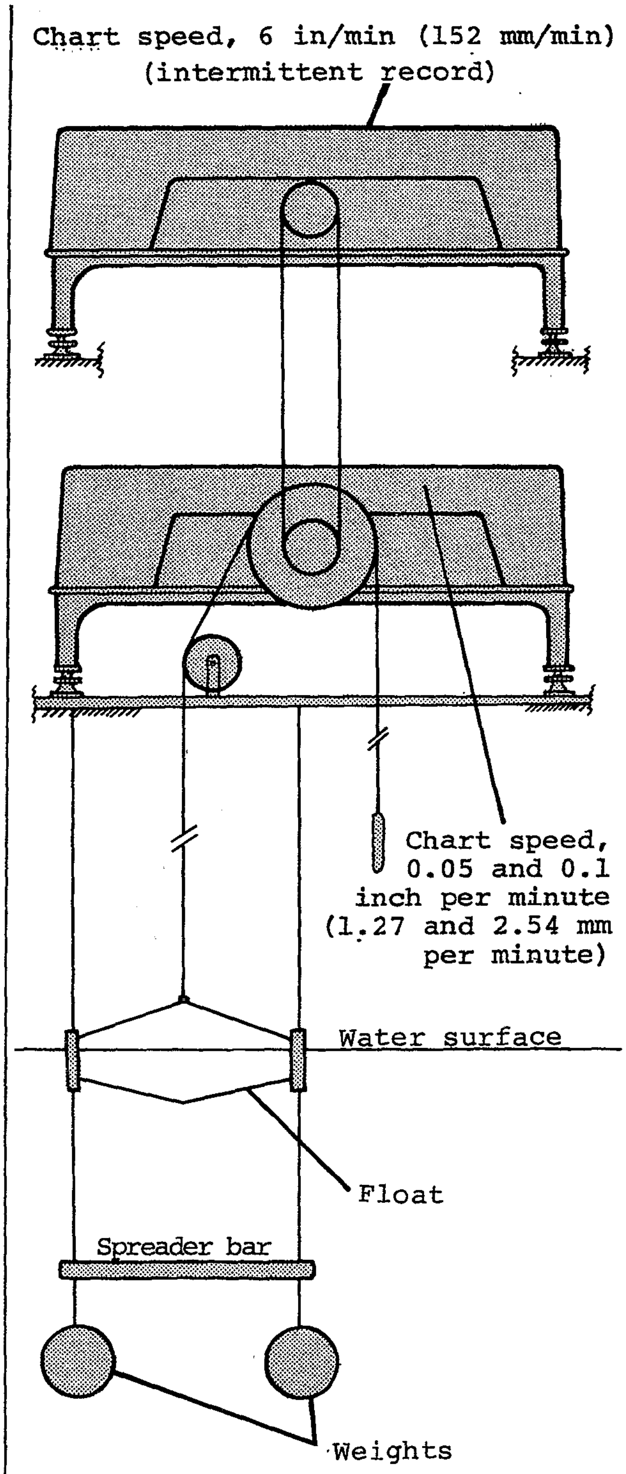


FIGURE 5.— Schematic drawing of wave and tide gage equipment.

TABLE 4.—*Delta region boat-traffic statistics, 1972–73, and extrapolated estimates of traffic, 1967–72*

| Period | Boat county | |
|---|---|---|
| | Georgiana Slough | False River |
| | 1972 | |
| October | 284 | |
| November | 81 | |
| December | 16 | |
| | 1973 | |
| January | 13 | |
| February | 49 | |
| March | 35 | |
| April | 362 | |
| May | 605 | |
| June | 628 | 1,257 |
| July | 974 | 1,501 |
| August | 1,154 | 1,426 |
| September | 776 | 818 |
| Total | 4,977 | 5,002 |
| | Estimate of historical traffic | |
| Water year[1] | | |
| 1967-68 | 4,715 | |
| 1968-69 | 5,559 | |
| 1969-70 | 4,449 | |
| 1970-71 | 5,153 | |
| 1971-72 | 5,095 | |

[1]The water year is the period from September 1 to October 30 of the year given.

latter were based on the bridge tender's log of large boats in the channel, increased by the ratio of total traffic to large boat traffic logged during the 1972–73 observation period. Boat-traffic statistics for the False River channel were compiled from the wave-gage records and observations by Survey personnel.

## EVALUATION OF ENERGY DISSIPATION

The dynamic energy sources considered significant in causing levee erosion are the tractive shear stresses resulting from movement of water through the channels, the energies dissipated by wind-generated waves, and the energies dissipated by boat-generated waves. Because these waves are of small amplitude their energy is effectively dissipated in the region near the water surface, that part of the levee above the mean lower low water elevation. Tractive shear stresses are imposed on the entire wetted perimeter, but field observations suggest that these are important only on the upper part of the levees, that is, the actively eroding area in the range from mean lower low water elevation to the flood stage maximum.

Consideration of the geomorphology of the delta channels supports this theory. These channels were formed principally by natural processes which predate the present levee system. They are incised in the original delta deposits and have achieved a degree of stability which reflects the greater compaction and strength of the base materials. Little erosion is likely to occur in that part of the wetted perimeter lying below the elevation of mean lower low water. The active erosion appears to be taking place in recent materials which form the man-built levees. For this reason it has been assumed that evaluation of the relative effects of tractive shear stress energies and wave energies should be restricted to forces impacting on the actively eroding zone.

For the analyses that follow, the mean lower low water elevation was computed as the mean of the daily lower low water elevations for the period of record. For Georgiana Slough the period of record was October 1, 1972, through September 30, 1973. The period of record for False River was June 4, 1973, through September 30, 1973.

Tables 5 and 6 show the results of computations of the energy dissipation attributable to tractive shear forces, wind waves, and waves generated by boats for Georgiana Slough and False River.

Procedures used in these computations are described in following sections of this report.

Table 5 shows that energy dissipation from tractive shear stress is the dominant factor in Georgiana Slough during the winter months when floodflows occur and boat traffic and winds are at relatively low levels. However, during the summer months when boat traffic is heavy, the situation is reversed. During periods of low discharge in the river, computed tractive shear stress is almost negligible, and energies from wind-generated waves and boat-generated waves are dominant.

Table 6 shows that the distribution of tractive shear stress, wind-generated wave, and boat-generated wave energies for False River from June through September 1973 was comparable to that computed for the corresponding period at Georgiana Slough. Extrapolation of these data to provide an estimate of relative energies for the

TABLE 5.—*Summary of energy dissipation in Georgiana Slough, 1972–73*

| Month | Tractive shear stress energy | | Wind-generated wave energy | | Boat-generated wave energy | | Total energy |
|---|---|---|---|---|---|---|---|
| | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| October | 1.7 | 1.9 | 40.3 | 44.0 | 49.5 | 54.1 | 91.5 |
| November | 9.0 | 27.6 | 4.0 | 12.3 | 19.6 | 60.1 | 32.6 |
| December | 18.0 | 59.8 | 8.3 | 27.6 | 3.8 | 12.6 | 30.1 |
| January | 1,160 | 98.7 | 12.6 | 1.1 | 2.1 | .2 | 1,174.7 |
| February | 904 | 98.1 | 5.2 | .5 | 12.6 | 1.4 | 921.8 |
| March | 499 | 96.4 | 5.0 | 1.0 | 13.6 | 2.6 | 517.6 |
| April | 1.7 | 1.8 | 31.6 | 34.2 | 59.2 | 64.0 | 92.5 |
| May | 1.2 | 1.2 | 24.6 | 26.1 | 68.6 | 72.7 | 94.4 |
| June | 1.4 | 1.4 | 36.1 | 37.2 | 59.7 | 61.4 | 97.2 |
| July | 1.5 | .5 | 158.6 | 53.2 | 137.9 | 46.3 | 298.0 |
| August | 1.3 | .7 | 33.8 | 18.0 | 152.1 | 81.3 | 187.2 |
| September | 1.4 | .8 | 68.8 | 38.8 | 107.0 | 60.4 | 177.2 |
| Total | 2,600.2 | 70.0 | 428.9 | 11.5 | 685.7 | 18.5 | 3,714.8 |

12-month period clearly demonstrates that in this channel where flow is little affected by floods, tractive shear stress energy is minimal throughout the year.

A variety of results can be obtained by manipulation of the data obtained at the False River site. The variations in percentage of energy dissipation attributed to tractive shear stress, wind-generated waves, and boat-generated waves, shown in lines 5 to 10 of table 6, reflect differing assumptions used in the computation of wind-generated wave energy. The variations are discussed in more detail in the section "Wind-Generated Wave Energy." The significance of the results is that regardless of the assumptions made, the energy dissipated by boat-generated waves is the dominant dynamic energy source in this channel. Tractive shear stress energy is a minor factor in summer or winter, and energy from wind-generated waves exceeds that from boat-generated waves only if it is assumed that all wind-generated wave energy is absorbed in direct attack on the levees.

Extrapolation of the Georgiana Slough record to include the period October 1967 through September 1973 is shown in table 7. These computations were made to determine if the 1972–73 observation period was typical. Apparently that is the case. Significant high water occurred during January, February, and March 1973, but the total tractive shear stress energy was less, on an annual basis, than that for 2 of the 6 years analyzed. Examination of variations in wind-generated wave and boat-generated wave energies shows that they were relatively constant from year to year and that the 1972–73 period can be considered fairly representative of average conditions from 1968 to 1972.

It should be noted that tractive shear stress energy values for the 1972–73 period shown in table 7 are a little different than those shown for the same period in table 5. The difference results from applying the same extrapolation procedure to the 1972–73 period as was used for the other water years in the summary, and it shows the bias which may have been introduced by the extrapolation techniques described in the section "Georgiana Slough Extrapolations."

## COMPUTATION OF TRACTIVE SHEAR STRESS ENERGY

Energy is dissipated at channel boundaries as a result of shear stresses imposed by the tractive force of moving water. These stresses are a function of water velocity, channel roughness, and the weight of the water. For uniform flow, the equation

$$\tau_0 = WRS \qquad (1)$$

(Vennard, 1961, p. 352) is developed as an expression of mean shear stress. In this equation $\tau_0$ is in pounds per square foot if $W$, the specific weight of water, is given in pounds per cubic foot, and $R$, the hydraulic radius, is in feet. The channel slope $S$ is dimensionless. Equation 1 can be expressed in

TABLE 6.—*Summary of energy dissipation in False River, June–September 1973*

| Line number | Month | Tractive shear stress energy: Ft-lbs x $10^8$ | Tractive shear stress energy: Percentage of total | Wind-generated wave energy: Ft-lbs x $10^8$ | Wind-generated wave energy: Percentage of total | Boat-generated wave energy: Ft-lbs x $10^8$ | Boat-generated wave energy: Percentage of total | Total energy: Ft-lbs x $10^8$ |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| | **Bettencourt wind distribution** | | | | | | | |
| 1 | June | 0.22 | 0.5 | 10.0 | 25.0 | 29.8 | 74.5 | 40.0 |
| 2 | July | .25 | .5 | 6.0 | 11.8 | 44.6 | 87.7 | 50.8 |
| 3 | August | .28 | .5 | 9.4 | 18.2 | 42.0 | 81.3 | 51.7 |
| 4 | September | .22 | .6 | 7.2 | 20.0 | 28.6 | 79.4 | 36.0 |
| 5 | Total, June-September | .97 | .5 | 32.6 | 18.3 | 145.0 | 81.2 | 178.6 |
| 6 | Extrapolated to period October 1972-September 1973 | 3.9 | 1.5 | 47.0 | 17.5 | 217.7 | 81.0 | 268.6 |
| | **Travis Air Force Base wind distribution** | | | | | | | |
| 7 | Total, June-September | 0.97 | 0.4 | 116.0 | 44.3 | 145.0 | 55.3 | 262.0 |
| 8 | Extrapolated to period October 1972-September 1973 | 3.9 | 1.0 | 167.3 | 43.0 | 217.7 | 56.0 | 388.9 |
| | **All wind-wave energy assumed to be absorbed in direct attack on levees** | | | | | | | |
| 9 | Total, June-September | 0.97 | 0.3 | 180.4 | 55.3 | 145.0 | 44.4 | 326.4 |
| 10 | Extrapolated to period October 1972-September 1973 | 3.9 | .8 | 260.3 | 54.0 | 217.7 | 45.2 | 481.9 |

TABLE 7.—*Summary of energy dissipation in Georgiana Slough, 1968–73 water years*

| Water year | Tractive shear stress energy | | Wind-generated wave energy | | Boat-generated wave energy | | Total energy |
|---|---|---|---|---|---|---|---|
| | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ | Percentage of total | Ft-lbs x $10^8$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| 1967–68 | 169 | 13.6 | 428 | 34.6 | 642 | 51.8 | 1,239 |
| 1968–69 | 3,682 | 75.5 | 427 | 8.8 | 765 | 15.7 | 4,874 |
| 1969–70 | 4,729 | 81.9 | 424 | 7.3 | 622 | 10.8 | 5,775 |
| 1970–71 | 1,941 | 63.8 | 393 | 12.9 | 710 | 23.3 | 3,044 |
| 1971–72 | 33 | 2.8 | 422 | 36.2 | 712 | 61.0 | 1,167 |
| 1972–73 | 2,808 | 71.6 | 429 | 10.9 | 686 | 17.5 | 3,923 |
| Total | 13,362 | 66.7 | 2,523 | 12.6 | 4,137 | 20.7 | 20,022 |

terms of the mean velocity, $V$, in feet per second, in the channel and the Manning coefficient of roughness, $n$, by the following exercise: From the Chezy equation

$$V = C\sqrt{RS},$$

$$\text{or } RS = \left(\frac{V}{C}\right)^2;$$

$$\text{thus } \tau_O = W\frac{V^2}{C^2}. \qquad (2)$$

Since the relation between the Chezy $C$ and the Manning $n$ can be expressed by the equation

$$C = \frac{1.486R^{1/6}}{n},$$

substitution of this relation into equation 2 yields

$$\tau_O = \frac{WV^2n^2}{2.21R^{1/3}}. \qquad (3)$$

The energy dissipated per unit of time is the product of $\tau_O$ and $V$, and thus the energy dissipation rate can be expressed as

$$E' = \frac{WV^3n^2}{2.21R^{1/3}}. \qquad (4)$$

Units of $E'$ in equation 4 are in foot-pounds per square foot per second. In subsequent analyses energy is expressed in foot-pounds per square foot per day, and if $W$ is assumed equal to 62.4 pounds per cubic foot,

$$\text{then } E = \frac{(62.4)\,V^3n^2}{2.21R^{1/3}}(86{,}400),$$

or $E = 2.44 \times 10^6 \frac{V^3n^2}{R^{1/3}}$ foot-pounds per square foot per day. (5)

Parameters needed for evaluation of equation 5 are $n$, $R$, and $V$. In this study, the values for these parameters were derived from the output of the computer model of the Sacramento–San Joaquin Delta which was developed by the California Department of Water Resources (1968). This model computes a matrix of hydraulic data including velocities, on an hourly, bihourly, or daily mean basis, for several hundred reaches in the delta. The output is functionally related to discharge at the long term Geological Survey gaging station on the Sacramento River at Sacramento. Figure 6 shows the relation between daily mean discharge at Sacramento and the corresponding daily mean velocity in Georgiana Slough.

Two questions required resolution in the manner in which equation 5 should be applied. The first question relates to the velocity distribution in the channel cross section. The equation provides evaluation of shear stress energy resulting from a given mean velocity in the channel cross section. Velocities in the active zone of erosion are far less than the mean velocity in the channel, and an adjustment must be made to compensate for this. The second question was whether or not computations could reasonably be made on the basis of daily mean velocities, which would greatly reduce the volume of data manipuation, or whether it would be necessary to carry out computations on an hourly basis to accommodate the range in velocities resulting from the twice daily tidal fluctuations.

Lane (1955) has discussed the variation of tractive shear stresses along channel boundaries and

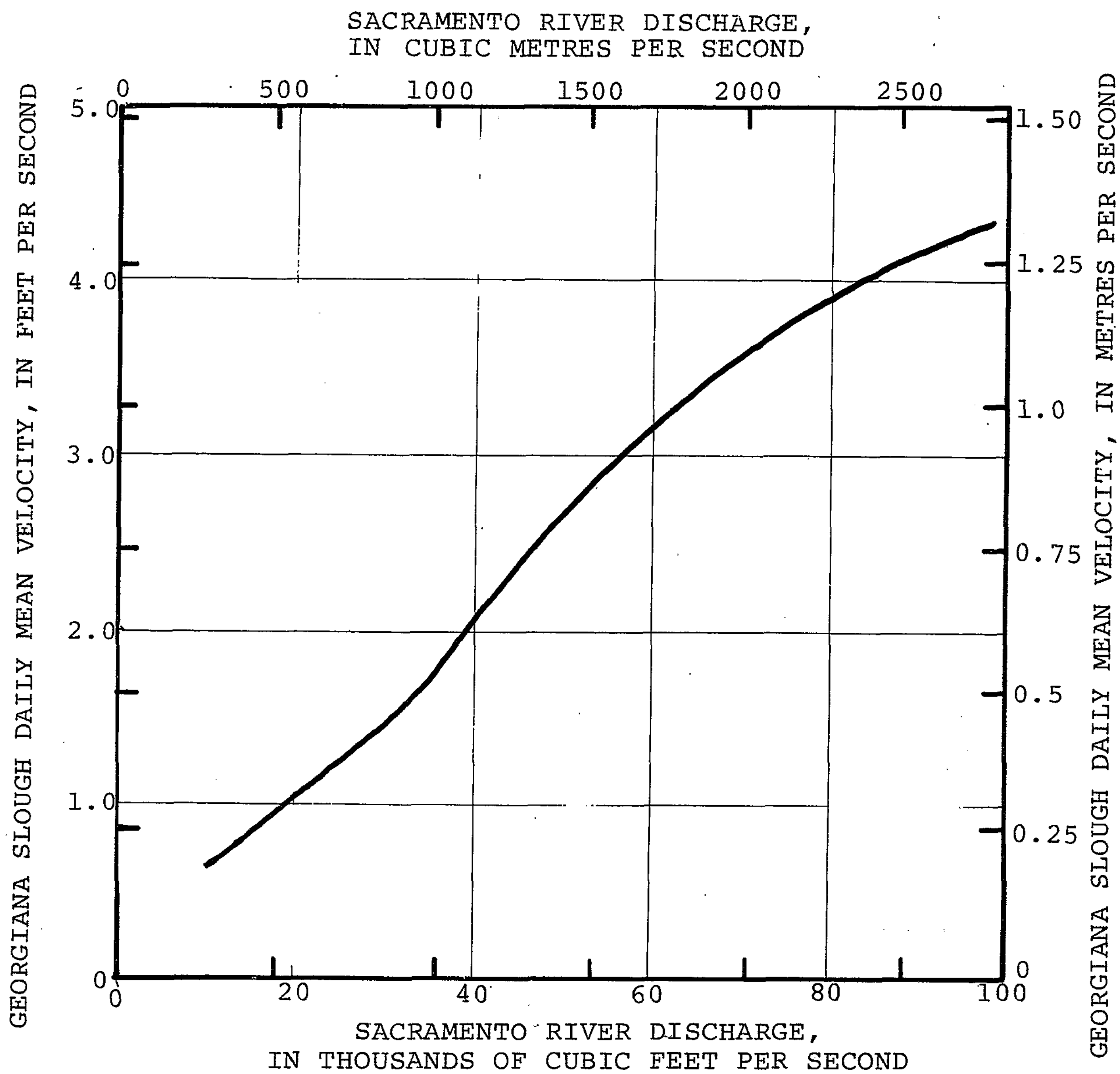


FIGURE 6.—Relation between daily mean discharge of the Sacramento River at Sacramento and daily mean velocity in Georgiana Slough.

has developed a series of distribution curves for various channel shapes that give correction factors to be applied to tractive shear stresses computed on the basis of the channel geometry. Figure 7 is the Lane data for a trapezoidal channel with a 2:1 side slope and bottom width 8 times the water depth, a shape which approximates that of many delta channels. This curve shows, for example, that the tractive shear stress applicable to a shear energy dissipation zone extending from the water surface to a point at 10 percent of the depth would average 0.06 times that computed on the basis of the cross-sectional mean velocity.

To resolve the question of the significance of variations in velocity due to tidal influence, sample computations were made using hourly velocity values for several days of record. Comparison of these results with the results obtained by use of the daily mean velocity showed insignificant differences for Georgiana Slough where tidal action does not produce flow reversals. In contrast, flow in the False River channel is almost completely dom-

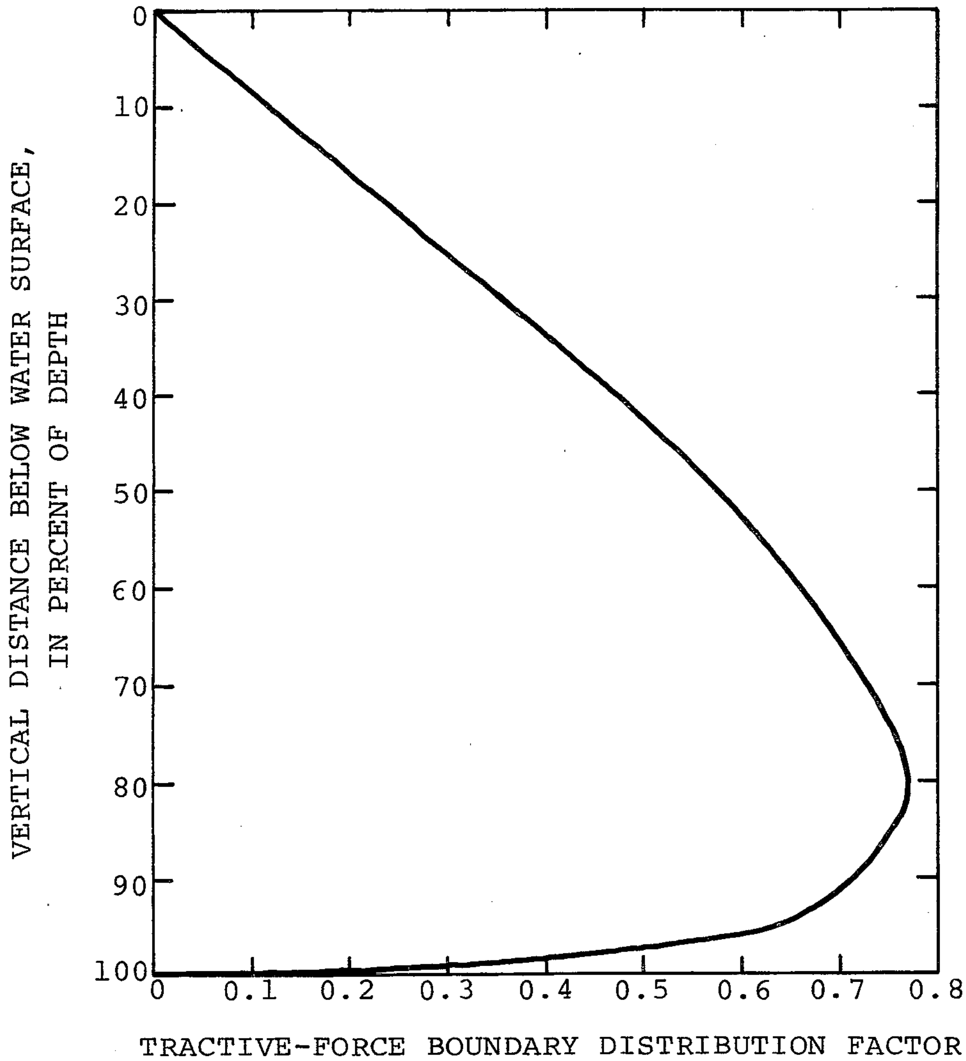


FIGURE 7.—Distribution of tractive shear stress on the side boundary of a trapezoidal channel (modified from Lane, 1955).

inated by tidal action with velocities ranging from about +0.8 ft/s (0.24 m/s) to −0.8 ft/s (−0.24 m/s). False River computations based on the absolute daily mean velocity are in error by as much as 30 percent, relative to those computed from hourly figures. However, since tractive shear stress energy was shown in table 6 to be a very minor factor, less than 1 percent of the total energy dissipation in this channel, refinement of those computations was not warranted.

The results of the tractive shear stress energy computations for Georgiana Slough and for False River are shown in column 2 of tables 5 and 6. These figures derive from computations made on a daily basis as illustrated in the reproduction of the computer printout for October 1972 for Georgiana Slough (fig. 8).

The step by step procedure, referring to the columns in figure 8, was as follows:

1. Column 1 is the day of the month.
2. Column 2 is the daily mean discharge in the Sacramento River at Sacramento.
3. Column 3 is the corresponding daily mean velocity in Georgiana Slough, in feet per second, which was computed from the function shown in figure 6.
4. Column 4 is the daily shear energy dissipation rate computed from equation 5:

$$E = \frac{2.44 \times 10^6 V^3 n^2}{R^{1/3}}, \qquad (5)$$

where $E$ = energy dissipation rate, in foot-pounds per square foot per day,
$n$ = Mannings $n$ = 0.035 for Georgiana Slough,
$R$ = hydraulic radius (obtained from computer output of Delta hydraulic model, approximate value, 20.1 ft),
$V$ = daily mean velocity, in feet per second, from column 3.

5. Column 5 is the percentage of time for each day that the water surface was above the mean lower low water elevation (7.3 ft local datum for the Bettencourt gaging site on Georgiana Slough). For example, on October 6 there were 19 hourly values above the mean lower low water elevation of 7.3 ft. Therefore, for 19÷24 = 79.167 percent of the day the water surface was above the mean lower low water elevation.
6. Column 6 is the ratio of the average depth of water above the mean lower low water elevation divided by the total depth.
7. Column 7 is the boundary distribution factor computed from the value shown in column 6 and the function illustrated in figure 7.
8. Column 8 is the shear energy dissipation zone which is the average depth of water above mean lower low water elevation used in the computation made in column 6.
9. Column 9 is the tractive shear stress energy dissipation rate for each day. It is the product of columns 4, 5, 7, and 8. This is expressed in foot-pounds per foot of levee (linearly) per day.
10. Column 10 is the total tractive shear energy dissipation for the day on the levees on Georgiana Slough. It is the product of rate from column 9 and the length of levees—129,400 ft. This value is given in foot-pounds per day.

The summation of values of column 10 for each month is the total energy dissipated by tractive shear stress against Georgiana Slough levees.

It is believed that this procedure probably overestimates the magnitude of shear stress energies for straight reaches (95 percent of Georgiana Slough) because the channel configuration is not symmetrically trapezoidal. There are many protuberances and small indentations and also areas of active erosion which include a panhandle. Velocities in these areas, sheltered from the main flow of the channels cannot be accurately estimated as a function of the mean velocity. Small eddies frequently result, eddies which require transference of energy across the flow separation boundary. It follows, logically, that shear energy dissipation is probably no larger than that which would occur along the projected area of the erosion zone.

## ANALYSIS OF WAVE ENERGY

Records obtained from the wave gages at the test sites provided, on a continuous basis, traces representing the magnitude and duration of wind-generated waves and spikes showing the maximum wave height of waves generated by boats. Examples of wind-generated and boat-generated waves traces are shown in figures 9 and 10. The wave traces were analyzed to provide summary data showing, on a monthly basis, the duration and respective magnitude of wind-generated waves and the number and magnitude of waves generated by boats.

The density of traces, recorded on the slow speed chart, precluded abstraction of the classical significant wave height ($H_{1/3}$) referred to in the literature and defined as the mean of the one-third highest waves in a record (Kinsman, 1965, p. 45). In consequence, the parameter chosen to represent the height of wind waves in this analysis was the height of the dense part of the wind-wave trace. This parameter could be scaled from the recorder trace with repeatable accuracy. Similarly, the only recognizable index on the slow speed trace for boat-generated waves was the maximum wave height, and this was used as an index for waves from this source.

The product desired from this analysis was a record of energies dissipated in the channels by the two wave forms. To accomplish this a correlation between the observed wave height indices and energy was required for data conversion. This was accomplished by spectral analysis of waves recorded on the fast chart speed recorder. An example of the expanded wave form is shown in the lower part of figures 9 and 10.

### WAVE ENERGY RELATIONS

Wave trains, developed by wind action over open water, are a composite of a variety of individual waves of differing lengths and amplitudes. If each of the component wave forms is assumed to be of sinusoidal configuration, then analysis of the wave train can be made by spectral analysis to determine the amplitude and frequency of each component. The frequency components which can be estimated are determined by the time interval at which the wave record is sampled (sampling interval) and the total length of time chosen for

TABULATION OF SHEAR STRESS ENERGY DISSIPATION (BASED ON AVE. OF

| DAY | SAC. R. SAC. DAILY FLOW (CFS) | GEORGIANA SL. VELOCITY (FPS) | DAILY ENERGY DISS. RATE (1) | % OF TIME W.S. IS ABV LOW TIDE |
|---|---|---|---|---|
| 1 | 17000 | 0.93 | 884.1 | 85.417 |
| 2 | 16800 | 0.92 | 855.9 | 85.417 |
| 3 | 16500 | 0.90 | 801.3 | 85.417 |
| 4 | 16100 | 0.89 | 774.8 | 89.583 |
| 5 | 15800 | 0.87 | 723.8 | 81.250 |
| 6 | 15300 | 0.85 | 675.0 | 79.167 |
| 7 | 14900 | 0.84 | 651.5 | 85.417 |
| 8 | 14900 | 0.84 | 651.5 | 93.750 |
| 9 | 14900 | 0.84 | 651.5 | 89.583 |
| 10 | 15000 | 0.85 | 675.0 | 87.500 |
| 11 | 15900 | 0.88 | 749.0 | 87.500 |
| 12 | 16100 | 0.89 | 774.8 | 83.333 |
| 13 | 16400 | 0.90 | 801.3 | 83.333 |
| 14 | 16600 | 0.90 | 801.3 | 85.417 |
| 15 | 16600 | 0.90 | 801.3 | 85.417 |
| 16 | 17000 | 0.93 | 884.1 | 81.250 |
| 17 | 17300 | 0.94 | 912.9 | 81.250 |
| 18 | 17800 | 0.96 | 972.4 | 83.333 |
| 19 | 17700 | 0.96 | 972.4 | 87.500 |
| 20 | 17300 | 0.94 | 912.9 | 83.333 |
| 21 | 16900 | 0.91 | 828.3 | 85.417 |
| 22 | 16200 | 0.89 | 774.8 | 81.250 |
| 23 | 15800 | 0.87 | 723.8 | 81.250 |
| 24 | 15500 | 0.86 | 699.1 | 81.250 |
| 25 | 15300 | 0.85 | 675.0 | 83.333 |
| 26 | 15300 | 0.85 | 675.0 | 83.333 |
| 27 | 15500 | 0.86 | 699.1 | 89.583 |
| 28 | 15600 | 0.87 | 723.8 | 85.417 |
| 29 | 15700 | 0.87 | 723.8 | 81.250 |
| 30 | 15500 | 0.86 | 699.1 | 58.333 |
| 31 | 15200 | 0.85 | 675.0 | 58.333 |

(1) UNITS ARE FT-LBS / FT**2-DAY
(2) UNITS ARE FT-LBS / FT-DAY
(3) UNITS ARE FT-LBS / DAY

MEAN (FOR ALL MONTHS) OF THE DAILY LOWS = 7.3

FIGURE 8—Sample computation sheet showing tractive shear

analysis. The sampling interval is chosen so that it hopefully defines the highest frequency component, and the sample length is chosen so that it defines the lowest frequency component in the wave train. The equation of the wave train can be approximated by a summation equation of the general form:

$$\widetilde{S}(t) = A_o + \sum_{m=1}^{n} A_m \cos(2\pi mft + \phi_m), \quad (6)$$

DAILY LOWS FOR ALL MONTHS) OCTOBEP 1972

| % OF INT. DEPTH ABV. LOW TIDE | BOUNDARY DISTRIBUTION FACTOR | ENERGY DISS. ZONE (FT) | ENERGY DISS. PER FT. (2) | ENERGY DISS. PER DAY (3) |
|---|---|---|---|---|
| 6.103 | 0.048 | 1.3 | 0.471E+02 | 0.610E+07 |
| 6.103 | 0.048 | 1.3 | 0.456E+02 | 0.590E+07 |
| 6.542 | 0.056 | 1.4 | 0.537E+02 | 0.694E+07 |
| 6.542 | 0.056 | 1.4 | 0.544E+02 | 0.704E+07 |
| 5.660 | 0.048 | 1.2 | 0.339E+02 | 0.438E+07 |
| 5.660 | 0.048 | 1.2 | 0.308E+02 | 0.398E+07 |
| 6.542 | 0.056 | 1.4 | 0.436E+02 | 0.565E+07 |
| 6.103 | 0.048 | 1.3 | 0.381E+02 | 0.493E+07 |
| 6.103 | 0.048 | 1.3 | 0.364E+02 | 0.471E+07 |
| 6.542 | 0.056 | 1.4 | 0.463E+02 | 0.599E+07 |
| 6.542 | 0.056 | 1.4 | 0.514E+02 | 0.665E+07 |
| 6.542 | 0.056 | 1.4 | 0.506E+02 | 0.655E+07 |
| 6.542 | 0.056 | 1.4 | 0.523E+02 | 0.677E+07 |
| 6.103 | 0.048 | 1.3 | 0.427E+02 | 0.553E+07 |
| 6.542 | 0.056 | 1.4 | 0.537E+02 | 0.694E+07 |
| 5.213 | 0.040 | 1.1 | 0.316E+02 | 0.409E+07 |
| 4.762 | 0.040 | 1.0 | 0.297E+02 | 0.384E+07 |
| 5.213 | 0.040 | 1.1 | 0.357E+02 | 0.461E+07 |
| 6.103 | 0.048 | 1.3 | 0.531E+02 | 0.687E+07 |
| 6.103 | 0.048 | 1.3 | 0.475E+02 | 0.614E+07 |
| 6.103 | 0.048 | 1.3 | 0.441E+02 | 0.571E+07 |
| 6.542 | 0.056 | 1.4 | 0.494E+02 | 0.639E+07 |
| 6.542 | 0.056 | 1.4 | 0.461E+02 | 0.597E+07 |
| 6.977 | 0.056 | 1.5 | 0.477E+02 | 0.617E+07 |
| 6.977 | 0.056 | 1.5 | 0.472E+02 | 0.611E+07 |
| 7.834 | 0.064 | 1.7 | 0.612E+02 | 0.792E+07 |
| 6.977 | 0.056 | 1.5 | 0.526E+02 | 0.681E+07 |
| 6.542 | 0.056 | 1.4 | 0.485E+02 | 0.627E+07 |
| 4.306 | 0.032 | 0.9 | 0.169E+02 | 0.219E+07 |
| 3.382 | 0.024 | 0.7 | 0.685E+01 | 0.887E+06 |
| 4.306 | 0.032 | 0.9 | 0.113E+02 | 0.147E+07 |

stress energy dissipation in Georgiana Slough October 1972.

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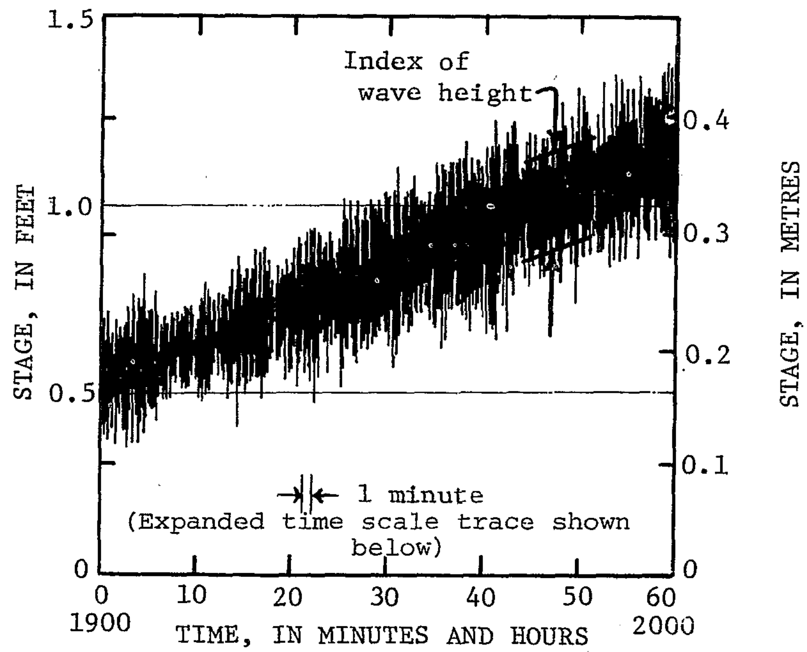
where $\widetilde{S}(t)$ is the estimate of the wave height at time $t$,
$A_o$ is the mean of the function $\widetilde{S}(t)$,
$A_m$ is the amplitude of the $m$th harmonic,
$\phi m$ is the phase of the $m$th harmonic relative to an arbitrary origin of time, and
$f$ is frequency of the fundamental.



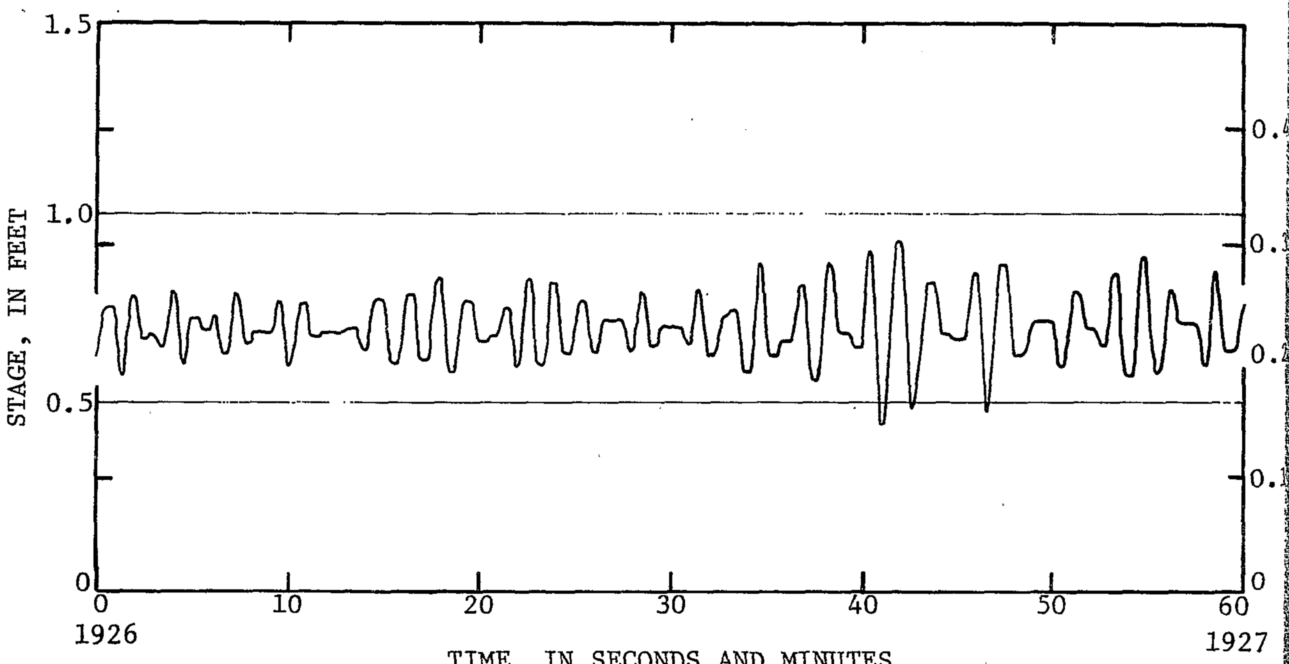




FIGURE 9.—Wind-generated wave traces for Georgiana Slough.

It can be further shown (Jenkins and Watts, 1969, p. 21) that average power of such a function can be expressed as the variance

$$\sigma^2 = \sum_{m=1}^{n} R_m^2, \quad (7)$$

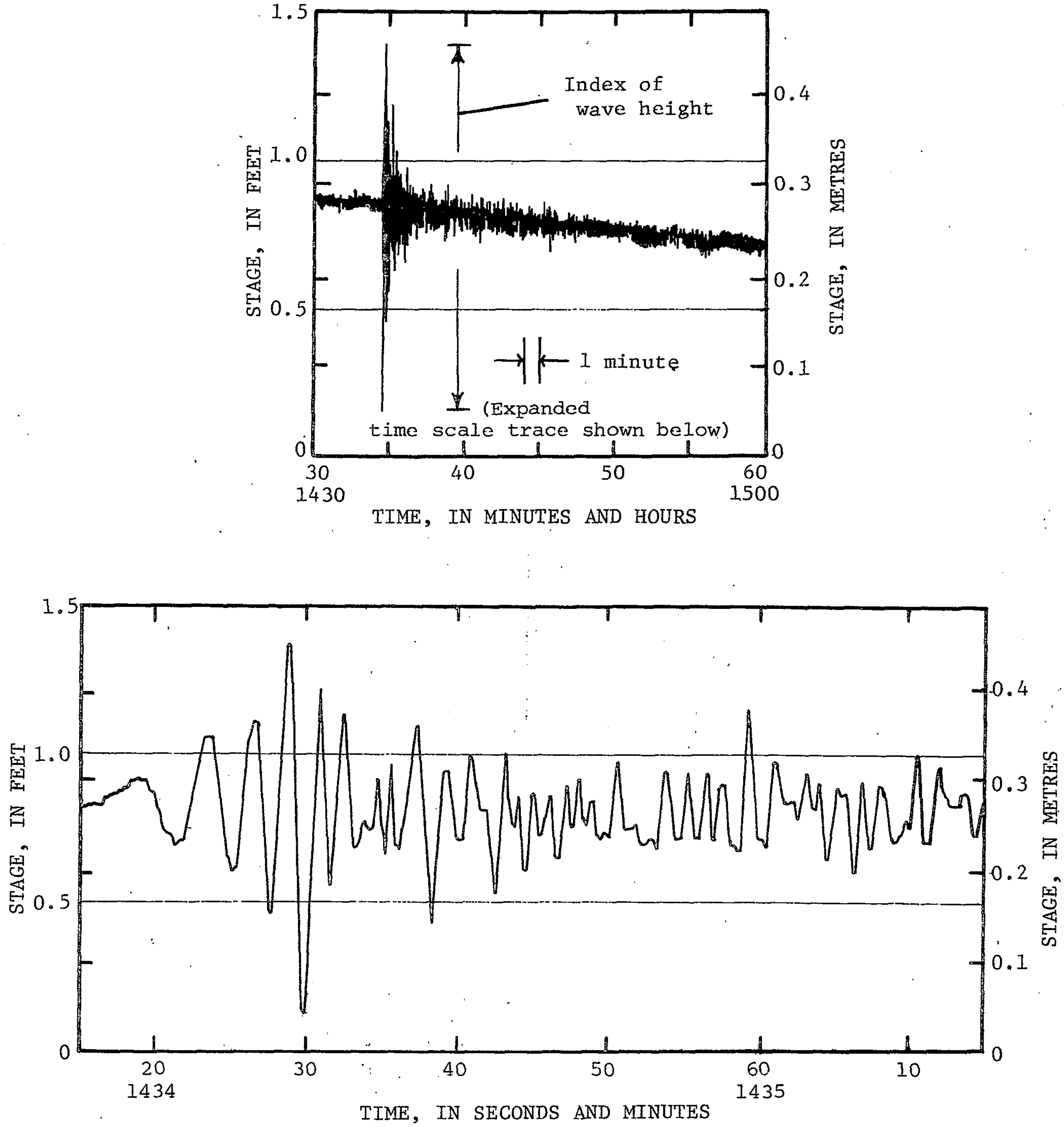



FIGURE 10.—Boat-generated wave traces for Georgiana Slough.

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where $$R_m^2 = \frac{A_m^2}{2}$$

For progressive sinusoidal waves of small amplitude moving in deep water the equation

$$P = \frac{\rho g^2}{32\pi} H^2 T \qquad (8)$$

applies (Kinsman, 1965, p. 154). In this equation $P$ is the power per unit length of wave crest, $\rho$ is the mass density of water, $g$ is the acceleration of gravity, $H$ is the wave height (equal to twice the amplitude), and $T$ is the wave period (equal to $1/f$). It follows from the rationale of the summation representation that for a wave train composed of sinusoidal components,

$$P \cong \frac{\rho g^2}{32\pi} \left( \sum_{m=1}^{n} H_m{}^2 T_m \right), \qquad (9)$$

Output from the spectral analysis of wave forms, using BMD02T autocovariance and power spectral analysis program (Health Sciences Computing Facility, Department of Biomathematics, 1973) provides a breakout of parts of the total variance attributable to designated frequencies within the spectrum. These are values equivalent to the factors $R_m^2$ and $mf$ in equations 6 and 7.

The values computed are the mean square values for the respective ordinates in the sinusoidal functions of the series. These must be increased by a factor of 8 for use in equation 9. This results from the fact that the wave height *(H)* is twice the amplitude *(A)*, and for a sine function, the square of the amplitudes is twice the mean square of the function *($R_m^2$)*. Thus the following equations hold:

$$H = 2A,$$
$$A^2 = 2R_m^2,$$
$$\text{and } H^2 = 4A^2 = 8R_m^2. \qquad (10)$$

Inclusion of the relation shown in equation 10 into equation 9 and substitution of $\frac{1}{mf}$ for $T_m$ results in the equation

$$P \cong \frac{\rho g^2}{32\pi}(8)\left( \sum_{m=1}^{n} \frac{R_m{}^2}{mf} \right) \qquad (11)$$

or $$P = 160 \sum_{m=1}^{n} \left( \frac{R_m{}^2}{mf} \right) \qquad (12)$$

Equation 12 was used in computing the power in the wind-generated wave and boat-generated wave recordings. Only those values of $m$ for which $R_m^2$ is greater than background noise need be considered.

## WIND-GENERATED WAVE ENERGY

Spectral analysis was made of wave traces for five different wind-generated wave trains to produce the wave height versus power relation for wind-generated waves shown in figure 11. For each analysis a 5-minute part of the wave trace on the fast chart speed record was analyzed by picking off points at one-half-second intervals for a total of 600 points. The corresponding index of wave height was scaled from the slow chart speed record.

Figure 11 shows the power of the advancing wave front in foot-pounds per hour per foot. This is the rate of energy that would be dissipated by waves advancing normal to the levees, and it is the energy level assumed active against levees on the outside of bends. Computations of energy dissipation along banks parallel to waves traveling down a channel based on shear action of the moving wave result, for waves of the size and frequency generated in the delta channels, in ratios ranging from 1/2,500 to 1/6,000 of energies computed for direct attack wave fronts.

For this analysis it has been assumed that energies dissipated by waves traveling down a channel should be conservatively estimated as 1/1,000 of the direct attack energies. This ratio was selected to allow for the fact that even in straight reaches the banks are irregular, being made up of many small bays and protrusions. Field observations in the two study waterways noted that waves moving parallel to the bank do not turn into the bank, apparently because water depth is sufficient to minimize the effects of bottom resistance. Accordingly, wave refraction was assumed to be negligible.

Computation of wind-generated wave energy dissipation in the test channels was made on a monthly basis using the following procedure:

1. Wave gage traces produced on the slow speed recorder chart were analyzed to determine the number of hours in each month for wave trains in selected height ranges. Excluded from this listing were periods during which the water level was below the mean lower low water elevation.

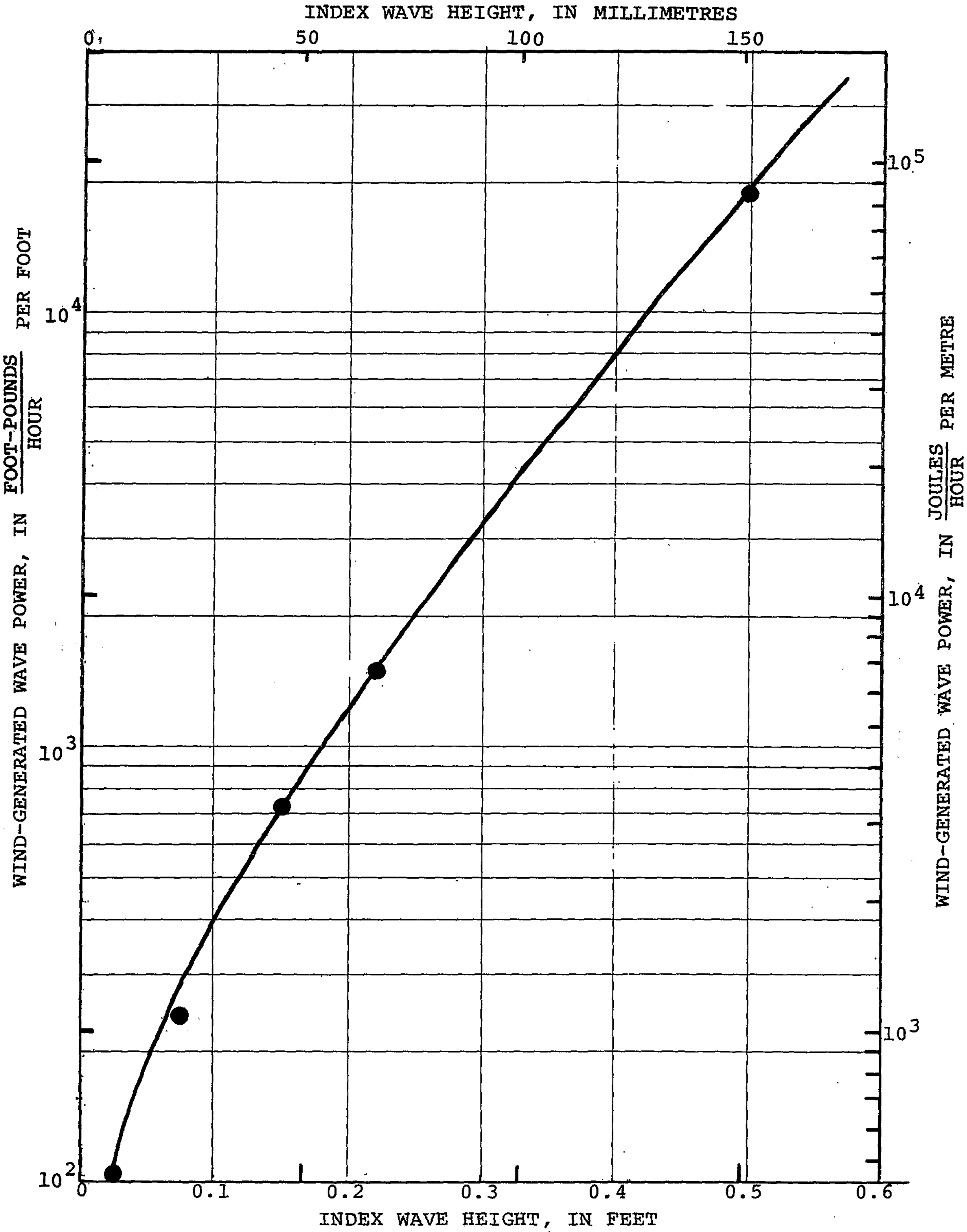


FIGURE 11.—Relation of wind-generated wave energy to index wave height.

| Wind wave height (ft) | Energy rate per hour [(ft-lbs/ft)/h] | Number of hours | Total energy rate (ft-lbs/ft) |
|---|---|---|---|
| (1) | (2) | (3) | (4) |
| <.01 | | 346 | |
| 0.01-0.05 | 130 | 159 | 20,670 |
| .06- .10 | 300 | 53 | 15,900 |
| .11- .20 | 750 | 29 | 21,750 |
| .21- .30 | 2,100 | 16 | 33,600 |
| .31- .40 | 5,250 | 7 | 36,750 |
| .41- .50 | 13,000 | 1 | 13,000 |
| .51- .60 | 31,000 | | |
| Subtotal | | 611 | 141,670 |
| Missing record | | 18 | |
| Total | | 629[1] | |

Adjustment for missing record $\frac{629}{611} \times 141{,}670 = 145{,}900$

[1]Number of hours when stage was above 7.3 ft (MLLW).

FIGURE 12.—Sample computation sheet showing wind-generated wave energy dissipation rate in Georgiana Slough, October 1972.

2. The resulting duration table of wind wave-height index data was converted to energy dissipation by use of the relation defined in figure 11. Energies produced by each wave class were summed to determine the total energy dissipated per month.

These procedures are illustrated in figure 12 which shows computations for Georgiana Slough, October 1972. Wave height classes are given in column 1. The corresponding energies for each class are listed in column 2. The number of hours during the month when waves were within each class and the stage was above the mean lower low water elevation are listed in column 3. The energy contribution of each class, shown in column 4, is the product of columns 2 and 3. If the record for the month was incomplete the monthly total was adjusted by the ratio of the total hours per month when flow was above mean lower low water elevation to the actual hours of observation. These adjustments were minor. The final figure is the monthly wind-generated wave energy dissipated, in foot-pounds per foot of levee.

*Distribution of wind-generated wave energy in Georgiana Slough.*—The energy-dissipation rate computed by the procedure described in this section is that which would be applicable to waves moving normal to a levee. It is the energy which would be applied to bends perpendicular to the orientation of the channel on which the recorder was located provided all waves were moving parallel with the channel. A dissipation rate equal to 1/1,000 of this was assumed to apply along the sides of this channel under the same situation.

Data on the actual direction of wave travel was not recorded by the wave gage recording equipment; however, field observations indicate that winds blowing at right angles to the high levees along Georgiana Slough produce practically no waves on the protected water surface of the channel. It may be assumed that in Georgiana Slough the wind waves develop from winds moving along the channel and that the wind-wave records do represent waves traveling parallel with the reach. Waves recorded at the Bettencourt site are accordingly assumed to be generated by winds, or com-

Outside bends

| Channel direction | Projected length (ft) | Wind distribution (Bettencourt) | Proportionate distribution to NE↔SW wind | Unit energy (ft-lbs / ft) | Monthly energy (ft-lbs x $10^8$) |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| N↔S | 1,050 | 41.5 | 11.9 | 145,900 | 18.2 |
| NE↔SW | 950 | 3.5 | 1.0 | 145,900 | 1.4 |
| E↔W | 900 | 32.0 | 9.1 | 145,900 | 12.0 |
| SE↔NW | 800 | 23.0 | 6.6 | 145,900 | 7.7 |
| Subtotal | 3,700 | 100.0 | | | 39.3 |

Straight channels and inside bends

| Channel direction | Length of levees (ft) | Wind distribution (Bettencourt) | Proportionate distribution to NE↔SW wind | Unit energy (ft-lbs / ft) | Monthly energy (ft-lbs x $10^8$) |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| N↔S | 19,400 | 41.5 | 11.9 | 145.9 | 0.34 |
| NE↔SW | 51,600 | 3.5 | 1.0 | 145.9 | .07 |
| E↔W | 22,000 | 32.0 | 9.1 | 145.9 | .29 |
| SE↔NW | 29,000 | 23.0 | 6.6 | 145.9 | .28 |
| Subtotal | 122,000 | 100.0 | | | 0.98 |

Total 40.3 x $10^8$ ft-lbs

FIGURE 13.—Sample computation sheet showing procedure used in computation of wind-generated wave energy for outside bends and for straight channels and inside bends in Georgiana Slough, October 1972.

ponents of winds, moving either northeast or southwest, parallel to this reach of the slough. To apply this wave data to channels of differing orientation it is assumed that the unit wave energy rates developed would be proportional to the relative wind movement parallel with the respective channels. If, for example, the monthly wind movement parallel to an east-west channel was twice as large as the wind movement in the northeast-southwest channel at the Bettencourt site, then it was assumed that the wave energy rate in the east-west channel would be twice that recorded at the Bettencourt gage. Sample computations based on these assumptions are shown in figure 13.

Computations are shown of energy dissipation for direct attack waves acting on the outside of channel bends and for straight sections and the inside of bends. The step by step procedure for outside bends can be summarized as follows:

1. Column 1 shows the orientation of Georgiana Slough channels limited to eight directions and combined diametrically.
2. Column 2 shows the corresponding projected lengths of channel bends normal to the indicated directions.

3. Column 3 shows the percentage distribution of wind movement in the indicated directions. Winds from opposite directions are combined in this tabulation. The statistics on wind movement were obtained from the wind-speed and direction recorder installed for this study at Georgiana Slough (Bettencourt ranch).
4. Column 4 shows the proportionate distribution factor which is computed as the ratio of wind movement in a given channel direction to the wind movement in the northeast-southwest channel in which the wave data were collected.
5. Column 5 shows the unit energy dissipation rate in foot-pounds per foot for direct attack waves in the channel at the test site. This value was obtained from the computations shown in figure 12.
6. Column 6 shows the energy dissipation for direct attack on levees normal to the channel directions shown in column 1. This is the product of values in columns 2, 4, and 5, expressed in foot-pounds per month.

The total of values in column 6 represents the total energy dissipated on the outside of bends by direct attack waves during the month.

The same step by step procedures were used to compute wind-wave energy dissipated along straight channel sections and on the inside of bends. Only two differences are involved: Different lengths of levees (column 2), and the reduction of the unit energy by a factor of 1/1,000 in accordance with previous discussion. Values tabulated in column 4 of table 5 (summary table) are the sums of total energies shown in figure 13.

Basic wind-wave theories state that wave energy is related to the fetch over which the water is exposed to the wind and to a power function of wind velocity. The simplified distribution procedure outlined above ignores variations in fetch length and assumes linearity in the relation between developed wave energy and wind movement. Consequently the results must be considered approximations. However, sophistication of the procedures was deemed unwarranted because of questions as to the validity of transference of wind statistics from the observation point to the channel and the unknown shielding effects on the levees along either side of the narrow delta channels.

The wind-generated wave energies listed in tables 5 and 7 for Georgiana Slough were computed using the wave-gage record at the Bettencourt site which is located on the longest reach in the slough. Similar computations, based on wave-gage records collected at the Fong site, where the reach and corresponding effective fetch length is much shorter, produced energy levels lower, on the average, by almost 50 percent. Accordingly the adopted distribution technique may bias the wind-generated wave energies given in tables 5 and 7 on the high side.

*Distribution of wind-generated wave energy in False River.*—The configuration of the False River channel which lies just north of the wide expanse of Franks Tract—a shallow lake since 1938—is such that wind-generated waves may be expected to travel in almost any direction. The wave-recording gage was located near the north bank levee which protects Webb Tract, and it seems logical to assume that waves reaching this point are generated almost entirely by winds from the south, east, or west. Remmants of the old levees along the north bank of Franks Tract still provide some protection from southern winds, effectively preventing comingling of waves generated in Franks Tract. Thus, waves may move directly across the channel against the north bank levee or at any other angle until the wind is parallel to the north bank.

The total energy developed by wind-generated waves, expressed in foot-pounds per foot per month, was computed from the wave-gage record in the same manner as that used for Georgiana Slough (fig. 12). It was assumed that the direction of wave travel was parallel with wind movement and that energy dissipation could be proportioned in accordance with wind-movement data and the corresponding angle of attack on the north levee.

The total energy of component wave travel normal to the levee was assumed to be dissipated. Energy of component wave travel parallel to the bank was assumed to equal 0.1 times the total. This rough estimate is much larger than might be used for parallel waves moving along a smooth bank. The increase (a factor of 100 over that used in Georgiana Slough) was made to account for the relatively large bank roughness and local protrusions.

This rationale results in the following distribution formula:

$$E_m = (L_L)(E_R)(W_m)(\cos \alpha_m + 0.1 \sin \alpha_m), \quad (13)$$

where $E_m$ is total energy dissipated against the levee in any given month by wind from a given direction,

$L_L$ is the length of levee,

$E_R$ is the wave energy developed for the month computed from the wind-wave record,

$W_m$ is percent of total wind movement in a given direction, and

$\alpha_m$ is angle of attack. For direct attack waves $\alpha = 90°$.

These procedures are illustrated in figure 14, which shows the computations made for June 1973, based on wind records for Travis Air Force Base. During this month 94.6 percent of the monthly total wind movement was from the southern region. It was assumed that all of the wind-generated wave energy resulted from this fraction of the monthly total wind movement. The wind-movement statistics were accordingly adjusted upward in direct ratio, yielding the effective percentages shown in column 3. The factor shown in column 4 is the cosine of the effective attack angle plus 0.1 times the sine of this angle. The energy dissipation rate for direct attack waves shown in column 5 was computed from analysis of the wave record explained earlier. The effective dissipation rate, column 6, is the product of columns 3, 4, and 5. The total energy dissipation for the month, shown in column 7, is the product of values in column 6 and the length of the levee (16,400 ft) (5,000 m). The sum of column 7 values for the 4-month period, June through September 1973, is shown in table 6, column 4, line 7.

One significant problem in this analysis is that wind records were not available at the wave-recording site. This required the assumption that wind-movement statistics from some other location could be transposed to the study channel. The figures shown in column 4, lines 5 and 7 of table 6 reflect the differences in computations of energy from wind-generated waves that result from use of the wind record at Bettencourt ranch for the period June–September 1973 and the average June–September wind statistics for Travis Air Force Base for the period 1943–65.

The computations summarized above show energies impacting only along the north bank levee of False River. There is only a partly effective levee on the south bank, and there are no sharp bends in the reach. However, for academic interest, alternative computations were made as-

| Wind direction | Percentage of total wind movement | Adjusted percent (effective direction) | Effective wind factor | Energy dissipation rate [(ft-lbs/ft)/month] | Effective rate [(ft-lbs/ft)/month] | Total levee energy dissipation $\left(\frac{\text{ft-lbs}}{\text{month}} \times 10^8\right)$ |
|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) |
| | | | | | (3)x(4)x(5) | (6)x16,400 ft |
| N→S | Effective wind only | | | | | |
| NNE→SSW | | | | | | |
| NE→SW | | | | | | |
| ENE→WSW | | | | | | |
| E→W | 0 | 0 | 0.1 | 284,700 | 0 | - |
| ESE→WNW | 0 | 0 | .475 | 284,700 | 0 | - |
| SE→NW | 0 | 0 | .778 | 284,700 | 0 | - |
| SSE→NNW | 0 | 0 | .962 | 284,700 | 0 | - |
| S→N | .3 | .3 | 1.0 | 284,700 | 854 | 0.14 |
| SSW→NNE | 2.9 | 3.1 | .962 | 284,700 | 8,490 | 1.39 |
| SW→NE | 52.9 | 55.9 | .778 | 284,700 | 123,817 | 20.31 |
| WSW→ENE | 32.0 | 33.8 | .475 | 284,700 | 45,708 | 7.50 |
| W→E | 6.5 | 6.9 | .1 | 284,700 | 1,964 | .32 |
| WNW→ESE | | | | | | |
| NW→SE | | | | | | |
| NNW→SSE | | | | | | |
| Total | 94.6 | 100.0 | | | | 29.66 x $10^8$ |

FIGURE 14.—Sample computation sheet showing procedure used in computation of wind-generated wave energy in False River, June 1973.

suming there were sharp bends at each end and a complete levee along the south bank. The resulting energy distributions, not shown here, were not significantly different from those computed for the single levee on the north bank being in the range of figures given in table 6.

The validity of assumptions made in the distribution of wind-wave energy cannot be demonstrated, but a measure of possible errors can be indicated by computations which assume that all of the wave energy recorded is dissipated in direct attack on the north levee. Computations based on this assumption result in figures shown in lines 9 and 10 of table 6. The contribution of wind-generated wave energy to total energy dissipated during the June through September period is increased to 55.3 percent from 44.3 percent, and the contribution of boat-generated wave energy is correspondingly reduced to 44.4 percent from 55.3 percent. This comparison supports the conclusion that boat-generated waves contribute a very large proportion of the energy dissipated against levees in this channel regardless of the assumptions made in computation of wind-generated wave energy.

### BOAT-GENERATED WAVE ENERGY

Waves generated by boats are not continuous wave trains as are those generated by winds but consist of a large initial wave front with successive waves decreasing in exponential manner. This decay, modified by waves reflected from either bank and by turbulence developed in the propeller wash, may continue from 3 to 5 minutes. Analysis of these wave trains, using the spectral analysis procedures discussed previously, must be modified to convert the expression of energy from foot-pounds per unit of time to foot-pounds per boat passage. This was done by assuming that all of the energy from a given boat passage would be dissipated within a period of 5 minutes. Records of this length were accordingly analyzed to produce an energy rate, corresponding to the average power dissipation over the period, and this rate was then multiplied by the time period (5 min) to obtain the total energy per boat passage.

Most of the data required for development of the relation of an index boat wave to energy, shown in figure 15, was collected on April 12–13, 1973, in Georgiana Slough, when a 35-ft (10.7 m) power boat traveling at controlled speeds in the center of the channel was used to generate waves of varying heights. Analyses were also made of other wave traces selected from the spectrum of data collected routinely. Scatter of the computed points is apparently random and not related to the direction of travel, with or against the current.

Values of boat-generated wave energy for Georgiana Slough, shown in column 6 of table 5, were computed on the basis of the relation shown in figure 15 and the statistics of boat waves recorded by the wave gages.

The procedure followed is illustrated in figure 16 which shows the computations of boat-generated wave energy for Georgiana Slough, October 1972. Boat waves were sorted into classes depending on their index wave heights as shown in column 1. Corresponding energies per boat passage obtained from figure 15 are given in column 2. The number of boat-generated index waves in each class is listed in column 3, and the resulting energy dissipation in foot-pounds per month for each wave height class is listed in column 4, which is the product of columns 2 and 3. The total monthly energy produced by boat-generated waves (figure shown in column 6 of table 5) is computed as the sum of values in column 4 multiplied by a small adjustment factor to compensate for any periods of lost record during the month and by the total length of levees on Georgiana Slough.

Only those boat passages occurring at times when the water surface elevation was above the mean lower low water elevation were included in column 3. This follows the rationale used in computation of tractive shear stress and wind-generated wave energies.

## EXTRAPOLATION OF COMPUTED ENERGY DISSIPATION

The significance of a short period of record, such as the 1 year of data collected at Georgiana Slough and the 4 months of data collected on False River, must be appraised in relation to a longer period if valid conclusions are to be made from the analysis. This requires extrapolation by some technique which relates the findings of the observation period to longer term streamflow records, wind records, and boat traffic statistics.

### GEORGIANA SLOUGH EXTRAPOLATIONS

The computed distributions of energy dissipation for Georgiana Slough were extended to include 6 complete water years from October 1967 through September 1973. The results of these

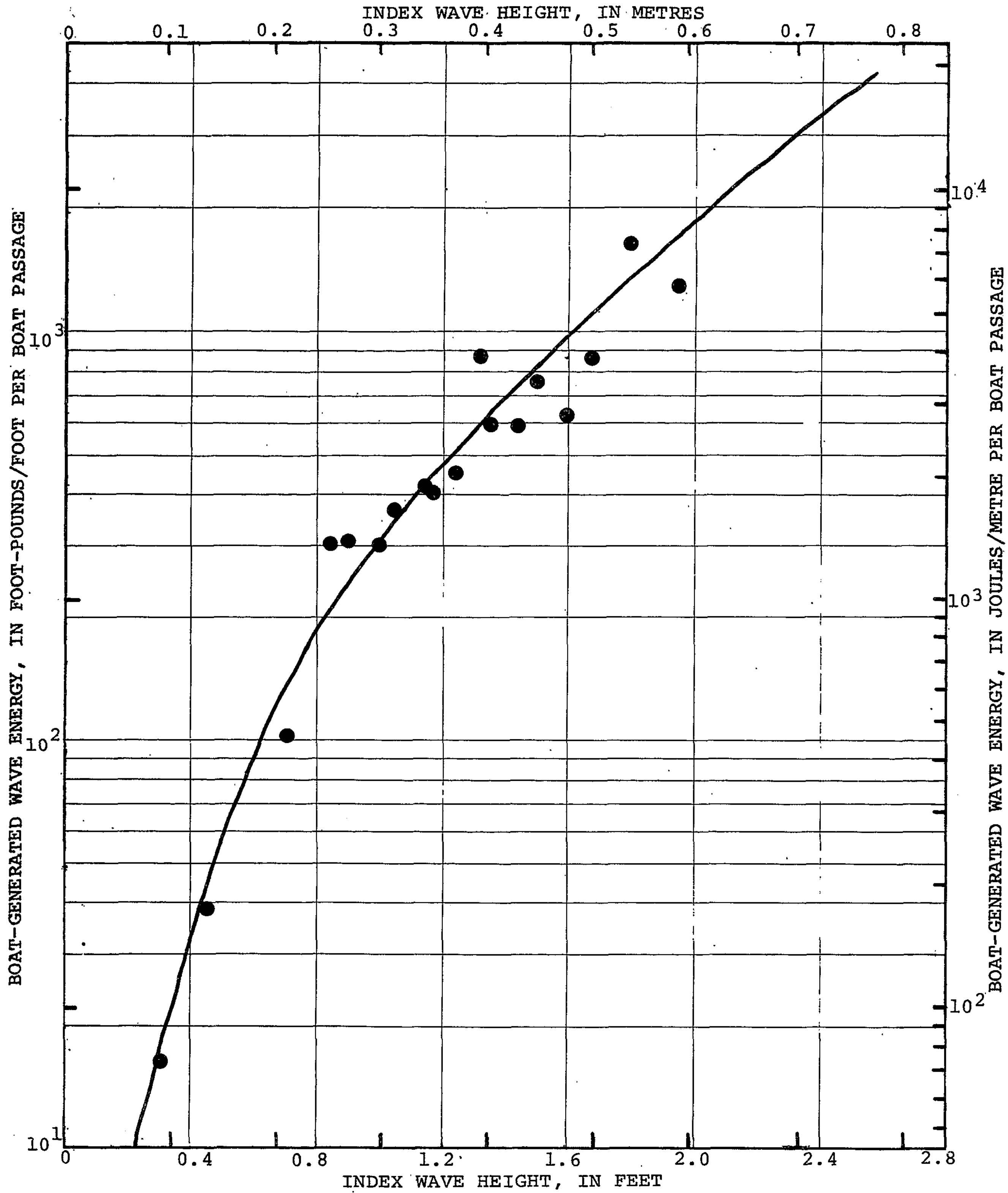


FIGURE 15.—Relation of boat-generated wave energy to index wave height.

| Index wave height | Energy dissipation rate $\left(\frac{\text{ft-lbs}}{\text{ft}}\right.$ per boat passage$\left.\right)$ | Number of boats | Total energy dissipation rate $\left(\frac{\text{ft-lbs}}{\text{ft}}\right)$ |
|---|---|---|---|
| (1) | (2) | (3) | (4) |
| 0.05–0.15 | 0 | 0 | 0 |
| .16– .25 | 8 | 3 | 24 |
| .26– .35 | 17 | 12 | 204 |
| .36– .45 | 33 | 22 | 726 |
| .46– .55 | 59 | 19 | 1,120 |
| .56– .65 | 92 | 28 | 2,580 |
| .66– .75 | 135 | 21 | 2,840 |
| .76– .85 | 190 | 16 | 3,040 |
| .86– .95 | 245 | 18 | 4,410 |
| .96–1.05 | 310 | 14 | 4,340 |
| 1.06–1.15 | 390 | 10 | 3,900 |
| 1.16–1.25 | 480 | 7 | 3,360 |
| 1.26–1.35 | 580 | 8 | 4,640 |
| 1.36–1.45 | 700 | 5 | 3,500 |
| 1.46–1.55 | 830 | 1 | 830 |
| 1.56–1.65 | 990 | 1 | 990 |
| 1.66–1.75 | 1,160 | – | – |
| 1.76–1.85 | 1,360 | 1 | 1,360 |
| 1.86–1.95 | 1,600 | – | – |
| Total | | 186 | 37,864 |

Adjustment for missing record (1.01)(37,864) = 38,240
Total boat-generated wave energy dissipated in
Georgiana Slough 129,400 ft x 38,240 =

$49.5 \times 10^8$ ft-lbs

FIGURE 16.—Sample computation sheet showing procedure used in computation of boat-generated wave energy in Georgiana Slough, October 1972.

computations are summarized in table 7. Tractive shear stress computations were based on the long-term records of river flow in the Sacramento River at Sacramento, the wind-generated wave energies were related to the wind records at Travis Air Force Base, and boat-generated wave energies were estimated on the basis of statistics furnished by the bridge tender at Tyler Island.

Tractive shear stress energy was computed by the following procedure: A relation, shown in figure 17, was developed between monthly mean discharge at Sacramento and the total tractive shear stress energy dissipated per month computed for the 12 months of record in 1972–73. Then for each month, beginning in October 1967, the monthly mean discharge at Sacramento was used to determine the corresponding tractive shear stress energy dissipation in Georgiana Slough. An example of this computation is shown in figure 18.

Procedures for extrapolating wind-generated wave energy were based on the assumption that energy dissipation would be proportional to wind movement at the Travis Air Force Base wind gage. Figure 19 shows monthly computations for the

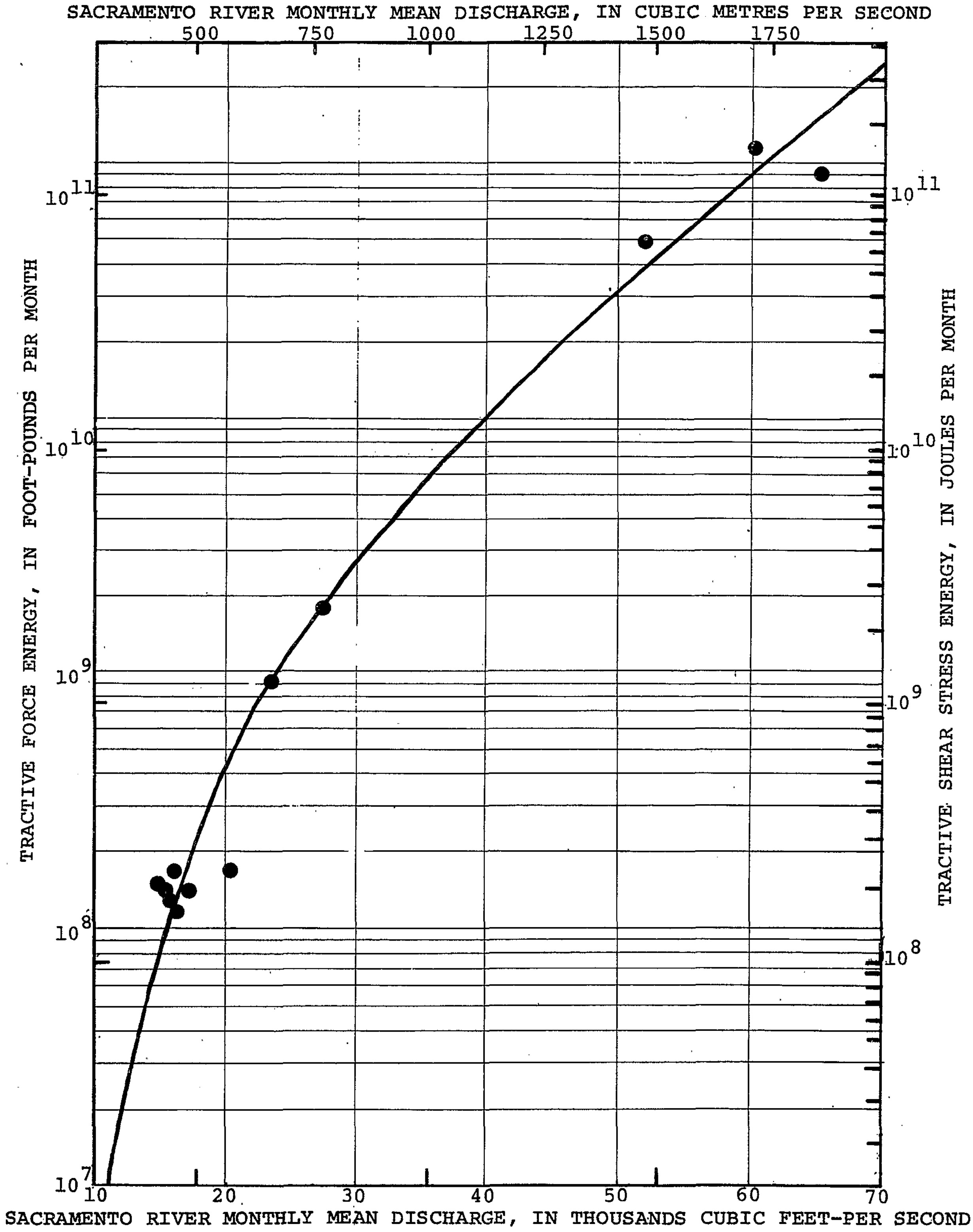


FIGURE 17.—Relation of monthly total tractive shear stress energy in Georgiana Slough to monthly mean discharge in Sacramento River at Sacramento, October 1972 through September 1973.

| Month | Sacramento River monthly mean discharge ($ft^3/s$) | Tractive shear stress energy[1] ($\frac{ft\text{-}lbs}{month} \times 10^8$) |
|---|---|---|
| October | 15,260 | 0.9 |
| November | 22,520 | 7.5 |
| December | 63,970 | 1,340 |
| January | 52,320 | 400 |
| February | 31,200 | 32 |
| March | 30,480 | 29 |
| April | 38,270 | 82 |
| May | 22,190 | 7.2 |
| June | 27,550 | 19 |
| July | 20,980 | 5.2 |
| August | 22,460 | 7.5 |
| September | 24,390 | 11 |
| Total | | 1,941.3 |

[1]From curve based on 1972-73 computation (fig. 16).

FIGURE 18.—Sample computation sheet showing procedure used in extrapolating tractive shear stress energy in Georgiana Slough, 1971 water year.

1971 water year. Wind-movement statistics are tabulated in columns 2 and 3. The ratio of the 1971 water year wind movement to that recorded in the 1973 water year is shown in column 4. The wind-generated wave energy computed from the 1973 water year wave record is listed in column 5, and the wind-generated wave energy is computed in column 6 as the product of columns 4 and 5.

Statistics on boat travel in Georgiana Slough, required for estimation of energy dissipated by boat waves during the 1967–73 period, were obtained from the bridge tender's log at the Tyler Island drawbridge.

This log provides a monthly total for large boats, those for which the bridge had to be opened. It does not include a count of the small boat traffic which passes under the bridge. However, as part of this study a complete log of traffic was made for the October 1972 through September 1973 period. If it is assumed that the ratio of large boat traffic to total boat traffic is virtually the same from year to year, then the relative number of small boats will not change. It follows, then, that the energy dissipated by waves from boats can be estimated for any month as the product of the boat-generated wave energy, calculated for that same month in the 1972–73 period, and the ratio of the number of bridge openings during the given month to the number of bridge openings in the corresponding month during the 1972–73 period. This procedure is illustrated in figure 20, which shows computations for the 1971 water year.

### FALSE RIVER EXTRAPOLATIONS

The results of computations based on the four months of records for False River shown in the first four lines of table 6 were extrapolated to cover the 12-month period from October 1972 through September 1973, because the period of record covered only the summer period which is one of intense boat activity and low flow. Extrapolation to cover a full year permitted assessment of the effects of a high water period in the annual distribution of relative energies dissipated by tractive shear stress, wind-generated waves, and boat-generated waves.

Computations of tractive shear stress energy followed the same procedure outlined previously

| Month | Travis Air Force Base wind movement 1970-71 (mi) | Travis Air Force Base wind movement 1972-73 (mi) | Wind movement ratio $\left(\frac{1970\text{-}71}{1972\text{-}73}\right)$ | Wind-generated wave energy 1972-73 (ft-lbs x $10^8$) | Wind-generated wave energy (col 4 x col 5) (ft-lbs x $10^8$) |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| October | 7,645 | 6,569 | 1.16 | 40.3 | 46.8 |
| November | 5,299 | 4,664 | 1.14 | 4.0 | 4.6 |
| December | 4,306 | 5,989 | .72 | 8.3 | 6.0 |
| January | 3,367 | 6,182 | .54 | 12.6 | 6.8 |
| February | 4,830 | 5,575 | .87 | 5.2 | 4.5 |
| March | 7,397 | 8,197 | .90 | 5.0 | 4.5 |
| April | 7,535 | 8,666 | .87 | 31.6 | 27.5 |
| May | 8,418 | 10,378 | .81 | 24.6 | 19.9 |
| June | 11,068 | 9,908 | 1.12 | 36.1 | 40.4 |
| July | 11,537 | 12,668 | .91 | 158.6 | 144.3 |
| August | 11,896 | 11,896 | 1.00 | 33.8 | 33.8 |
| September | 7,397 | 9,522 | .78 | 68.8 | 53.7 |
| Total | | | | | 392.8 |

FIGURE 19.—Sample computation sheet showing procedure used in extrapolating wind-generated wave energy in Georgiana Slough, 1971 water year.



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| Month | Number of bridge openings 1972-73 | Number of bridge openings 1970-71 | Ratio of bridge openings (1970-71 / 1972-73) | Monthly boat-wave energy (ft-lbs x $10^8$) | Monthly boat-wave energy (ft-lbs x $10^8$) 1970-71 |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| | | | (3) ÷ (2) | | (4) x (5) |
| October | 173 | 140 | 0.81 | 49.5 | 40 |
| November | 56 | 44 | .79 | 19.6 | 15 |
| December | 11 | 24 | 2.18 | 3.8 | 8 |
| January | 9 | 19 | 2.11 | 2.1 | 4 |
| February | 31 | 24 | .77 | 12.6 | 10 |
| March | 23 | 30 | 1.30 | 13.6 | 18 |
| April | 129 | 101 | .78 | 59.2 | 46 |
| May | 201 | 177 | .88 | 68.6 | 60 |
| June | 254 | 213 | .84 | 59.7 | 50 |
| July | 430 | 443 | 1.03 | 137.9 | 142 |
| August | 518 | 607 | 1.17 | 152.1 | 178 |
| September | 350 | 455 | 1.30 | 107.0 | 139 |
| Total | 2,185 | 2,277 | | 685.7 | 710 |

Note: Columns (2) and (3) are counts at Tyler Island bridge.
Column (5) previously computed.

FIGURE 20.—Sample computation sheet showing procedure used in extrapolating boat-generated wave energy in Georgiana Slough, 1971 water year.

in "Computation of Tractive Shear Stress Energy," except that the computations were made on a monthly basis rather than on a daily basis. Because there were only 4 months of stage records for False River, tractive shear stress energy computation data were approximated by transference from Georgiana Slough. The percentage of time that the water surface was above the mean lower low water elevation, and the corresponding boundary distribution factors and height of the energy dissipation zone, were assumed to be the same on a monthly mean basis for both waterways.

These computations (fig. 21) show that tractive shear stress energies are not of significant magnitude. This is because velocities are dominated by tidal action and are not affected by floodflows. The mean velocity (absolute mean) is nearly constant throughout the year. The only factors which change are the time that the zone of erosion is covered by water, the height of the erosion zone, and the corresponding boundary coefficients. These seasonal changes are not large enough to produce significant tractive shear stress energy dissipation in a low velocity channel such as False River.

Extrapolation of wind-generated wave energy is based on the assumption that the energy for the entire year (October 1972 through September 1973) on False River bears the same ratio to energy for the entire year on Georgiana Slough as do the energy values for the common 4-month (June-September) period when recorded wave data were available for both waterways. This results in the equation

$$F_{12} = G_{12}\left(\frac{F_4}{G_4}\right), \quad (14)$$

where $F_{12}$ = False River wind-generated wave energy for the 12-month period,

| Month | Sacramento River flow ($ft^3/s$) | False River velocity (f/s) | Energy dissipation rate $\left(\frac{\text{ft-lbs}}{\text{ft}^2\text{-month}}\right)$ | Percentage of time water is above MLLW at Georgiana Slough | Boundary distribution factor at Georgiana Slough | Energy dissipation zone for Georgiana Slough (ft) | Energy dissipation per month (ft-lbs x $10^8$) Col (4)x(5)x(6)x(7) x 16,400 ft |
|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| October | 16,080 | 0.65 | 12,030 | 80 | 0.05 | 1.3 | 0.10 |
| November | 23,200 | .65 | 11,640 | 86 | .05 | 1.4 | .11 |
| December | 27,420 | .65 | 12,030 | 88 | .06 | 1.5 | .16 |
| January | 60,130 | .67 | 13,180 | 98 | .12 | 3.5 | .89 |
| February | 65,200 | .67 | 11,900 | 100 | .13 | 3.9 | .99 |
| March | 51,640 | .66 | 12,590 | 98 | .10 | 2.8 | .57 |
| April | 20,500 | .65 | 11,640 | 74 | .04 | 1.1 | .06 |
| May | 16,400 | .65 | 12,030 | 74 | .04 | 1.1 | .06 |
| | | | | | October-May total | | $2.94 \times 10^8$ ft-lbs |
| | | | | | June-September total (from table 5) | | $0.97 \times 10^8$ |
| | | | | | October 1972-September 1973 | | $3.91 \times 10^8$ ft-lbs |

FIGURE 21.—Sample computation sheet showing procedure used in extrapolating tractive shear stress energy in False River, October 1972 through May 1973.

$G_{12}$ = Georgiana Slough wind-generated wave energy for the 12-month period,

$F_4$ = False River wind-generated wave energy for the 4-month period, and

$G_4$ = Georgiana Slough wind-generated wave energy for the 4-month period.

Values for $G_{12}$, $G_4$, and $F_4$, can be abstracted from tables 5 and 6. The computation of $F_{12}$, based on the Bettencourt wind record is

$$F_{12} = (428.9 \times 10^8)\left(\frac{32.6 \times 10^8}{297.3 \times 10^8}\right) = 47.0 \times 10^8$$

foot-pounds per year, and the corresponding computation based on the Travis Air Force Base wind record is

$$F_{12} = (428.9 \times 10^8)\left(\frac{116.0 \times 10^8}{297.3 \times 10^8}\right) = 167.3 \times 10^8$$

foot-pounds per year. These are the values entered in lines 6 and 8 of column 4 of table 6.

The procedure used for extrapolation of boat-generated wave energy rests on the same types of assumption used in extrapolation of the wind-generated wave energy. It is assumed that boat traffic in False River varies proportionately with that in Georgiana Slough because both channels are used for the same kind of boat traffic. Using figures abstracted from tables 5 and 6, the boat-generated wave energy for the 12-month period was computed as

$$F_{12B} = G_{12B}\left(\frac{F_{4B}}{G_{4B}}\right), \qquad (15)$$

where $F_{12B}$ = False River boat-generated wave energy for the 12-month period,

$G_{12B}$ = Georgiana Slough boat-generated wave energy for the 12-month period, and

$F_{4B}$ and $G_{4B}$ = respective energies for the 4-month period,

$$\text{or } F_{12B} = (685.7 \times 10^8)\left(\frac{145.0}{456.7}\right) = 217.7 \times 10^8$$

foot-pounds per year,

which is the figure carried in lines 6, 8, and 10 of column 6 in table 6.

## ANALYSIS OF EROSION DATA

Two techniques were used to document changes in the levees attributable to erosion by tractive shear stress, wind-generated waves, and boat-generated waves. For the first approach, gross changes in bank profile were recorded at two or more levee cross sections at each of seven sites on Georgiana Slough and at two sites on False River. An arbitrary datum was used for each site. Bank profiles were surveyed by standard rod and level methods at about monthly intervals.

The sites were selected to provide a measure of erosion during the short term field study. This necessitated that they be placed in areas of active erosion, sections of the levee which are by no means representative of profiles along the entire waterway.

Figures 22 and 23 show representative changes caused by erosion and deposition on Georgiana Slough during the period October 1972 through September 1973. To avoid confusion and better illustrate the sequence of changes the plotting has been limited to bimonthly surveys. Figures 24 and 25 show the profile changes indicated by the monthly surveys on False River from June through September 1973.

Quantitative evaluation of these rod and level surveys has not been made. On Georgiana Slough it is apparent that floodflows during January caused large losses of the weak sand or clay levee materials located on the upper bank which were accompanied by deposition of both fine and coarse material on the berm. In some instances, as illustrated in figure 22, some of the material deposited during the major runoff period remained until late summer, but typically, as shown in figure 23 erosion was more rapid. In all cases there was a net loss from this process during the year.

On False River, the cross-sectional surveys were made during the period June through September 1973. Wind-generated waves and boat-generated waves produce nearly all the erosional energy dissipated in this channel; the effects of tractive shear stress are minimal. The False River levees, built of peat material excavated from the channel bottom, is organic material that tends to break down from wave action and cyclical wetting and drying related to the tidal activity. The same material in an undisturbed condition along the flat berm section appears to be highly resistant to erosion.

At both study channels, one with levees built from sand and clay and the other with levees built from excavated peat, it is apparent that erosion is occurring in the unstable levee material, while the

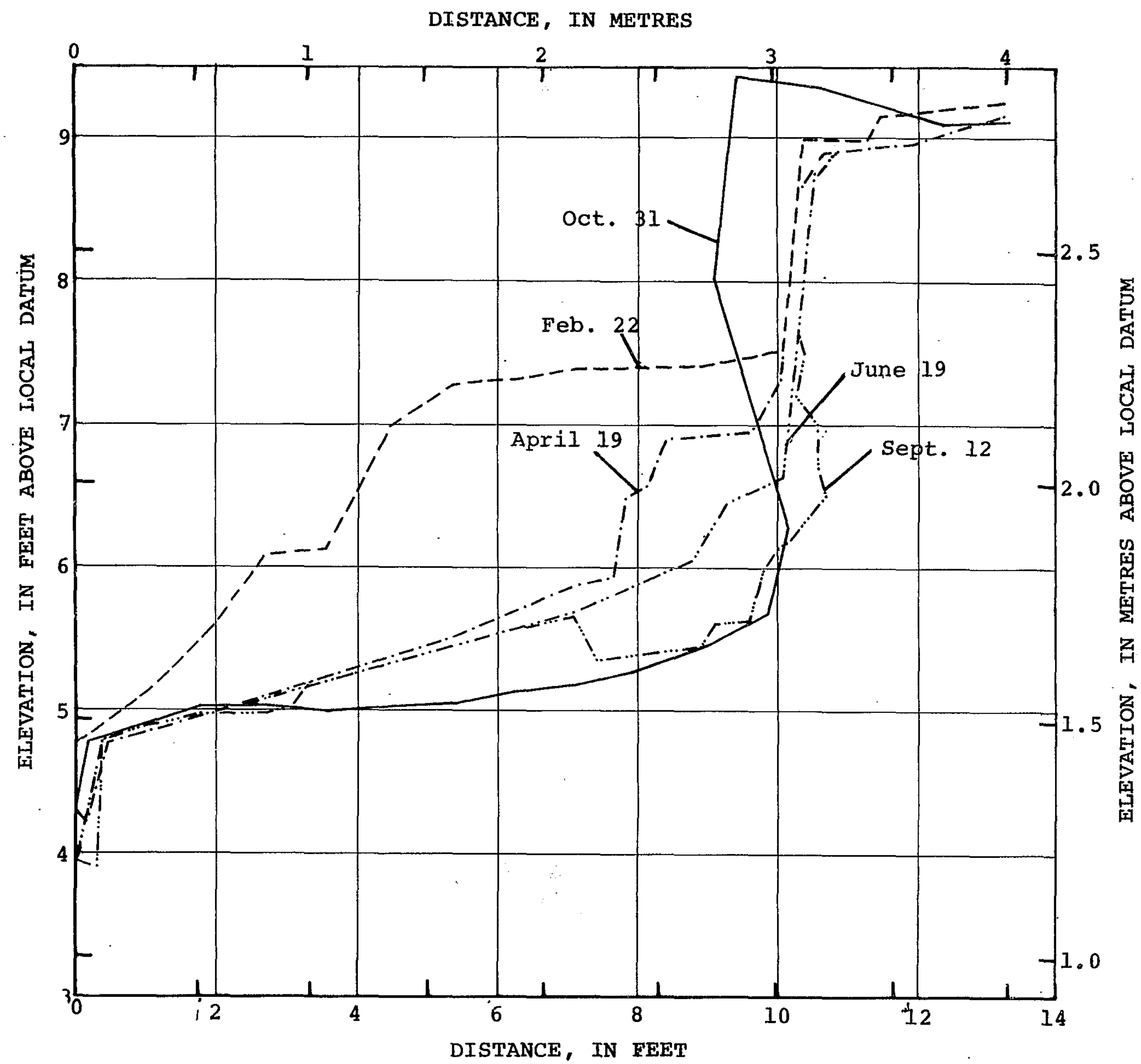


FIGURE 22.—Bank profiles for site G9, Georgiana Slough, October 1972 through September 1973.

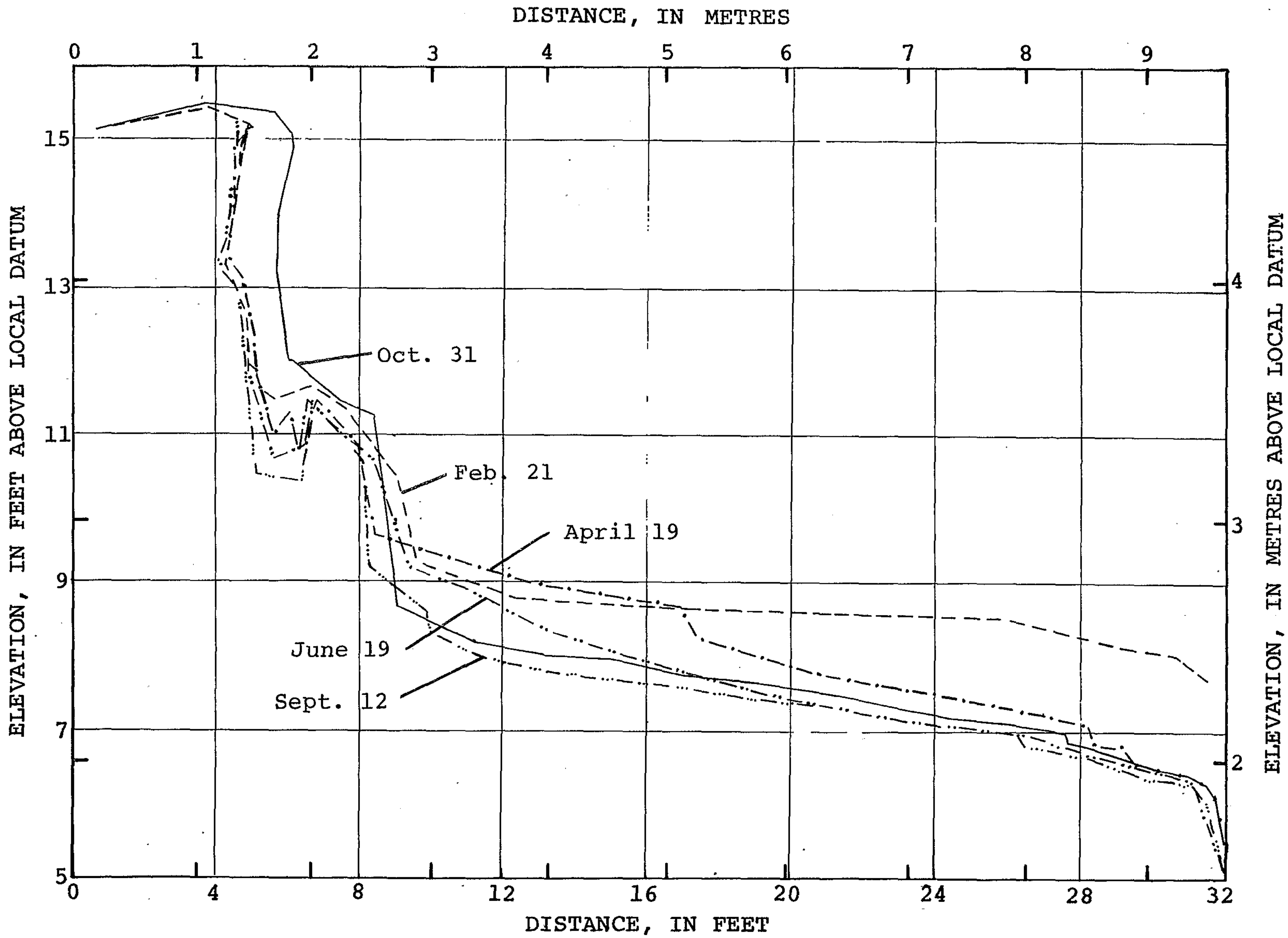


FIGURE 23.—Bank profiles for site G4, Georgiana Slough, October 1972 through September 1973.

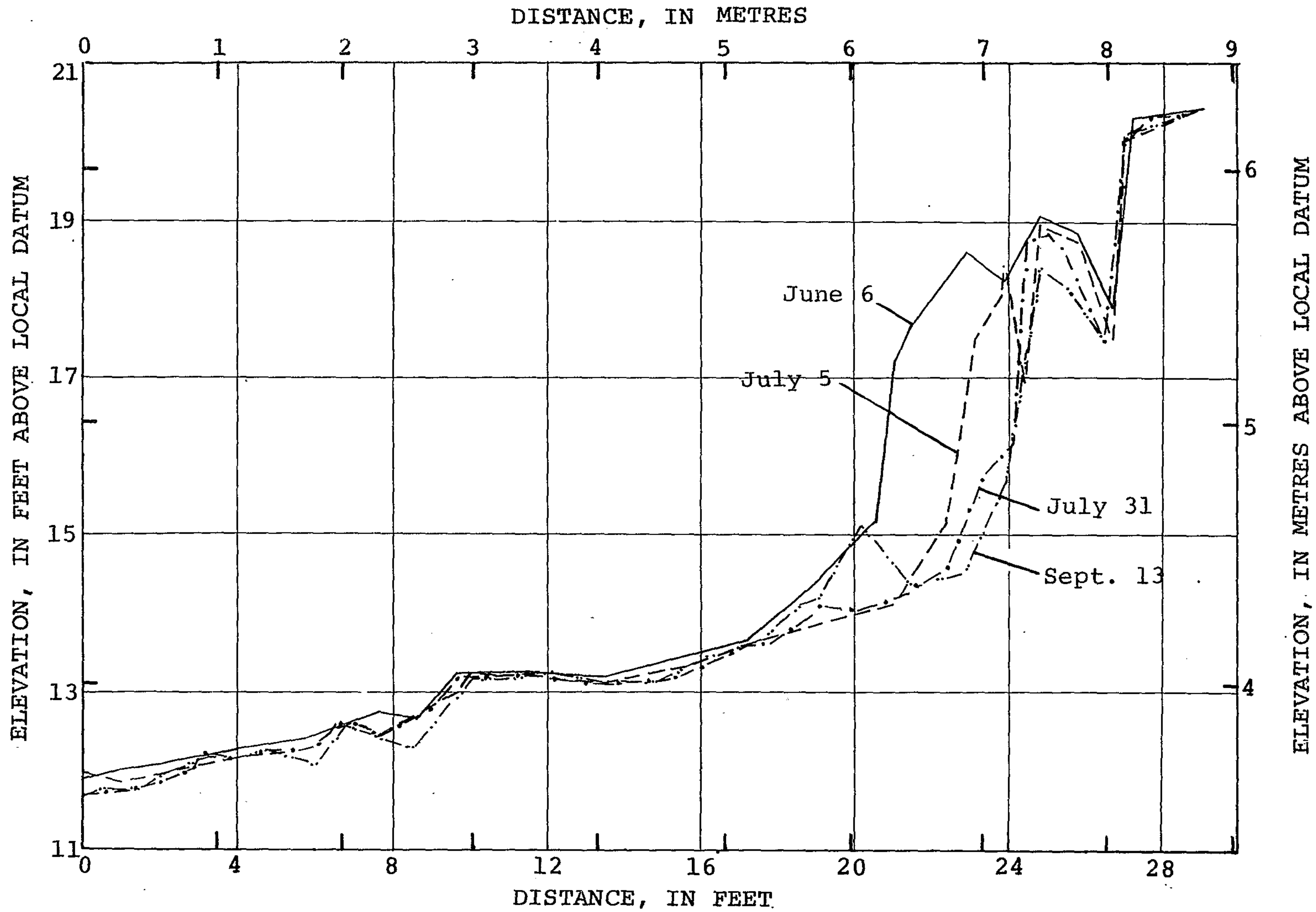


FIGURE 24.—Bank profiles for site F5 line 1, False River, June through September 1973.

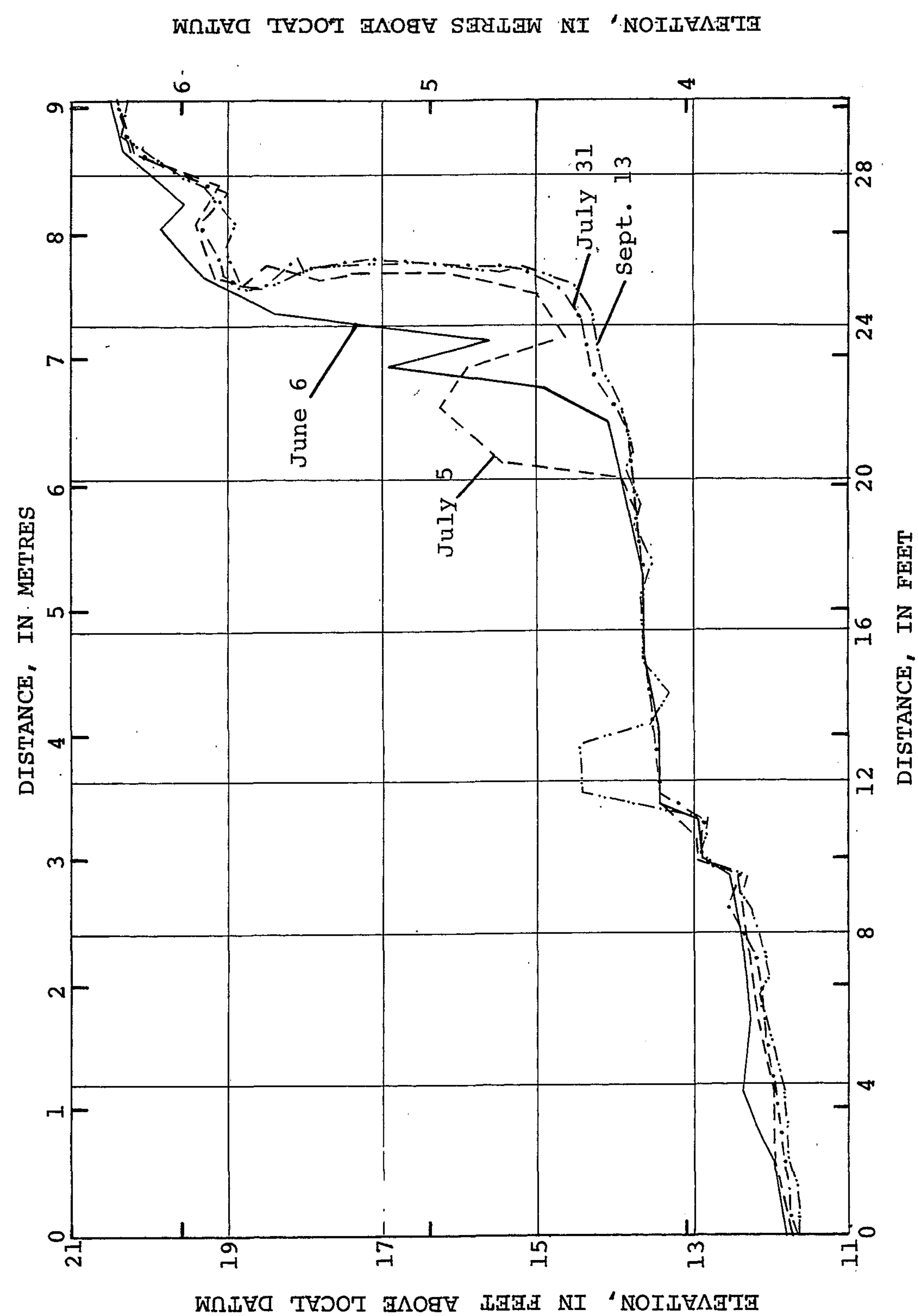


FIGURE 25.—Bank profiles for site F5 line 2, False River, June through September 1973.

original delta deposits forming the low berm are stable and apparently resistant to erosion forces.

Figures 26 and 27 are typical of observations made on Georgiana Slough. Figures 28 and 29 show results of measurements on False River. During the course of the investigation it was noted that changes in profile were cyclical, particularly on Georgiana Slough. Periods of erosion were sometimes followed by deposition, and several weeks might elapse before the deposited material was eroded away. Curves plotted in figures 26–29 show the net erosion from the original profile established at the beginning of the study. Periods of deposition followed by scour to previously recorded elevations are shown as dotted lines in these graphs.

The average change in each profile, at each of the pin sites, is shown in table 8. These statistics were compiled for comparison with energy dissipation attributed to tractive shear stress, wind-generated waves, and boat-generated waves. The total erosion for the period of record between December 1972 and September 1973 at Georgiana Slough sites is shown in column 2 of table 8. The increment from December through March when tractive shear stress energy was predominant is shown in column 3, and the increment from April through September when virtually all energy dissipation was attributed to wind-generated waves and boat-generated waves is shown in column 4. Erosion at Georgiana Slough and False River, during the common period of record from June through September 1973 is shown in column 5.

The second method for documenting changes or levee erosion involved installation of erosion pins, permitting more precise measurement of the changes in the bank profile. A set of erosion pins included from four to seven pairs of steel pins driven perpendicularly to the bank on either side of a transverse section extending from about 1 ft (0.3 m) above low tide to about 1 ft (0.3 m) above high tide. The horizontal distance between the pins in each pair was 18 in (0.46 m), with pairs located at intervals along the transverse section as shown in figures 26(*A*)–29(*A*). Length of pins used varied depending upon the resistance of levee material encountered.

Changes in the bank profile were measured from a 36-in (0.9 m) long template placed flush with the tops of each pair of pins. Distances to the bank were measured at seven equally spaced points along the template. At each set of pins the transverse profile was computed as the average of these seven measurements. Observations were made at least once a week, tide and stage permitting, from December 1, 1972, to September 30, 1973.

Twenty erosion pin sites were established on Georgiana Slough; however, eight of these were destroyed by levee maintenance operations early in the year. The sites were selected to include different channel configurations and levee soils. Six erosion pin sites were located on False River; all were on levees composed of dredged peat material.

## COMPARISON OF ENERGY DISSIPATION AND OBSERVED EROSION

One of the objectives of this study was to relate, if possible, observation of active erosion to calculated energy dissipation to show that a cause and effect relation existed between erosion and the dynamic energy sources. This could be done by direct correlation if observations were obtained during selected periods when each of the dynamic energy sources was the sole contributing source. The spectrum of data collected on False River provides no clear cut differentiation between periods of wind-wave dominance and boat-generated wave activity. Winds were almost constant during the summer period which is also the heaviest period for boat traffic. However, the results of computations shown in table 6 strongly suggest that, in this channel, boat-generated waves develop much more energy than wind-generated waves.

Data from Georgiana Slough does provide an opportunity for differentiating the relative energies, on a time basis, between tractive shear stress energy and the combined effects of wind- and boat-generated wave energies. Table 5 shows that from December 1972 through March 1973 nearly all of the energy dissipated in the channel was derived from tractive shear stress. In contrast, from April through September 1973 tractive shear stress energy was minimal, and almost all of the energy dissipated was from wind- and boat-generated waves. A comparison of these energy dissipation levels with observed erosion computed from the erosion pin data is shown in table 9. Analysis of these figures shows that of the total energy dissipated and observed erosion that occurred from December through September:

1. December–March accounted for 73.6 percent of the total energy dissipated and 50.2 percent of the observed erosion. Tractive

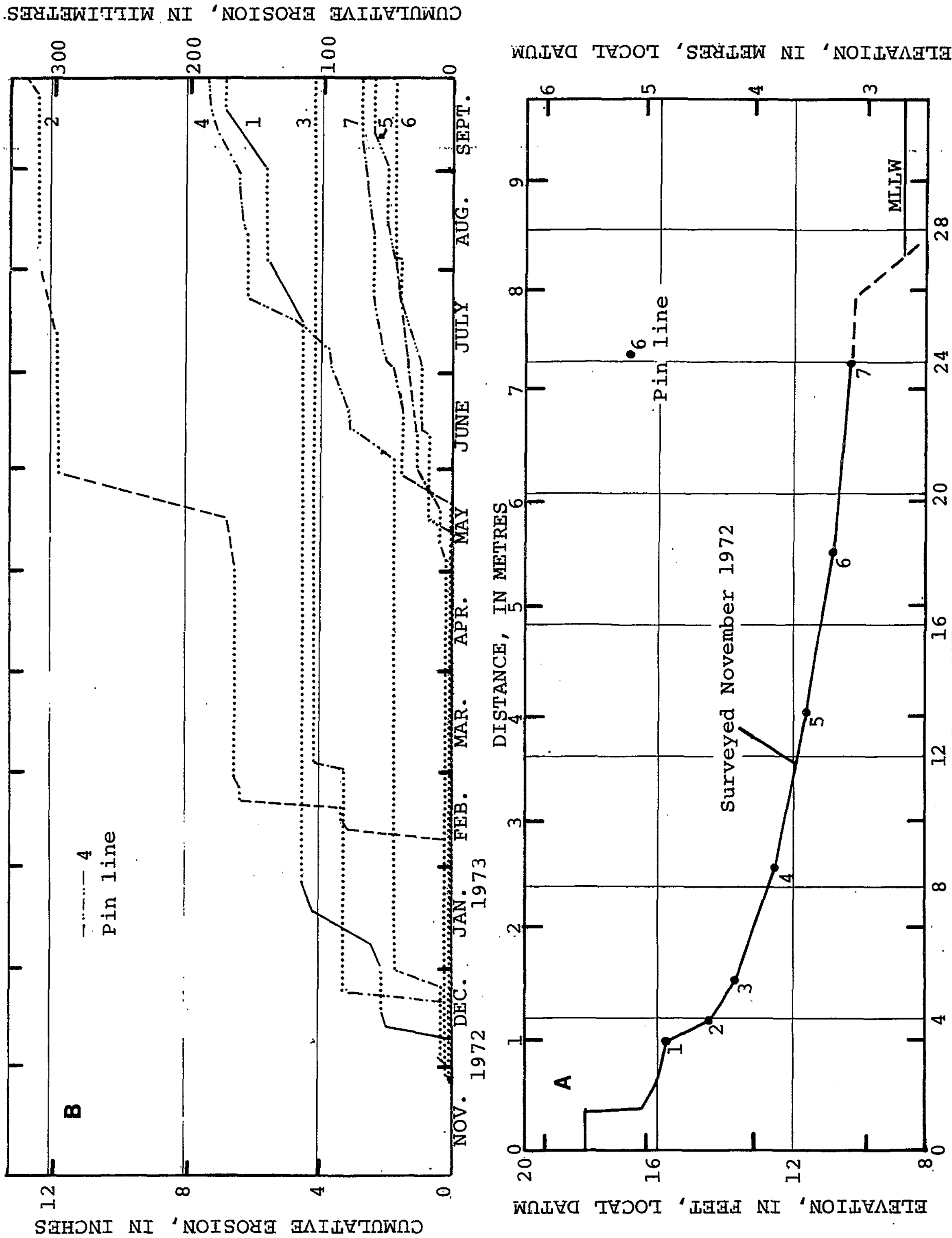


FIGURE 26.—Transverse profile (*A*) and cumulative erosion (*B*) at site G7, Georgiana Slough, December 1972 through September 1973.

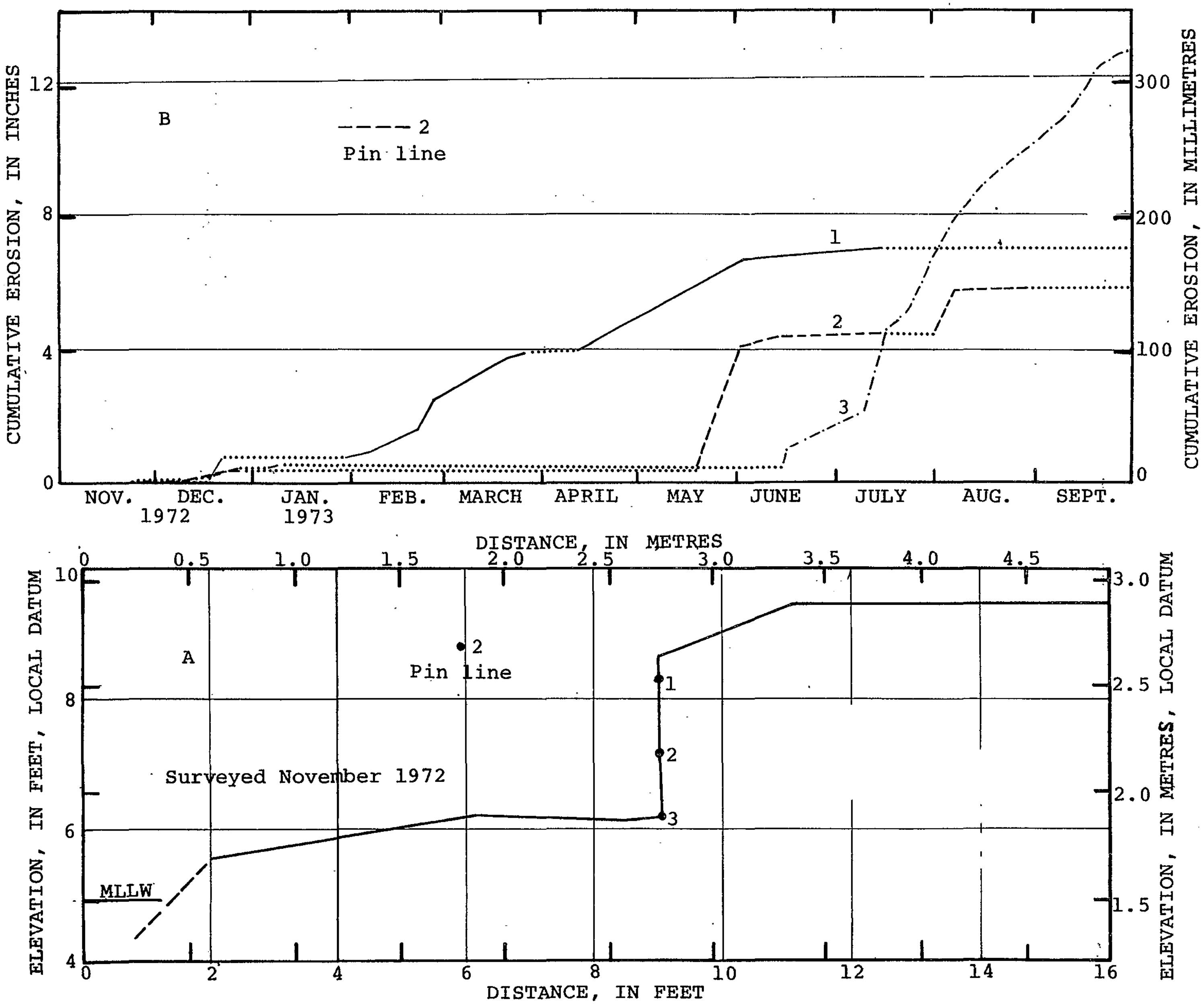


FIGURE 27.—Transverse profile (*A*) and cumulative erosion (*B*) at site G9, Georgiana Slough, December 1972 through September 1973.

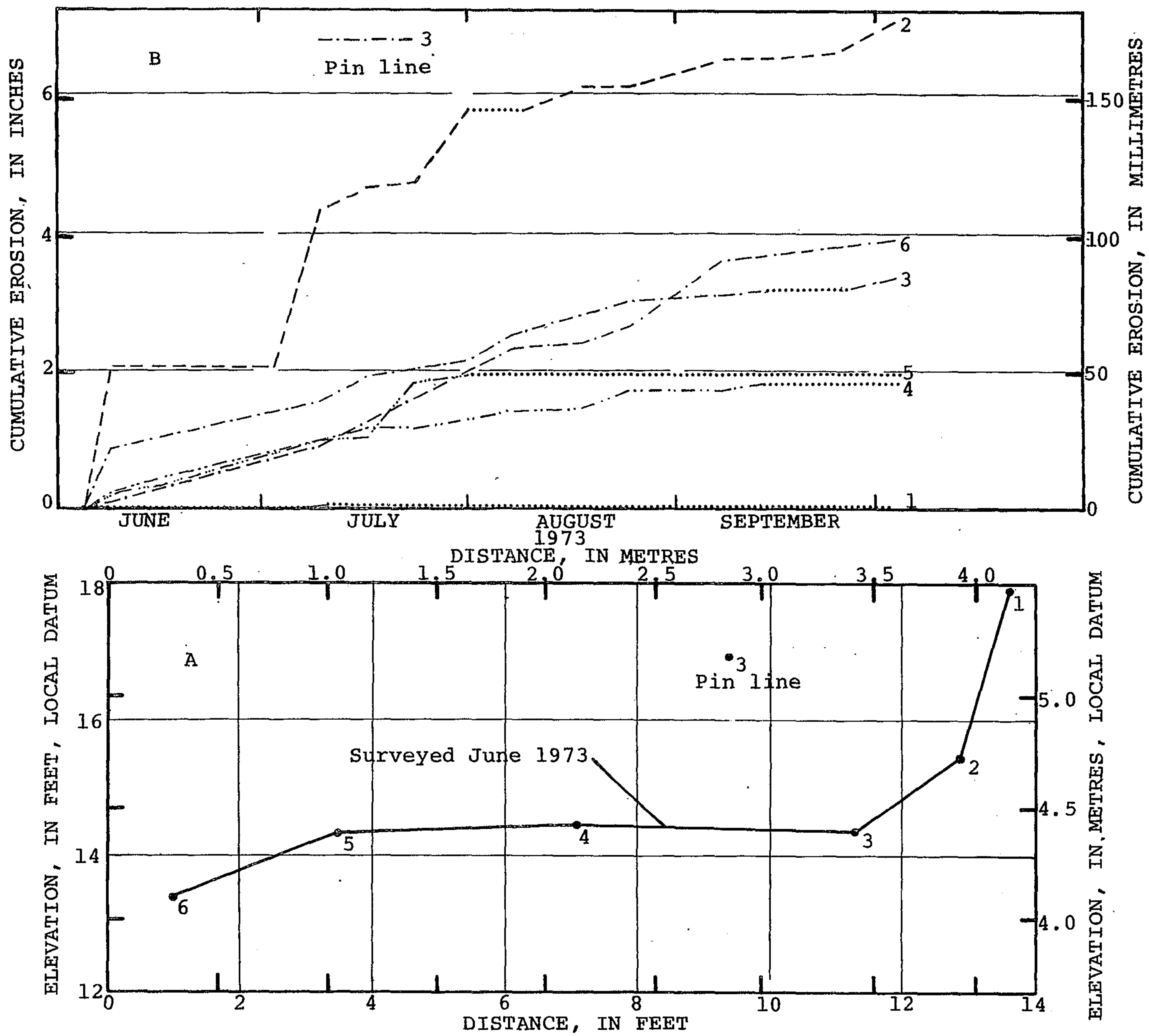


FIGURE 28.—Transverse profile (*A*) and cumulative erosion (*B*) at site F5, False River, June through September 1973.

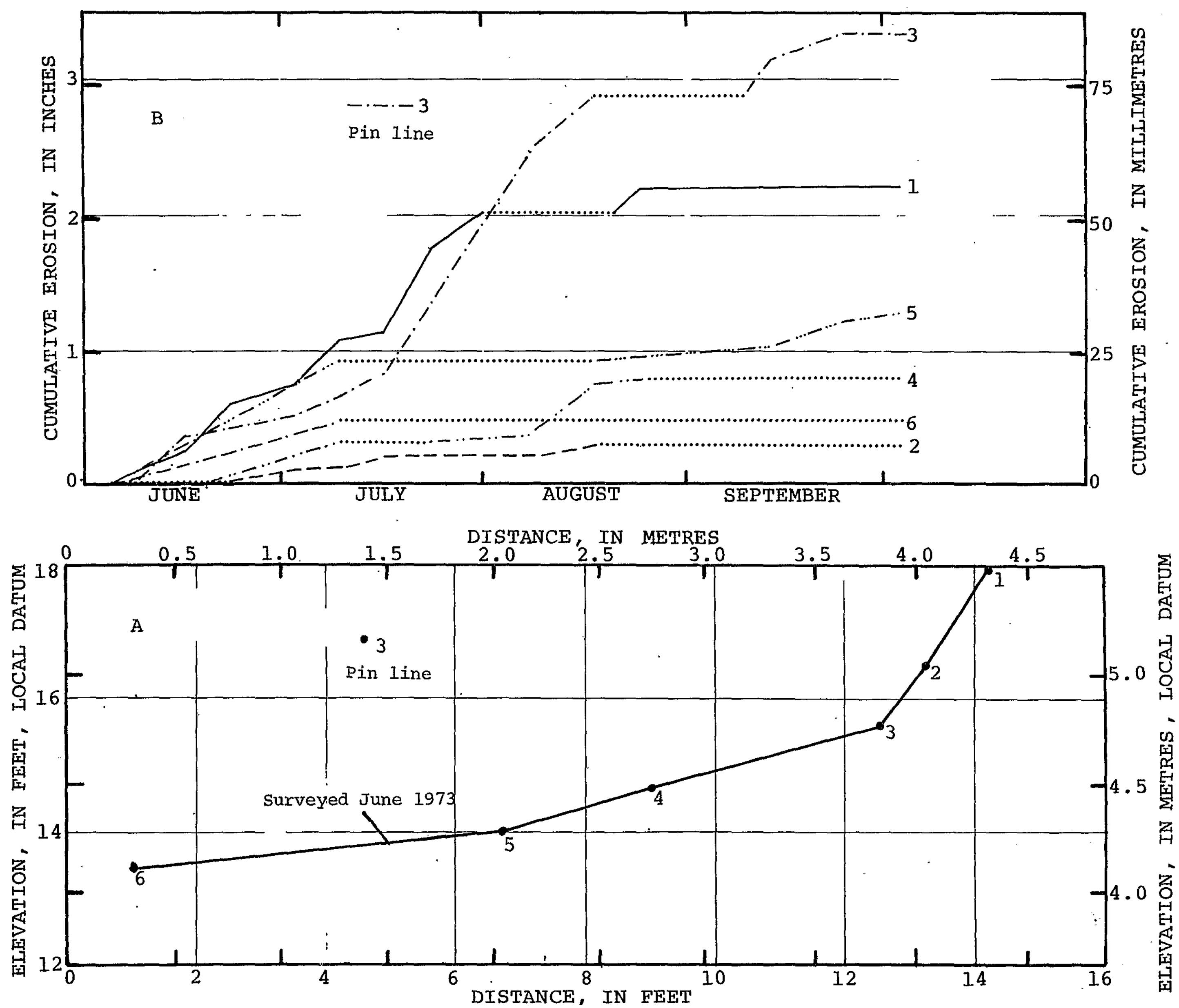


FIGURE 29.—Transverse profile (*A*) and cumulative erosion (*B*) at site F3, False River, June through September 1973.

TABLE 8.—*Erosion-pin statistics for Georgiana Slough and False River, December 1972–September 1973*

| Channel and site | Erosion, in inches | | | |
|---|---|---|---|---|
| | December 1972–September 1973 | December 1972–March 1973 | April–September 1973 | June–September 1973 |
| (1) | (2) | (3) | (4) | (5) |
| Georgiana Slough | | | | |
| G1 | 5.1 | 3.3 | 1.8 | 0.4 |
| G2 | 2.5 | .9 | 1.6 | .8 |
| G3 | 1.0 | .1 | .9 | .4 |
| G4 | 5.2 | 3.1 | 2.1 | .7 |
| G5 | 6.8 | 3.2 | 3.6 | 1.0 |
| G6 | 3.5 | 1.0 | 2.5 | 1.3 |
| G7 | 5.1 | 2.4 | 2.7 | 1.7 |
| G8 | 1.5 | .5 | 1.0 | 1.0 |
| G9 | 8.5 | 1.5 | 7.0 | 4.0 |
| G10 | 6.2 | 2.0 | 4.2 | 2.8 |
| G11 | 16.2 | 13.6 | 2.6 | 2.5 |
| G12 | 2.7 | .7 | 2.0 | 1.3 |
| Total | 64.3 | 32.3 | 32.0 | 17.9 |
| Average | 5.4 | 2.69 | 2.67 | 1.5 |
| Percentage of total | 100.0 | 50.2 | 49.8 | - |
| False River | | | | |
| F1 | - | - | - | 1.1 |
| F2 | - | - | - | .5 |
| F3 | - | - | - | 1.4 |
| F4 | - | - | - | .5 |
| F5 | - | - | - | 3.0 |
| F6 | - | - | - | 8.6 |
| Total | | | | 15.1 |
| Average | | | | 2.5 |

shear stress accounted for 98 percent of the total energy dissipated from December through March.

2. April–September accounted for 26.4 percent of the total energy dissipated and 49.8 percent of the observed erosion. Tractive shear stress was negligible during this period, but the combined wind- and boat-generated wave energy accounted for 99 percent of the total energy dissipated.

Conclusions suggested by the comparison are that:

1. Erosion rates observed are not linearly related to computed energy dissipation. Erosion resulting from wind and boat-wave energies is at a higher rate than that resulting from tractive shear energy. This implies that other factors may enter into the equation. For example, it can be argued that more erosion might result from the cumulative effects of several boat waves of large magnitude, where the energy dissipation rate from the individual waves is large, than from a protracted period of low stress from tractive shear, even though the total energies applied in the two instances were the same.
2. It is obvious that the erosion which occurred during the summer can be attributed to



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TABLE 9.—*Comparison of computed energy dissipation with observed erosion in Georgiana Slough, December 1972–September 1973*

| Period | Percentage of energy dissipated in period relative to total for December 1972–September 1973 | | | | Percentage of erosion in period relative to total erosion from December 1972–September 1973 |
|---|---|---|---|---|---|
| | Shear energy | Wind-wave energy | Boat-generated wave energy | Total energy for period | |
| December 1972–March 1973 | 71.9 | 0.9 | 0.9 | 73.7 | 50.2 |
| April–September 1973 | .2 | 9.9 | 16.3 | 26.4 | 49.8 |

energy developed by boat waves and wind waves. However, it cannot be concluded that the relative erosion caused by each of these two factors is related linearly to the relative energy levels. Wind waves are typically of low amplitude and of several hours duration. Boat waves are generally of much higher amplitude but occur at random intervals and are of short duration.

3. If, however, linearity is assumed, then it can be conservatively estimated that approximately two-thirds of the levee erosion taking place during the summer period resulted from waves generated by boats. The assumption of nonlinearity would increase the erosion attributable to this factor by an indeterminate amount.

Computations made to evaluate the average energy dissipation per inch of erosion along the transverse levee sections in the two test channels are summarized in table 10. The computations were made to determine if identifiable differences existed between the resistance to erosion of the False River levee, which is composed largely of peat, and the levees on Georgiana Slough, which are constructed with a mixture of sand and clay.

Erosion of the levees for the common period, June through September 1973, was greater at False River than at Georgiana Slough. However, total energy dissipation levels were proportionately higher at False River. The statistics, which are controlled by the assumptions made in the distribution of wind-generated wave energy, do not demonstrate a striking difference. More important is that both the peat levees and the sand and clay levees do erode in response to energy levels produced in these channels during the summer months.

## APPLICATION OF STUDY FINDINGS TO OTHER DELTA CHANNELS

The ultimate goal of the study was to devise a technique for applying the findings derived from the selected study channels to other delta channels. Refinement needed in the technique will de-

TABLE 10.—*Relation of energy dissipation to levee erosion in Georgiana Slough and False River, June–September 1973*

| Delta channel | Total energy dissipation (ft-lbs x $10^8$) | Energy dissipation rate[1] $\left(\frac{\text{ft-lbs}}{\text{ft}}\right) \times 10^3$ | Average levee erosion (in) | Ratio of energy dissipation rate to average levee erosion $\left(\frac{\text{ft-lbs}}{\text{ft}}\right) \times 10^3$ per inch |
|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) |
| Georgiana Slough | 759.6 | 587 | 1.5 | 391 |
| False River[2] | 178.6 | 1,089 | 2.5 | 436 |
| False River[3] | 262.0 | 1,598 | 2.5 | 639 |

[1]Total energy in column 2 divided by levee length.
[2]Bettencourt wind statistics used for wind-wave energy analysis.
[3]Travis Air Force Base wind statistics used for wind-wave energy analysis.

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pend on whether estimates of relative energy dissipation are wanted for a particular channel, for groups of channels, or for large areas of the delta.

The findings of this study obviously cannot apply to the large channels in the western delta where wind-formed waves, created by wind movement over long fetches, probably generate almost all of the erosive energy. Some of these channels are also traveled by ocean-going vessels, which can produce waves whose energy far exceeds the energy levels studied. However, the Georgiana Slough channel is typical of the majority of the minor waterways, and transfer of findings from this test area to other parts of the delta should be feasible. It is believed that first order approximations could be made by the techniques discussed below.

Estimates of tractive shear stress energies could be generated from statistics produced by the California Department of Water Resources model, which can furnish values for velocity, stage or elevation, hydraulic radius, and the Manning $n$ for any reach in the system. This output provides all of the information needed in equation 5. Stage output could be manipulated to determine when the water was above the mean lower low water elevation, permitting estimation of the height of the erosion zone and the boundary coefficients required in the procedure. This computation could be computerized to produce analysis of tractive shear stress energy on an hourly basis. Values obtained could be averaged over any desired period, but it seems probable that average annual figures would be more meaningful than most other averages.

Estimates of energies resulting from wind-generated waves could be based on available wind records and channel geometry. However, the results would be questionable because of the uncertainty involved in transference of wind data from recording sites outside the delta. Direct application of the annual wind-generated wave energy dissipation rate observed at Georgiana Slough would probably be a more valid estimate of the energy generated by wind-formed waves. The wind-generated wave energy dissipation rate computed for the 12-mi (19-km) reach of Georgiana Slough, which includes several bends, should be a reasonably representative value for application in other sinuous channels.

Evaluation of energies from boat-generated waves will be more difficult. Boat traffic observed in Georgiana Slough is heavier than in most of the channels, and it probably includes a higher percentage of large boats. Therefore, boat traffic statistics must be obtained in other delta channels.

Boat traffic data could be obtained on a sampling basis by observations covering a few weekends at a dozen or more sites. If simultaneous data were also collected at Georgiana Slough, then the annual boat-count statistics from this site could be used in estimating annual traffic rates at the short-term observation sites. Statistics on total traffic and number of boats in various size classifications will be required.

A precise relation cannot be established between boat size and boat-generated wave energy. However, a rough approximation can be made; figure 30 shows boat-generated wave energy, computed from recorded wave heights at the Georgiana Slough wave gage, plotted against boat size. Scatter of the data reflects variability in boat speed, hull design, position of the boat relative to the wave gage, and unknown factors.

Two curves are shown in figure 30. The upper curve,

$$E_{CB} = 0.0066 L_{CB}^{3.28}, \qquad (16)$$

is the least squares fit to data for conventional boats, and the lower curve,

$$E_{HB} = 0.00011 L_{HB}^{3.84}, \qquad (17)$$

is the least squares fit to data for houseboats, which are large but generally travel at low speeds.

$E$ is the energy dissipation rate in foot-pounds per linear foot of bank, per boat passage,
$L$ is the boat length, in feet,
$CB$ denotes conventional boat, and
$HB$ denotes houseboat.

If boat-traffic statistics are generated for selected areas by the techniques suggested above, then rough estimates of energies attributable to boat-generated waves could be derived from the relations shown in figure 30.

In summary, the suggested technique for applying the study results to other areas involves the following:

1. Compute tractive shear stress energy dissipation rates by manipulating output from the California Department of Water Resources delta model.
2. Assume wind-generated wave energy rate to

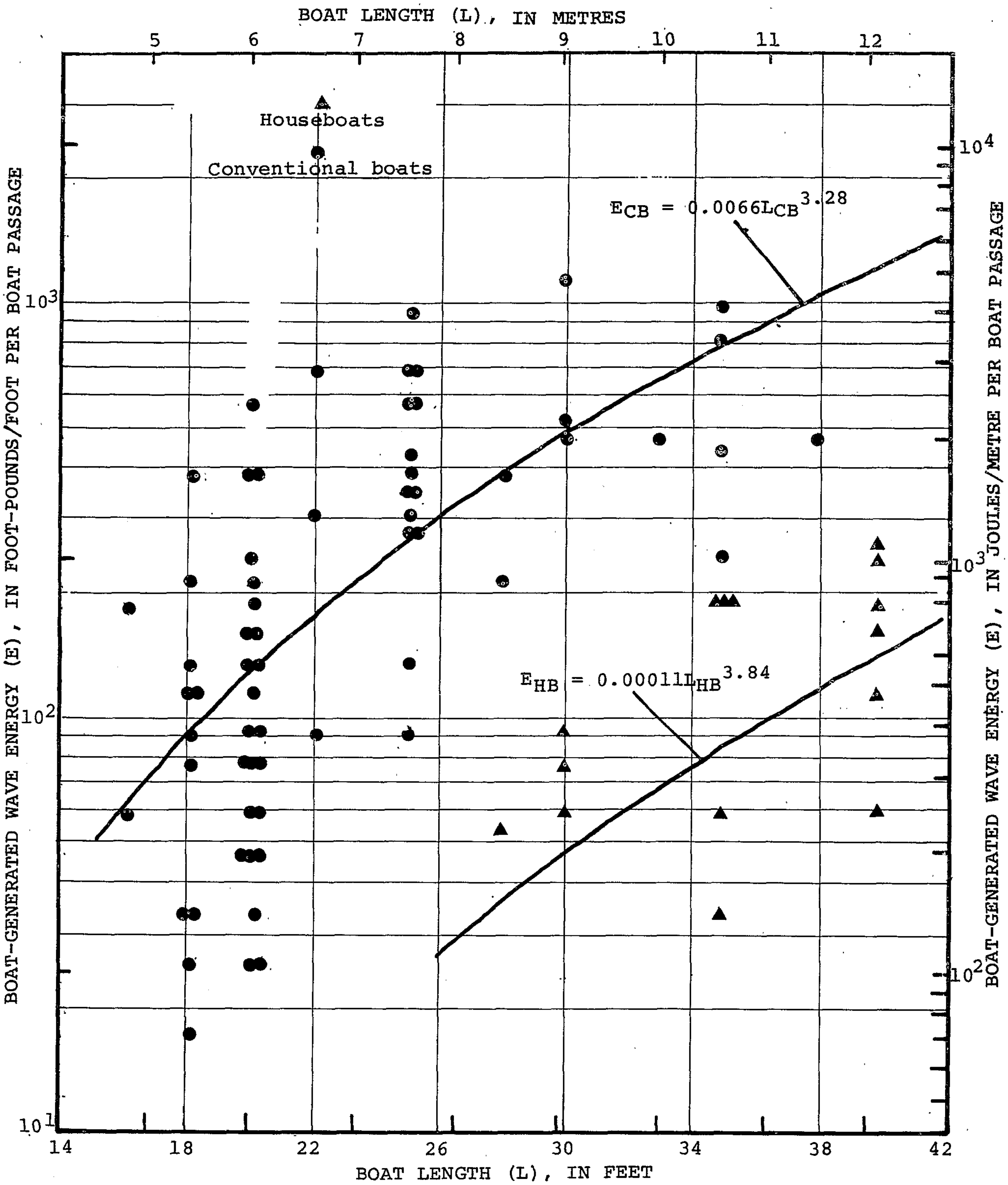


FIGURE 30.—Relation of boat-generated wave energy to boat length for conventional boats and houseboats.

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be equal to that observed in Georgiana Slough.

3. Compile boat-traffic statistics by a sampling technique and compute boat-generated wave energies from figure 30.

Computations made by this process will be approximations at best. The treatment given to wind-generated wave energies is crude, making no allowance for variations in fetch length, orientation of channels, or variation in movement over the delta. However, in the absence of detailed wind statistics providing data applicable on the surface of the protected channels of the delta there is no justification for use of classical wind-wave theories. The approach also implies a linear relation between energy dissipation and erosion, which is at variance with the evidence presented in tables 8 and 9. This assumption tends to underestimate the erosion caused by boat waves.

If more precise analysis is required, it is suggested that data be obtained from a dozen or more wave recorders located in representative delta channels, and that laboratory investigations be made to determine, more precisely, the relation between energy dissipation and erosion of the types of material used in the delta levees. Combination of representative field statistics and laboratory results could lead to more definitive findings.

## SUMMARY AND CONCLUSIONS

The paucity of long-term records of levee maintenance precludes the demonstration of a relation between levee erosion problems and the increased use of the delta waterways for recreational boating. Lack of these accurate records, combined with the absence of acceptable long-term wind movement statistics in the delta frustrates attempts to definitively relate problems of erosion to channel orientation and dominant wind movement across the region. Assessment of the relative importance of the natural and man-controlled forces contributing to levee erosion must accordingly be based on evaluation of the relative energies contributed by these dynamic forces and observations of the active erosion process. Only short-term observations of the pertinent data were available for this study.

Comparison of erosion rates observed at the test sites and computations of energies dissipated in the channels suggests that erosion cannot be related linearly to the total computed energy dissipation; furthermore, erosion may also be affected by the rate of applied energy.

The studies made here show on an annual basis that for channels such as Georgiana Slough, which carry significant floodflow, the energy developed by tractive shear stress is about two times that due to the combined effects of wind and boat waves. Boat-generated waves produced about 20 percent of the total energy dissipated against the levees from October 1967 through September 1973. Because of assumptions made in the computation procedures for tractive shear stress and wind-generated wave energies it is likely that the relative contribution to delta levee damage from these two forces is overestimated. Conversely, the contribution to levee damage produced by boat-generated waves is probably underestimated.

In channels such as False River, which are almost unaffected by floodflows, nearly all of the energy dissipated annually on the levees is produced by either wind- or boat-wave action.

In this channel, the relative energy contribution from boat-generated waves ranges from 45 percent to 80 percent of the annual total depending on the assumptions made in computation of wind-generated wave energies. This leads to the general conclusion that erosion caused by boating activities is a significant factor in these waterways.

The functional relation between erosion and energy dissipation is obviously related to the type and condition of material used in the levee construction and to the rate at which energy is applied. This is apparent from the variance of erosion observed at the erosion pin sites; however, data collected for this study represents only a short-term period and incomplete coverage of the variety of materials used in levee construction. Hence, valid functional relations between erosion rates, levee material, and energy dissipation have not been established.

The technique proposed for transference of findings from the studies in Georgiana Slough to other channels in the delta can be used for rough estimates of the relative erosional contribution from boat-generated wave energy if the relevant statistics on the numbers and sizes of boats using the waterways are obtained.

## REFERENCES CITED

California Department of Water Resources, 1968, Hydrologic water quality model development and testing, tidal hydrodynamics model: 151 p.

California Water Resources Control Board, 1971, Delta water rights decision D-1379: 63 p.

Health Sciences Computing Facility, Department of Biomathematics, 1973, Biomedical computer programs: Calif. Univ. Press, Los Angeles, 773 p.

Jenkins, G. M., and Watts, D. G., 1969, Spectral analysis and its applications: San Francisco, Holden-Day, 525 p.

Kinsman, Blair, 1965, Wind waves, their generation and propagation on the ocean surface: New Jersey, Prentice-Hall, Inc., 676 p.

Lane, E. W., 1955, Design of stable channels: Am. Soc. Civil Engineer Trans., v. 120, p. 1234–1260.

Saville, Thorndike, Jr., 1954, The effect of fetch width on wave generation: Tech. Mem. No. 70, Beach Erosion Board, U.S. Army Corps of Engineers, 9 p.

Spearman, C., 1904, American journal of psychology: v. 15, 88 p.

Vennard, J. K., 1961, Elementary fluid mechanics: New York, John Wiley & Sons, 570 p.

Limerinos and Smith—EVALUATION OF THE CAUSES OF LEVEE EROSION IN THE SACRAMENTO-SAN JOAQUIN DELTA, CALIFORNIA