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HYDRAULIC-MINING DÉBRIS IN THE SIERRA NEVADA

BY

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PREFACE.

The principal field work of this investigation was performed in the years 1905 to 1908. The primary motive of the study was economic, and for this reason especially a prompt report of the results should have been submitted, but the actual long delay was caused by illness. After some progress had been made in the preparation of this paper, I found great need for the results of a laboratory study which had been undertaken as ancillary to the field work, and the manuscript was laid aside until the laboratory data could be discussed.[1] During the period of delay some supplementary field work has been done—in the summer of 1909 by Mr. W. D. Johnson, in 1910 by Mr. W. C. Mendenhall, in 1913 by Mr. A. M. Gilbert, and in 1913 and 1914 by me.

In 1907 I was assisted in field work by Mr. George Manship and in 1908 by Mr. H. S. Pond. Mr. S. K. Baker, Mr. C. L. Nelson, Mr. E. C. Murphy, Mr. N. C. Nelson, and Mr. R. C. Rice also aided me by independent pieces of field work, the results of which are reported in other places.

In a few localities I encountered an atmosphere of secrecy in regard to mining operations—a secrecy possibly indicative of illicit hydraulicking—but the mine owners and the mining community as a class gave cordial aid to my work. I am especially indebted to Mr. W. B. Bourn and Mr. W. G. Shand for facilities in visiting a group of high-level reservoirs and to Mr. W. W. Waggoner and Mr. W. T. Ellis for the generous contribution of records and other information.

Having my headquarters for a long period in Berkeley, Cal., I was able to appreciate the hospitality of the University of California and its officers toward research and the high quality of its library and library administration.

The United States Coast and Geodetic Survey not only gave me free access to original records and other archives but promoted my inquiries through the cooperation of its experts. My study of tidal volume and tidal currents has in particular been aided by the counsel and criticism of Dr. R. A. Harris, of that corps. I have been aided by the United States Weather Bureau not only by special compilations of statistical material but through inquiries made at my request by its station officers. A special study of tidal currents in the Golden Gate was made possible by the efficient cooperation of the Lighthouse Service and of the Board of Engineers for Rivers and Harbors at San Francisco. For facilities and assistance in the study of sands I am indebted to the curators of the United States National Museum and especially to Mr. W. L. Schmitt.

The manuscript has had the advantage of a critical reading by Mr. C. E. Grunsky, Eng. D.

Through the interlocking of subjects my attention has been drawn to matters apparently remote from problems of mining débris. Mining débris merged, both bodily and in its effects, with débris sent to the streams by agriculture and other industries; the aggravation of valley floods due to the clogging of channels by débris was inseparable from the aggravation due to the exclusion of floods from lands reclaimed for agriculture; the weakening of tidal currents at the Golden Gate by the deposition of débris in the bays is inseparable from the weakening by the reclamation of tide lands; and the attention given to these collateral subjects has not only delayed the completion of the report but has added materially to its volume.

[1] Gilbert, G. K., The transportation of débris by running water, based on experiments made with the assistance of E. C. Murphy: U. S. Geol. Survey Prof. Paper 86, 1914.

ABSTRACT.

Chapter I.—Historical outline of the development of hydraulic mining in the Sierra Nevada, the encroachment of its tailings on valley lands, its subsequent restriction and regulation, and the circumstances leading to a study of the subject by the Geological Survey.

Chapter II.—Physical features of the northern part of the Great Valley of California. Sacramento and Feather rivers are bordered by natural levees which separate their channels from lateral basins of exceptional magnitude. Flood waters received by these basins are returned gradually to their channels, which are too small for the prompt conveyance of the flood discharges. The rivers have a large confluent delta, consisting of marshes regularly flooded by tides and also subject to inundation when the rivers are in flood.

Chapter III.—Subsidence of the land. In the region of the bays the latest recorded crustal movement has been downward. Carquinez Strait and the Golden Gate are river gorges invaded by the sea, and the bays are submerged valley lands. The relations of tidal marshes to shore cliffs suggest that the downward movement has not yet ceased, and this view is supported by the fact that certain shell mounds, the "kitchen refuse" of prehistoric villages, stand below tide level. An attempt to demonstrate present-day subsidence by the study of tidal observations was not successful, but presumptive evidence of subsidence is afforded by certain changes in the outline of San Francisco Bay between 1858 and 1898. In the region of the river deltas subsidence is inferred, because the delta lands appear to be growing upward instead of extending bayward.

Chapter IV.—The tailings from hydraulic mines were in part deposited on neighboring slopes and in neighboring stream valleys and canyons and in part delivered to rivers that carried them forward. At the base of the range were large deposits on the piedmont slopes and other deposits in the beds of valley rivers. As a consequence of the piedmont and river-bed deposits rivers rose higher in time of flood and lands previously immune were inundated. The reclamation of basin lands and delta lands for agriculture by surrounding them with levees also aggravated flood conditions, and the results of the two causes were inseparable.

Chapter V.—The bays of the San Francisco system have been mapped, with soundings, more than once. Comparison of maps of early and late dates shows that large deposits have shoaled the bays and reduced their areas. These deposits, ascribed to hydraulic mining and to the increase of soil waste by agriculture and other industries, have been measured for the periods between surveys and estimated for other periods; their total volume since the discovery of gold is more than 1,100 million cubic yards.

Chapter VI.—As a basis for estimation of the volume of mining tailings many hydraulic-mining pits were surveyed. The results were combined with measurements and estimates by others, with results of a study of soil waste in the Yuba River basin, with data on deposits in bays (Chapter V), and with results of a study of the detrital load of Yuba River (Chapter VII), and estimates were made of the volume of débris moved in the basins of Sacramento and San Joaquin rivers as well as of its present distribution.

Chapter VII.—(1) A barrier erected by the California Débris Commission arrested débris in transit along the bed of Yuba River. By means of surveys of the bed at three dates the arrested débris was measured; débris in suspension was also measured by means of water samples, and a discussion of the results gives an estimate of the normal detrital load of the river. (2) The water passing over the barrier was underloaded and therefore eroded the bed below the barrier. The erosion was measured. (3) A series of maps of the river bed above the

barrier, made for various purposes, serve to illustrate the shifting of the deep channel from season to season. An explanation is suggested. (4) The response of the Yuba to engineering works at Daguerre Point illustrates further the adjustment of channel bed to detrital load.

Chapter VIII.—The future movements of débris in the river basins are discussed, with consideration of modification by engineering works for the restraint of débris of the Yuba and of modifications by the execution of the plan adopted for the control of flood waters in the Sacramento basin.

Chapter IX.—Golden Gate bar lies outside the strait, its crest having a semicircular outline. Its position and the depth of water on its crest depend on the volume of tidal discharges through the strait and on the volume of sand annually brought to the bar. The tidal volume is affected by changes in progress in the bays. Deposits on shoals, encroachments on the areas of the bays, and the reclamation of bordering marsh lands reduce the tidal volume. The reclamation of delta lands affects the tidal volume but little. It is estimated that past changes have reduced the volume about 4 per cent, and further reduction is to be expected. Surveys of the bar made by the United States Coast and Geodetic Survey in 1855, 1873, and 1900 show a retreat of the crest toward the land but do not demonstrate a reduction of depth of water. The sand brought to the head of Suisun Bay by Sacramento and San Joaquin rivers is swept onward in the bays by tidal currents but is not believed to reach the bar in any appreciable quantity.

Chapter X.—The stress which caused the restriction of hydraulic mining no longer exists. Under conditions to be created by works for the control of floods the capacity of valley rivers for transportation of débris will be increased, so that the mining might be partly resumed without prejudice to any valley interest except navigation. The important interest which now dictates that débris should be controlled is that of the commerce which traverses the Golden Gate. Possibilities for resumption of mining on a large scale, with storage of débris, lie in cooperation with irrigation and electric-power development for the control of Sierra streams.

HYDRAULIC-MINING DÉBRIS IN THE SIERRA NEVADA.

By Grove Karl Gilbert.

Chapter I.—INTRODUCTION.

In the early days of gold mining in the Sierra Nevada only a moderate amount of earth was disturbed. An army of men were engaged, but they worked as laborers, with pick, shovel, and rocker. It was only gradually that more efficient methods were developed; but finally the resources of the engineer were brought to bear, water power was substituted for man power, and vast quantities of earth were handled. At the height of hydraulic mining, when hundreds of large jets of water were turned on the auriferous deposits, the material annually overturned was reckoned in scores of millions of cubic yards.

The material thus washed from the hillsides consisted chiefly of sand and the finer detritus called "slickens," but included also much gravel and many cobbles and boulders. The slickens was taken in suspension by the water used in mining and went with it to the creeks and rivers. Much of it escaped from the mountains altogether and found eventual lodgment in the Great Valley of California or in the tidal waters of San Francisco Bay and its dependencies. The coarser stuff tarried by the way, building up alluvial deposits on the lower hill slopes, in the flatter creek valleys, and in the river canyons. (See Pls. I, VI, and VII.) When rains and floods came the sands and gravels were moved forward toward the lowlands, and in 1862 a great flood washed so large a quantity into the lower reaches of the Sierra rivers and into the rivers of the Great Valley that the holders of riparian lands became alarmed. The mining-débris question, then for the first time generally recognized, assumed greater and greater importance and prominence in subsequent years and led to protest and litigation which in 1884 culminated in a series of injunctions whereby the miners were restrained from casting their tailings into the streams. The petitioners were valley dwellers, and the evils cited by them included the burial of alluvial farming lands by the flood of débris, the obstruction to navigation from shoaling of Sacramento and Feather rivers, and the raising of the flood levels of the valley streams whereby the area of periodic inundation was increased and protection against inundation became more difficult and expensive.

In connection with the litigation the subject was elaborately discussed, and the testimony included the evidence of a number of engineers who differed as widely in opinion as in point of view. Impartial and valuable investigations and reports were made by a series of officials and commissions at the instance of National and State governments. In 1880 the State engineer of California, William Ham. Hall, reported on the flow of mining detritus.[1] In the same year Lieut. Col. George H. Mendell, Corps of Engineers, United States Army, was designated to conduct a general investigation authorized by Congress, and his preliminary and final reports were printed in 1881 and 1882.[2] In 1888 a commission constituted of three Army engineers, Lieut. Col. W. H. H. Benyaurd, Maj. W. H. Heuer, and Maj. Thomas H. Handbury, began a still more extensive study, the report on which was printed in 1891.[3] As an outcome of this discussion and especially of the report of the Benyaurd commission, a per-

[1] California State Eng. Rept. to Legislature, sess. 1880, pt. 3, Sacramento, 1880.

[2] Mendell, G. H., Protection of the navigable waters of California from injury from the débris of mines: Chief Eng. U. S. Army Ann. Rept. for 1882, pt. 3, pp. 2543–2640; also in 47th Cong., 1st sess., Ex. Doc. 98.

[3] Report of board of engineers on mining débris in the State of California: Chief Eng. U. S. Army Ann. Rept. for 1891, pt. 5, pp. 2996–3118; also in 51st Cong., 2d sess., Ex. Doc. 267.

manent board, known as the California Débris Commission, was appointed in 1893, with authority under an act of Congress[1] to regulate hydraulic mining in such way as to prevent any injury to the navigable waters of Sacramento and San Joaquin rivers. Hydraulic mining was prohibited except as specifically licensed by the commission after inspection and approval of arrangements for the impounding of tailings. The commission was placed in charge of all works for the protection and improvement of navigation in those streams and was instructed to devise plans for the control of the movement of detritus in the rivers and their tributaries, with a view to the general resumption of hydraulic mining without prejudice to other interests. "The constitutionality of such an enormous interference with the interior affairs of one of the States of the Union as was embraced in this law was based on the provision of the Constitution of the United States assigning to the Federal Government the duty of regulating the commerce between States and incidentally of protecting the navigable highways."[2] Appropriations were afterward made for impounding works to be erected under the direction of the commission, and the expense was equally divided between the National and State governments. The State of California appointed a débris commissioner to cooperate with the national commission, and his reports,[3] as well as the reports of the commission,[4] continue the discussion of the débris question.

There is also a question of general control of the flood waters in the Sacramento River basin which is intimately connected with the problem of mining débris, and this likewise has been the subject of a series of investigations and reports. A plan submitted by the Débris Commission in 1911[5] has been adopted by the State legislature,[6] and a beginning has been made in its execution. It provides for great enlargement of the channel of Sacramento River near its mouth, and for a system of by-passes (p. 65) in the middle part of its valley to supplement the river channel, which is there too small for the conveyance of the flood discharge; and it includes Government control of all plans for the construction of levees.

Under licenses granted by the California Débris Commission a small amount of hydraulic mining has been carried on; but the available sites for economic impounding are few, and the experience of the first 10 years seemed to demonstrate that the great deposits of auriferous gravel, in which the average content of gold per unit of volume is small, can not be exploited with profit to the owners under such restrictions. Such restraining works as were erected by the commission on the main lines of the rivers did not succeed in controlling the movement of the débris which had been excavated in earlier years, and the published plans of the commission did not promise such comprehensive storage as would rehabilitate the hydraulic-mining industry.

On December 8, 1904, the California Miners' Association adopted in convention the following memorial, which was forwarded to the President of the United States and by him referred to the United States Geological Survey:[7]

SAN FRANCISCO, *December 8, 1904.*

To the President of the United States,
Washington, D. C.:

Whereas the placer and hydraulic miner who originally developed the resources of California and opened them to the world obtained title from the Government of the United States to his placer lands with the common understanding that they were to be worked and their gold contents recovered in accordance with methods of sluicing and hydraulic mining publicly known to have been devised and used for the purpose from the earliest stages of placer mining;

Whereas many deposits of gold to the value of millions of dollars are now idly buried in the ancient river channels of California under such conditions that they can not be profitably worked either by dredging, by drifting, or by any other process than that of hydraulic mining;

Whereas the gold extracted by the hydraulic miner was generously poured into the Treasury of the United

[1] An act to create the California Débris Commission and regulate hydraulic mining in the State of California: U. S. Stat. L., vol. 27, pp. 507-511, 1893; also in Chief Eng. U. S. Army Ann. Rept. for 1894, pt. 6, pp. 3184-3187.

[2] Harts, W. W., The control of hydraulic mining in California by the Federal Government: Am. Soc. Civil Eng. Proc., vol. 32, No. 2, p. 98, 1906.

[3] Waggoner, W. W., Reports of the débris commissioner, May 28, 1901, to Dec. 1, 1902, Sacramento, 1903; Dec. 1, 1902, to Nov. 1, 1904, Sacramento, 1905; Nov. 1, 1904, to Dec. 31, 1906, Sacramento, 1907.

[4] The reports of the commission are contained in the annual reports of the Chief of Engineers, U. S. Army, from the year 1894. Those for 1894, 1899, 1900, 1907, and 1911 are of special importance.

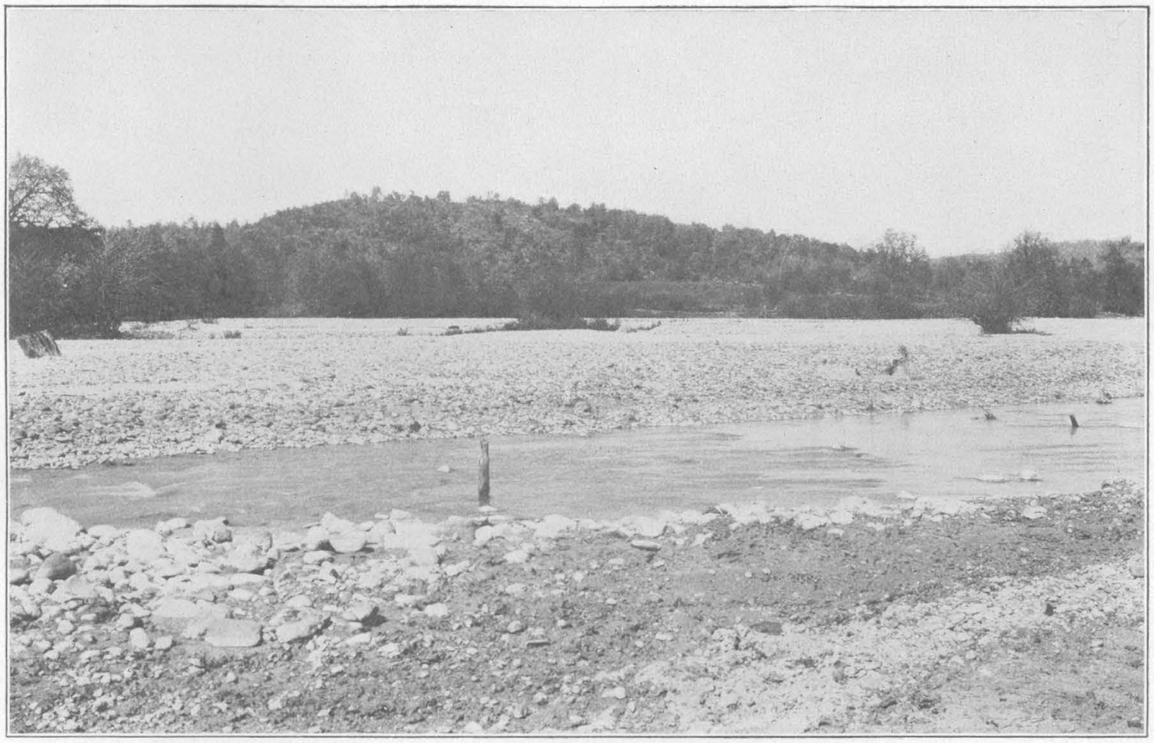
[5] 62d Cong., 1st sess., H. R. Ex. Doc. 81. This report gives summaries of earlier plans for the same purpose.

[6] California Stat., ch. 25, extra sess., 1911.

[7] The memorial was accompanied by a copy of an address by Prof. S. B. Christy on "Mining débris and natural sediment," which is printed in the proceedings of the Thirteenth Annual Convention of the California Miners' Association, pp. 137-156.

A. A HYDRAULIC GOLD MINE.

The water is conveyed by pipe, under a head of several hundred feet, and delivered through a nozzle that can be turned in any direction. The jet washes the auriferous earth from the cliff and thence to a sluice, seen at the left. The sluice is several hundred feet long and contains pockets of mercury by which the gold is caught. Photographed in 1908.



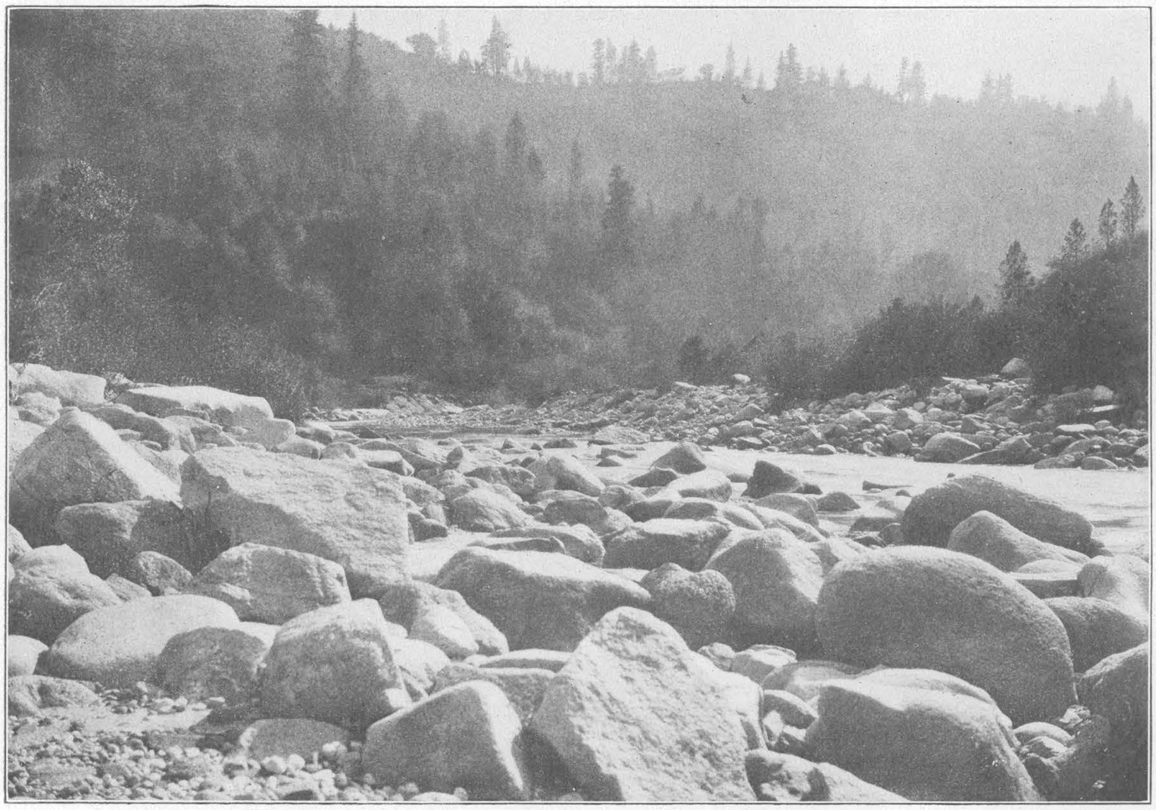
B. A RIVER VALLEY FLOODED BY MINING DÉBRIS.

The locality is among the foothills of the Sierra Nevada, and the estimated thickness of the deposit is 70 feet. Only coarse débris is lodged here; the finer part of the tailings has been carried farther. Photographed in 1908.

HYDRAULIC MINING AND MINING DÉBRIS.

A. PENN VALLEY.

One of a series of valleys lying among the hills that constitute the upland between the canyons of Yuba and Bear rivers. Some of the hills appear in the distance.



B. CANYON OF MIDDLE FORK OF YUBA RIVER AT FREEMAN'S BRIDGE.

Above the canyon wall is a rolling upland, and here the transition from one topographic type to the other is abrupt.

TOPOGRAPHIC TYPES IN THE WESTERN PART OF THE SIERRA NEVADA.

States Government in the dark days of the Civil War when the national currency was worth less than 50 cents on the dollar, thus materially assisting in maintaining the credit of the Government and in saving the Union;

Whereas the hydraulic miner has been restrained by the United States courts from discharging boulders, gravel, sand, clay, and other matter in suspension into the navigable waters of the State, whereby the industry of hydraulic mining has been destroyed and property to the value of over $100,000,000 has been rendered idle and unproductive since 1884, the natural wealth of the State rendered unavailable, and a deadlock has resulted between the fundamental industries of agriculture and mining;

Whereas while admitting the injurious effect of mining débris where not effectually restrained, the unavoidable effect of natural erosion and sedimentation has been ignored in the minds of the courts as well as of the farmers, and all the injury due to natural causes has been charged to hydraulic mining;

Whereas should hydraulic mining forever cease, to the injury of the miner, the natural process of erosion and sedimentation would still continue to the injury of the farmer and the navigable waters of the State;

Whereas we are firmly convinced that by a rational application of the laws governing the deposition of sediment from torrential streams, the industries of hydraulic mining and agriculture can both be carried on in this region, not only without prejudice to each other but to their mutual advantage; and

Whereas this question is primarily a geological one and can be solved only by geologists who have devoted their lives to the study of erosion and sedimentation, in mountain as well as in valley regions; therefore be it

Resolved, By the California Miners' Association, that we beg you, as President of the United States, to assist in the solution of this problem affecting all the interests of a great Commonwealth, by instructing the Director of the United States Geological Survey, through the Secretary of the Interior, as part of his study of the storage of flood waters and the reclamation of waste lands, to undertake a particular study of those portions of the Sacramento and San Joaquin valleys affected by the detritus from torrential streams.

The points we wish particularly considered are:

First. The most favorable sites for reservoirs for water, whereby destructive floods may be averted and the waters stored and utilized for the benefit of agriculture, mining, and other industries.

Second. The selection of suitable tracts of waste lands and of the most suitable means whereby the detritus from torrential streams may be deposited on such waste lands, so as to reclaim them and convert them gradually into lands suitable for forestry and other agricultural purposes, and at the same time to remove from such streams their burden of detritus so that they may cease to be a menace to the navigable waters of the State.

In view of the importance of this inquiry to the three great fundamental industries of agriculture, mining, and commerce, we beg that this inquiry be undertaken at the earliest opportunity and pushed to completion as rapidly as consistent with thoroughness.

At the time of the presentation of this memorial the United States Geological Survey included as one of its branches the Reclamation Service, an organization specially equipped for the study of practical engineering problems connected with the control of surface waters, and this branch was intimately associated with the water-resources branch, which was devoted to statistical and scientific studies of the waters of the country. An investigation on the lines proposed by the memorial was accordingly arranged by the water-resources branch, but the present writer was detailed from the geologic branch because the study of the transportation of detritus by running water belongs to geology as well as to engineering. The investigation as planned included (1) a field study of the phenomena connected with the "débris problem"; (2) a laboratory study of the laws of transportation of detritus by running water; and (3) an engineering study, for which no immediate provision was made. The separation of the Reclamation Service, which was made an independent bureau of the Department of the Interior in 1906, removed from the Geological Survey the body of engineers specially selected to deal with the problems of construction for the control of rivers, and the specific engineering questions connected with the débris problem have not been adequately studied. The laboratory research, which has a bearing much broader than the local problem, has been made the subject of a separate report.[1]

The present report, which deals largely with geologic and physiographic aspects of the subject, is not restricted to the specific questions raised by the memorial of the California Miners' Association but takes account of various other factors. In order to consider the feasibility of a resumption of hydraulic mining in the Sierra Nevada, it traces the physical effects, past and future, of the hydraulic mining of earlier decades, the similar effects which certain other industries induce through stimulation of the erosion of the soil, and the influence of the restriction of the area of inundation by the construction of levees. Such constructive suggestion as it makes is in the direction of cooperation by several interests for the control of the streams now carrying heavy loads of débris.

[1] Gilbert, G. K., The transportation of débris by running water, based on experiments made with the assistance of E. C. Murphy: U. S. Geol. Survey Prof. Paper 86, 1914.

CHAPTER II.—NATURAL CONDITIONS OF THE SACRAMENTO BASIN WITH RESPECT ESPECIALLY TO THE MOVEMENT OF DETRITUS AND THE REGIMEN OF RIVERS.

The Great Valley of California lies between the Sierra Nevada on the east and the Coast Ranges on the west; at the north and south mountains close in about its ends. Midway of its length the Coast Ranges are divided by an arm of the sea comprising San Francisco, San Pablo, and Suisun bays, and this arm receives Sacramento and San Joaquin rivers, which drain the valley. Northward from Suisun Bay for more than 100 miles the valley has a width of 30 to 40 miles; farther north it is narrower and of different habit. In the broader part three belts may be distinguished—on the east an alluvial slope descending from the foothills of the Sierra, on the west an alluvial slope descending from the Coast Ranges, and between these two a flatter lowland which is inundated annually by the flood waters of the rivers. Through the belt of periodic inundation runs the trunk river—the Sacramento—bordered on each side by a raised bank or natural levee which stands higher than the inundated land beyond but is itself submerged at extreme flood. The lowlands thus partitioned from the river are appropriately called basins. Feather River, which joins the Sacramento midway in the valley, has the same habit for the lower 25 miles of its course. The inundated belt east of the Feather and Sacramento is divided into three parts by the alluvial plains of Yuba and American rivers, and those streams discharge directly to the trunk rivers. The minor streams from east and west deliver their waters to lateral basins. The arrangement of the basins is shown in figure 1.

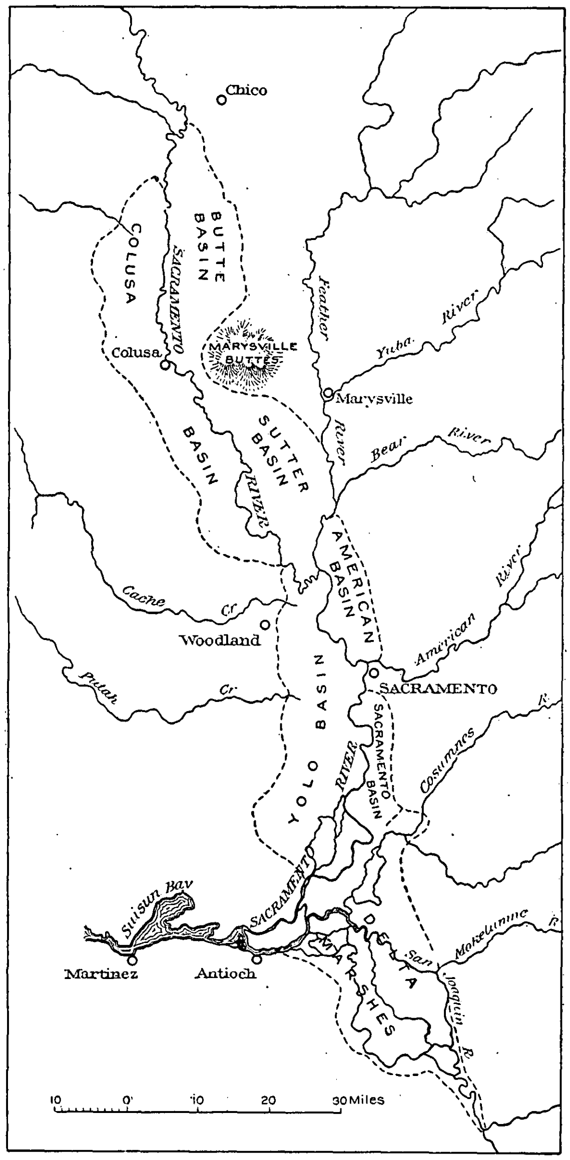


FIGURE 1.—Flood basins of Sacramento Valley and the Sacramento-San Joaquin delta.

Such entrainment of a river between banks of its own building and such flanking by lowlands periodically inundated are features of the depositional phase of a stream when and where the material brought for deposit is so fine as to be carried in suspension. They are most frequently found near the mouths of long rivers but may occur also at other points where, for any reason, the stream is engaged in deposition instead of erosion.

Along the lower course of the Sacramento the phase just described merges into a delta phase. The lateral inundated tract assumes the character of a permanent marsh, the water level of which oscillates regularly with the tides. The natural levees become lower. The channel divides, giving to parts of the marsh lands the character of islands, and some of its divisions connect with the channels of other rivers. The delta marsh of the Sacramento is continuous with the delta marshes of the Mokelumne and the San Joaquin, so that much of it may be inundated by a flood of either river.

The Sierra Nevada is a broad range, whose crest line is near the eastern edge and whose altitude gradually decreases from east to west. A belt near the crest line was occupied by glaciers during the ice age, with the result that its surface now has much bare rock, many lake basins, and little ground suited for the growth of forests. In this region precipitation is heavy, and winter snow banks store water for the summer flow of the streams. The larger rivers heading in this upper region traverse the middle and lower belts of the range in steep-walled canyons, and before the advent of the white man the streams at nearly all points rested on the rock bottoms of the canyons and were engaged in deepening them. Between the rivers there are in places upland valleys a thousand feet higher than the canyon bottoms (Pl. II), and creeks traversing these valleys were comparatively sluggish, their slopes, like those of the adjacent lands, being gentle. On leaving the valleys the creeks tumbled rapidly through short gorges down to the rivers. The rivers continued to the western base of the range with steep descent and rocky beds, but at the base their habit was abruptly changed, the slopes of the beds becoming gentle and the material of the beds changing to gravel and sand. As they approached the trunk rivers of the valley their grades became still flatter and the visible materials of their beds became finer.

During the low stages of summer and autumn the Sacramento and other rivers of the valley were confined to their channels and their waters were clear; the bordering basins were either empty or partly occupied by swamps with a growth of rushes. In its lower course the Sacramento carried deep, slack water with a conspicuous tide extending to Sacramento, 62 miles north, and a less notable tide to the mouth of the Feather, 20 miles farther north. In the early days seagoing vessels ascended regularly to Sacramento and occasionally to Marysville, on the Feather.

In times of flood the waters regularly overtopped the banks and filled the adjacent basins, through which they moved slowly and from which they drained gradually back to the main channel as the flood subsided. The detrital load of the flood was spread by them over the whole inundated tract, including the delta marshes, which acted as a system of settling basins. Some of the coarser silt was added to the natural levees, maintaining them at an adjusted height, and as these depended for their existence on such deposition they could never rise above the highest floods. Such of them as now remain unmodified serve to record the level of flood waters in those early times. A portion of the suspended load carried forward by the swifter current of the main channel found its way through the mouth of the river and came to rest in the bays beyond, but it is probable that the principal portion was received by the inundated lands.

The lateral basins affected the channel characters in important ways. They conveyed a large part of the flood discharge and thus left for adjacent portions of the channel only a small part. They acted as reservoirs for the storage of flood waters and fed them gradually to the lower course of the Sacramento, so that the channels in the delta region were only moderately taxed by the floods. The channels in consequence were adjusted for the conveyance of only a fraction of the flood discharge; they were of moderate section and their meanders were of small radius. Between the town of Colusa and the mouth of Feather River the channel of Sacramento River grows gradually smaller downstream until its estimated capacity is only 10 per cent of the flood discharge.

CHAPTER III.—SUBSIDENCE OF THE LAND.

There is some reason to think that the areas in which the mining and other débris comes finally to rest are undergoing a slow downward movement. Such a movement would tend to diminish the injurious influence imposed on various industries by the deposition of the débris. After a review of the evidence I am satisfied that the possible economic significance of land subsidence is limited to San Francisco Bay, so that the subject might with propriety receive only scant attention in this paper, but as a negative result has a value of its own, space will be given to such evidence as has been assembled.

Lawson,[1] in two important papers, discussed movements of elevation and subsidence in the coastal regions of California in the later geologic periods. Some of the movements affected large areas with approximate uniformity. Others affected adjacent areas very differently. We are here concerned with the latest movements, because the latest are most likely to continue in progress at the present time. On parts of the coast near the Golden Gate the latest recorded movement was downward and involved about 80 miles of the coast. The evidence of the change consists chiefly in the occupation by tidal water of hollows that are shown by their forms to have been shaped by streams on the land. The subsidence was greatest at the Golden Gate, where its approximate measure is the depth of the strait, 378 feet, and its amount diminished in both directions along the coast. Before the subsidence the Golden Gate passage was the lower gorge of Sacramento River, and the basin now occupied by San Francisco Bay was a valley with gentle alluvial slopes crossed obliquely by Sacramento River. That basin is part of a long, straight structural trough extending many miles southeastward; and the downwarping of the trough that created the bay was accompanied by a gentle upwarping farther south. This diversity of associated movements serves to put us on our guard against the assumption of uniformity of change in contiguous areas.

The basins of San Pablo and Suisun bays and Carquinez Strait, by which they are connected, have a general resemblance to the San Francisco basin and the Golden Gate, and the most salient facts of their recent history are the same. Subsidence has created bays where previously there were open valleys and has produced a tidal strait where once there was a river gorge. Certain details of their history, however, are different.

Trask,[2] who visited the region in 1853, observed "a littoral seabeach, having an elevation of about 30 feet above high tides" and "composed of fragmentary and entire shells mixed with a little sand and clay." It was visible as "a distant white line" for 8 miles on the north shore of San Pablo Bay and also at Benicia. Newberry,[3] a few years later, described a similar feature, 20 feet above sea level, on the south shore of the same bay. Both geologists inferred a recent uplift of the land, and Newberry noted that the uplift was not shared by the basin of San Francisco Bay. The terraces have been observed more fully by A. C. Lawson, and I am permitted to quote some of his unpublished results, communicated in a letter:

> On the east side of San Pablo Bay, between Pinole Point and Mare Island, there are terraces ranging from 12 to 30 feet above the sea level, and these extend in remnants into the Carquinez Strait. These terraces are in many places characterized by an abundance of marine shells, such as oysters and pectens; the terrace on Mare Island is a particularly distinct wave-cut feature. On the stretch of country between Pinole Point and Vallejo Junction the same shells that characterize the surface of the terraces in other places exist beneath a rather heavy mantle of later Quaternary alluvium about 100 feet thick, containing numerous remains of the *Equus* fauna.
>
> Both the terrace with its marine shells and the overlying alluvium have been dissected to a level below the present tide, and the valleys due to such dissection are drowned to a moderate extent.

[1] Lawson, A. C., The post-Pliocene diastrophism of the coast of southern California: California Univ. Dept. Geology Bull., vol. 1, No. 4, pp. 115-160, 1893; The geomorphogeny of the coast of northern California: Id m, No. 8, pp. 241-272, 1894.

[2] Trask, J. B., Report on the geology of the Coast Mountains and part of the Sierra Nevada, p. 27, 1854.

[3] Newberry, J. S., U. S. Pacific R. R. Expl., vol. 6, pt. 2, p. 14, 1857.

N. C. Nelson, of whose observations further mention will be made, noted a terrace near Antioch, with similar dissection by streams and with invasion of the stream valleys by tidewater and tidal marshes. The height of the terrace plain is about 25 feet at its outer edge, bordering San Joaquin River, and increases to about 50 feet at the base of the Mount Diablo foothills, which rise abruptly from its southern margin.

The presence of these terraces shows that the history of recent change has not been the same in the eastern area as in the basin of San Francisco Bay, but the character of the dissection of the terraces indicates that here also the latest recorded movement was downward. The local series of changes since Sacramento River excavated the Carquinez gorge includes, first, a subsidence of more than 100 feet; second, an elevation of more than 50 feet; and third, a subsidence of about 30 feet.

The two areas of unlike history do not merge at their common boundary but are sharply separated by one of the master faults of the region, the Haywards fault. This fault is characterized along its line of outcrop by peculiar topographic features—rift features—which California geologists have learned to recognize as indicative of differential movement in very recent times; and a portion of the fault near Haywards was in fact the focus or origin of a notable earthquake in 1868. The rift has been traced along the southwestern face of the Berkeley Hills to Pinole Point and also along the northeastern edge of Petaluma Valley. The fault therefore crosses San Pablo Bay in a northwesterly direction. (See fig. 2.) The basin of the western division of this bay, which is slightly smaller than the eastern, belongs to the same crustal block as the basin of San Francisco Bay and apparently shares its history of recent subsidence. The block that holds the basin of the eastern division appears to extend eastward to the line separating the Coast Ranges from the Great Valley of California, and through this space the recent movements of elevation and subsidence have been harmonious.

Because the latest determined movement in the two areas was downward it does not necessarily follow that subsidence is now in progress, for the movement may have ceased, and it is not always easy to discriminate from physiographic data between a subsidence in progress and a subsidence completed. In the present case, however, the evidence is more than usually satisfactory. Many arms of the bays are occupied or partly occupied by tidal marshes—level tracts which are submerged only at high tide. Parts of the coast fringed by such marshes are protected from the action of waves, but other parts are exposed to wave attack. The exposed parts have been eroded by the waves and shore cliffs have been developed, but similar cliffs do not appear where the marshes protect the coast. (See Pl. III.) The plains occupied by the marshes are not plains of the original pre-subsidence topography but have been built up in the water. They are composed of mud brought in suspension and distributed by the tides and of the decayed remains of marsh vegetation. Had the subsidence taken place rapidly and reached completion before the building of the marsh lands the waves would have made their record on the coastal slopes, and that record would now be visible. From its absence I infer that subsidence was so slow that the building of marsh lands kept pace with it and the cliffless coasts were thus continuously protected.

Another change continuously in progress has been the deposition of débris brought to the bay by streams from neighboring hills. The finer part has been distributed by tidal currents and has helped to build the marsh plains. The coarser material has been arrested at the creek mouths, and its deposition has tended and still tends to build deltas with subaerial slopes. The actual construction of deltas above tide level depends on the relation of the supply of delta material to the rate of subsidence. With cessation of subsidence the deltas would be extended on the marsh plain. The development of deltas is in reality small, as it should be if subsidence is still in progress.

The features just described have been studied in a systematic way only on that part of the west coast of San Francisco Bay which lies north of the Golden Gate. They have been noted elsewhere from car windows and have been inferred from the topographic details of Coast and Geodetic Survey charts of San Pablo and Suisun bays and from large-scale maps by the Geological Survey covering the eastern part of Suisun Bay and the mouths of Sacramento and San Joaquin rivers. They serve to show that the subsidence which constitutes the latest of the known geologic movements has continued so nearly to the present time as to establish a presumption that it is still in progress. And they show that the general rate of subsidence is no more rapid than that of the upward growth of the marsh lands.

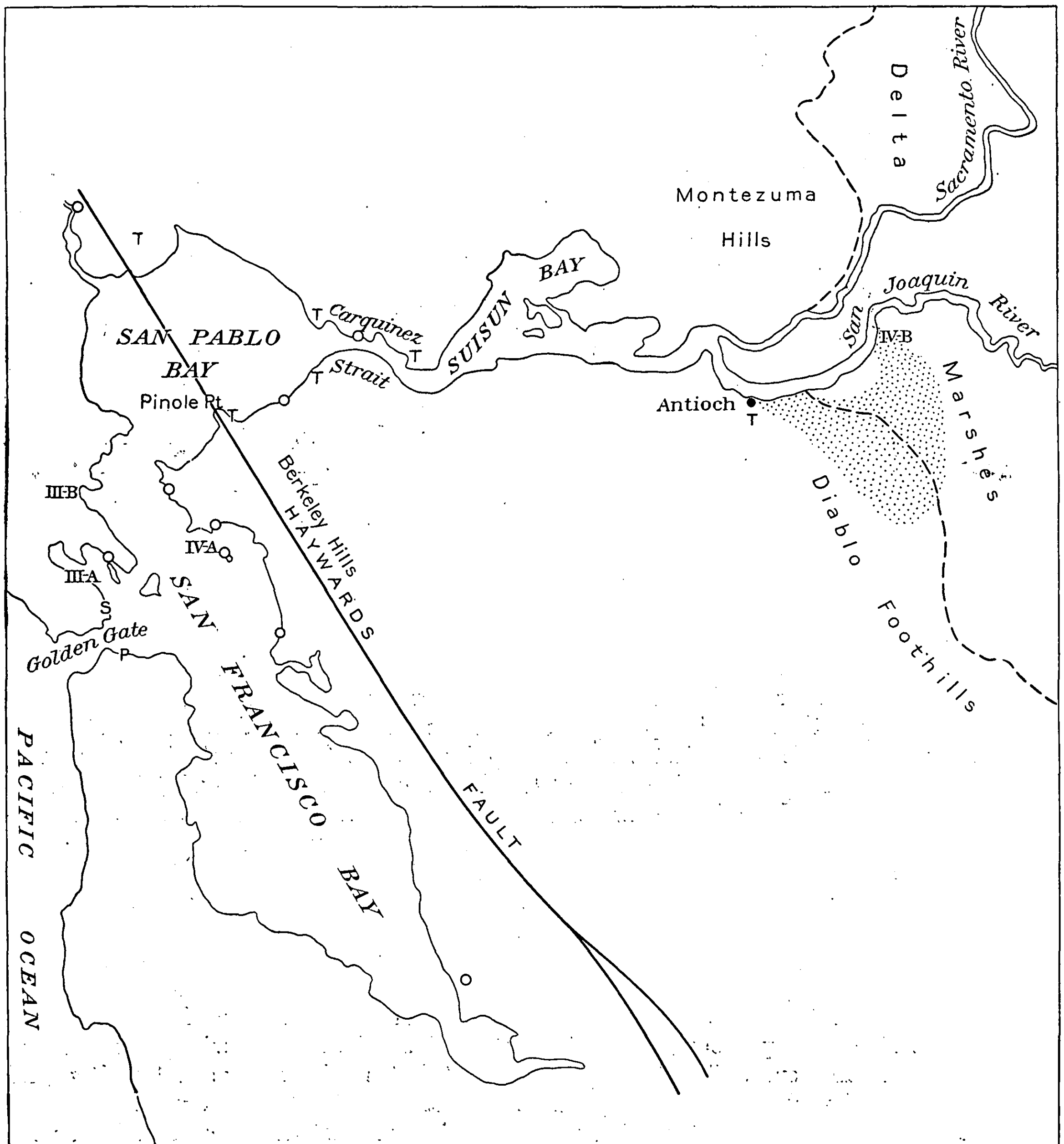


FIGURE 2.—Distribution of data bearing on subsidence. The dotted area is that in which dunes occur; circles show shell mounds now within reach of tidewater or waves; III-A, III-B, IV-A, IV-B, indicate localities shown in Pls. III and IV; P, the Presidio; S, Sausalito; T, localities of the 30-foot terrace.

The presumption thus established is supported by archeologic data. All about the shores of San Francisco and San Pablo bays are shell mounds, the prehistoric kitchen middens of the region. These mounds have been mapped and a scientific investigation of them has been begun under the direction of John C. Merriam. It has been shown by excavation that three of them have their bases below water

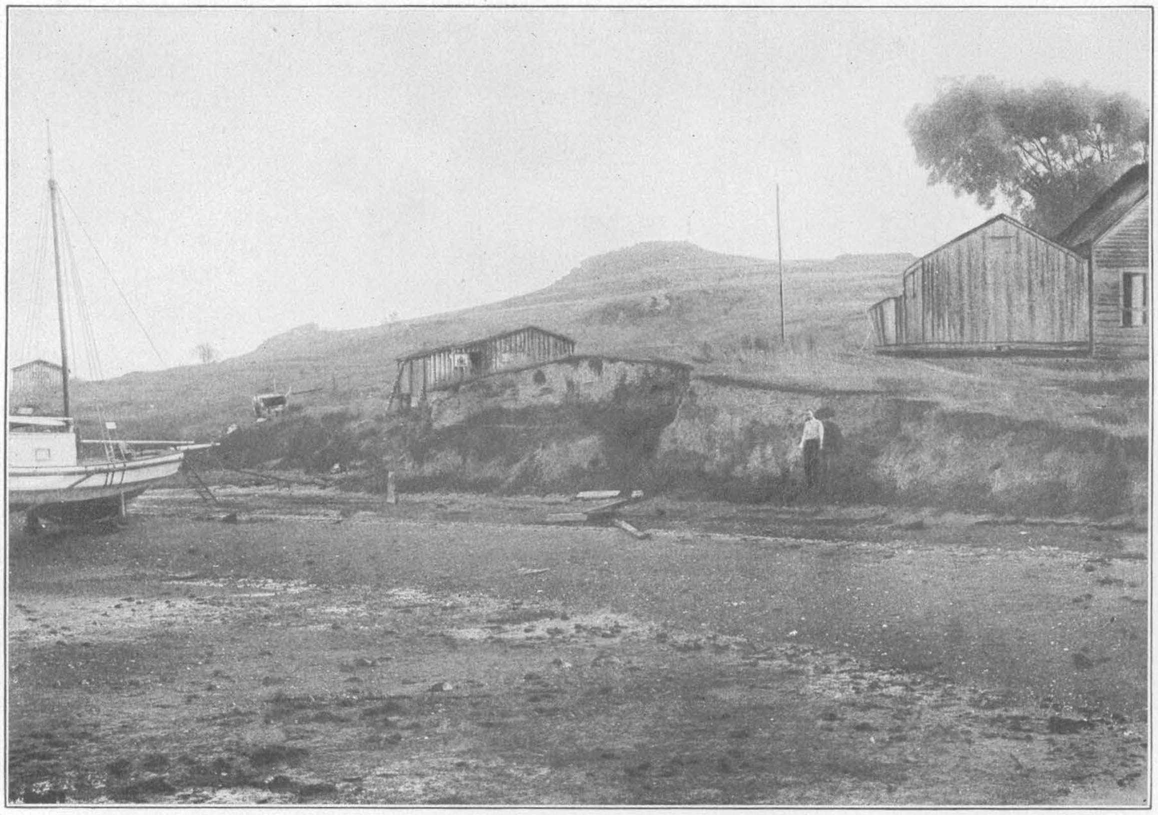
A. RICHARDSON BAY, AN ARM OF SAN FRANCISCO BAY.

This is a typical "drowned valley"—that is, it is a valley shaped by streams as part of a land surface and afterward depressed, along with the bordering hills, so as to admit the water of the ocean. The hilltops now make capes and islands, and each salient point has been eroded by the waves so as to end in a cliff. The head of the bay and some of the lateral coves are occupied by tidal marshes.

B. EMBAYMENT DIRECTLY NORTH OF RICHARDSON BAY.

Almost wholly occupied by a marsh. The view was taken at low tide. At high tide the marsh is covered by water, but the water is shallow and its waves are feeble. They make no attack on the spur that descends from the hill at the right, and the spur retains its original form without erosion.

FEATURES ILLUSTRATING SUBSIDENCE.



A. REMNANT OF A SHELL HEAP ON BROOKS ISLAND, SAN FRANCISCO BAY.

Prehistoric inhabitants, living near the shore and using shellfish as food, accumulated shells and other refuse on their sloping village site until the deposit had a depth of about 20 feet. Owing to subsidence of the land the base of the heap is now 15 feet below high-tide level, and a portion has been washed away by the waves. Photograph by N. C. Nelson, 1907.

B. A WIND-FORMED SAND HILL ON BRADFORD ISLAND, SAN JOAQUIN DELTA.

The island was originally a tidal marsh and has been converted to "tule land" by levees and drainage. The peaty soil surrounds the sand hill and must have been accumulated after the formation of the hill. The sandy plain that presumably supplied the material of this hill now lies at too low a level to be reached by wind. Photograph by N. C. Nelson, 1908.

FEATURES ILLUSTRATING SUBSIDENCE.

level, and the partial submergence of seven others is inferred from their relation to marsh lands. As there is no reasonable doubt that the shellfish of which these piles are the refuse were consumed on land, the present relations show that subsidence has occurred since the advent of man to these shores. Nelson,[1] from whose recent publication the facts of distribution are taken, states that the greatest demonstrated subsidence is 18 feet. One of the more striking examples is illustrated by Plate IV, *A*.

The ten mounds recorded as now standing on ground below tide level are all west of the Haywards fault, the most southerly being near the south end of San Francisco Bay and the most northerly on the Petaluma Marsh, north of San Pablo Bay. East of the fault are two which are believed to have been lowered from their original position, because they are now so near the level of high tide that they may sometimes be reached by storm waves. One is on the south shore of San Pablo Bay; the other on the north shore of Carquinez Strait. (See fig. 2.)

The movement indicated by physiographic features and kitchen middens is evidently very slow—so slow that there need be no surprise that it has not attracted the attention of our own race during the brief period of our occupation. Where the tide has a range of several feet the mean water level is apprehended as a somewhat indefinite matter; and even with regular observations of the tides the position of the mean level is not very accurately determined unless exceptional precautions are taken. The only locality in the region where such work has been carried on with high precision is the Golden Gate. Tidal observations have been made there by the United States Coast and Geodetic Survey since the beginning of its operations on the Pacific coast, and from the year 1878 the work has been of adequate quality. From 1878 to 1897 the station was at Sausalito, on the north shore of the strait, and since 1897 at the Presidio, on the south shore.

The relative height of the zeros of the two stations was measured in 1897 by means of a series of simultaneous observations on the two gages. In 1906, a few months after the earthquake of that year, a remeasurement was made by means of the spirit level, the instrumental work being of the highest grade but involving sightings across the strait, at the great distance of 1.25 miles. The results from the two measurements, 1897 and 1906, differed by about 0.13 foot. In the following discussion I have made use of the earlier measurement only, my preference being determined not by the belief that its method, considered as a method of measuring vertical difference, is the more trustworthy but by considerations connected with the purpose of the discussion. If constant errors are involved in leveling from Sausalito to the Presidio through the water surface, the same errors are presumably involved in the comparison of determinations of mean sea level at the two points, and the use of the water-level measurement of the difference of zeros tends to eliminate the effect of such errors from the discussion; and if the localities of the two stations are affected differently by a progressive movement of the land, or were affected differently by disturbance at the time of the earthquake of April, 1906, the measurement made at the time of transfer of the tidal work is the one which avoids complication from such a cause.

To aid my inquiry the Superintendent of the Coast and Geodetic Survey kindly had a separate determination of mean sea level made from the observations of each year from 1878 to 1913, excepting only the year of transfer, 1897, when neither station was occupied for the entire year. The results of these computations are given in the following table:

TABLE 1.—*Height of mean tide above zero of United States Coast and Geodetic Survey tide gage at the Presidio, Cal., separately computed from the observations for each year.*

Year.	Mean sea level.	
	Annual mean (feet).	Five-year mean (feet).
1878	8.73	....
1879	8.42	....
1880	8.51	8.53
1881	8.55	8.48
1882	8.44	8.55
1883	8.49	8.57
1884	8.77	8.56
1885	8.62	8.55
1886	8.49	8.55
1887	8.40	8.51
1888	8.46	8.52
1889	8.60	8.51
1890	8.65	8.50

[1] Nelson, N. C., Shell mounds of the San Francisco Bay region: California Univ. Pubs. in Archæology and Ethnology, vol. 7, No. 4, pp. 329-330, 1909.

TABLE 1.—*Height of mean tide above zero of United States Coast and Geodetic Survey tide gage at the Presidio, Cal., separately computed from the observations for each year*—Continued.

Year.	Mean sea level.	
	Annual mean (feet).	Five-year mean (feet).[a]
1891	8. 43	8. 50
1892	8. 35	8. 45
1893	8. 45	8. 44
1894	8. 39	8. 47
1895	8. 59	[a] 8. 49
1896	8. 57	[a] 8. 46
1897	[8. 47]	[a] 8. 47
1898	8. 30	[a] 8. 46
1899	8. 44	[a] 8. 43
1900	8. 50	8. 45
1901	8. 46	8. 50
1902	8. 57	8. 54
1903	8. 53	8. 57
1904	8. 63	8. 60
1905	8. 65	8. 62
1906	8. 60	8. 60
1907	8. 68	8. 57
1908	8. 44	8. 53
1909	8. 50	8. 56
1910	8. 43	8. 50
1911	8. 64	8. 51
1912	8. 49	....
1913	8. 50	....

[a] The five-year means for 1895-1899 are derived by aid of the interpolated annual mean for 1897.

The observed relations of land and sea level are shown in figure 3. They are expressed in feet and are reckoned from an arbitrary datum,

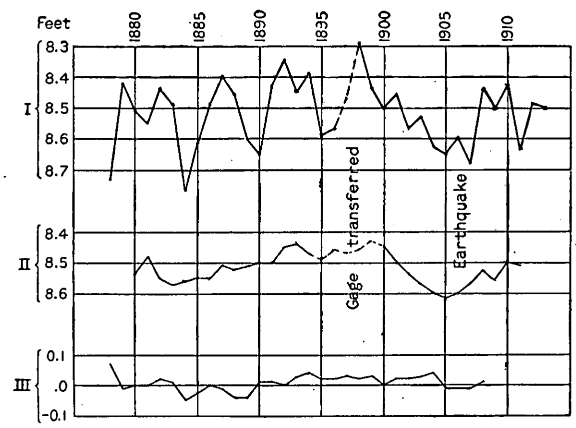


FIGURE 3.—Observed relations of land and sea level. I, Annual means of tidal observations at the Golden Gate; II, five-year means of tidal observations at the Golden Gate; III, deviations of atmospheric pressure at San Francisco from the normal, expressed in terms of balancing column of water.

the zero of the present tide gage at the Presidio. In the diagram the scale of feet is intentionally inverted. If it were erect each upward inflection of the curve would express an apparent rise of mean sea level, on the assumption that the land is stable. With the inversion, each upward inflection may be thought of as expressing an apparent rise of the land, on the assumption that mean sea level is stable; and as this assumption is actually made, the inverted curve presents the data in form convenient for inspection.

The curve exhibits a general tendency, at first upward, then downward; but this is largely masked by fluctuations of large amplitude and short period. Preconceptions which I believe well founded discountenance the view that these fluctuations, which attain 0.3 foot, can be ascribed either to the land on which the gages stood or to the general mean level of the ocean. They must have some adventitious cause. It has occurred to me that they might be in part systematic errors of observation, changing with change of observer and with modifications of the mode of observation; but I have no data by which to test this possibility. It has occurred to me also that they may be due to actual fluctuations of the local (as distinguished from the general) sea plane occasioned by variations in the annual mean of atmospheric pressure, or by variation in the mean of wind effects in pushing water toward or away from the coast. Through the courtesy of the United States Weather Bureau I have been furnished the means of air pressure at San Francisco from 1878 to 1908, except only 1906, when the record was interrupted; and these means, originally expressed in terms of balancing columns of mercury, I have converted into deviations from normal of the equivalent balancing column of sea water. Thus converted they are strictly comparable with the means of sea level and they have been plotted in figure 3. Their range is so small that they manifestly fail to explain the fluctuations of the tidal means.[1] The wind effect is less easily evaluated and its comparison has not been attempted.

On the assumption that the apparent rapid fluctuation of the vertical relation of land at the Golden Gate to the great standard of reference, normal sea level, belongs to the general category of imperfect observation, it is in order to reduce its effect by smoothing the

[1] The recorded air-pressure means have a lower average before 1890 than afterward. This difference is not believed to represent a fact of nature but to be connected with the removal of the observing station to a new site or with some other accident of observation.

observational curve. This has been done by substituting five-year means for annual means, and the result is plotted in the middle line of figure 3. The general features of the smoothed curve include (1) a small and somewhat doubtful descent, (2) a slow, well-marked ascent, (3) a comparatively rapid descent, also well marked, and (4) an ascent. The total ascent from about 1883 to about 1899 is 0.14 foot; the descent to about 1905 is 0.19 foot. The mean for the first 10 years of observation, 1878–1887, is nearly identical with the mean for the last 10 years, 1904–1913.

The change from well-marked ascent to well-marked descent coincides approximately with the transfer of the observations from Sausalito to the Presidio, and this fact suggests that crustal movements at the two points are not the same. The change from well-marked and nearly uniform descent to a slower ascent coincides approximately with the occurrence of the earthquake of 1906, which had its origin in the San Andreas fault, 7 miles west of the Presidio; and this fact suggests that slow movements of the crust recorded by the tide gage are intimately related to the sudden movements which cause sensible jars. Both these suggestions appear to me plausible. The warping implied by diversity of movement between points on opposite shores of the Golden Gate does not differ in kind from the warping of the trough of San Francisco Bay, described by Lawson. And the intimate relation between slow crustal movements and the strains relieved by earthquakes is a thesis of modern seismology.

Though the evidence given by the gage records is not so harmonious as to be beyond question, it appears to me probable that the progressive movements of the land indicated by the smoothed curve in figure 3 were actual, that the land about the Golden Gate, and also the land of a large including region, is in a state of unrest, its movements being part of the same general system of crustal change to which the modern faults and earthquakes belong. The record is too short to demonstrate a tendency toward subsidence or elevation, but the fact of unrest is harmonious with the idea that subsidence continues to the present time.

Another piece of evidence is connected with the boundaries between tidal marshes and the open water of the bays. Those boundaries have been twice mapped with care, and a comparison of charts shows that changes have occurred. About Suisun and San Pablo bays the marsh lands have grown at the expense of the open water, the growth being closely associated with the deposition of mining débris on the shoals, and there are places where marsh lands have encroached on the water of San Francisco Bay. But there are also long stretches of the San Franciscan coast, stretches with an aggregate length of 18 miles, in which the marsh front has retreated. It is true that the marsh edge is not everywhere a well-defined and unmistakable line and that its mapping involves questions of interpretation (see Chapter IX), but as to the general fact of wave encroachment there can be no question, for the erosion of the marsh front has opened new outlets for marsh waters and thus caused new tide channels to be scoured out and old channels to be silted up. A conspicuous example of this is found in the history of San Mateo Slough. In 1858 the mouth of the slough was at a point about 1 mile west of Guano Island, and a bend of the slough approached the coast at a point three-quarters of a mile farther west. The bend was then separated from the open water by a strip of marsh 1,000 feet wide. By 1898 the coast had retreated so far that the slough communicated with the bay at the bend, and a new mouth had been established at that point, the old mouth having become so nearly obsolete as to carry no water at low stages of tide. Examples of similar character are afforded by Mountain View Slough, Newark Slough, and Guadalupe River; and a change in the mouth of Ravenswood Slough that had been barely initiated in 1898 was nearly complete when I visited the locality in 1914.

If crustal change were the only factor concerned in the modification of the marsh boundaries, it would be possible to indicate a number of crustal blocks underlying San Francisco Bay which are moving more or less independently, for the distribution of marsh advance and marsh retreat is somewhat systematic. South of Dumbarton Point on the east coast and Ravenswood Slough on the west all recorded changes are of the nature of marsh retreat. Thence northward to Johnson Landing on the east coast and to Belmont Slough on the west the records indicate marsh advance, and beyound those points they show retreat. This distribution suggests that under the second of these tracts crustal change is so slow that the silting up of the bay finds expression in marsh enlargement, while adjoining parts are sinking so rapidly as to prevent that expression.

After the earthquake of 1906 it was observed that certain structures in the southwestern part of the marsh drained by Ravenswood Slough bore a different relation to the levels of high tides, and the observer inferred that the land had gone down several inches. At the same time some cottonwood trees standing on firm ground at the edge of the marsh died, having presumably been killed by the admission of brine to their roots. The locality is within a tract of subsidence, as indicated by the retreat of the marsh front between 1858 and 1898.

Though the evidence as to changes in progress in the bay region is not so coherent as to be demonstrative, it still has cumulative weight. Considering together the physiographic proof of general subsidence in very recent time, the evidence of dissimilarity in the geologic history on two sides of the Haywards fault, the testimony of the shell mounds to continued subsidence during aboriginal human occupation, the testimony of earthquakes and tidal observations to present unquietness, and the testimony of retreating marsh fronts, I have little hesitation in concluding (1) that crustal changes are now in progress, (2) that they are somewhat unequal and diverse in their vertical elements, and (3) that their most general characteristic in relation to sea level is subsidence.

The basin of Suisun Bay is separated from the Great Valley of California by low hills, which constitute locally the eastern member of the Coast Ranges. North of Sacramento River they bear the name Montezuma. The passage through them is much wider than the straits farther west and is largely occupied by marsh lands of the confluent delta of Sacramento and San Joaquin rivers. Valleys of small streams on both sides of the passage and also on the east side of the Montezuma Hills are invaded by tidewater in such a way as to indicate recent subsidence. Features of the same character occur also on a gentle slope northeast of the Montezuma Hills, but within short distances farther east and north such evidence of subsidence ceases to be available.

The evidence of extreme recency of subsidence which is connected with shell mounds does not extend so far eastward, the easternmost available locality being near the west end of Carquinez Strait. N. C. Nelson, after his work about the western area, on the results of which I have already drawn, undertook for the United States Geological Survey an archeologic study of the region of Suisun Bay and the delta marshes, with special reference to the question of subsidence. He found shell mounds about the western shore of Suisun Bay but not farther east, the distribution of the mounds apparently depending on that of the edible marine and brackish-water mollusks. On and near the delta marshes many sites of aboriginal occupation are mounds, natural or artificial, but in none of the places examined is the mode of occurrence of refuse deposits, etc., such as to demonstrate subsidence during the epoch of human occupation. Aboriginal remains were indeed found below tide level but not in places where the possibility could be excluded that they had been lowered by the settling together of an underlying soft deposit.

The 30-foot terrace is not known in the Great Valley. In the region of the Sacramento-San Joaquin delta the delta marshes occupy a belt along the west side of the valley. From their eastern edge an alluvial plain rises to the base of the Sierra. The lower part of the plain slopes so gently that 8 miles is taken for the first 50 feet of ascent, and on this part the streams from the mountains have no valleys. In its natural condition the plain grows by deposit from the streams. We may infer that had it been submerged at the time of the making of the 30-foot terraces the water level would have been marked upon it by deltas or other features of shore topography, but none have been reported. The slope has been accurately mapped with 5-foot contours, and a study of the map fails to discover any littoral features, but only those characteristic of alluvial fans. Although the results of map study are less satisfactory than those of field examination, I regard the presence of a shore line equivalent to the 30-foot terraces as improbable.

The sloping plain at Antioch, which ends northward in a bluff facing the broad strait, appears to descend eastward as well as northward and to pass beneath the marsh lands of the San Joaquin Delta. Near Antioch its surface is even, except for incised channels of drainage and a parapet of dunes along the river front, but eastward the surface undulates. The sand of which the plain is composed has there been molded by winds, and the general relations of the plain are somewhat obscured by the diversification of surface. It is probable, however, that the plain actually extends, without any abrupt break or flexure, well into the Great Valley, and that its continuity may be interpreted as evidence that the recent elevation and subsidence in the San Pablo-Suisun district affected also in some degree an adjacent part of the Great Valley.

The delta marshes of the San Joaquin and Sacramento lie within the range of the tides. They are divided by a plexus of winding channels into islands. In its natural condition each island was bordered by a raised rim, the "natural levees" of the surrounding channels. In part the rims were so low as to be regularly overtopped by high tides; in part they were submerged only during river floods. The rims are composed chiefly of river silt and sand. The interiors of the islands are made up of peat with small admixtures of silt. Below the peat is a floor of "hardpan," and the slopes of this floor continue the alluvial slopes which border the delta region. Manson and Grunsky [1] give the depth of the peat "near the outfall of the rivers" as 40 to 60 feet. Measurements collected by Mr. Nelson give a maximum depth of 50 feet in the strait north of Antioch. The general fact appears to be that the delta deposits, including the peat marshes and their silt rims, rest on a preexistent surface with alluvial slopes, and that the outlet of the earlier drainage, like that of the present, was westward to the Suisun basin. In all probability these slopes record for the Great Valley an epoch in which the Sacramento and San Joaquin waters flowed as a river through the Carquinez and Golden Gate gorges to the ocean, and the present bays did not exist. Since that epoch the delta region has subsided through a vertical distance equal to the maximum depth of the peat plus the fall of the ancient river between the passage at the Montezuma Hills and its mouth.

This subsidence is the latest recognized vertical movement of the land in the delta region. It may have been slow and continuous. It may have been interrupted by periods of rest or of elevation. It may have been completed long ago or it may be still in progress. If it was completed long ago, it created a bay in the Great Valley, a fourth bay of the San Francisco chain, and within this bay the delta plain was afterward built. If it occurred gradually and slowly and is still incomplete, the growth of the delta plain may have kept pace with it, preventing the formation of a bay.

The hypothesis of a bay, or inland sea, has been advanced with confidence by engineers who have studied the problems of flood control. According to Manson and Grunsky,[2] "Suisun Bay may be regarded as the remnant of the inland sea which at one time covered the interior valley and which more recently covered all those portions of this valley which are now embraced in the deltas of the two rivers." Heuer, Handbury, and Harts,[3] speaking of the Great Valley, say: "From an examination of the geology of the surrounding country it seems probable that Suisun Bay is all that is left of a large inland sea, the leveling of the weather and rainfall having filled the remainder and converted it into land by the eroded material carried down by the rivers from the surrounding mountains." Foote [4] speaks of "the Great Valley of California, as nature built it, by filling an inland sea with débris from the hills." So far as I have gleaned from the reports of geologists, the latest known marine formations in the Great Valley are of middle Tertiary age and were deposited not long after the valley was created by the upraising of the Coast Ranges, but it is not probable that the inland sea to which the quoted passages refer was so ancient. A sea of which Suisun Bay is the remnant could not have existed before the creation of the present bay system by post-Tertiary subsidence.

Under the hypothesis of an inland sea subsidence preceded delta building and probably has now ceased. Under the simplest alternative hypothesis subsidence was continuously accompanied by delta building and probably has not ceased. Evidence bearing on either hypothesis bears also on the question of present subsidence.

[1] Manson, Marsden, and Grunsky, C. E., Comm. Public Works California Rept. for 1893-94, p. 26, 1895. Details are given by Manson in Tech. Soc. Pacific Coast Trans., vol. 5, No. 4, 1888.

[2] Op. cit., p. 25.

[3] Heuer, W. H., Handbury, T. H., and Harts, W. W., 59th Cong., 1st sess., H. Doc. 262, pp. 4-5, 1905. Also, in the same words, Biddle, John, Jackson, T. H., and Leeds, C. T., 62d Cong., 1st sess., H. Doc. 81, p. 6, 1911.

[4] Foote, A. D., Am. Soc. Civil Eng. Proc., vol. 35, p. 830, 1909.

Mention has already been made of drowned stream valleys northeast of the Montezuma Hills. The alluvial foreland of the hills descends below sea level in Yolo basin, one of the basins lateral to Sacramento River. Small streams from the hills crossing this foreland have carved valleys in it, and the valleys descend below sea level. When these valleys were carved the foreland must have stood higher than now, and the preservation of the valleys shows that the time of their making was not remote. This feature therefore indicates modern subsidence. The eastern face of the Montezuma Hills, having been pared away by Sacramento River, has no corresponding foreland. South of the strait the foreslope of the Diablo foothills has been so far remodeled by the wind that its evidence is not altogether clear, but the fact that some of the wind-made hills are now surrounded by marsh lands of the delta (see Pl. III, *B*) shows subsidence without indicating its date. The apparent continuity of the wind-modeled plain with the dissected plain at Antioch, where the condition of the dissecting channels indicates subsidence in progress, suggests without demonstrating a common history.

If the delta was formed in a body of standing water its process of formation would presumably be that which is illustrated on the lower Delta of the Mississippi. The water would first be shoaled by subaqueous deposits of silt, then the channels would be outlined by the projection of pairs of flanking embankments, and then the shoal spaces between embankments would be occupied by vegetation and the formation of peat would begin. If the formation of the delta kept pace with subsidence the silt embankments and the peat beds would alike begin their growth on the foundation of old alluvium and would be built up simultaneously. In one case the peat would overlap the silt deposit, thinning as it approached an embankment; in the other it would normally be about as deep near an embankment as in the middle of an island. The distribution of peat beds of different depths, so far as I know it, favors the second hypothesis; and so does the great maximum depth of 50 feet or more. The structure of the delta, being thus indicative of continuous slow subsidence up to a very recent date, is favorable to the hypothesis of subsidence now in progress.

Another feature suggesting modern subsidence—the one, in fact, which first directed attention to this subject—is the exceptional magnitude of the lateral basins of the Sacramento Valley. All rivers traversing alluvial plains to which they are making additions build their banks higher than the land beyond and thus make lateral basins, but I know of no other river system in which the upbuilding of the banks has so far outstripped that of the adjacent valley. Over an area of about 50 square miles the floor of Sutter Basin lies below the low-water level of adjacent parts of Sacramento and Feather rivers, and nearly twice that area in Yolo Basin lies lower than the adjacent water of the Sacramento. As there evidently are several different ways in which such a condition may have originated, its existence does not demonstrate a history of development, but one of the possible origins is connected with subsidence. With slow subsidence of the valley the rivers would tend to raise their banks gradually by deposition of silt as fast as they were lowered by subsidence, but the quantity of sediment brought to the lateral basins would not be correspondingly increased.

The hypothesis of present subsidence in the middle and northern parts of the Great Valley finds its strongest support in the depth of the peat accumulated under the delta marshes. It is less surely supported by drowned stream valleys at the south end of Yolo Basin and by the imperfectly studied relations of sand dunes, and it accords well with the exceptional development of flood basins in the Sacramento Valley.

If subsidence is accepted as the general character of crustal movement at the present time, alike in the bay region, the delta region, and the Sacramento Valley, it does not follow that the change has everywhere the same rate. Diversities such as have characterized the movements of the past in different areas may plausibly be ascribed to those of the present.

Chapter IV.—CHANGES IN THE CONDITION OF RIVERS FROM ARTIFICIAL CAUSES.

The changes in streams brought about by the activities of white men, practically dating from the discovery of gold in 1848, have arisen (1) from the overloading of the streams with detritus and (2) from the surrounding of parts of the inundated area by levees so as to restrict the freedom of the valley rivers to expand in time of flood. The overloading was caused chiefly by hydraulic mining. Agriculture and other industries which disturb the soil and expose it to wash by rain contributed to the effect, but their influence was relatively small.

CHANGES DUE TO MINING.

Some of the hydraulic mines discharged their tailings directly into streams, others upon gentle slopes of the land, where the coarser material accumulated in fan-shaped heaps or dumps. Usually the coarser material accumulated also in the streams, forming local deposits which were gradually swept forward. Examples of mine dump and coarse stream deposit are shown in Plate V.

Initially, as the tailings issued from the mining sluices, there was a division of the débris, the coarser part being swept along the bed and constituting the bed load of the stream, the finer being borne in the body of the current and constituting the suspended load. The partition of débris into bed load and suspended load continued throughout its journey, but the nature of the partition varied, because sluggish currents could suspend only the finest clay, whereas swift currents might suspend fine or coarse sand.

Some of the creeks flowing through the uplands that stand between river canyons acquired very heavy deposits, and there were large accumulations also in the mountain canyons of some of the rivers. (See Pl. VI, *B*.) After the checking of the mining operations these deposits were attacked by the streams, those of the upland creeks being trenched and those of the river canyons largely removed.

Where the rivers leave the mountain gorges and enter the Great Valley there was an abrupt reduction of slope and of velocity. Consequently in each river the capacity for transportation was reduced at this point, and part of the load of débris was arrested. The resulting deposit extended toward the valley from the foot of the range, and usually reached quite to the mid-valley trunk stream. It may conveniently be called a piedmont deposit. Its material was very coarse near the head and finer below.

Continuous with the piedmont deposits were deposits in Sacramento and Feather rivers, the trunk streams of the Sacramento Valley. Their characteristic material was at first mud, or "slickens," and afterward sand.

Each mining dump had a somewhat conical form, its slopes radiating from a vertex. The deposits of the upland creeks made broad gravelly plains on which channels shifted with every flood, and later they were carved into terraces. The same description applies to the piedmont deposits, except that not all of them have been excavated to such an extent as to develop terraces. The deposits of the trunk rivers are little wider than the original channel beds.

With the building up of stream beds the planes of high water were raised and the area of inundation was increased. In the mountain and piedmont districts this has been accompanied by a decreased flood depth, a change tending to reduce velocities and limit the ability of the streams to transport débris. Along the trunk streams it has turned a larger share of the flood water into the lateral basins, thus reducing the discharge in the channels and tending to reduce the ability of the streams to transport. On each stream, however, the tendency to reduce transportation was a tendency only, being opposed and overpowered by the influence of increased slope.

CHANGES DUE TO RECLAMATION.

During the entire period of the invasion of the Sacramento Valley by mining débris, the regimen of the rivers has been modified also by the construction of levees. Tract after tract belonging to lateral basins or to the deltas has been surrounded by embankments so as to shut out the flood waters, and eventually the entire area of natural inundation will be reclaimed in the interest of agriculture. Restricted in area, the flood waters have increased in depth, and each great flood has risen higher than its predecessor. As the waters have been more and more confined to the channels the channel velocities have increased, and with them the ability to transport débris. If these changes had been independent of those wrought by mining débris they would have resulted in the automatic deepening and widening of the channels.

Mining débris and reclamation by levees work together in producing high floods, and their flood effects can not be fully discriminated. They work in opposed ways on depth of channel, the mining débris tending to build up the bed and reclamation to scour the channel deeper.

TRANSPORTATION OF DÉBRIS.

The series of changes thus outlined have been effected under the natural laws controlling the work of streams. Changes are still in progress and their results may be forecast, provided the stream laws are known. The following paragraphs summarize such of the laws as are specially involved in the movement of mining débris and the associated problems of flood control.

The quantity of débris which a given stream transports is its load; the quantity it can transport may be called its capacity. The load may be less than the capacity but not greater.

Capacity varies with slope. The greater the slope the greater the capacity; and the change in capacity is always larger than the change in slope.

Capacity varies with discharge. When discharge is increased the resulting increase in capacity is greater than the increase in discharge; the capacity per unit of discharge is increased. But an increase in discharge does not enhance capacity so much as the same ratio of increase in slope.

Capacity varies with the character of the débris transported. The lower the specific gravity of the débris the greater the capacity—that is, the greater the weight of load which may be transported. The finer the débris the greater the capacity. Capacity is affected also by the shapes of the particles of débris. The range of variation in respect to size is so much greater than the range in respect to density and shape that only the size factor is usually considered in relation to capacity. Size may be measured by diameter or by volume. In whichever way it is measured, an increase in fineness causes a somewhat greater increase in capacity.

Capacity varies with the ratio of depth of water to width of stream. In the main, capacity increases with increase of the ratio (and this is true of the streams of Sacramento Valley), but the opposite rule applies to very small values of the ratio.

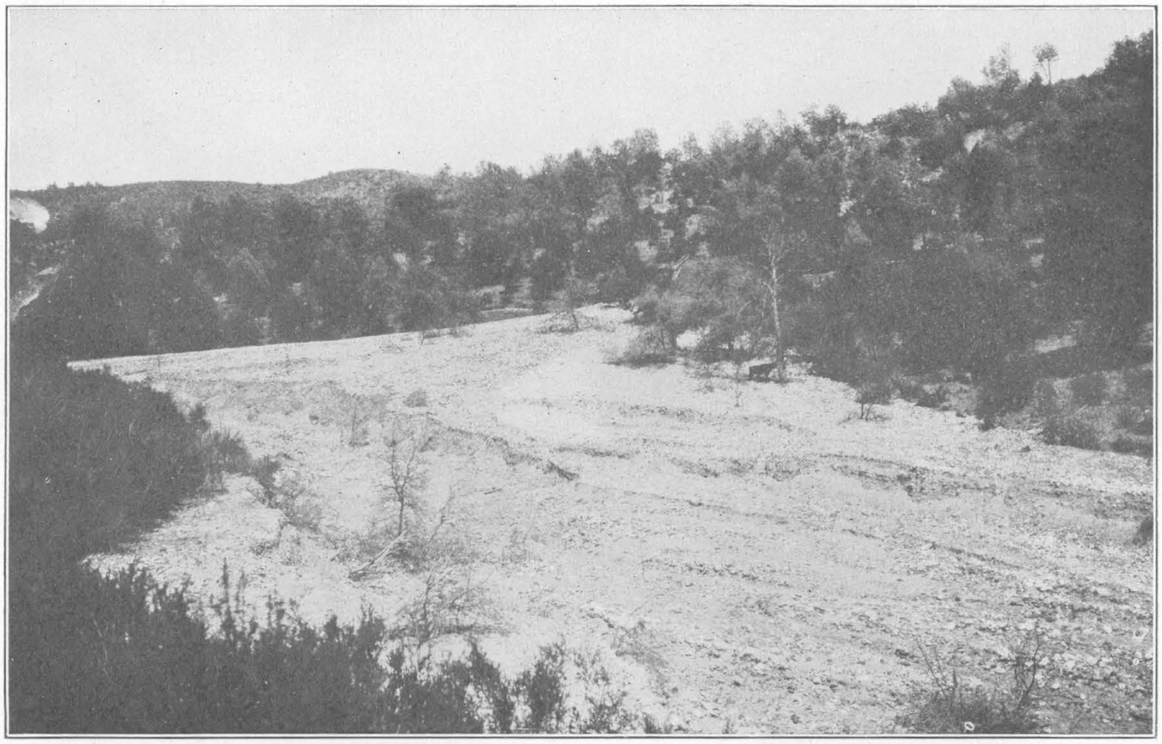
The fact that there is a limiting condition below which transportation does not take place finds expression in the word competent. For a stream of given discharge, flowing in a given channel and dealing with débris of a given fineness, there is a competent slope; in a channel of given form and slope and with débris of given fineness there is a competent discharge; and for a given discharge in a given channel there is a competent fineness.

The ratio in which capacity is modified by a change in slope, discharge, fineness of débris, or depth of current is greater when the conditions are near competence than when they are far above competence. In other words, capacity is most sensitive to changes in the conditions which control it when near its lower limit.

These laws have been experimentally determined for the bed load[1] treated by itself, and they are believed to be approximately true for the suspended load by itself. Nevertheless they can not be affirmed of the total load, because of certain complications growing out of the shifting of material from one load to the other. For most of the purposes of this report their important application is to capacity for the transportation of bed load.

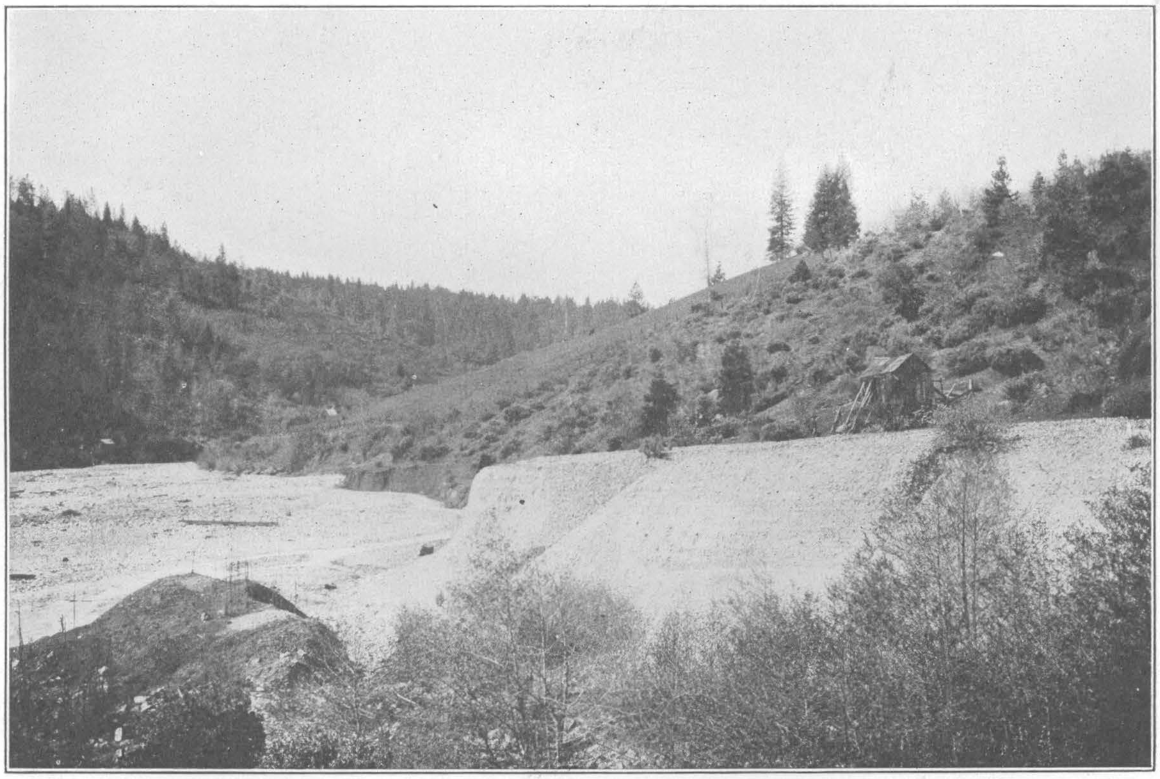
If a stream which is loaded to its full capacity reaches a point where the slope is less, it becomes overloaded with reference to the gentler slope and part of the load is dropped, making a deposit. If a fully loaded stream reaches a point where the slope is steeper, its enlarged capacity causes it to take more load, and the taking of load erodes the bed. If the slope of

[1] See U. S. Geol. Survey Prof. Paper 86, 1914.



A. A MINING DUMP ON THE SIDE OF A SMALL CREEK VALLEY.

The mine (not shown) is at the right. The tailings, discharged from the mining sluice, have built a fan-shaped deposit, but this deposit contains only the coarser part of the tailings. At its lower edge the dump is attacked by the creek, and some of it is washed away whenever the creek is in flood. Photographed in 1905.



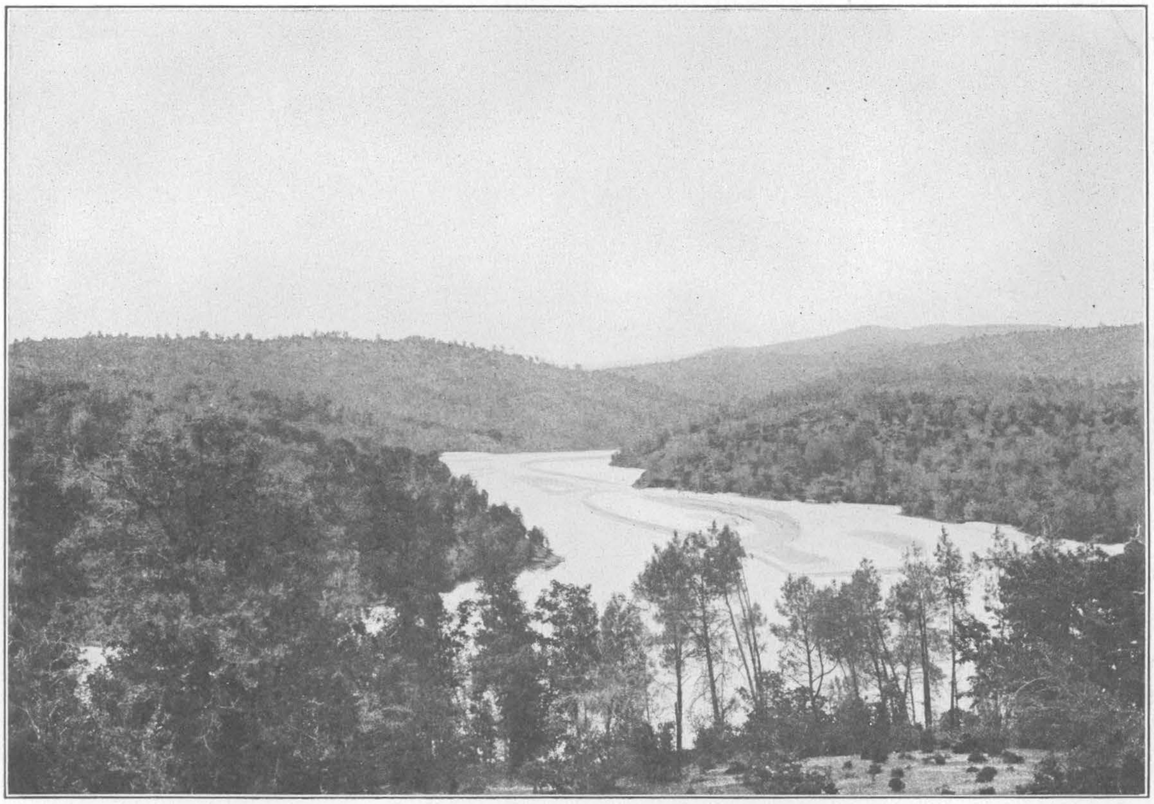
B. ONE OF THE LARGER CREEKS OF THE UPLAND, WITH ITS DEPOSIT OF MINING DÉBRIS.

At the right is a partly eroded mining dump. The photograph was made in 1908, and at that time the mining dumps were furnishing so much débris to the creek that the erosion of its deposit had scarcely begun.

MINING DÉBRIS NEAR ITS SOURCE.

A. A SIERRA CANYON BED IN ITS NATURAL CONDITION.

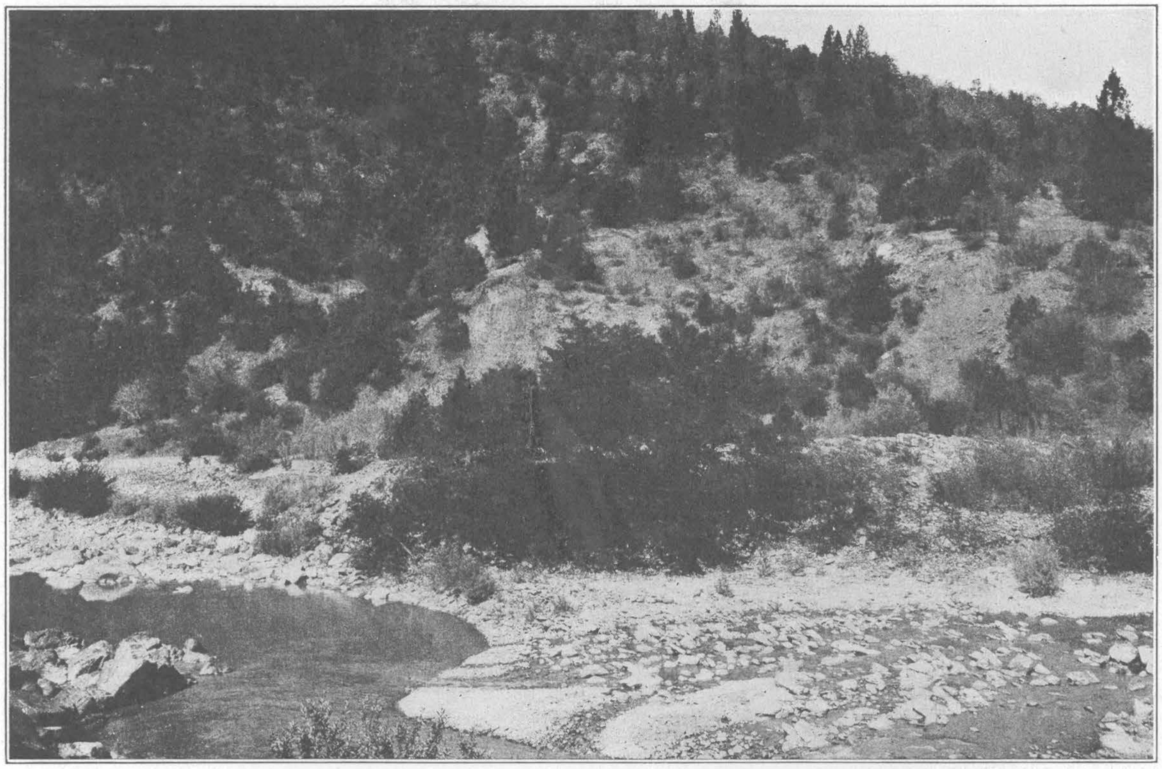
The water channel occupies the entire width.



B. A SIERRA CANYON CLOGGED BY MINING DÉBRIS.

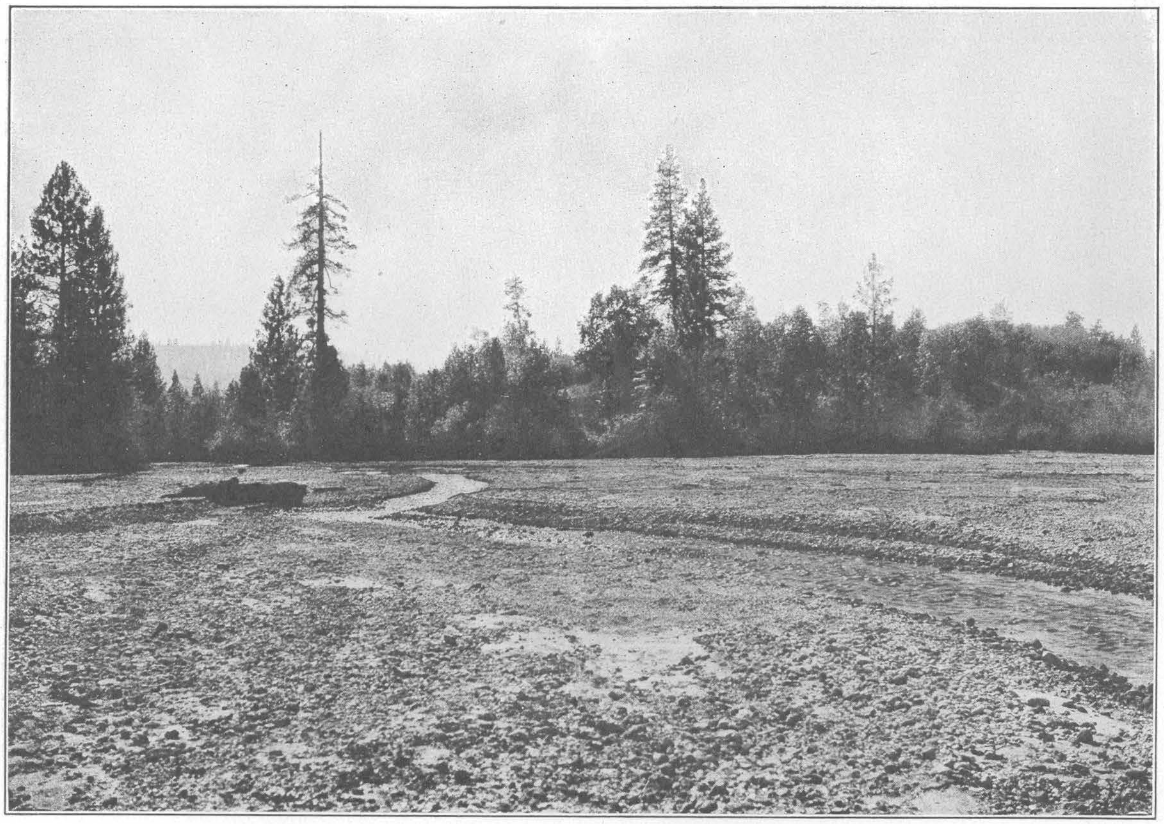
The surface of the débris constitutes a broad plain that is covered by water only when the stream is in flood. The low-water channels traverse this plain. The photograph was made in 1908. At that time most of the canyon deposits had been removed. (See Pl. VII, *A.*) This one is the head of a piedmont deposit. (See pp. 28, 52.)

CHANGE OF CONDITION CAUSED BY MINING DÉBRIS.



A. MIDDLE FORK OF YUBA RIVER NEAR NORTH SAN JUAN IN 1905.

The canyon received a deposit of very coarse mining débris, which was afterward eroded. The terrace here shown is a remnant of this deposit. The exposure of bedrock at the left indicates that the river has nearly recovered its original profile.



B. AN UPLAND CREEK NEAR NORTH SAN JUAN IN 1905.

The débris deposit has not been trenched by the stream and may still be growing at this point.

MINING DÉBRIS OF RIVER CANYONS AND UPLAND CREEKS

A. AN UPLAND-CREEK DEPOSIT IN A REGION OF MANY MINING DUMPS.

During the growth of the deposit a forest was overwhelmed, and its stumps and logs are now being disentombed. New vegetation takes possession of parts of the valley where erosion is least active and helps to restrain the erosive work. Photographed in 1905.

B. A HEAVY CREEK DEPOSIT OF THE UPLAND, NOW SUFFERING EROSION.

Photographed in 1905.

MINING-DÉBRIS DEPOSITS OF UPLAND CREEKS.

a stream's bed is not adjusted to the stream's discharge and to the load it has to carry, then the stream continues to erode or deposit, or both, until an adjustment has been effected and the slope is just adequate for the work.

Any change of conditions which destroys the adjustment between slope, discharge, fineness, and load imposes on the stream the task of readjustment and thus initiates a system of changes which may extend to all parts of the stream profile. The mining débris disturbed the adjustment of streams by adding to their load. Reclamation by levees disturbs it by increasing the flood discharge in certain parts of the river channels.

The law of adjusted profiles applies to streams with mobile beds—alluvial streams. Streams with fixed beds are normally underloaded, and their beds are modified only by abrasion. This process works toward an adjustment of slopes but with exceeding slowness, and the factors involved are different from those of alluvial streams.

The channel of an alluvial stream is composed of an alternation of deeps and shoals. The dimensions of these are related to the discharge. With variable discharge they are continually modified, each particular discharge tending to adjust them to its needs. Because of the greater power of streams during flood, the pattern of the bed is more nearly adjusted to flood conditions than to any other.

An alluvial stream which is not confined by rigid banks shapes for itself a course made up of curves. The curves are not stationary but undergo continual changes. The curve pattern is large for a large stream and small for a small one. In a variable stream the pattern is adjusted to the needs of the flood discharge.

The general slope of a stream bed is determined chiefly by the magnitude of the load that travels at time of the larger floods.

The laws thus far stated apply to the transportation of débris along a bed composed of similar débris. When a stream is made to sweep débris along the unyielding bed of a sluice or flume other laws apply. Capacity is greater for smooth beds than for rough. It is greater for coarse débris (up to the limit of competence) than for fine. It is in general greater for a flume than for a natural stream of the same size.

ACCUMULATIONS OF DÉBRIS IN THE MOUNTAINS.

The stream of water by which tailings were delivered to a mining dump was artificially guided and usually ceased to flow after cessation of mining. If the dump lay wholly on a hillside it was afterward washed only by rain, and no important fraction of it was removed. Many of the smaller dumps thus became essentially permanent deposits. The larger hillside dumps extended to waterways, and these were excavated by the streams on whose courses they encroached. Other dumps were built wholly in stream valleys and were subject to excavation from their beginning. As a whole the dumps have yielded and are still yielding a large annual tribute to the streams. Their contribution will continue, with gradual diminution, for an indefinite period; but a portion of their store of débris may be regarded as permanently placed.

Drifting forward from the dumps, during the mining and afterward, a large amount of débris gathered in the valleys of the upland creeks. This material is being fed to the rivers gradually and is perhaps at present the chief source of the rivers' supply of débris. (See Pl. VIII.) The excavation of such deposits leaves a terraced valley, and as the stream works down toward its original channel patches of terrace are here and there stranded on the slope in such positions as to be exempt from further attack.

Some mines discharged their tailings directly into the canyons of rivers, and the mountain rivers have received also the outwash from dumps and creek valley deposits. Before the hydraulic mining the river beds were made up largely of bedrock and great boulders, with only a few reaches of coarse gravel. (See Pl. VI, *A*.) Their normal load of débris was less than their capacity. In the period of most active mining they received more débris than they could carry, and the overload was deposited. When mining was checked they again became underloaded and the new deposits were excavated. (See Pl. VII, *A*.) Little débris now remains in their beds, and the rivers deliver promptly to the piedmont deposits all that they receive from the dumps and upland creek deposits.

PIEDMONT DEPOSITS.

The piedmont deposits began with the beginning of hydraulic mining and grew not only during the mining period but for years afterward. The coarse gravel of the canyon deposits was all caught by them, and their growth probably continued until the canyons were emptied. They received also both gravel and sand from the upland creeks. Their building was accompanied by a sorting of the débris, the coarser portion lodging high on the slope and the finer farther down. Their growth continued long after the culmination of the upland deposits but eventually ceased and was followed by excavation. In the piedmont deposit of American River the stream is well intrenched, and stages of its erosional work are recorded by terraces. Low terraces have appeared also along Bear River. On Yuba River the main channel has been deepened near the head of the deposit, and farther down the natural development of excavation has been modified by a dam.

At Parks Bar Bridge, which crosses the Yuba where its bed begins to broaden outside the mountain canyon, the summit plain of the deposit was well recorded by a photograph in 1905 (see Pl. IX, *A*), and in 1913 it was observed to retain the same height, but the depth of the channel dividing it had increased in the interval from 11 to 21 feet, showing a scour of 10 feet in the eight years. Three miles above, in the mouth of the canyon (see Pl. IX, *B*), where the passage is too narrow for the development of terraces, is a gaging station of the Geological Survey, and the changes in the channel bed are well shown by the records of low-water stages in successive autumns. The gage readings corresponding to a discharge of 500 cubic feet per second are as follows:[1]

	Feet.		Feet.
1903	13.6	1909	5.0
1904	13.5	1910	4.8
1905	11.6	1911	4.4
1906	9.3	1912	4.0
1907	8.3	1913	4.0
1908	7.1		

These readings not only confirm the record at Parks Bar Bridge, by indicating a total scour of 9.6 feet in 10 years, but show that the deepening of the channel has been progressive.

[1] Based mainly on data published in U. S. Geol. Survey Water-Supply Paper 298, pp. 254-255, 1912.

At Marysville, where the Yuba joins the Feather, the record of low-water stages for the same period (see p. 29) shows a total lowering of 2.9 feet. The sequence of levels is here less orderly than at the upper gaging station, partly because the low-water stages for different years correspond to different discharges and partly because the local conditions have been modified by engineering works for the control of the rivers, but the two records are of the same general tenor. The maximum phase of the piedmont deposit has been passed, and the work of excavation has begun. The maximum came earlier at the head of the deposit, having already been passed when the definite record began in 1903; at the river mouth it occurred between 1903 and 1906. But for artificial interference with the work of the river the rate of scour at the head of the deposit would have been considerably greater and the scour at its foot less.

The excavation of the deposit is accompanied by further sorting of the débris. That which is swept out at Parks Bar Bridge consists of coarse and fine gravel, with a generous filling of coarse sand, but that which reaches the mouth of the river at Marysville consists of fine and coarse sand, with a small amount of fine gravel. The coarse gravel is arrested on the way,[2] doubtless in company with other gravel brought from the upper river, while part of the sand which had been incorporated with the gravel at the head of the deposit joins with the finer débris in transit from above. It is not to be assumed that the coarse débris is permanently arrested, but only that its forwarding is delayed until the upper river shall cease to send down a heavy load of sand. On the exhaustion of the mining débris stored above, the transportation of the coarse débris of the piedmont deposit will become more active, and gravel will largely replace the sand in the lower Yuba and lower Feather. A return toward the normal profile will tend to restore the "gravelly ford" of the Yuba by which travel is said to have approached Marysville in early days.

The piedmont deposits of Yuba and Bear rivers extend to their mouths in Feather River and are there continuous with deposits in the Feather. That of American River is continuous with a deposit in Sacramento River.

[2] These statements as to the movements of gravel at the mouth of Yuba River were written several years ago and were then accurate. The present condition is described in the closing paragraphs of this chapter.

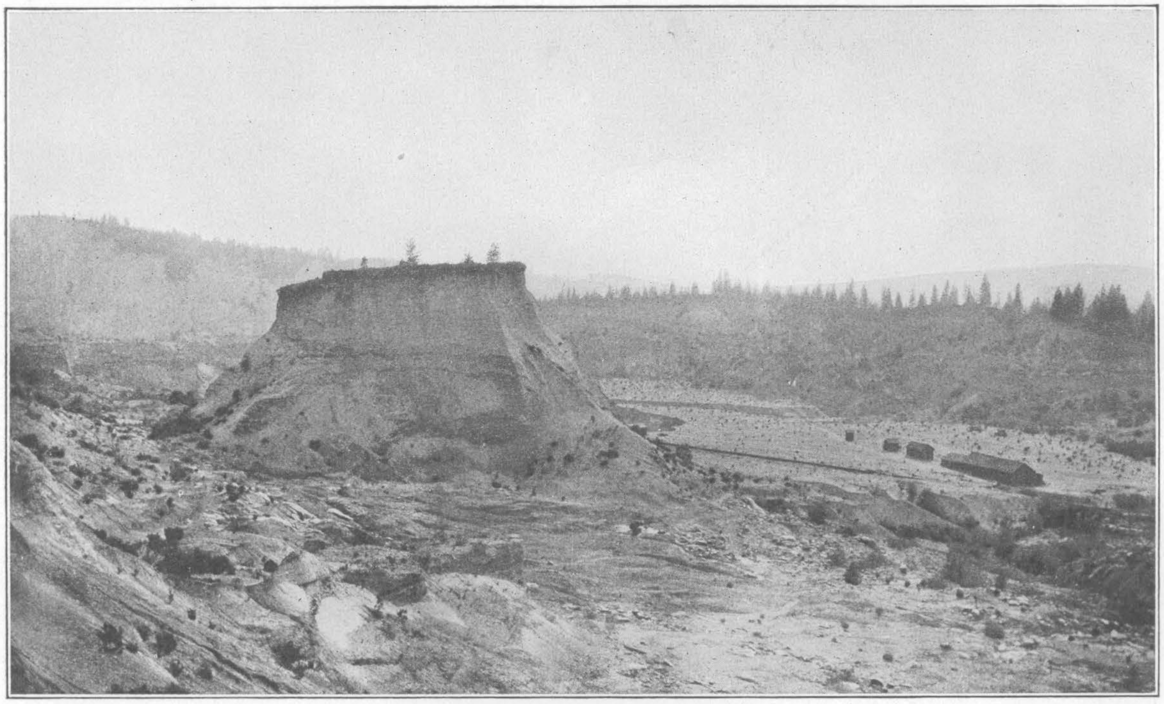
A. TREES ON THE LEFT BANK OF THE RIVER PARTLY BURIED BY MINING DÉBRIS.

Photographed June 6, 1905. In July, 1913, the locality was revisited, photograph in hand, and the height of the deposit found to be unchanged.

B. THE "NARROWS" OF YUBA RIVER IN 1905.

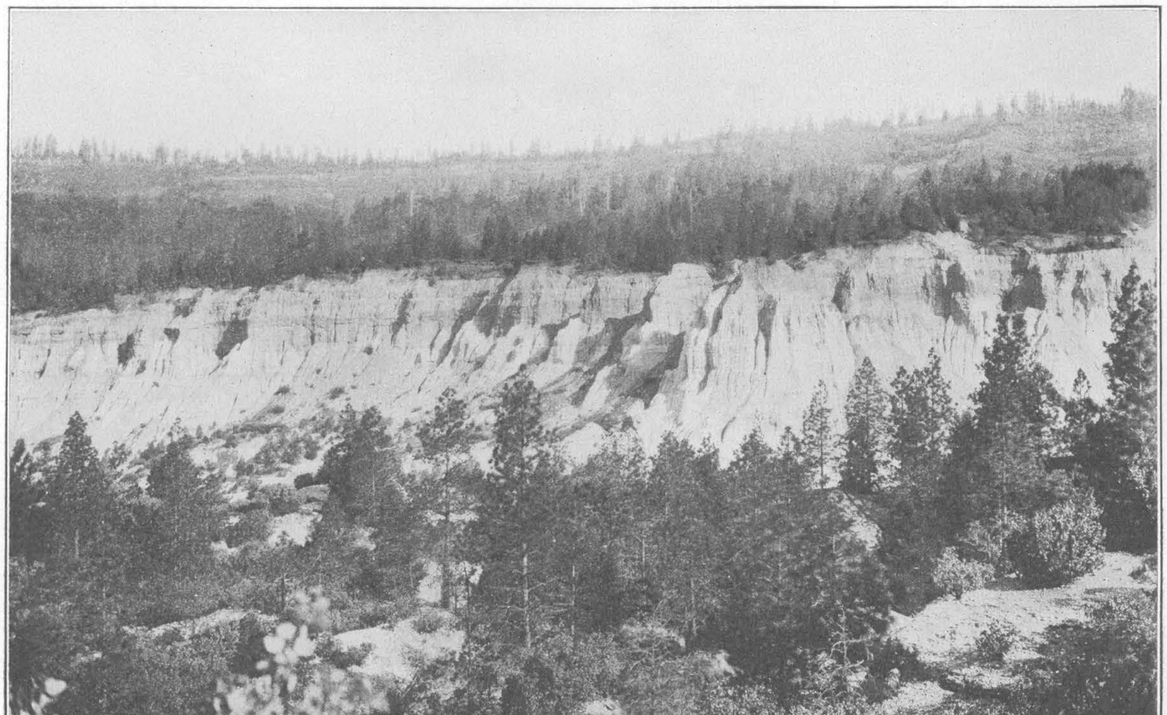
The Geological Survey's gaging station is at this point. A short distance above it the deposit was sounded in 1899 and found to have a depth of 85 feet.

CULMINATION OF THE YUBA RIVER PIEDMONT DEPOSIT AT PARKS BAR BRIDGE.



A. MANZANITA MINE, NEAR SWEETLAND.

Beyond the buildings is a ridge bearing trees on its crest. The camera stood on a similar ridge. The outer slopes of the ridges and the tabular top of the intervening hill are parts of the original surface before the mining. In the survey to measure the quantity of earth removed they helped to indicate the original configuration of the land. The greatest depth of excavation within the field of view was 180 feet, and the volume of the visible part of the opening is about 13,000,000 cubic yards. The estimated volume of the entire excavation at this point, including the Manzanita and American mines, is 47,900,000 cubic yards.



B. NORTH WALL OF THE WEST ARM OF THE NORTH BLOOMFIELD MINE.

The height of the wall is 250 feet. The photograph was made in 1908, about 20 years after the last mining in this part of the opening. Storm waters have continued the work of excavation, sculpturing the cliff into alcoves and buttresses. Part of the excavated earth has lodged in a lower part of the mine and part has escaped to a neighboring creek. On the cliff the surface wash has been so active that vegetation has found no foothold, but elsewhere the work of reforestation has begun. The trees in the foreground all stand within the mine.

HYDRAULIC PLACER MINES.

Other piedmont deposits clog only the streams from which they originate. The largest is that of the Feather, which has a visible length of about 30 miles and then passes under a slack-water pool occasioned by the deposit from the Yuba, which acts as a dam.

DEPOSITS IN THE VALLEY RIVERS.

The débris delivered by the piedmont streams to the trunk rivers of the valley imposed a load which those rivers could not transport without increase of slope, and the necessary increase was made by depositing part of the load on the channel beds and building them up. The depth of the deposit was thus related to the magnitude of the load transported on its slope. The deposit grew through the period of active mining and afterward until the piedmont deposits had passed their maximum, and then it began to decline. The depth of the deposit was also affected by the quantity of water flowing through the channel in time of flood, a quantity which tended to increase as access to lateral basins was restricted by levees.

The history of change is most definitely known through records of low-water level at Marysville and Sacramento, the variations of lowest water surface from autumn to autumn corresponding approximately to variations of the general level of the channel bed. At Marysville the observations were made on a gage established in Yuba River about 0.7 mile from its junction with the Feather, and a daily series has been kept since 1893 under the direction of the levee commissioners of the city, to whom I am indebted for data contained in Table 2. The gage was established in 1873, and the low-water record is continuous from 1883. For years earlier than 1873 there are no exact data, but estimates of different observers indicate an original low-water level at least 10 feet below that of 1873.

At Sacramento gagings of Sacramento River were made, and continuous readings have been reported by the United States Weather Bureau since 1896.[1] For certain earlier years records of low-water are reported or cited by Mendell[2] and by Rose.[3] In the original condition of the river there was a tide at Sacramento with a range of about 3 feet. In 1871, when the low-stage level had been raised 4 or 5 feet, there was still a tide of 9 inches,[4] and Hall records 2 inches in 1879.[5] Rose also gives the range for years earlier than 1860 as "about 2 feet." The United States Coast and Geodetic Survey tide tables give 1.5 feet as the mean range and 3.2 feet as the great tropic range, the figures being based on observations made in 1857. As the bed continued to rise the tide disappeared, but it was again observable when the bed was afterward reduced. In 1913 the range was reported as 1.5 feet. The freedom of tide transmission from Suisun Bay to Sacramento is related to depth of water in the lower river, and the periods of larger tide at Sacramento are also periods of greater depth of water. During such periods the deposits in the channel were relatively shallow, and because of these correlations the range of variation of the annual low-stage levels is less than the range of variation in the depth of the river deposit. The raising of the low-stage plane from the vicinity of mean tide level to a position 13 feet higher was associated with more than 13 feet of deposit in the channel.

TABLE 2.—*Low-water records of Yuba River at Marysville and of Sacramento River at Sacramento.*

[Feet above mean sea level.]

Year.	Marysville.	Sacramento.
1849	[36.8]	0
1856		0
1869		2.9
1873	46.8	
1874	47.8	4.9
1875		4.5
1876		7.1
1877		5.3
1878		5.5
1879		5.8
1880	52.8	7.4
1881		6.5
1883	52.0	
1884	52.8	
1885	51.1	
1886	52.6	
1887	51.3	
1888	52.0	
1889	52.3	
1890	52.4	10.5
1891	52.7	
1892	53.6	
1893	53.0	
1894	53.0	7.5
1895	53.0	
1896	53.4	10.0
1897	54.5	10.8
1898	54.0	9.6
1899	53.8	9.9
1900	54.1	7.6
1901	54.5	7.2

[1] Daily river stages at river gage stations on the principal rivers of the United States, 1896–1910, pts. 6–10, U. S. Weather Bur.

[2] Mendell, G. H., Chief Eng. U. S. Army Ann. Rept. for 1882, p. 2507.

[3] Rose, A. H., California Comm. Pub. Works Rept. for 1894, p. 33.

[4] Rose, A. H., op. cit., p. 33.

[5] Hall, W. H., California State Eng. Rept. for 1880, p. 68.

TABLE 2.—*Low-water records of Yuba River at Marysville and of Sacramento River at Sacramento*—Continued.

Year.	Marysville.	Sacramento.
1902	55. 0	6. 9
1903	55. 3	7. 0
1904	55. 8	8. 2
1905	55. 9	6. 3
1906	55. 7	6. 8
1907	55. 3	7. 3
1908	55. 1	5. 3
1909	53. 0	5. 5
1910	52. 5	5. 1
1911	52. 9	5. 5
1912	52. 2	4. 1
1913	52. 4	3. 0

Table 2 contains the low-stage gage readings at Marysville and Sacramento, together with water-level records of less precision for earlier years; and the same data are plotted in figure 4. The zero of the Marysville gage was placed

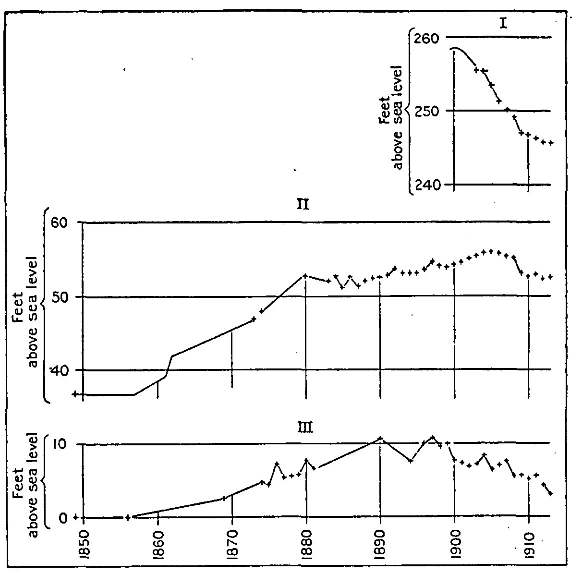


FIGURE 4.—Fluctuations of low-water level due mainly to the deposition of mining débris on river beds and its subsequent erosion. I, Yuba River in narrows near Smartsville; II, Yuba River at Marysville; III, Sacramento River at Sacramento.

at the low-water level of 1873. At Sacramento there were two gages. The zero of one is reported to correspond to the low water of 1856, and the readings from the other, as tabulated, are reduced to the same zero. A certain amount of ambiguity is occasioned by the tides, but it is probable that the lower low-water records at Sacramento all represent the combination of low tide with the autumnal low-river stage; and the graphic record has been adjusted under this assumption.

The irregularities of the plotted curves are connected largely with inequalities of maximum and minimum discharges from year to year. Exceptional flood discharges leave exceptional configurations of channel bed, which affect local details of low-water plane, and the low-water plane also varies in position with the magnitude of the low-stage discharge. Minor details of the curves may therefore be ignored in reading from them the general history of the building up and paring down of the channel deposits.

The bed of Feather River at Marysville was built up rapidly during the period of increasing output of débris from the hydraulic mines of the Yuba River basin. It continued to be upbuilt, but more slowly, after the checking of mining and during the chief excavation of the débris banks in the mountains, and accretion was not exchanged for reduction until five or six years after the excavation of the head of the Yuba piedmont deposit had begun. The downstream movement of the great body of débris is thus analogous to the downstream movement of a great body of storm water, the apex of the flood traveling in the direction of the current. The apex of the débris flood, leaving the mines in 1883, passed the mouth of the mountain canyon in about the year 1900 and the mouth of Yuba River in about 1905.

The stream of débris from the Yuba is joined in the Feather by a smaller stream from the Bear and in the Sacramento by a stream from the American. Water levels at the Sacramento gaging station are affected by all these streams. The débris wave from the Yuba may be assumed to be flattened and greatly extended during its long journey from Marysville, so that its influence on the water plane at Sacramento is gradual and of moderate amount. Its apex has perhaps not yet arrived, and if it has arrived it can not be discriminated in the composite effect. The wave from the American, having a much shorter course, reached the station while less expanded and has been the dominant factor in the determination of the low-water curve. Its apex seems to have passed in about the year 1896; and the reduction of the river deposit began here a decade earlier than at the mouth of the Yuba.

So far as the flow of débris from the hydraulic mining of the past is concerned, the future history of the channel deposits will be one of continual diminution, a progress toward the restoration of the river conditions of the early fifties. That progress might be arrested by the resumption of hydraulic mining. It will be promoted by the reclamation of the lands now subject to overflow. The confinement of flood waters of the Sacramento and Feather to the channels of those streams would greatly increase their capacity for transporting débris and would eventually reduce the channel beds to lower levels than have been known. The partial confinement contemplated in the engineering plans for flood control will probably obliterate the effect of the invasion by mining débris.

The deposit built in the Feather River channel by débris from the Yuba has the effect of a dam, causing slack water in the Feather just above. The pool had at one time a length of 10 miles or more, being limited upstream by the piedmont deposit of the Feather. Afterward it was diminished by the encroachment of that deposit and in recent years by the lowering of the low-water plane at Marysville. Its length in 1913 was said to be about 6 miles. There is a similar ponding of Sacramento River by débris brought to its channel by Feather River.

The piedmont deposits in the basin of San Joaquin River are reported to be of moderate extent, and so little mining débris has reached the trunk stream that the river has remained tidal and navigable.

As already stated, the flood of mining débris is analogous to a flood of water in its mode of progression through a river channel. It travels in a wave, and the wave grows longer and flatter as it goes. Where the channel is too small to contain it, the water wave spreads out over adjacent lands, and the volume thus escaping from the channel is temporarily stored, so as to regulate the flow at points below. The débris wave differs from the water wave in the fact that part of its overflow volume is permanently lodged outside the river channel, and in the additional fact that the material of the wave is not homogeneous. From the start there is a sorting of the débris, and the finer parts travel faster than the coarser, except that some of the finer material is held in the interstices of the coarser. The visible part of the wave, that which at any time is exposed to the action of the current, exhibits a gradation from fine at the front to coarse at the rear. The débris in transit at any point is first silt—the "slickens" of the miners—and then in succession sand, fine gravel, coarse gravel. At the mouth of Yuba River all these phases have been observed, the sequence being automatic or normal as far as fine gravel. The appearance of coarse gravel, recently observed, has been hastened by engineering works that have narrowed, and thereby strengthened, the flood current a few miles upstream. In the lower Sacramento silt has been succeeded by fine sand and coarser sand.

The progress of such a wave and its manifestation in the texture of bed material are complicated by two other factors—progressive comminution of débris and variation of flood discharge. The débris in transit is continually ground upon itself, and its particles are worn to smaller size, so that the coarser débris characteristic of the upper reaches of a stream does not appear in the lower reaches, and the load of fine débris is greater.

A great flood, as compared to a small flood, is able to carry coarser débris, or to carry more débris, or to do its work on a gentler slope. Which of these phases of its comparative activity shall be manifested in a particular division of the stream's course will depend on the character and quantity of the load brought from above. It may reduce the slope of its channel by scouring and leave behind a low-level channel bed of coarser débris, and in that event the minor floods of succeeding years will tend to steepen the slope by depositing débris, and the deposited débris will be finer than that on which it rests. As the closing work of each flood is performed by a discharge less than its maximum, it often happens, especially in the lower part of a river's course, that the coarsest part of a flood's load is so buried by fine material as not to be visible when the bed is exposed at low stage.

Chapter V.—CHANGES IN THE CONDITION OF BAYS.

The streams that discharge to the chain of bays (Suisun, San Pablo, and San Francisco) deliver along with the water a quantity of fine detritus, consisting of mud and sand. Lodging on the bottom the detritus tends to shoal the bays, and combining with vegetation along the margins it tends to contract them. These tendencies are opposed by the slow subsidence of the land, and in the natural condition of the region there may have been an approximate balance between the opposed factors. If such a balance existed, it has been overthrown by the activities of the white man, which have so increased the detrital loads of the streams that the bays are now losing in depth and area.

The water of Sacramento and San Joaquin rivers reaches first Suisun Bay, then San Pablo and San Francisco bays, and then escapes through the Golden Gate to the ocean. The forward movement is not continuous but is reversed twice a day by the tides, with the result that many eddies are formed and the river water is gradually mingled with ocean water. The river water is also carried to all the remoter reaches of the bays. The sediment is widely spread within the bays, mingling with smaller quotas from minor streams. It is evident also that a part of it reaches the ocean, for in times of flood, while the rivers are turbid and opaque, the outgoing tide through the Golden Gate shows a tinge of yellow.

Some information as to the extent and distribution of the recent deposits is afforded by the charts of the United States Coast and Geodetic Survey, which give soundings in all parts of the bays and at different dates. Complete surveys of Suisun Bay were made in 1867–68 and in 1887–88. A complete survey of San Pablo Bay was made in 1856, a small part was resurveyed in 1887, and the remainder was resurveyed in 1896. The northern part of San Francisco Bay was surveyed in 1855 and again in 1895–1901; its southern part in 1857–58 and in 1895–1899.

The interval of 20 years between the two surveys of Suisun Bay included 16 years of the most active hydraulic mining, together with the 4 years immediately following, when the temporary deposits of débris in the mountains presumably yielded their maximum quantity of waste. The interval between surveys of San Pablo and San Francisco bays, averaging for all parts about 41 years, covered the same time as the Suisun Bay interval, with the addition of an earlier decade during which hydraulic mining was advancing toward its maximum and a later decade during which the flow of mining débris was slowly diminishing.

Suisun Bay is relatively deep in the southern and middle parts, where it is traversed by a group of channels from the river mouths to Carquinez Strait. Among the channels are islands and a broad, irregular shoal, to part of which the name Middle Ground is given. At the north are two arms, broad and shallow, known as Grizzly Bay and Honker Bay. In the period of 20 years the shoals, having a total area of about 30 square miles, received an average deposit of 1.63 feet, the quantity of sediment being 51,000,000 cubic yards. The depth of fill was greatest in Honker Bay (2.17 feet) and least on the Middle Ground (1.25 feet). The channels are so irregular in form that it is not practicable to compute their changes with close approximation by means of the published soundings, but the general nature of their modifications is quite clear. Almost without exception they became narrower and deeper; almost without exception, also, the quantity of material added at the sides was notably greater than the quantity scoured out between, so that a net fill resulted. A rough estimate places the net fill of channels at 13,000,000 cubic yards, and makes the total deposit in the bay 64,000,000 cubic yards.

In Carquinez Strait, which connects Suisun and San Pablo bays, the bottom is irregular. The depth changes so greatly within short distances that the magnitude of each recorded sounding may be assumed to depend in part on an accident of location, and computations of average depth are subject to considerable uncertainty. Moreover, the surveys on which the earliest and latest maps are based were made at uneven dates, so that the intervals between dates contrasted in different parts of the maps range from 20 to 41 years. A comparison was made by dividing the area into 14 parts and studying each part separately, and it was found that the depth had apparently increased in 3 divisions and diminished in 11. The average apparent loss of depth in the 11 divisions was much greater than the average gain in the other 3. From the data thus obtained it was estimated that the total amount of material deposited in the strait from the beginning of hydraulic mining to the year 1890 was 40,000,000 cubic yards.

San Pablo Bay is traversed, from Carquinez Strait to the constriction separating it from San Francisco Bay, by a broad channel of simple contour. North of this is a great shoal occupying more than half the total area, and south of it are minor shoals. In the 41 years between surveys the channel was much reduced in width and was also reduced in depth. The filling along the middle line was small compared to the marginal filling. The great northern shoal received a large deposit, and the eastern division of the southern shoal an important though small deposit; but the western division of the southern shoal suffered a loss. To give quantitative expression to some of these facts the computations were made by divisions, the channel being arbitrarily limited by the position of the 3-fathom contour in 1856, and the northern shoal being separated into two parts, distinguished by different dates of resurvey. The data are exhibited in Table 3. It is worthy of note also that the eastern part of the northern shoal received a much heavier deposit than the western part.

TABLE 3.—*Data on sedimentary deposits in San Pablo Bay between the survey of 1856 and later surveys.*

Part of bay.	Period (years).	Area (square miles).	Depth of deposit (feet).	Volume of deposit (million cubic yards).
Channel	42	29.4	4.86	147.2
North part of north shoal	31	8.4	2.11	18.3
Main part of north shoal	41	60.9	2.97	186.3
Southeast shoal	42	7.3	2.84	21.4
Southwest shoal	42	7.2	−1.25	− 9.3
Means and totals	41	113.2	[a] 3.13	[a] 366.0

[a] The mean depth and total volume of the deposits are adjusted to the mean period of 41 years.

San Francisco Bay is divided by a moderate constriction at Goat Island into a northern third and a southern two-thirds. The northern division is traversed by the Sierra waters on their way to the sea. The southern receives drainage from valley plains and coastal hills. The deposits in the southern division must be derived chiefly from soil waste, but they may include also a small tribute of mining débris, for the tidal currents tend to mingle the waters of the two divisions, and the strong day winds of summer promote the mingling by driving the surface waters southward.

Table 4 contains estimates of the mean depth of deposits not only for the entire bay but for certain subdivisions. It fails to include, however, any estimate for Raccoon Strait or for deep-water tracts south and west of Angel Island. In those regions the bed is so uneven that soundings made at different dates and at slightly different places are not comparable. The omission is thought to be unimportant, because the currents there are so strong that the formation of deposits is not probable.

TABLE 4.—*Data on sedimentary deposits in San Francisco Bay between the survey of 1855–1858 and the survey of 1895–1901.*

Part of bay.	Period (years).	Area (square miles).	Depth of deposit (feet).	Volume of deposit (million cubic yards).
Channels:				
North of Goat Island	43	36	2.7	100
Goat Island to San Bruno Point	41	36	−1.8	− 67
San Bruno Point to Dumbarton Point	40	15	1.9	29
Shoals:				
North of Goat Island	43	37	1.0	38
Goat Island to San Bruno Point	41	53	.5	27
South of San Bruno Point	40	95	.7	69
Means and totals	41	272	.70	196

In two of the tracts separately recorded in the tables there is indication of negative deposition—that is, the charts show for those tracts increase of depth of water instead of decrease. One tract is a shoal in San Pablo Bay lying south of the channel and east of Pinole Point; the other is the deeper water south of Goat Island. For each tract the mean increase in depth is more than 1 foot. There are at least three possible modes of explaining these exceptional indications—by local scouring of the bottom, by local subsidence, and by errors in the charting. As to the first-mentioned possibility, the shifting of deposits on the beds of channels is a common occurrence, but the scouring of muddy shoals is less common. Usually such a shoal presents at its surface a layer of soft mud resting on firm tenacious clay, the one being easily disturbed and the other opposing a strong resistance to current action. Ordinarily the mobile layer is thin, and for this reason the scouring of a foot or more from the general surface of one of the lateral shoals is improbable.

The evidence adduced in Chapter II leads to the belief that the general region is affected by slow subsidence and that some changes are more or less localized. The two tracts under consideration both lie in the district west of the Haywards fault, where prehistoric subsidence has been most pronounced. The hypothesis of present subsidence is therefore worthy of consideration, but neither of the two localities affords corroborative evidence. If subsidence had occurred in the tract between Pinole Point and San Pablo Point the level of the adjacent marsh would have been lowered and its margin would have retreated landward; but instead of that its margin was somewhat advanced so as to encroach on the open water of San Pablo Bay. If subsidence had affected the channel between Goat Island and San Bruno Point it presumably would have affected also the adjacent shoals, but the shoals were found to stand higher at the time of the second survey.

As to the possibility that the exceptional indications arise from errors of survey it is safe to say that the later survey is not at fault Its methods, which are fully recorded in the archives of the Coast and Geodetic Survey, were thorough and adequate. The records of the earlier work are less complete and leave doubt as to some matters of method. A comparative study of earlier and later charts, undertaken with reference to encroachments on the tidal prism (see pp. 86–88), revealed discrepancies which may be significant. In localities where a tidal marsh adjoins a shoal of gentle slope one would expect the high-water line (represented by the marsh margin) and the low-water line to advance or recede together, whether their positions are modified by deposition, by scour, or by subsidence. There are three such localities near the junction of San Pablo and San Francisco bays, one just east of San Pablo Point, the second north of San Quentin Point, and the third south of San Quentin Point. In each locality the recorded change in the high-water line between 1855–56 and 1899–1901 has been slight, but the recorded change in the low-water line has been great. If it is assumed that the actual change in the position of the low-water line was small, and that the line is correctly placed on the later charts, its position as given on the earlier charts is on the average nearly half a mile too far out. This is such a discrepancy as would be occasioned if the "plane of reference" for the earlier soundings were 1.5 to 2.0 feet lower than the plane of reference for the later soundings. Planes of reference are determined by the discussion of tidal observations, but the records discovered fail to show what observations were used for the reduction of soundings in these localities in 1855 and 1856. Negative evidence indicates that the plane of reference and tidal corrections in 1855 were based on tidal observations at Fort Point, and the Fort Point plane of reference used in 1855 was 1.0 foot too low. In computing the averages assembled in Table 4 I have applied a correction for this recognized error.

Because the Coast and Geodetic Survey charts are prepared for the use of navigators, and because an overestimate of depth involves danger to vessels, the general principle is recognized that such errors as affect the charted soundings should be on the side of safety. The application of this principle has affected observations of depth and their reduction and also the selection of "characteristic" soundings for the charts and has been embodied in rules for the rejection of fractions, etc. The result is, first, that the charted depths are on the average less than the actual depths and, second, that the average difference between the charted and actual depths is greater for rough surveying than for refined surveying. As the earlier work was relatively rough and the later was refined, the charted depths are likely to be less on the old charts than on the new in localities where the actual depth was unchanged.

In view of these considerations I think it probable that the indication of increased depth on the shoal west of Pinole Point is due to error connected with planes of reference and possible that the apparent increase of depth south of Goat Island is due also to some difference in method between earlier and later surveys. If this opinion is correct it follows that other results based on surveys of the same dates are questionable and that generalizations from them must be regarded as of low precision. This qualification applies to the results for the northern half of San Francisco Bay, where the earlier soundings were made in 1855, and to the results for the whole of San Pablo Bay, where the earlier surveys were made in the first half of the year 1856. For these dates there is no record of tide stations in close association with the field work, but there was a permanent station at Fort Point. The southern part of San Francisco Bay was surveyed in 1857–58, and in connection with that work the tide observations at Fort Point were supplemented by observations at local stations. The first comprehensive survey of Suisun Bay was made 10 years later and had the advantage of progress in the development of methods. Not only were there local tide stations, but provision for the stability of the plane of reference was made by connecting some of the tide gages with bench marks. So far as I am able to judge, the estimates of deposition in Suisun Bay are well founded, and the estimates for the southern part of San Francisco Bay rank next in credibility.

No attempt is made to improve the estimates by applying corrections for the inferred inaccuracy of the plane of reference; the general averages may have been affected by compensatory inaccuracies in the planes used for other tracts. On the other hand, the least trusted estimates of average deposition are not discarded, because there is independent evidence accordant with their general tenor.

A corroborative fact is found in the contraction of the channel through San Pablo Bay, which has been brought about by the extension of the banks or shoals that border it. The deposits involved in that extension have in some places a recorded depth of 8 feet and over considerable areas a recorded depth of 5 feet; and these quantities are much too large to be charged to errors of survey.

Other corroboration is found when the estimates for the three bays are compared. Limiting attention to the deposits on shoals, and expanding the Suisun estimate, which is based on surveys only 20 years apart, so as to make it properly comparable with the San Pablo and San Francisco estimates, I obtain:

Estimates of average deposition on shoals in a period of 41 years.

	Feet.
Suisun Bay	3.3
San Pablo Bay	2.5
San Francisco Bay	.7

The general aspect of this sequence, which places the heaviest deposit in the bay that is nearest the river mouths and the lightest in the bay that is most remote, is such as might have been anticipated, but my first impression in making the comparison was that a greater difference should be expected between the first and second terms and a less difference between the second and third. There is, however, a modifying condition of which account should be taken. The material deposited on the shoals is fine mud that is brought by the rivers in suspension. Deposition is determined in part by the slackening of current as the muddy water enters a bay and in part by flocculation as it is mingled with salt water. Deposition from slackening would be much heavier in the first settling reservoir than in the second, but deposition from flocculation would begin wherever the salt water was met. At low stages of the rivers the principal meeting occurs in Suisun Bay, but at low stages there is little mud in suspension. In times of great flood, when the largest load of mud is brought down, the river current dominates over tidal currents in Suisun Bay, and the principal meeting with brine takes place in the larger water body beyond Carquinez Strait. (See Chapter IX.) When account is taken of this factor there appears no improbability in the relative magnitudes of the estimates of deposition for Suisun and San Pablo bays.

If the figures are taken at their face value it appears that heavy deposits have been made in Suisun and San Pablo bays and the connecting strait, and a moderate deposit in San Francisco Bay. These deposits have been caused primarily by the surcharging of the valley rivers by mining débris and the detritus contributed by other industries, and secondarily by the outwash of soil waste from the country immediately surrounding the bays.

As the periods covered by the comparison of charts do not in any case represent the entire period of augmented detrital load, considerable allowances are necessary in order to pass from the measured volume of deposit to the total volume accrued since the beginning of

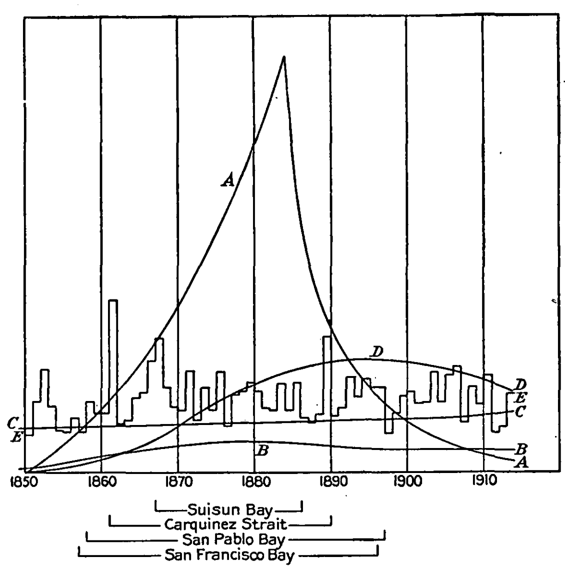


FIGURE 5.—Graphic statement of factors controlling estimation of deposition in bays and strait for periods not covered by measurements. The periods covered by measurement are indicated for the several units. *A*, Output of mining débris; *B*, soil waste; *C*, percentage of fine débris not deposited on inundated lands; *D*, delivery of débris to bays; *E*, relative precipitation.

placer mining in the Sierra. In estimating these allowances account has been taken of variation in the activities which have contributed débris to the streams, of variation in the transporting power of the streams, and of variation in certain conditions that have tended to retard or prevent the delivery of débris in the bays. As most of these factors are to be discussed in following chapters they will be only briefly considered here.

The output of mining débris increased in geometric ratio until the year 1884, when it was suddenly checked, and since that time it has diminished, at first rapidly and then slowly. These facts are expressed in curve *A* of figure 5.

The waste of the soil by rains, which under natural conditions was slow, has been greatly hastened by agriculture, by grazing, and by traffic over roads and trails. Its supposed history of variation is expressed by curve *B*.

The débris brought to the bays is dominantly fine. Fine débris is also deposited on inundated lands, including the lateral basins of the Sacramento Valley, the delta marshes, and marshes bordering the bays. Therefore the bays receive only a fraction of the entire suspended load of the streams. The fraction has been varied by the construction of levees, the direct effect of which is to reduce the inundated area. In the Sacramento Valley the protection of tracts from inundation has raised the flood plane, and this has caused floods to spread over other tracts, so that the construction of levees has indirectly enlarged the inundated area. Clogging of stream channels by mining débris has also tended to increase the inundated area. The supposed history of the variation of the percentage of the fine débris carried to the bays is expressed by curve *C*.

Up to and somewhat beyond the epoch of most active hydraulic mining a part of the mining débris was temporarily deposited along the lines of stream conveyance, and the stores thus created were afterward drawn upon. The general effect of such stores was to delay and equalize transmission, causing the crest of the great wave of mining débris to reach the bays some years after it left the mountains, and giving the wave a broader and flatter profile. With the addition of this consideration to those involved in curves *A*, *B*, and *C*, curve *D* was constructed to represent in general terms the history of the delivery of débris to the bays.

The remaining factor of recognized importance is the variation in the carrying power of the streams. The work of transportation has been performed chiefly by floods, and the efficiency of great floods is much higher than that of small floods. The greater floods of the rivers are associated with heavy rainfall, and it is during heavy rain that soil waste occurs. Because the records of floods are imperfect except for recent years, and because data as to heavy rains are not readily accessible, I have made use, instead, of precipitation records, which are published by the United States Weather Bureau in convenient form. Curve *E* in figure 5 shows for each rainy season

(July 1 to June 30) the relative precipitation (in rain and snow) from 1850 to 1914.

The transporting capacity of the streams depends largely on the concentration of rainfall into short periods, and the printed record tells little about such concentrations, but the relation of precipitation in the Sierra to cyclonic disturbances tends toward a sort of rhythmic concentration, and there is a rough correlation between seasonal floods and seasonal precipitation. In a general way transporting capacity varies with precipitation, and it varies in greater ratio than precipitation. On the basis of this law a set of factors of relative stream efficiency were derived from the data of relative precipitation, and these were multiplied, for the several annual seasons, by the ordinates of curve *D*. The products were then assumed to be proportional to the delivery of débris to the bays in the corresponding seasons.

To the results of the computations thus made a further qualification was applied, to take account of special conditions affecting channel portions of the bay system. Carquinez Strait is essentially a channel for the flow of waters, and its depth is determined automatically, being so adjusted that the traversing currents may be able to transport sand along the bed. It is probable that the strait received its principal deposit rather early in the history of the mining-débris invasion and that later additions have been small. A similar statement applies to the central portions of the channels through Suisun and San Pablo bays.

The estimates of the total deposition in the bays for the period 1849–1914 are contained in Table 5

TABLE 5.—*Estimates of the volumes of débris deposited in the San Francisco Bay system from 1849 to 1914, inclusive.*

Body of water.	Dates of surveys.	Volume of deposits between dates of survey.	Volume of deposits, 1849–1914.
		Cu. yds.	*Cu. yds.*
Suisun Bay	1867–1886	64,000,000	200,000,000
Carquinez Strait	1861–1890	40,000,000	50,000,000
San Pablo Bay	1857–1897	366,000,000	570,000,000
San Francisco Bay	1856–1896	196,000,000	326,000,000
Bay system			1,146,000,000

These estimates take no account of subsidence, although it is probable that the period to which they pertain witnessed subsidence, especially of the crustal block west of the Haywards fault. If it were possible to make the proper allowance the estimates would be somewhat larger.

The shoaling of the bays has been accompanied by a lessening of their areas. The salt marshes, whose margins are intimately associated with the lines of high tide, have steadily encroached on the muddy shoals, and the lines of low tide have as steadily encroached on the areas of continuous open water. Such encroachments diminish the tidal prism, on the magnitude of which depends the depth of entrance to the Golden Gate, and their relations to foreign commerce give them special importance, but it is convenient to defer their consideration until estimates have been made of the total volume of the mining débris.

Chapter VI.—QUANTITY AND DISTRIBUTION OF DETRITUS.

DATA TO BE DETERMINED.

Nearly all phases of the economic questions connected with the débris from hydraulic mining are concerned with quantities. It is desirable to know (1) how much detritus—gravel, sand, and clay—was excavated by the miners and started toward or down the streams; (2) how much detritus the streams received from other sources; (3) what is the present distribution of this material; and (4) what changes are in progress and toward what results do they tend. The present chapter will consider the first three of these subjects. With reference to each of them there is a certain amount of definite information, but this falls so far short of complete knowledge that the field remaining for conjecture is regrettably large. The lack of satisfactory data has been shown by the wide diversity in the earlier estimates, and the task of adding to a series of ill-supported and conflicting conjectures is not attractive. Nevertheless it is undertaken, first, because the contribution of a body of new measurements gives presumptive advantage to a new system of estimates, and second, because the importance of the question of quantities gives value to a demonstration of their order of magnitude, even where actual magnitudes may be only roughly approximated. I shall not hesitate, in the pages that follow, to base estimates on personal judgment when no better foundation is available.

QUANTITY OF MINING DÉBRIS.[1]

The belt of hydraulic mining in the Sierra Nevada traverses the drainage basins of a series of streams tributary to the Sacramento and the San Joaquin. On the tributaries of the San Joaquin the quantities of mining débris were relatively small—so small as to produce little or no effect on the navigability of the rivers. On Feather River proper the mining operations were more extensive but still small as compared to those on the Yuba, the Bear, and the American. Of the quantity of material excavated in the basins of those three rivers a number of estimates have been made, and the estimated amounts vary through a wide range. The latest estimate that makes use of first-hand data is given in the report of a board of Army engineers headed by Lieut. Col. W. H. H. Benyaurd.[2] The data were collected and discussed chiefly by F. C. Turner,[3] assistant engineer, and apply to the year 1890. For the present purpose this estimate is the most available, especially as it was made some years after the stoppage of general hydraulic mining, whereas a number of the earlier estimates were made during the progress of the mining. It constitutes part of the report of a detailed reconnaissance of the region of hydraulic mining, in which a large body of valuable data was accumulated. The method of making the estimate is not stated by Turner, but may be assumed to have been indicated in general terms in the following passage from the report of the board:

> The usual manner of estimating the amount of material moved is to determine the amount of water used, in miner's inches, and assign a duty to the inch. This, however, varies in different localities, in some places being as low as 2,000 and in others as high as 2,600 cubic feet in 24 hours. In the usual determination the quantity is taken at 2,230 cubic feet in that time. The duty depends upon the quantity of water used, the pressure, the character of the material washed, and the grade and size of the sluices; character of material and grade are the ruling elements. With heavy material the duty may be as low as 1.5 to 2 cubic yards, and with light material as high as 10 cubic yards per inch. Instances are quoted in the report of the State mineralogist for 1889 where, with increased grade of sluices (12 and 18 inch grades), the duty attained was 24 and 36 yards, respectively. The usual calculations are upon a basis of 3½ cubic yards. It will therefore be seen that great variations must exist in the estimates of amount of material that has already been mined out.

Impressed by the uncertainty of this mode of estimation, in which no engineer appears to have reposed great confidence, I undertook to check it by an independent estimate based on

[1] A part of this text has already been printed, with small verbal differences, as pp. 18-21 of U. S. Geol. Survey Prof. Paper 73, 1911, The Tertiary gravels of the Sierra Nevada of California, by Waldemar Lindgren.

[2] Chief Eng. U. S. Army Ann. Rept. for 1891, pp. 2996-3118.

[3] Idem, pp. 3041-3087.

an entirely different procedure, namely, the measurement of the cubic contents of the cavities produced by the excavation. This work was carried on in the spring and autumn of 1908, and after a few preliminary experiments the following method was adopted and followed:

The surveying instruments were a plane table and a stadia rod. With these a traverse was run through the bottom of each cavity or along its edge, and where the area was large a traverse circuit was completed. From the stations of the traverse numerous points were determined by stadia and others by angulation, the position and altitude of each being fixed. A complete sketch was made of the rim or outer margin of the excavation, and for a short distance outside the rim the ground was contoured. The scale adopted was 200 feet to 1 inch, and the contour interval was 20 feet. After the completion of the field work the contours of the ground previous to the excavation were restored by estimate, use being made of the determined contours outside the rim and of the determined courses of drainage lines outside the rim. With the aid of these restored contours and the determined points within the area of excavation a series of cross sections were constructed, and from these the volume of the excavation was computed. Some of the features of the excavated cavities are illustrated by Plate X.

The precision of this method can not be definitely stated, as there were no absolute checks on the accuracy of the restored contours; and the data controlling the restoration varied in cogency through a considerable range. In the opinion of the writer, who was also the surveyor, the general accuracy is such that the grand totals are true within 10 per cent, although many individual measurements have a lower precision.

The work was not carried on through the entire hydraulic district, but comparison with the Turner estimate indicates that it covered about four-fifths of the excavation in the basin of Yuba River and three-sevenths of the total excavation of Yuba, Bear, and American rivers. The table on page 40 gives the results in some detail and also compares them, so far as practicable, with the items of the Turner estimate. The difference in method of estimate led to a difference in the classification of the excavations, so that the comparison can not be refined, but it serves nevertheless as an effective check on the Turner estimate.

Examination of the table shows that a few of the earlier estimates are higher than the later, but the majority fall below and the new general totals exceed the earlier by 51 per cent. The difference is in part explained by the fact that some mining took place in the interval between 1890 and 1908. A number of mines were worked for short periods or in a small way under permits from the Débris Commission, and there was some surreptitious work without permits. During the surveys in 1908 it was easy to see that certain parts of the excavations, on which a young forest growth had sprung up, were of early date, and that other parts, still bare of vegetation, were relatively recent; but it was not practicable either to infer dates with approximate accuracy or to estimate separately the more recent work. It is believed, however, that the work subsequent to 1890 can account for only a small part of the discrepancy between the two estimates, and that the greater part of the 51 per cent of difference inheres in the methods of estimation and the data employed. Assuming the substantial accuracy of the later estimate, and assuming further that the ratio of difference derived from the totals of the table may be applied as a correction to the other parts of the Turner estimate, I have deduced revised estimates for the total hydraulic excavation in the combined Yuba, Bear, and American basins. Turner's summary is as follows:[1]

Material excavated by hydraulic mining in the basin of—	Cubic yards.
Yuba River	452, 690, 000
Bear River	234, 650, 000
American River	170, 330, 000
	857, 670, 000

The application of the ratio 1.51 to these quantities yields for the Yuba basin 684,000,000 cubic yards, for the Bear basin 354,000,000 yards, and for the American basin 257,000,000 yards. The values thus derived have been adopted for the Yuba and American basins but have not proved satisfactory for the Bear basin. The quantity of mining débris accumulated in the canyons of the Bear and its tributaries has twice been estimated with more

[1] Chief Eng. U. S. Army Ann. Rept. for 1891, pt. 5, p. 3080.

care than was bestowed on similar deposits along the other rivers, and something is known also of the volume of the river's piedmont deposit. (See p. 48.) When these estimates are considered in connection with the small discharge of the Bear and other factors affecting the ratio of the local arrest of débris to the total output of the mines, good reason is found for regarding the estimate of 354,000,000 cubic yards as excessive. As all the quantities involved in the discrepancy were subject to considerable uncertainty, the adjustment was of the nature of a compromise, and the correction assigned to the estimate of output of débris was a deduction of 100,000,000 cubic yards, reducing the estimate to 254,000,000 cubic yards.

The only other stream to receive mining débris and convey it eventually to the Sacramento is the main branch of the Feather. Turner's estimates do not include the mines of its basin, and my own observations covered but a small area. W. H. Hall,[1] in 1880, estimated the "water used and material washed out per annum" for the several river basins of the Sierra from the American northward. For the basin of the Feather the estimate of material washed is 12,687,500 cubic yards, and the sum of the estimates for the Yuba, Bear, and American is 36,480,500 cubic yards. Lieut. Col. Mendell[2] makes a similar estimate for the

TABLE 6.—*Volume of hydraulic excavation in part of the Yuba River basin as estimated by G. K. Gilbert in 1908 and by F. C. Turner in 1889–90.*

[Excavation expressed in thousands of cubic yards.]

District, mine, or locality and excavation therein.		Total excavation.	
1908	1889–90	1908	1889–90
Camptonville (7,100), Youngs Hill (7,500), Galena Hill (4,400), Weeds Point (3,000).	Willow Creek and Camptonville (5,800+1,500).	22,000	7,300
Indian Hill	Indian Hill	7,800	4,500
Moores Flat (21,000), Orleans Flat (3,400), Snow Point (3,900).	Moores Flat, Orleans Flat, and Snow Point	28,300	26,000
Woolsey Flat	Woolsey Flat	20,700	4,100
Badger Hill and English Co	Badger Hill and Cherokee (10,000), English Co. (7,000).	22,600	17,000
North Bloomfield (main pit, 64,400; minor pits, 13,600).	North Bloomfield (29,000) Last Chance, Porter, etc. (3,000).	78,000	32,000
North Columbia (main pit, 89,500); Howleys, Ohio, Neversweat, etc. (2,560).	Columbia Hill (20,000+20,000)	92,060	40,000
Union Gravel	Union Gravel	9,100	10,000
Yuba (Grizzly)	Grizzly Hill	1,400	1,000
Paterson and vicinity	Paterson claims (5,000), Montezuma Hill (500)	7,800	5,500
North San Juan (25,350), Manzanita and American (47,900), Bed Rock (10,050), Buck Eye (12,650).	North San Juan and part American (20,000+500), Sweetland Creek, Birchville, Manzanita and part American (60,000).	95,950	80,500
Esperance (and Kinney)	Esperance	3,500	1,500
French Corral	French Corral	16,050	31,000
Omega	Omega	22,700	12,000
Alpha and vicinity	Alpha (5,000), Place, Merrill, etc	9,000	7,000
Sailor Flat and Blue Tent	Sailor Flat and Blue Tent	46,200	15,000
Cement Hill (?)	Nevada City, Cement Hill	1,800	2,550
Rough and Ready, Randolph Hill and vicinity	Rough and Ready, Randolph Hill	910	3,000
Nevada City (Manzanita or Sugar Loaf, 6,000; Hirschman, etc., 6,400).	Nevada City, Sugar Loaf	12,400	10,000
Murchies, McCutcheon, Charonnat, etc	Murchies, Gold Flat, etc	2,100	500
Scotts Flat	Scotts Flat	18,600	12,000
Smartsville and Timbuctoo (24,460), Mooney Flat (3,800).	Smartsville, Timbuctoo, and Mooney Flat	28,260	44,800
Sicard Flat	Sicard Flat	3,030	1,700
Depot Hill	No record	3,900	
Railroad Hill	do	2,700	
Two miles west of Parks Bar Bridge	do	320	
Dry Creek	do	40	
Two miles west of Grass Valley	do	30	
		557,250	368,950
Percentage		151	100

[1] California State Eng. Rept. for 1880, pp. 23–24.
[2] Chief Eng. U. S. Army Ann. Rept. for 1881, pp. 2486–2487, 2494–2501.

year 1880 in which the corresponding figures are 4,407,770 and 31,070,094. Mendell also gives with full detail the assessors' returns of the water used in mining. Hall and Mendell both qualify their estimates—Hall because his data were incomplete and Mendell because the method was unsatisfactory. In 1881 the canyons and mining regions of the Feather and the Yuba were inspected by Marsden Manson, and his report[1] tends to discredit the estimates based on assessors' returns. He found that much of the water ascribed to hydraulic mining was actually used in drifting and quartz mining and in other ways not involving the handling of large quantities of earth.

Disregarding for the moment Manson's implied criticism, accepting the estimates of Hall and Mendell, and assuming further that the total output of débris for the several basins for the whole period of hydraulic mining was proportional to the annual output, I have made two computations of the total output of the Feather. The figures quoted from Hall's table give 366,200,000 cubic yards, and the figures from Mendell's table 186,600,000 cubic yards. The details reported by Manson and Turner, as well as data from other sources, indicate the probability that both these figures are excessive. On the other hand, a minimum estimate is suggested by the volume of the piedmont deposit of the Feather, which occupies the river bed between Oroville and Marysville. Hall estimated this, from surveys probably made in 1879, at 18,257,000 yards,[2] and the observations of Turner indicate that only moderate additions were made in the following decade. The suggested minimum is 40,000,000 cubic yards, and this might serve as a practical estimate, so far as conditions of the lower river are concerned; but it would probably not be coordinate with the estimates for the other basins, which aim to show the full extent of the exploitation of the auriferous deposits. According to Manson, most of the tailings from the greatest operations were lodged in a permanent way in the American Valley, an opening in the heart of the mountains. Between the limits 40,000,000 and 186,000,000 cubic yards, the value of 100,000,000 cubic yards is arbitrarily chosen. Adding the estimate for the Feather basin to that for the three basins farther south gives a total of 1,295,000,000 cubic yards as the output of the hydraulic mines on streams whose waters join the Sacramento.

With reference to problems connected with the flow of mining débris there is no occasion to discriminate between the tailings of the hydraulic mines and the waste from three other sources—ordinary placer mining, placer drifting, and quartz mining. All through the auriferous belt the initial mining was done with pick, shovel, and cradle, and only a small quantity of tailings resulted from the work of each miner, but the miners were an army. They attacked first the gravel bars of creeks and rivers and the associated low-lying alluvial terraces (see Pl. XI), and gradually extended their activities to the unconsolidated formations that sheathed or composed the hills. The material was worked over with the aid of water, the pebbles and boulders were left on the ground, and the finer particles were washed away, for the most part quickly reaching the river. So far as the deposits were stream bars, the fine stuff that floated off was soon afterward replaced by the streams, so that there was no permanent local loss of material, and there seems to be no occasion to take account of such washings in this connection. It was different, however, with the washings on the hillsides. The pits thus excavated still remain, and the material removed has been added to the detrital load of the streams. The cradle was soon supplemented by appliances that used water to better advantage, and the system of work in which excavation is accomplished by a powerful jet of water—the system that has appropriated as its title the comprehensive adjective hydraulic—was gradually developed. Where the hill deposits were deep the earlier work was superficial or marginal, and the rims of its shallow pits were effaced by the greater operations that followed. In this way a portion of the volume of pre-hydraulic work came to be included in the measurement of hydraulic pits and is thus covered by the revision of the Turner estimate. To complement that estimate allowance should be made only for the shallow excavations remaining outside the areas of the hydraulic work.

The data are vague. In traversing the Yuba mining region on various errands and especially in the search for outlying hydraulic pits hidden

[1] Chief Eng. U. S. Army Ann. Rept. for 1882, pp. 2604-2612.
[2] California State Eng. Rept. for 1880, p. 11.

in the forest, I often came across shallow workings. At half a dozen localities the evidence of placer work was almost continuously visible for a mile or more; at numerous localities it was seen for only a few rods. Usually the view was obstructed by forest or chaparral, so that casual observation gave little information as to areal extent. An arbitrary estimate of 10 square miles for the entire Yuba area includes not only tracts that were imperfectly seen but many other tracts assumed to be distributed through the hillsides of the basin. It is estimated that earth was removed from this area to an average depth of 3 feet; and these assumed dimensions give as the estimated total volume of the débris 30,000,000 cubic yards. As the basins of the Bear and American together nearly equaled that of the Yuba in hydraulic output, the same volume of placer débris is ascribed to them.

The large expense of drifting, as compared to surface washing, tends to limit the extent of operations, but its waste is of the same character as that from hydraulic washings except that it includes more boulders. The mining of quartz veins, however, produces much waste of a type unsuited for transportation unless it is dumped directly into the streams. Ordinarily the mine refuse is so coarse and angular that it lies permanently where it is originally thrown; and only the ore that is milled goes to swell the load of the streams. An estimate of the débris from drifting might therefore be based on the volume of the mine openings, and an estimate for quartz mining on the work of the stamp mills. The statistics of the stamp mills, though irregular and discontinuous, give the amount of ore crushed for a number of individual years and yield, with generous interpolation, an estimate of 35,000,000 cubic yards for the whole mining belt from the Feather to the Tuolumne. To this I add 15,000,000 yards as an allowance for unmilled mine waste dumped directly into streams or otherwise finding its way to them, thus raising the estimate for quartz-mining débris to 50,000,000 yards. There are practically no statistics of the output of débris from drifting, and the allowance of 30,000,000 cubic yards which I make is a mere guess. It does not include the output for the basin of the Feather, which was practically covered in estimating the débris from hydraulic mining.

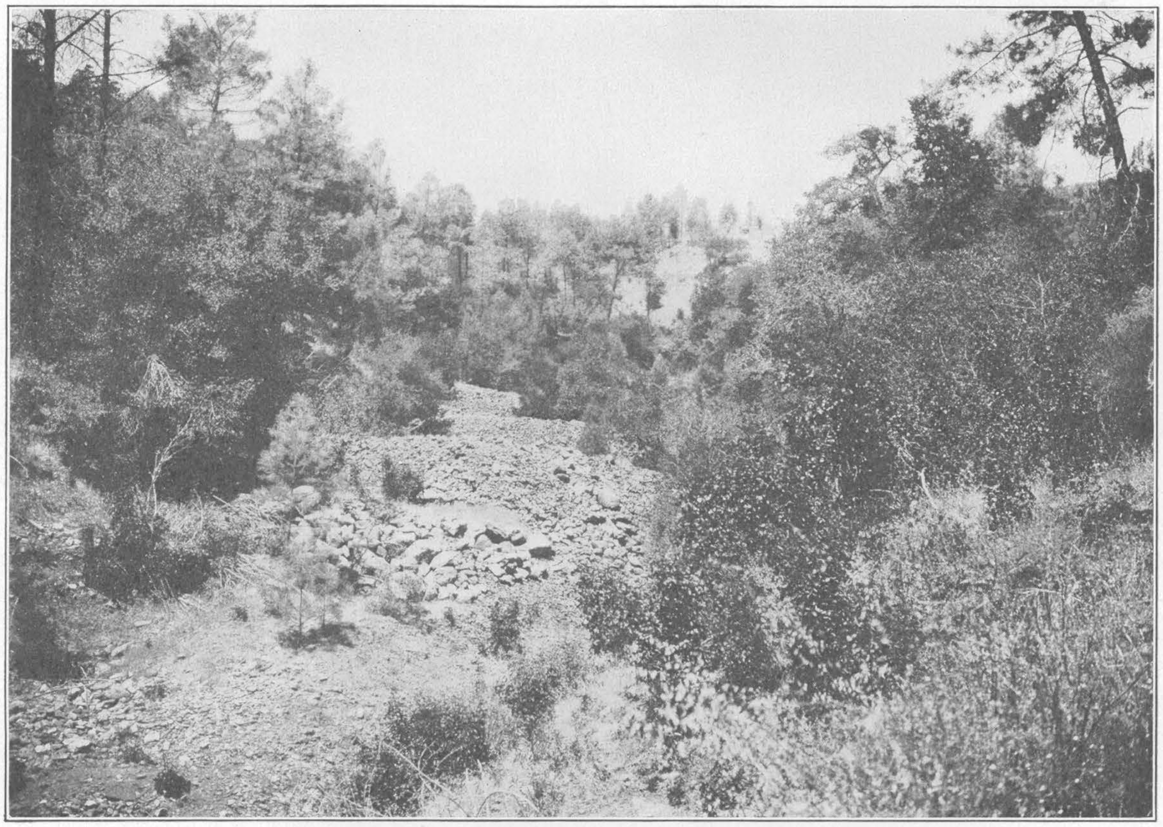
Two other bodies of débris remain to be considered. A few of the hydraulic mines of the Sierra are on streams which belong to the general hydrographic basin of the Sacramento but do not send their detrital loads either directly or in any considerable share to that river, because they discharge directly to one or another of the lateral overflow basins of the Sacramento Valley. Their débris belongs to the general total for the mining industry of the Sacramento River basin but has little if any connection with the "débris problem." A greater number of mines are associated with rivers south of the American that are not tributary to the Sacramento but send their waters either to the San Joaquin or to the delta plexus east of the mouths of the Sacramento and San Joaquin. The débris from these rivers has no recognized connection with the problem of the economic treatment of the Sacramento but may affect economic problems in the tidal waters of the bays.

The only important group of mines sending débris to the lateral basins of the Sacramento Valley are on Table Mountain Creek, north of Feather River, and their output is estimated at 25,000,000 cubic yards. An allowance of 5,000,000 cubic yards is added for mines on Butte Creek, north of Table Mountain, and creeks between Bear and American rivers.

The hydraulic mines south of the American, discharging tailings to Cosumnes, Mokelumne, Calaveras, Stanislaus, and Tuolumne rivers and to a group of creeks between the Cosumnes and Mokelumne, were the subject of a critical examination by Lieut. A. H. Payson [1] in 1880. He reported that profitable hydraulicking was limited by natural conditions in much of the region, that local storage of tailings was practicable at many points, that the damage to farming lands, although noteworthy, was far less than in the Sacramento River basin, and that the injury to navigation was very small. He made a detailed estimate of the annual output of the mines, placing the total at 7,352,465 cubic yards. In 1889 or 1890 C. L. Higgins [2] examined the same district for the Benyaurd commission. He found that only minor changes had taken place in the condition of farming lands affected by the débris,

[1] Chief Eng. U. S. Army Ann. Rept. for 1881, pp. 2501–2514; idem for 1882, pp. 2584–2604.

[2] Idem for 1891, pp. 3114–3118.



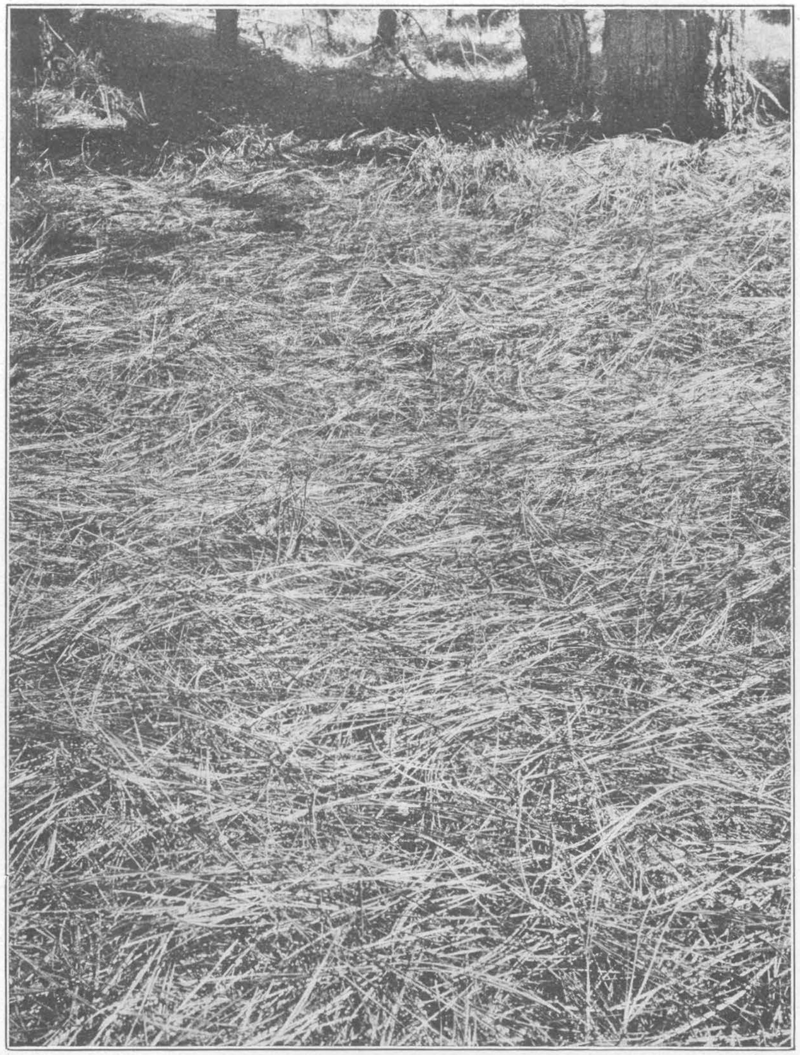
A. WORKED-OVER DEPOSITS IN THE BED OF A RAVINE.

The coarse gravel was stacked on the ground, and the finer stuff washed to a neighboring river.

B. OLD "DIGGINGS" ON A GENTLE SLOPE OR "FLAT."

The fertile soil was washed away, and reforestation is a slow process.

EXHAUSTED PLACER DIGGINGS.

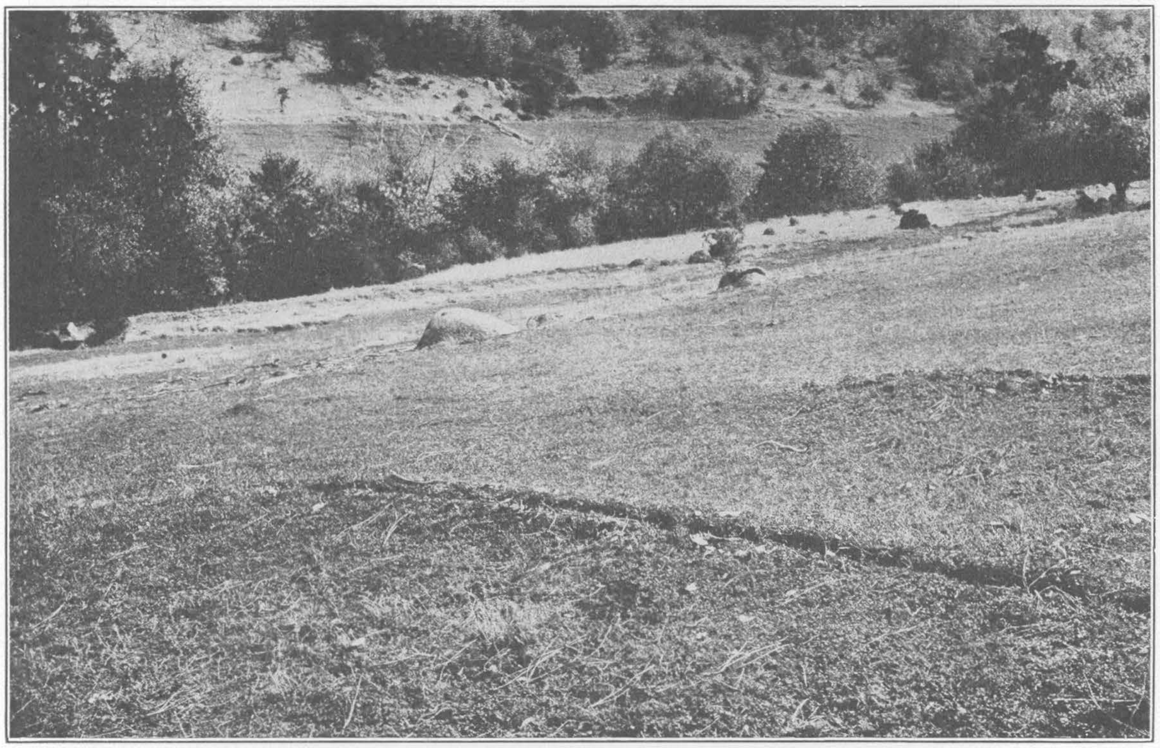


A. LITTER OF PINE NEEDLES IN A FOREST.

B. LITTER OF MANZANITA LEAVES IN A THICKET OF BUSHES.

NATURAL PROTECTION AGAINST SOIL WASTE.

The blanket of dead leaves with which trees and bushes cover the ground is usually more efficient than the living foliage, and always more efficient than the roots, in protecting the soil from waste. The movement of soil is initiated by the blows of raindrops, and the leaves receive the blows. It is greatly promoted by the concentration of the rain sheet into rills, and the leaf blanket obstructs the formation of rills. Compare with Plates XIII and XIV.



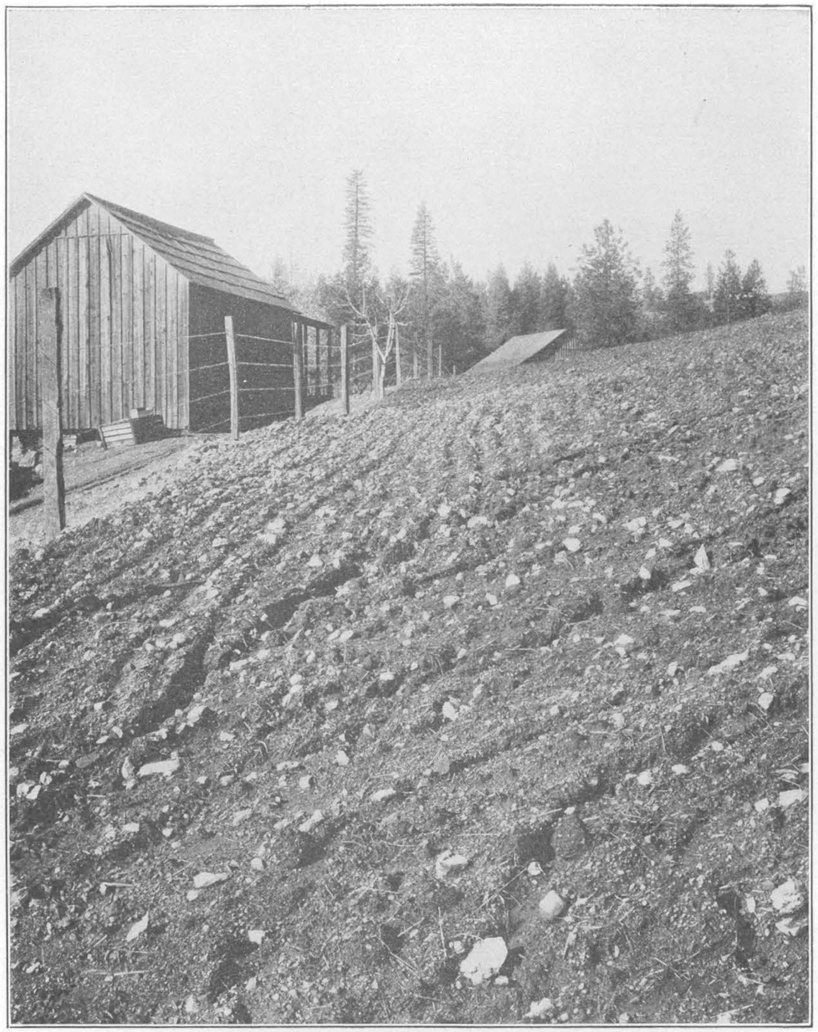
A. CONSERVATION OF SOIL BY A CLOSE GROWTH OF GRASS.

This sloping meadow is irrigated by a ditch that follows its upper edge. Short lateral ditches descend the slope at intervals of 20 feet. The ends of two laterals appear in the view. Sometimes the water of the ditch carries mud, and at such times the grass acts as a strainer, separating and arresting the mud. A double ridge has been created by the deposit along the line of each lateral. The grass also prevents the gathering of the water into rills. Receiving the water in a system of artificial rills, the grass causes it to spread uniformly over the land. Compare with Plate XIV.

B. THE ATTACK OF RAIN ON BARE GROUND.

Because the direction of rain is usually downward the erosive effect of a single shower is not easily discriminated from the effects of previous rains. For this reason the power of rain as an agent in soil waste is apt to be underestimated. In this instance the raindrops were carried by a strong wind that swept obliquely up the slope from right to left. All previous rain records were obliterated and a series of furrows having the trend of this particular rain were carved. The exact duration of the rain is not known, but the storm of which it was a feature lasted only a few hours.

SOIL PROTECTION AND THE ATTACK BY RAIN.



A. A FIELD ON THE WESTERN SLOPE OF THE SIERRA.

A rainstorm lasting three days drenched the field after it had been plowed and harrowed. In flowing off the water gathered into rills, which washed away soil, leaving such gullies as appear in the foreground. The water also carried fine soil from the general surface, but the effect of this removal is shown in the picture only by the cleanness of the stones. The soil thus wasting under artificial conditions was developed under the protection afforded by a pine forest. Compare Plate XIII, *A*.

B. A FIELD ON AN EASTERN SLOPE OF THE BERKELEY HILLS.

The records of cultivation and of rain are lacking, but it is evident that the little gullies were excavated by rain-made rills after the harrowing. In its natural condition the slope, despite its steepness, was protected from soil waste by grass. The hill consists chiefly of rock, and the soil created under the vegetal covering by the decay of the rock is now in process of removal.

SOIL WASTE DETERMINED BY AGRICULTURE.

and he estimated the annual output of the hydraulic mines at 4,348,600 cubic yards. One of these estimates preceded and the other followed the great restriction of mining by injunctions, but the restriction appears to have been much less in the southern field than in the northern. Taking these estimates at their face value and applying them, with what appears reasonable qualification, to the whole period of placer and hydraulic mining, I deduce 230,000,000 cubic yards as an estimate of the entire body of earth moved from its original place to the present time in the region from Mokelumne River to Tuolumne River, inclusive.

The estimates brought together in Table 7 cover a period closing with the year 1909, which was the last year of my personal observation in the region of the mines. No definite data are available for the five years that have followed, but it is believed that a proper allowance would increase the totals by less than 10,000,000 and possibly by less than 5,000,000 cubic yards.

TABLE 7.—*Summary of mining débris, 1849–1909.*

	Million cubic yards.
From hydraulic mining in basin of—	
Upper Feather River	100
Yuba River	684
Bear River	254
American River	257
Streams tributary to lateral basins of Sacramento River	30
Mokelumne River to Tuolumne River, inclusive	230
From ordinary placer mining	60
From quartz mining (one-fourth in Sacramento basin)	50
From drifting (three-fourths in Sacramento basin)	30
Total mining débris:	
From hydraulic mining	1,555
From all mining tributary to Sacramento River	1,390
From all mining tributary to Suisun Bay	1,665

To most laymen, and possibly to some engineers not concerned with great movements of earth, the term 1,000,000 cubic yards conveys no definite meaning. It helps us to a conception of the actual magnitude of the hydraulic-mining operations of the Sierra to know that the volume of earth thus moved was nearly eight times as great as the volume moved in making the Panama Canal.

QUANTITY OF DÉBRIS FROM SOURCES OTHER THAN MINING.

Besides mining, the chief sources of detritus in the rivers are agriculture, roads and trails, grazing, and the natural wash of the soil. A similar influence is commonly ascribed to deforestation, and in some regions this is a cause of much soil waste, but within the field of my personal study of the Sierra deforestation without agriculture or grazing is a negligible factor. The protective efficiency of bushes is there practically the same as that of trees, and by their growth a deforested surface is quickly reclothed and effectually shielded. (See Pl. XII.)

In attempting to evaluate the non-mining detritus I have made a special study of a single district, the drainage basin of Yuba River, and then extended the results to other districts by aid of inferences based on evident differences in local conditions.

AGRICULTURE.

The farmer destroys all vegetation except that which he sows or plants, and the only protection against rain which his soil receives is that afforded by the plants he cultivates. (See Pls. XIII and XIV.) Many of these are set so far apart that their protection is slight. Some constitute a good shield during part of the year but leave the ground bare for the remainder. Only a few give shelter comparable with that of a natural growth. The rains consequently wash great quantities of earth from farming lands, and the contrast between agricultural and natural conditions is strong. To realize it, one has only to compare during a moderate rainstorm the rills of muddy water that flow from a cultivated field with the clear rills from land in its natural condition. There are indeed methods of cultivation by means of which soil waste may be almost eliminated, but they are not yet extensively used in the Sacramento basin.

To learn the area of farming land in the mountain and foothill part of the Yuba River drainage basin, I made inquiry of the county assessors and learned that in 1908 it was about 50,000 acres. For this area I estimate an average loss of 2 inches. There are no statistical data for abandoned farms; I estimate their area at 15,000 acres, with an average loss from the surface of 4 inches. These estimates give for the tribute of the total waste from existing farms 13,000,000 cubic yards and from the abandoned farms 8,000,000 cubic yards, a total of 21,000,000 cubic yards. But not all of this waste has reached the streams; a portion has lodged in stable deposits on gentler slopes, especially on meadows; and an allowance of 3,000,000 cubic yards for these lodgments leaves 18,000,000 cubic yards as the estimate of the addition to the load of the streams. The period during which this addition has been made is the same as that to which the mining waste pertains.

ROADS.

In the foothill part of the Yuba River basin very few of the roads are so nearly level as to escape wash. In their grading and by their use the natural vegetation is destroyed, so that the surface is exposed to rains and running water. Moreover, the wheels and hoofs grind the soil, converting it to dust in summer and to mud in the rainy season, with the result that it is easily washed away. And the ruts and side drains concentrate flowing water that would otherwise be widely diffused. (See Pl. XV.) In many places the gullying of a road has so interfered with its use that a new track has been laid out at one side, and in some places a dozen or more of these tracks may be seen. Where a new track can not readily be made and the original course is repeatedly restored to a passable condition by repair, the road surface may be lowered year by year until the track comes to pass through a miniature canyon. Much the greater part of the material thus excavated finds its way to the streams, but there are two fractions which do not. Some of the dust rises into the air and is carried to neighboring land and, so far as it falls on chaparral or in forest, receives the same protection as the ground beneath. And there are side-hill roads systematically drained at points so near together that the outflowing mud-laden storm streams, being too feeble to carry the coarser parts of their loads to a distance, build stable deposits close by.

The roads outside the mountains are not included in the present estimate. Those in the higher parts of the mountain area are also omitted, because whatever detritus is washed from them is caught by the lakes which there interrupt the courses of the streams. In the intervening district of mountains and hills the mapped public roads have a total length of 920 miles. From these I estimate an average loss of 1 foot in depth over an average width of 10 feet, and I assume that 85 per cent of this reached the streams. The unmapped roads and private roads are estimated to have about the same aggregate length, and the aggregate loss from these is estimated to be one-fourth as great. There are also obsolete roads, the sites of which have been reoccupied by forests. Their extent is unknown, and there may be much error in the estimate that their aggregate tribute to the streams was one-fourth as great as that of the existing roads. These assumptions give for the mapped public roads 1,600,000 cubic yards, for the unmapped and private roads 400,000 cubic yards, for the obsolete roads 500,000 cubic yards, a total of 2,500,000 cubic yards.

TRAILS.

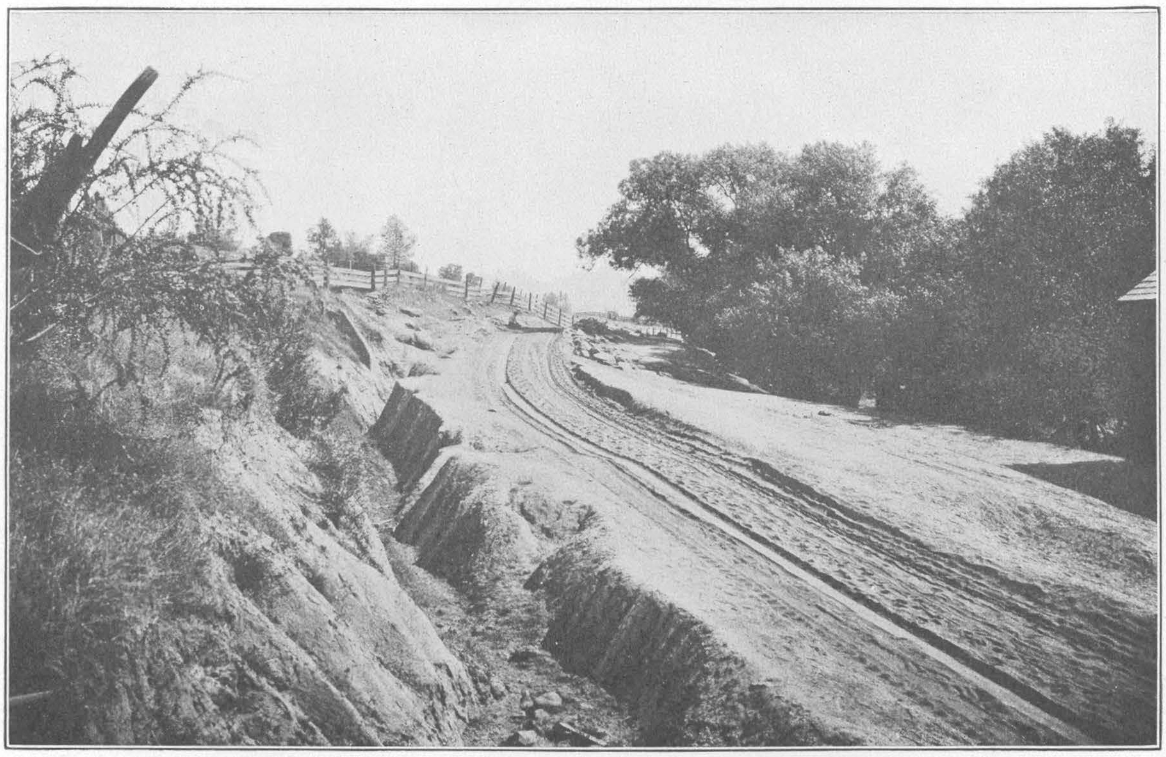
The trails of the country affect the débris output in precisely the same manner as the roads. Their use and their grading destroy the natural protection; they catch and concentrate the flow of water on the surface; they frequently become gullied so as to be difficult of passage, and new lines are opened at the side. (See Pl. XVI.) Their aggregate length in the Yuba River basin is greater than that of the roads, but their area is less, and here also account should be taken of those that are obsolete as well as of those in use. Their tribute to the Yuba is roughly estimated at 800,000 cubic yards.

GRAZING.

Ordinary grazing of the forest land and meadows of the Sierra—such grazing as is consistent with permanent occupation by horses and cattle—seems to have but a slight effect on the mineral outwash; and as all the land areas are or have been grazed it has not been found possible to discriminate outwash depending on grazing from the natural outwash. Therefore no estimate is made for it in this paragraph. Overgrazing, on the other hand, has a very notable effect on the outwash. (See Pls. XVII and XVIII.) Along the main lines of travel

A. A ROAD IN THE SIERRA AT AN ALTITUDE OF 2,000 FEET.

The sunken passage through which the road runs was eroded by storm waters. The road intercepts and guides the waters, and the traffic on it facilitates their work by preventing the accumulation of forest litter. The traffic usually breaks up the structure of the earth, converting a coherent body into sand or dust, which is easily washed away.



B. A SIDE-HILL ROAD IN THE FOOTHILLS OF THE SIERRA.

The ditch dug to intercept storm water from the hill and thus keep it from the wheel ruts has been enlarged by action of the water, and the earth removed from ditch and road has gone to a neighboring creek.

EROSION OCCASIONED BY ROADS.

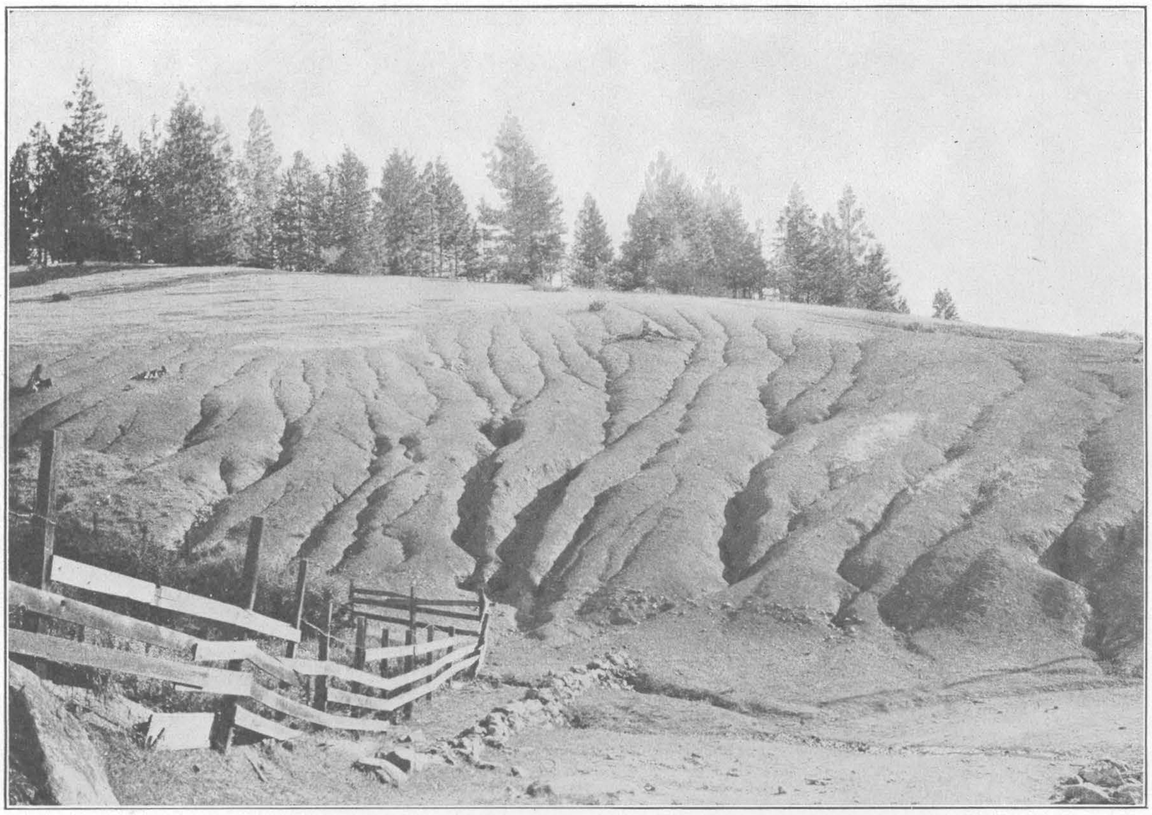
A. A CATTLE TRAIL IN THE SIERRA.

This trail, by intercepting storm water as it flowed down a gentle slope, created a strong rill that carved a channel through the thin soil cap. The cattle then avoided this line and made parallel trails at the side. The excavated soil was carried to a near-by river.

B. CATTLE TRAILS FOLLOWING THE CREST OF A GRASS-COVERED RIDGE AND DESCENDING AT ITS END.

Erosion by storm water is made possible by the killing of the grass and is promoted by concentration of the flow in certain trail grooves.

EROSION OCCASIONED BY TRAILS.



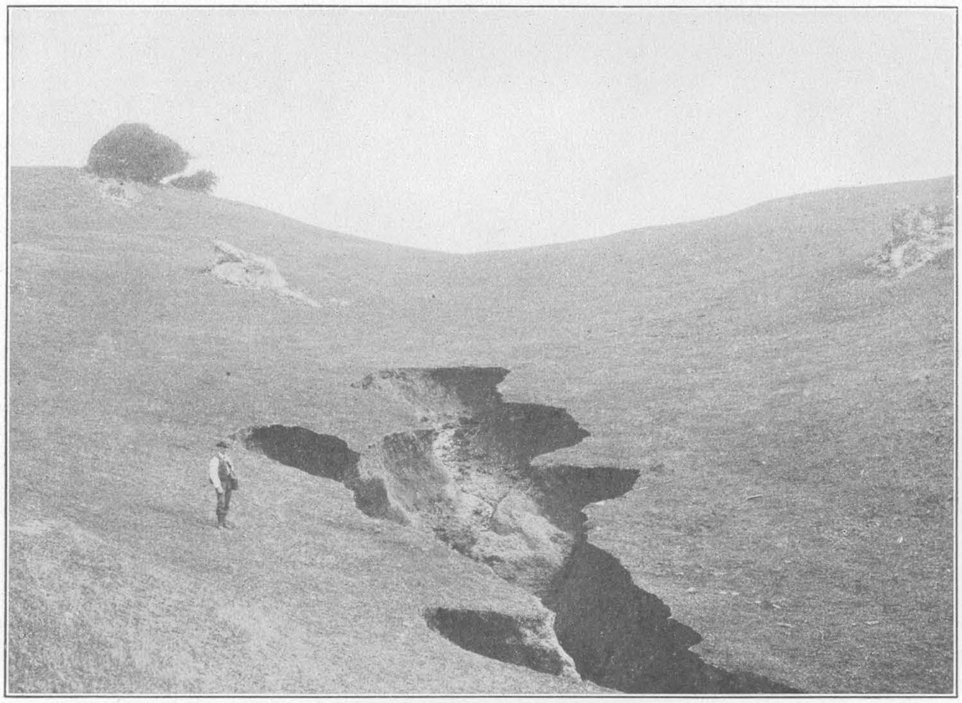
A. A FIELD NEAR COLFAX ORIGINALLY CLOTHED BY FOREST AND AFTERWARD BY GRASS.

Sheep in transit between mountain and valley pastures lingered here and consumed the grass, leaving the ground bare. Deprived of its protection, the soil was washed away and the subsoil gullied by storm waters. Compare with Plates XII and XIII.

B. A FIELD NEAR NEVADA CITY AT ONE TIME COVERED BY GRASS.

Its present condition resulted from the extermination of the grass by overgrazing.

EROSION OCCASIONED BY OVERGRAZING.



A. A GRASSY HILLSIDE NORTH OF THE GOLDEN GATE.

The slopes were developed by the slow processes of nature, soil being produced by rock decay and its sculpture regulated by a close blanket of grass and other herbs. The balance of conditions having been upset by excessive grazing, the sculpture of a new system of slopes has begun. The initial gully of the new régime has sharp edges, because the remaining grass still gives the surface a power of resistance greater than that of the earth beneath.

B. A TRENCHED MEADOW IN THE SIERRA.

This meadow, interrupting the course of a small stream, had for untold centuries arrested the fine silt washed from neighboring hills. Its mat of vegetation was destroyed by grazing, and the stream then began the excavation of the accumulated silt. The fence stands on a terrace at the level of the original meadow.

EROSION OCCASIONED BY OVERGRAZING.

meadow lands, whether fenced or unfenced, are apt to be overgrazed, and the result is the complete or approximate destruction of the herbaceous mat and an attack on the meadow deposit by the small stream flowing through it. In some places the entire deposit underlying the meadow has been washed away; in many other places it has been deeply gullied. On hill slopes overrun by herds of sheep in transit from range to range the vegetal protection is likely to be so nearly obliterated that the soil washes away or is deeply dissected by gullies. Some of the upland meadows used for summer grazing by sheep are also subjected to gullying, but these need not be considered here, because whatever earth has been washed away has been caught by the upland lakes. For the product of overgrazing within the Yuba River basin I estimate 1,000,000 cubic yards.

NATURAL DEGRADATION OF THE SURFACE.

As human agency has affected the entire area the natural outwash can not be deduced from any direct observations, but over the greater part of the region natural influences are modified only by ordinary grazing. From such lands there is an appreciable outwash of material, which may be observed in the occasional discoloration of storm water as it flows toward the streams. In some localities the arrangement of long ditches, which contour the slopes, is such as to catch a portion of this outwash and accumulate it in reservoirs farther on. (See Pl. XIX.) The material thus gathered eventually fills the reservoirs, and in many places it has been excavated one or more times for the purpose of restoring the capacity of the reservoirs. No attempt was made to measure either the catchment areas tributary to such reservoirs or the rate of accumulation, but the observations show that the natural outwash, with such acceleration as it receives from grazing, is a notable factor in the carrying of detritus to the streams. In estimating the amount of outwash for the Yuba district, since 1849, at 10,000,000 cubic yards, I am largely influenced by a comparison of the local conditions with those of the Mississippi River basin, for which a general estimate is afforded by Humphreys and Abbot's measurements of the river's sedimentary load.[1]

[1] Humphreys, A. A., and Abbot, H. L., Report upon the physics and hydraulics of the Mississippi River, 1861.

SUMMARY.

The estimates for the non-mining waste in the Yuba area since 1849 are summarized as follows: Agriculture, 18,000,000 cubic yards; roads, 2,500,000; trails, 800,000; overgrazing, 1,000,000; and ordinary grazing plus natural waste, 10,000,000; a total of 32,300,000 cubic yards. The district to which this estimate applies has an area of about 1,000 square miles.

Treating this district as representative of the mountain and foothill part of the Sacramento River basin, I have based on it estimates for other districts. In making these estimates I have assumed, first, that the waste from farming land has been proportional to the average acreage for the period of occupation; second, that the waste from roads, trails, and overgrazing has been proportional to the average population; and, third, that the natural waste and waste from ordinary grazing have been proportional to area. The resulting estimate for the entire basin, except the valley lands, is 360,000,000 cubic yards.

In estimating the waste from the valley lands the same assumptions were made, and account was taken also of the fact that, with the same exposure to storm action, the valley lands lose much less than the hill lands, by reason of their gentle slope. Because of the infinite gradation of slopes in both provinces, a satisfactory integration of the slope factor is impossible, and there are no quantitative observations on relative outwash. The numerical relation actually assumed was that the waste from valley lands, under similar conditions, has been one-tenth that of hill lands. The resulting estimate of the total waste from valley lands is 60,000,000 cubic yards, making a total of 420,000,000 cubic yards for the non-mining waste of the Sacramento basin during 65 years beginning with 1850.

Two groups of tracts were omitted from the computations because they have furnished no waste to the river. These are, first, the tracts which drain to lakes and whose waste has been caught by the lakes; and, second, the annually inundated basins of the Sacramento Valley, which instead of contributing to the river's waste have arrested a portion of it.

A similar estimate has been made of the non-mining waste from the San Joaquin River basin, the Yuba estimates being combined, as before, with data of area, population, cultivation, and slope, and also with data of precipitation and run-off. Because rainfall is lighter and run-off less copious in the San Joaquin River basin than in that of the Sacramento, the waste of exposed soil is presumably less rapid. The result of the estimate is 280,000,000 cubic yards. Its addition completes the estimate of waste in the area tributary to Suisun Bay from the beginning of placer mining to the present time.

TABLE 8.—*Summary of waste from the land surface of the Sacramento and San Joaquin basins from 1850 to 1914.*[a]

	Tributary to Sacramento River.	Tributary to Suisun Bay.
	Cubic yards.	*Cubic yards.*
Mining débris	1, 400, 000, 000	1, 675, 000, 000
Non-mining waste	420, 000, 000	700, 000, 000
	1, 820, 000, 000	2, 375, 000, 000

[a] In transferring the figures for mining débris from Table 7, 10,000,000 cubic yards was added as allowance for the period 1909–1914.

DISTRIBUTION OF THE DETRITUS.

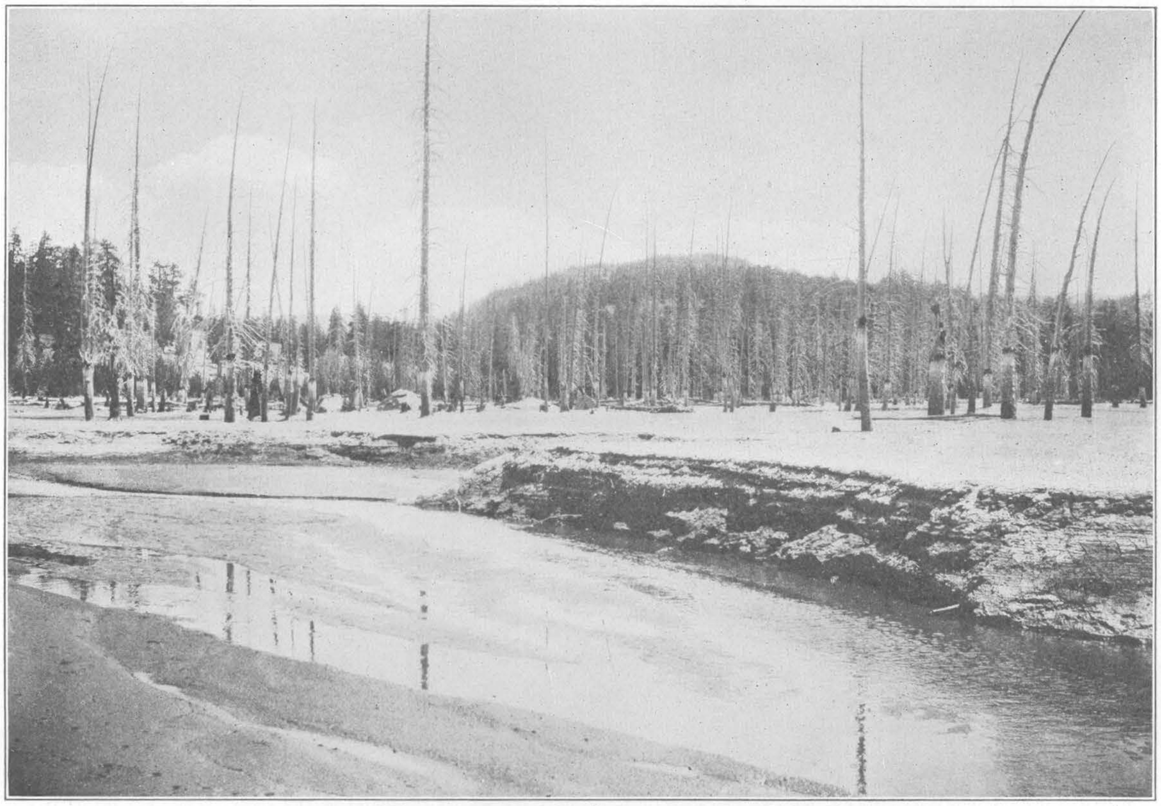
Of the entire body of waste that has been disturbed from its original position only a part has come finally to rest. The remainder has lodged by the way in temporary deposits. Deposits consisting almost wholly of mining débris were arrested in the canyons and valleys of the mountains, and these are partly permanent but chiefly temporary. Piedmont deposits likewise consisting mainly of mining débris are likewise largely temporary. The channels of the valley rivers contain other temporary deposits. Permanent deposits are lodged in the lateral basins of the lower Sacramento and the Feather and on the delta marshes of the Sacramento and the San Joaquin. Deposits which are chiefly permanent rest in the bays and in the ocean.

The estimates of the deposits in bays, of the deposits in the channels of valley rivers, and of the largest piedmont deposits have a basis of measurement, but these estimates together account for less than two-thirds of the entire amount of waste. The estimation of the other deposits is a matter of apportionment. In the study of the problem of distribution attention was given first to the items with quantitative control, and considerations affecting the relative magnitude of other items were then brought to bear; but for purposes of presentation it is more convenient to follow approximately the order of position, taking up in sequence the deposits of the Sierra, the piedmont, the valley rivers, the bays, the ocean, and the valley lands.

DEPOSITS WITHIN THE SIERRA NEVADA.

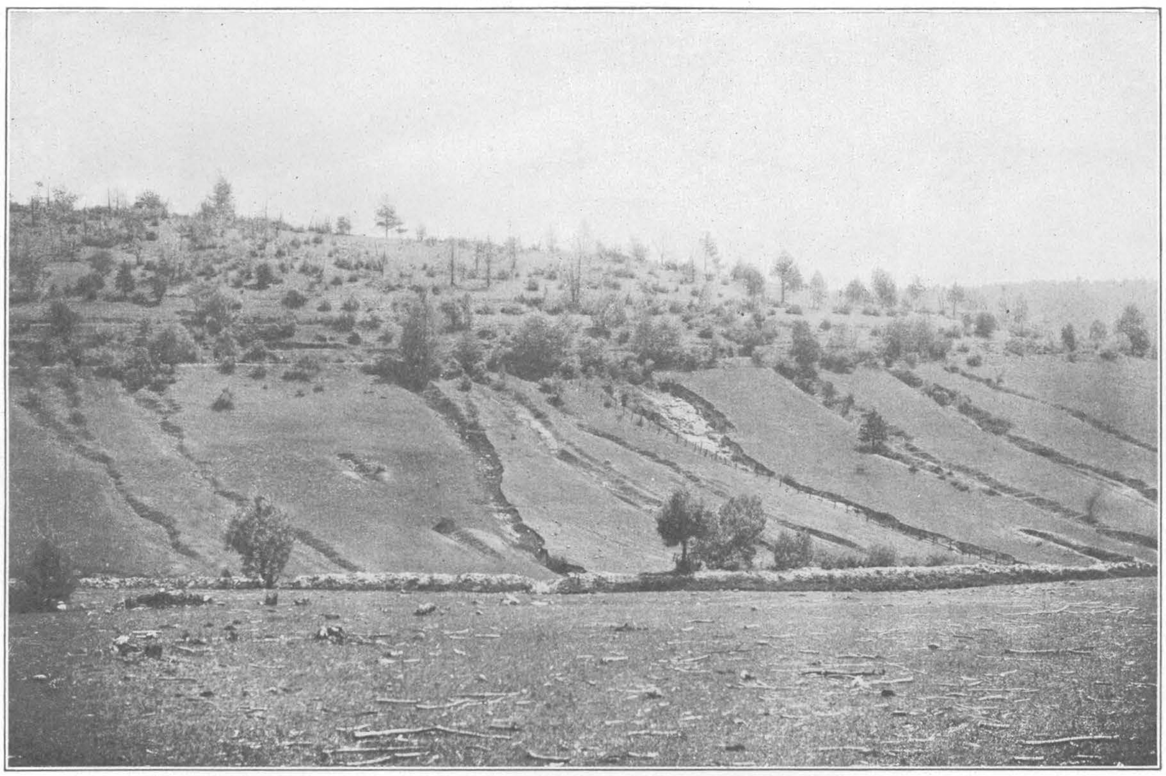
Marsden Manson[1] in 1879 examined the canyons of the Yuba and estimated that they contained 25,577,000 cubic yards of mining débris. This estimate covered only the débris lodged in the canyons and included neither the accumulations in the valleys of the upland creeks nor the mining dumps. Eleven years later F. C. Turner[2] went over the same ground, finding that only 6,170,750 cubic yards remained in the canyons. All these canyons are traversed by large streams discharging from the higher parts of the range, and after the checking of hydraulic mining their accumulations of gravel were rapidly washed out. Turner also reported on the upland creeks, estimating their deposits at more than 18,000,000 cubic yards, but this estimate explicitly omitted Deer Creek and apparently did not include the hillside mining dumps. My own observations, made chiefly in 1908, after a further lapse of 18 years, were incidental to other work and covered only a part of the ground; but they enabled me to check the work of Manson and Turner at several points and also to compare the conditions which they found with a later condition. The canyon deposits, greatly reduced in 1890, were nearly gone in 1908. Some of the creek deposits had been eroded near their heads but had elsewhere been increased, and the mining dumps above the creek beds, though everywhere trenched, were still of formidable volume. I made no attempt at measurement—in fact an adequate evaluation was then impossible without borings—but I derived the impression that the quantities calculated or estimated in 1879 and 1890 were greatly exceeded by the deposits occupying creek valleys and hill slopes in 1908. This impression was afterward fortified by studies (set forth in the following chapter) on the rate of delivery of débris to the piedmont deposit, and the estimate I have adopted is independent of those of Manson and Turner. Brought down

[1] California State Eng. Rept. for 1880, pp. 58–61.
[2] Chief Eng. U. S. Army Ann. Rept. for 1891, pp. 3058–3059.



A. RESERVOIR ON HERRING CREEK, A TRIBUTARY OF STANISLAUS RIVER.

This reservoir received drainage from about 11 square miles of woodland and meadow, ranging in altitude from 8,000 to 9,500 feet. The natural condition of the land surface was modified chiefly by grazing. After the emptying of the reservoir its silt deposit was partly washed away by the creek. Photographed in 1905.



B. A HILLSIDE NEAR SMARTSVILLE.

Altitude, 900 to 1,100 feet. A water ditch contours the slope at midheight. Soil waste from the upper slope repeatedly clogged the ditch, causing breaks and the erosion of the lower slope.

PHENOMENA INCIDENTAL TO OVERGRAZING.

to the year 1914, it ascribes to the mountain and foothill portion of the Yuba River basin a débris volume of 65,000,000 cubic yards. This material is chiefly in the beds of the upland creeks and in the mining dumps, but a portion is stored behind perishable dams.

The débris lodged along Bear River and its tributaries was estimated in 1878 by E. C. Uren at 88,977,160 yards.[1] Mendell quotes from the testimony in a mining suit (1878) an estimate of 88,000,000 cubic yards. Turner,[3] accepting Uren's estimate in the main, questions one portion as probably too large by 10,000,000 yards and gives 66,051,000 yards as the result of his own examination in 1890. It is not clear from his statement whether he included all the mining dumps, but as most of the mines of this district cast their débris directly into the streams this question is not important. An estimate of 60,000,000 cubic yards as the present quantity allows something for the amounts held behind storage dams.

Manson,[2] in 1882, estimated the débris along North Fork of American River at 20,000,000 to 25,000,000 cubic yards and stated that there was a smaller quantity on Middle Fork and none on South Fork. In 1890 Turner[4] estimated North Fork deposits at 34,661,541 cubic yards, but part of his data were observations by Uren in 1881. For Middle Fork he estimated 10,000,000 to 15,000,000 cubic yards, but with a qualification tending to reduce the amount. Only the canyon deposits are mentioned in his descriptions, but the general character of the slopes indicates that the deposits outside the canyons were not large. I have no information of later date, and an estimate of 30,000,000 cubic yards is arbitrarily assigned to represent the present status. A similarly arbitrary estimate of 15,000,000 yards is made for the Feather River basin. An estimate of 95,000,000 cubic yards for the mining region south of the American River area is an apportionment of the total output of 230,000,000, the assignment being influenced by the fact that a number of the larger mines in that region are on small streams of so low a gradient that their operation is limited by deficient outfall, by the fact that the Cosumnes and Calaveras, not heading in high mountains, have small discharge, and by the fact that the piedmont deposits of this region are small.

The total estimate for the débris deposits within the Sierra is 265,000,000 cubic yards.

DEPOSITS OF THE PIEDMONT BELT.

The largest of the piedmont deposits, that of the Yuba, is also the one with which I am best acquainted. It heads within the mountain canyon a short distance above the mouth of Deer Creek and ends at Marysville, 21 miles below, where the Yuba joins the Feather. Near the foot of the "narrows" (see Pl. IX, *B*, p. 28), at a point nearly 2 miles from its head, the deposit was sounded in connection with a project for a dam and was found to be 85 feet deep. Half a mile farther downstream its thickness probably exceeds 100 feet. At Marysville it is 15 to 25 feet thick. The surface width, 260 to 300 feet at the narrows, expands gradually to nearly 14,000 feet at a point 6 miles from the Feather. Thence to the Feather the main body narrows, being limited by levees, but a thinner division continues or increases the width. Its volume has been variously estimated, but I quote only the estimate of Maj. W. W. Harts, who for several years, as a member of the California Débris Commission, had immediate charge of engineering works at the locality. The value he assigned in 1906 is 333,000,000 cubic yards.[5] A computation of my own yielded an estimate somewhat larger, but I prefer his result, because the data at his command were exceptionally full.

Since the date of his observations the deposit has received an addition in consequence of the completion of a barrier at Daguerre Point (p. 62) but has suffered loss from the scouring of a deeper channel near its head (p. 28) and also between Daguerre Point and Marysville. The net change has probably been a small loss, and the volume in 1914 is estimated at 330,000,000 yards. Of this quantity rather more than half, as judged by the reports from borings, would be classed as gravel, about one-fourth as sand, and the remainder as silt; but this classification is qualified by the fact that much of the gravel contains a very large admixture of sand.

The deposit on Feather River heads at the canyon mouth at Oroville and extends down-

[1] Chief Eng. U. S. Army Ann. Rept. for 1891, p. 3068.
[2] Idem for 1882, p. 2572.
[3] Idem for 1891, pp. 3063, 3068.
[4] Idem for 1891, p. 3073.
[5] Am. Soc. Civil Eng. Proc., vol. 32, p. 104, 1894.

stream about 25 miles, terminating in the slack water occasioned by the débris brought to the river by the Yuba. Its volume was estimated in 1879 by W. H. Hall[1] at 18,256,222 cubic yards, and I am not acquainted with any subsequent estimate. Reports have been made, however, of increase in depth near the head and also of extension downstream. The present volume is roughly estimated at 25,000,000 cubic yards. Mendell[2] quotes an estimate of the Bear River deposit made by "experts" in 1878, the amount being 36,000,000 cubic yards. The Benyaurd commission[3] made the same estimate in 1890. I am led to make a larger estimate, not from later or better observations on the ground but as part of an adjustment between discrepant data. The estimates that have been made of the output of the mines near Bear River, of piedmont deposits, and of the deposits above the piedmont, when compared, indicate a percentage of arrested material much smaller than in the deposits of the Yuba and the American, although the small discharge of the Bear would lead one to anticipate a larger percentage. Of the three estimated quantities, the volume of the deposits above the piedmont seems most trustworthy, and I have accordingly reduced the estimate of output, as already mentioned, and increased that of the piedmont deposit, raising it from 36,000,000 to 60,000,000 cubic yards. The area of the piedmont deposit of American River is given by Manson[4] as 6,000 acres and its depth at 5 to 30 feet. These figures apply to the year 1880, and subsequent change has caused a reduction. The estimate of 60,000,000 cubic yards, here used, corresponds to a mean depth of about 6.5 feet. To the piedmont deposits of more southerly streams a volume of 70,000,000 cubic yards is assigned; and the total of estimates of piedmont deposits is 520,000,000 cubic yards.

DEPOSITS IN THE VALLEY RIVERS.

In 1879 Hall[5] estimated the quantity of detritus in the bed of Feather River below the mouth of the Yuba at 32,211,871 cubic yards and in the bed of Sacramento River below the mouth of the Feather at 83,346,913 cubic yards. The Benyaurd commission made a series of cross sections of the Sacramento in 1889 and estimated the addition during the preceding 10 years at 25,000,000 cubic yards. An elaborate survey has since been made by the California Débris Commission, but the results are not yet in a form convenient for comparison. We may infer, however, from the changes in the low-water planes, as exhibited in figure 4 (p. 30), that the deposit is about as deep near the mouth of the Yuba as in 1879 but has suffered a net loss near the mouth of the American, and a reduction of Hall's figures corresponding to these data gives 96,000,000 cubic yards as an approximate estimate of the deposits in both valley rivers at present.

There are two other river tracts which have undoubtedly received deposits but in which navigation has not been impeded and in which no measurements have been made. These are, first, that part of the Sacramento channel above the mouth of the Feather in which slack water has been caused by the deposit of sand brought by the Feather, and second, the tidal sections of the San Joaquin and of the tributaries that join it in the delta. An allowance of 4,000,000 cubic yards for these assumed deposits brings the total estimate for the filling of valley rivers to 100,000,000 cubic yards.

DEPOSITS IN THE BAYS AND IN THE OCEAN.

The deposits in the bays, the volume of which was estimated in the last chapter, consist chiefly of mud, but not all the mud delivered by the rivers comes to rest in the bays. The most finely divided portion remains in suspension while the river water is traversing the chain of bays and escapes at last to the ocean. Another portion, although deposited on shoals of the bays, is lifted again by the agitation of the water whenever wind storms sweep the bays and in this manner makes the journey to the ocean by a series of stages. If one views the ocean from some commanding high point when the tide is ebbing from the Golden Gate, he can usually—perhaps always—see that the outflowing stream is distinguished from the water it invades by a yellowish tinge, and the same tinge is recognized by the approaching mariner.

A portion of the discolored water returns to the strait along with the succeeding flood tide, but another portion remains in the ocean.

[1] California State Eng. Rept. for 1880, pp. 10, 11.
[2] Chief Eng. U. S. Army Ann. Rept. for 1882, p. 2572.
[3] Idem for 1891, p. 3006.
[4] Idem for 1882, p. 2573.
[5] California State Eng. Rept. for 1880, pp. 10–14.

The relative magnitude of the two portions is determined for each tidal cycle by the temporary condition of the local currents of the ocean, but when long periods are considered the volume permanently given to the ocean differs little from the volume of water which the bays receive from the streams of the land. (The equation of outflow with inflow is qualified only by evaporation from the bays and by rainfall upon them.) This relation makes it possible by means of systematic sampling of the effluent water, to obtain a valuable estimate of the quantity of débris delivered in suspension to the ocean, but the investigation has not been made. We have, in fact, no information more definite than the impression conveyed by casual observation of the discoloration, which is faint compared to the turbidity of a land stream during flood. The volume of the effluent water is so great, however, that even a faint discoloration may represent the annual transportation of millions of tons of débris. In order to discharge annually 1,000,000 tons of mud the ratio of suspended matter in the water of the Golden Gate need be only one six-hundredth as great as its average ratio in Colorado River at Yuma.

An independent train of débris, consisting of particles too large for suspension, follows the bed of the channel that traverses the chain of bays. The channel is maintained chiefly by tidal currents, which regularly alternate in direction, and the same currents move the débris forward and backward over the bed. The ebb currents have the greater strength, and the net result of the movement of the débris to and fro is an advance toward the ocean. The advance is most rapid when the rivers are in flood, and the activity of transportation at such times is shown by changes in the configuration of the channel beds. Through Suisun Bay and Carquinez Strait the material of the channel beds, as observed by soundings and recorded on the charts, is sand with scattered patches of mud, and this description applies also to the northern part of San Francisco Bay, but a peculiar condition is found in San Pablo Bay. Near the head there is a rapid change from sand to mud, and for a distance of 8 miles the charts record only mud as the material of the bottom. As already mentioned (p. 35), and as explained more fully in Chapter IX, there is reason to believe that the chief part of this "mud" is derived from the suspended load, here precipitated by the process of flocculation. The material includes also a portion of fine sand, presumably derived from the bottom load, and both mud and sand are moving forward toward the ocean. Nothing coarser than fine sand seems to pass this point, and it is believed that the stream of sand from the rivers here practically comes to an end. Both sand and gravel from the Sierra have been consumed by attrition as they were rolled by the currents and have been thus transferred to the suspended load, with the exception of a residuum of fine sand, and this remnant has been ground so small that little of it can survive the buffetings of a journey from San Pablo Bay to the ocean. To avoid reiteration this important conclusion is here stated somewhat baldly; it is in fact the outcome of a careful study, and the subject is discussed at length in the chapter on conditions affecting the bar at the entrance to San Francisco Harbor.

Any estimate of the tribute of débris to the ocean is, with present information, necessarily arbitrary. The estimate which will be used—for the period 1849–1914—is 50,000,000 cubic yards.

DEPOSITS ON VALLEY LANDS AND DELTA MARSHES.

The lateral basins of the Sacramento Valley and the marsh lands of the delta region are inundated, except for the interference of levees, when the rivers are in high flood. The turbid water of inundation loses velocity in traversing these lands, and part of its suspended load is deposited. When a levee breaks, the torrent which rushes across it carries sand also from the river channel, and the sand is deposited on the inundated land. Here, too, may be included the débris caught by the tidal marshes bordering the bays, débris which comes in part from neighboring creeks. It would be difficult to measure the débris thus arrested in 65 years, and the attempt has not been made.

If the estimates of volume made for deposits in the mountains, rivers, bays, and ocean are subtracted from the total estimated volume of mining and non-mining débris, there remains for the deposits of the inundated lands an estimated volume of 294,000,000 cubic yards. As this volume is composed chiefly of fine silt which has been carried in suspension, it may properly be compared with the volume of the silt deposits of the bays and the ocean. Of the 1,146,000,000 cubic yards of deposits estimated for the bays about 1,050,000,000 cubic yards is silt, so that the estimate of silt for bays and ocean together is about 1,100,000,000 cubic yards. Not all of this was in suspension when the débris was fed to the valley rivers, for a portion came from the comminution of sands in transit; but the ratio of suspended load to bed load was large in the period of most active mining. If one-fourth of the 1,100,000,000 cubic yards came from the comminution of coarse débris, there would remain 825,000,000 cubic yards to be compared with the 294,000,000 assigned to the inundated land, and we may roughly check the scheme of estimates by inquiring whether it is admissible to assume that the inundated lands caught rather more than one-fourth of the fine silt that came to the rivers in suspension.

It is probable that during a flood of exceptional magnitude considerably more than one-half of the silt-bearing water leaves the river channels and moves with relative slowness across valley lands and marshes.[1] The greater part of the diverted water returns to the channels in a few days; a minor part may be held in a nearly stagnant condition for weeks. Ordinary floods spread much less water over the lowlands, and the water is diverted for shorter periods. Normally the waters of great floods are more highly charged with silt than those of ordinary floods, but low-stage waters are silt-free. It is not improbable that under normal conditions more than half of the river water that is well charged with suspended débris is diverted from the channels and during its loitering journey parts with a large share of its load. During the era of extensive hydraulic and other placer mining the fine tailings were given to the rivers in all seasons, and a very large amount was carried forward during river stages so low that none escaped from the channels. This abnormal condition, though adding greatly to the total output of silt, did not add proportionally to the deposition on valley and delta lands.

The considerations thus outlined do not yield quantitative results, and I can only say of them that they contain nothing evidently inconsistent with the idea that the inundated lands caught rather more than a fourth of the suspended load of the rivers.

Table 9 gives a summary of the estimates as to the present distribution of the entire body of mining and non-mining débris. The deposits in the mountains, on the piedmont slope, and in the channels of valley rivers contain little besides mining débris. Non-mining débris enters largely into all the others.

TABLE 9.—*Estimates of the distribution in the year 1914 of débris moved by mining operations or by rains from lands draining to the San Francisco Bay system during the preceding 65 years.*

	Million cubic yards.
Deposits within the Sierra Nevada	265
Piedmont deposits	520
Deposits in the channels of valley rivers	100
Deposits on inundated lands, including tidal marshes	294
Deposits in the bays	1,146
Deposits in the ocean	50
	2,375

NEW WASTE FROM OLD MINES.

After the miners' jets have ceased to play on the walls of hydraulic mines the waste of the walls is continued for a long time by natural agencies. Vegetation, the great conservator of unconsolidated formations, does not quickly assume control, because the material lacks humus and is infertile. Rain, frost, and the flow of storm water detach and move the component particles, and the cliffs are gradually wasted. Taluses are formed, and graded slopes are established on which the débris is regularly transported. In some mines the system of slopes is such that much of the newly detached débris is stored within the mining cavities. From other mines the greater portion is freely discharged. Many decades will elapse before these bluffs of earth have acquired stable slopes and are clothed by protective vegetation. The cliff faces of the central hill of the

[1] Clapp, Murphy, and Martin (Am. Soc. Civil Eng. Trans., vol. 61, p. 317, 1908) estimate the mean run-off from the Sacramento drainage basin for the four days of maximum flood in March, 1907, at 554,700 second-feet, which is equivalent to 4,404,000 acre-feet in the four days. The California Débris Commission (62d Cong., 1st sess., H. Doc. 81, pp. 8-9) estimates the total capacity of five flood basins of the Sacramento Valley (omitting the sixth) during the floods of 1907 and 1909 at 4,022,000 acre-feet. The capacity of the river channel at Knights Landing is estimated at 10 per cent of the flood discharge, and corresponding estimates for points below the mouth of Feather River and the mouth of American River are 14 per cent and 15 per cent. These estimates take no account of the diversion of flood waters to delta lands. San Joaquin River, with a flood discharge half as great as that of the Sacramento, has no lateral basins but overflows extensive delta marshes.

Manzanita mine, pictured in Plate X (p. 29), had been exposed to the weather more than 20 years when their condition was recorded by the camera and were still bare and barren, with only a moderate building of talus. The softer formation of the North Bloomfield cliff, shown in the same plate, attacked by streams as well as by rain, had in 20 years been elaborately sculptured but did not yet approach a condition of stability.

No serious attempt has been made to estimate the volume of débris contributed to the creeks and rivers in this manner. All that had escaped from the mines before 1908 was included in the estimates of mining débris based on the measurement of mining cavities. The subsequent output and the future output have not been covered by any of the estimates of waste, but some account will be taken of them in another connection.

CHAPTER VII.—STUDIES ON THE LOWER YUBA.

The piedmont deposit of the Yuba is the largest single body of mining débris outside of the bays. Some of its features are portrayed in Plates IX (p. 28) and XX, and figure 6 shows its horizontal extent. Because of the great injury wrought by it and of the further injury threatened, it has received special attention from the engineers charged with the duty of controlling the movements of the débris. Some of the engineering works executed during the period of my own investigation have served, through their reactions, to illustrate matters of importance to river science, and I have availed myself of the opportunity to study the reactions. In part, but only in part, the studies have immediate application, yielding results that are used in the present paper. They are recorded in this chapter without special reference to their applications.

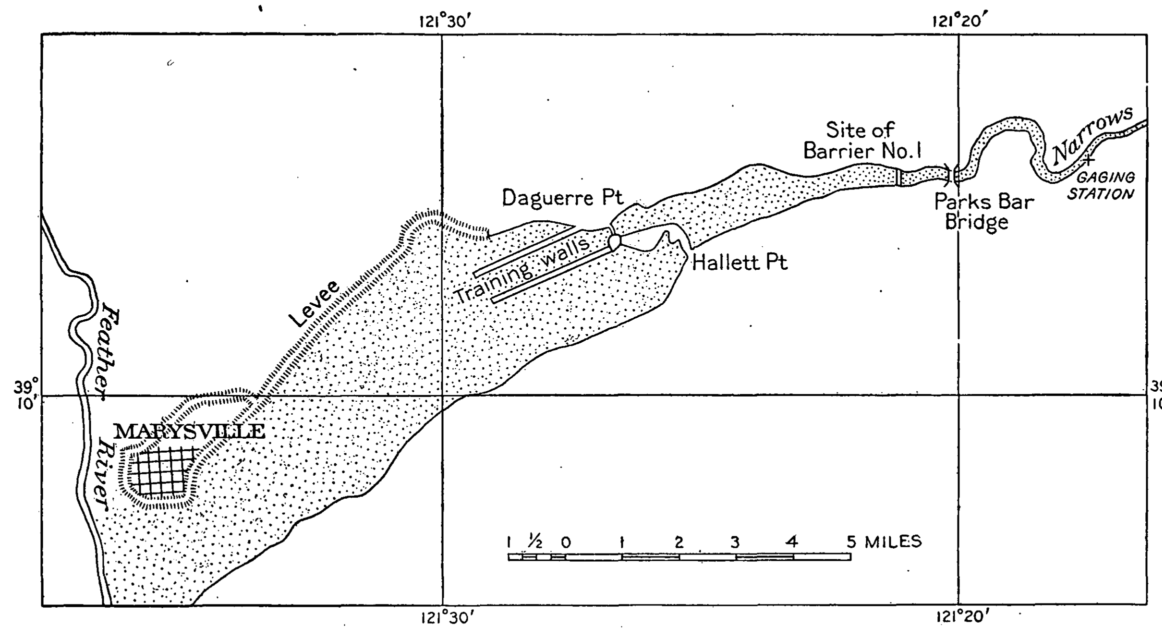
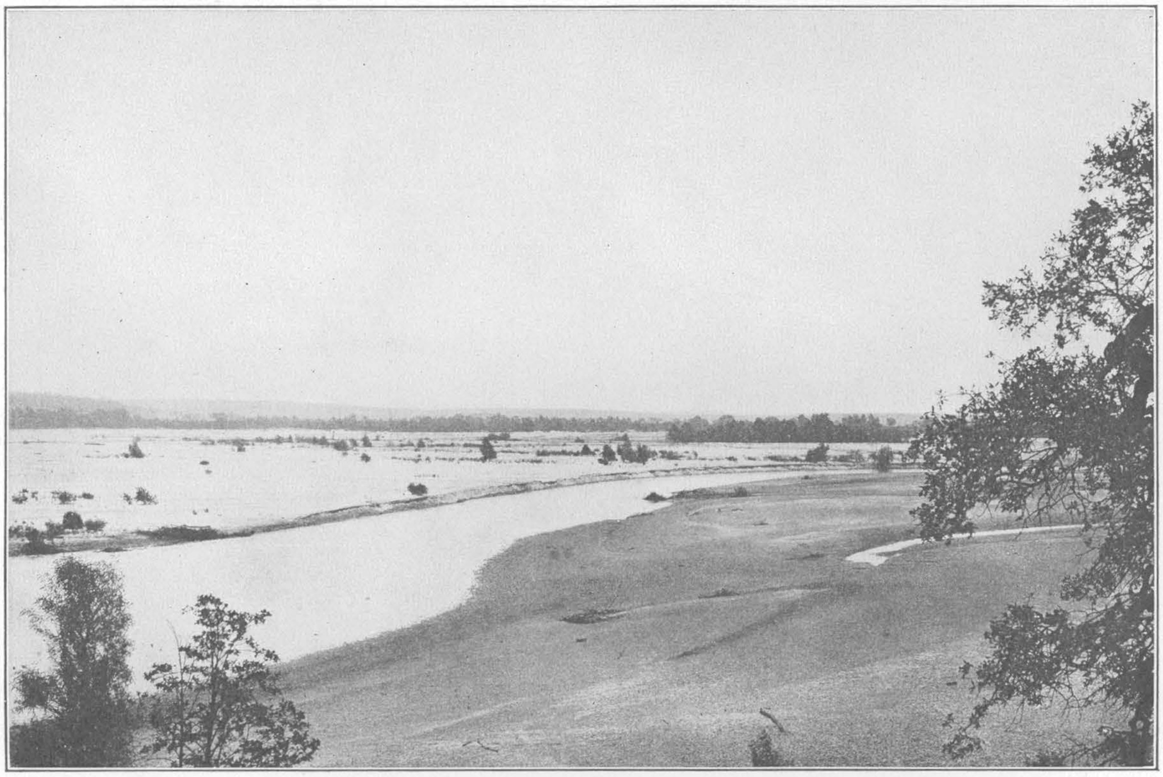


FIGURE 6.—Outline map of the piedmont deposit of Yuba River.

DETRITAL LOAD OF YUBA RIVER.

The report of the California Débris Commission for 1899[1] outlines a project for various works on the Yuba piedmont plain for the control of the river and the impounding of a portion of its detrital load. One of these works, called barrier No. 1, was located about 1 mile below Parks Bar Bridge, at a point where the flood channel of the river is about 1,500 feet wide. (See fig. 6 and Pl. XXIII, p. 58.) The first part of the barrier, about 6 feet high, was completed in 1904, and the second part, increasing the height by 8 feet, in 1905. The bed of the river at this point had been raised, during a series of decades, by a deposit of which the depth is not less than 50 feet; and the material serving as foundation for the barrier was gravel with generous admixture of sand. For a short distance at the north an earthwork was constructed, with a crest above the highest flood stage; for the remainder of the distance the crest of the dam served also as a spillway, and this part was 1,250 feet long. The project of the dam involved the building of a series of units, each unit increasing the height 6 or 8 feet. In the construction of the first unit several rows of piles were driven into the gravel, the spaces between them were filled by quarry rock and gravel, and the crest was protected by

[1] 56th Cong., 1st sess., H. Doc. 431.



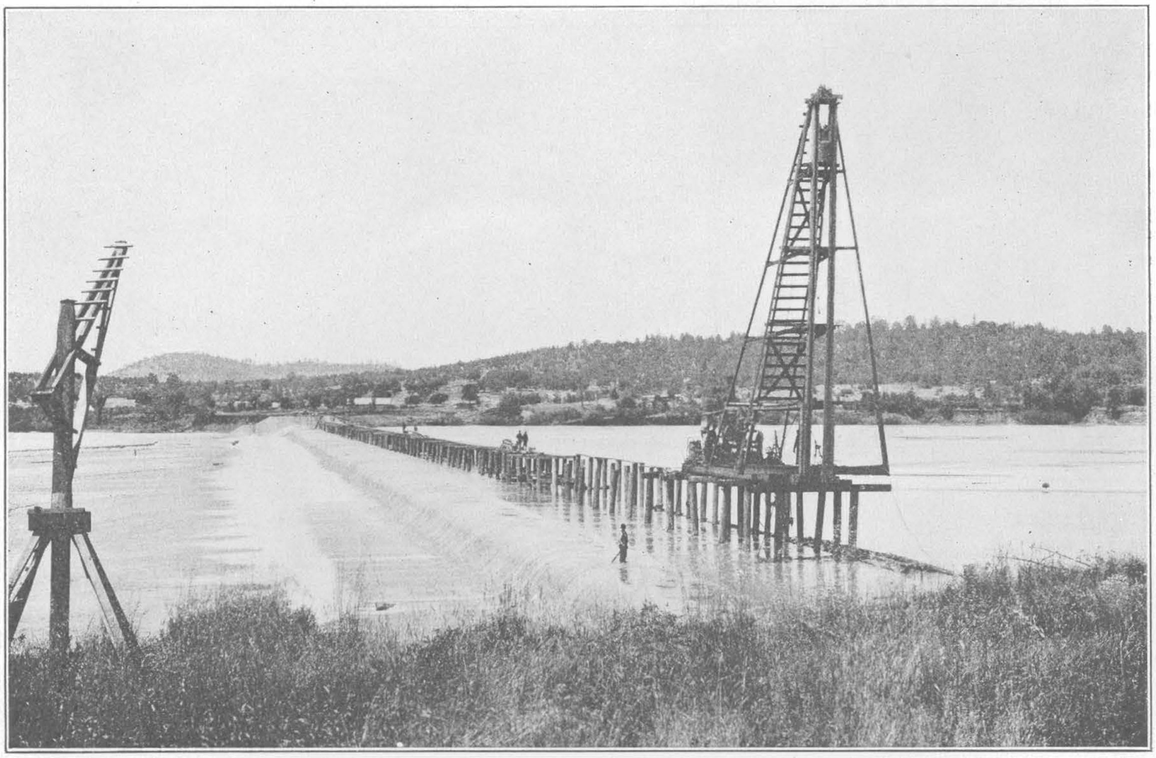
A. THE DÉBRIS PLAIN NEAR ITS BROADEST PART, AS SEEN FROM DAGUERRE POINT, ON THE NORTH BANK, IN 1905.

The greatest thickness of the deposit included within this view is 40 feet.

B. LEVEE BUILT TO EXCLUDE RIVER FLOODS FROM MARYSVILLE AND VICINITY AND TO LIMIT THE DÉBRIS INVASION.

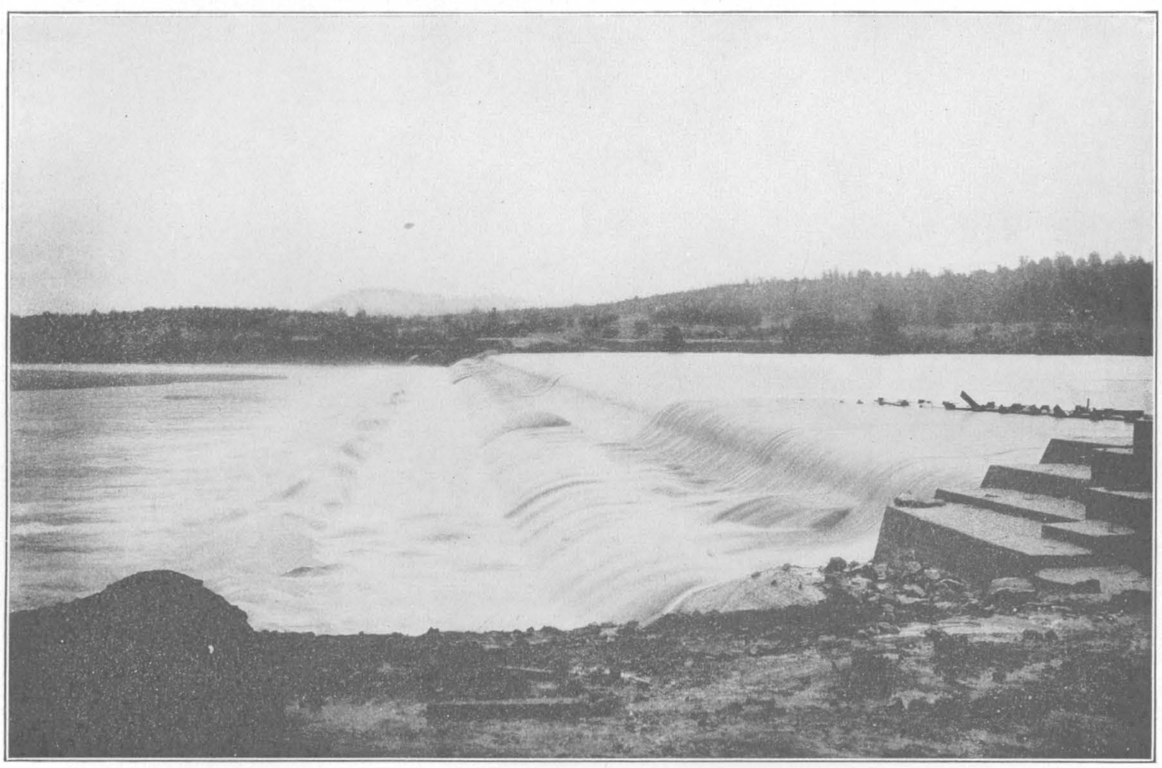
At this point the levee is 25 feet high. An arm of the débris plain is seen at the left. Photographed in 1905.

THE PIEDMONT DEPOSIT OF THE YUBA.



A. FIRST UNIT OF THE CONCRETE STRUCTURE.

This unit included a flat crest (on which a man is standing), a foreslope of double curvature, and a horizontal apron. The view shows a system of piles placed for the support of the second concrete unit. The first unit was completed in 1904. The photograph was made June 6, 1905. The floods of the intervening winter and spring had filled the new-made reservoir with débris. They had also excavated the river bed on the downstream side of the barrier, so that the apron, originally at the level of the bed, now stood several feet above it. At this stage of the barrier's history the first contour map of the river bed was made.



B. THE COMPLETED STRUCTURE.

The second unit was added during the low-water stage of 1905. It included a flat concrete crest and a curved foreslope connecting with the lower unit. The photograph was made during the passage of a flood, January 17, 1906.

BARRIER NO. 1, YUBA RIVER.

A. REMNANT OF THE DÉBRIS DEPOSIT ABOVE THE BARRIER, EXPOSED IN SECTION AFTER THE BREACHING OF THE BARRIER.

The coarse gravel at top is a veneer; the gravel below contains much sand. The resistant ledges visible near the bottom of the slope contain clay. Photographed June 11, 1907.

B. VIEW DOWNSTREAM FROM THE BARRIER, SEPTEMBER 19, 1906.

A year earlier the river bed had the level of the bench seen at the right. The subsequent erosion was in part selective. Large stones remain, but finer material was washed away. The gravel of the foreground is not representative of the whole deposit, but only of its coarsest elements.

ASPECTS OF DÉBRIS AT BARRIER NO. 1, YUBA RIVER.

a sheet of concrete that curved forward and downward and was continued downstream in a short horizontal apron. (See Pl. XXI.)

The basin created by the first unit was filled by the river with detritus, chiefly gravel, during the ensuing winter, and the piles for the support of the second unit were driven into and through this gravel. It was during the progress of the last-mentioned work that I first visited the locality. It appeared that an opportunity was here afforded to obtain information on an obscure question in river hydraulics—the amount of detrital load transported near the bottom of the current—and measures were immediately taken to utilize the opportunity. The plan included two surveys of the bed of the river for a distance above the barrier, one before the completion of the second unit, the other after the floods of the river had brought down their load of detritus and the heavier portions of it had been arrested in the basin. In the autumn of 1905 a plane-table map, with 2-foot contour interval, was made by S. K. Baker, of the reclamation branch of the Survey, and a short time afterward the addition to the barrier was completed, raising the sill over which the water flowed 8 feet. A portion of this map is reproduced in Plate XXIII (p. 58).

The first flood after the completion of the work occurred in January, 1906, the maximum stage being reached on January 18. (See Pl. XXI, *B*.) The stage was somewhat higher than other high stages of the winter season, and the flood continued for a week. A visit to the locality after the flood had nearly subsided showed that the basin above the barrier had been nearly filled by the work of that flood, and a resurvey was therefore made (by Mr. Baker) as soon as the stage of the river permitted. It was not practicable to follow the methods used at low water, and instead of attempting contours, a series of cross sections were run at intervals of 500 feet.

Other floods followed during the winter and spring, and at the low-water stage in the autumn of 1906 a second contour map was made (Pl. XXIV), the work being done this time by C. L. Nelson, a topographer of the Survey. During the summer of 1906 a series of shallow borings were made by E. C. Murphy for the purpose of ascertaining the character of the deposit, and especially the distribution within it of sand, fine gravel, and coarse gravel.

The map work by Mr. Baker in 1905 was extended half a mile below the barrier, and this portion was also surveyed in the fall of 1906 by Mr. Nelson. The purpose of the extension was to determine such changes in the configuration of the river bed below the barrier as might be occasioned by the addition to its height.

The barrier was afterward breached and destroyed by the flood of March, 1907, whereupon the original profile of the river channel was immediately restored. Only a few remnants of the deposit artificially induced by the barrier survived (Pl. XXII, *A*), but their preservation gave opportunity for observations that supplemented the data obtained from borings by Mr. Murphy.

From the discussion of these various data the following results were obtained:

The initial slope of the river bed in the vicinity of the barrier was about 16 feet to the mile, and there was a rapid increase upstream to 22 feet to the mile. This marked difference was probably of a temporary character, as it was not indicated in a profile constructed by the California Débris Commission in 1899 nor by the contours of the United States Geological Survey map of 1909; but apart from temporary accidents there is a general correlation of slope with coarseness of detritus in the portion of the river bed lying outside the mountain canyons. At Marysville, near the mouth of the river, where the chief material is sand, the slope is about 6 feet to the mile, and it increases upstream as the material changes successively to coarse sand, fine gravel, and coarse gravel. The erection of the first 6 feet of the barrier in 1904 caused a filling during the flood stages of the ensuing winter which extended at least 1½ miles upstream and probably somewhat more, reducing the average slope in that region to about 12 feet to the mile. When the second unit was added to the barrier, increasing its height 8 feet, deposition again began, and the flood of January, 1906, in filling the newly formed basin, extended its deposit upstream about 1¾ miles, reducing the average grade for that distance to about 9 feet to the mile. The subsequent storms of the same winter extended the area of fill somewhat farther upstream and nearly restored the slope of 12 feet to the mile which had been created by the floods of the preceding winter.

The completion of the upper unit of the barrier created immediately a basin of slack water, and the first deposit made by flood waters in this basin was of fine material, chiefly sand but also silt, these materials being afterward found at the bottom of the deposit near the barrier. Farther up the initial deposit was chiefly of gravel, and the gravel deposit was gradually extended downstream, so as to cover the sand. There was, however, a triangular area near the barrier not reached by the principal current, and here no gravel was deposited. When the surface of the deposit was first examined after the January flood it was found that fine gravel had been transported to the crest of the barrier, and it was thus shown that during the latter part of that flood not only sand but a certain amount of gravel had passed over the barrier. When the work of the season's floods was completed, a coarser gravel had extended its area to the barrier, but not the coarsest of all; and the presence of this coarser gravel at the crest and the vigorous erosion which had taken place on the concrete facing of the barrier showed that a large body of gravel had passed downstream. The deposit as measured therefore did not include the entire annual load of coarser material carried by the stream, but only a fractional part. The flood of March, 1907, which was of exceptional magnitude, brought down to the barrier the coarsest type of gravel seen in the river bed, and we may therefore assume that it raised the slope of the river bed above the barrier to an angle which would have been stable; but the full record of this grade was prevented by the destruction of the barrier. The erosion of the concrete facing by the gravel passing over it was great, amounting along the belt of principal action to an average of several inches and completely piercing the 18 inches of concrete at some points. This erosion was one of the causes to which the destruction of the barrier was ascribed by engineers.

The whole body of material arrested by the barrier in the winter and spring of 1906, as computed from a comparison of the contour maps made before and after that period, was 1,690,000 cubic yards. Of this total 920,000 cubic yards was arrested during the January flood. In the following table it is classified as silt, sand, and gravel. These terms are somewhat loosely used, and the lines of separation are not sharply drawn. In a general way, material of which the largest particles would pass a sieve having 80 meshes to the inch is called silt; material of which the largest particles would pass an 8-mesh sieve is called sand; and all material involving larger particles is called gravel. The gravel exhibits a wide range of constitution, the larger pebbles in some portions being less than an inch in diameter and the boulders in others being more than 1 foot. In some thin and local layers pebbles or boulders are segregated, with only enough finer material to fill the interstices; but such patches are comparatively rare, and the great body of the gravel is an intimate mixture of coarse and fine materials, in which the finer predominate and constitute a matrix for the coarser.

TABLE 10.—*Material (in thousands of cubic yards) arrested by barrier No. 1, Yuba River, between October, 1905, and October, 1906.*

Period.	Silt.	Sand.	Gravel.	Total.
Flood of January, 1906	5	260	655	920
Subsequent floods	5	30	735	770
	10	290	1,390	1,690

There was no measurement of the quantity of material passing over the barrier during the same period, and the total detrital load of the river at this point therefore can not be determined in an altogether satisfactory way, but an estimate has been made.

The fact that the flood of January, 1906, brought to the crest of the barrier no material coarser than fine gravel, although the upstream portion of the deposit included a large body of coarse gravel, indicates that nearly all the gravel that was in transit in January was caught by the barrier. As the amount of gravel arrested at that time has been measured, it is feasible to estimate the quantity of gravel transported in the entire year, if a suitable comparison can be made between the efficiency of the January flood and that of the floods which followed it.

Competent data as to the relative magnitudes of the floods are fortunately at hand, but information as to the relation of discharge to efficiency is less satisfactory. One of the regular gaging stations of the Survey—the Smartsville station—is on the Yuba about 5 miles above the barrier. From daily observations of river stage at that station the corresponding discharges have been computed, and Table 11 contains the daily discharges during the flood periods under discussion.

TABLE 11.—*Discharge of Yuba River during periods of high water between Oct. 1, 1905, and Oct. 1, 1906.*[a]

Day.	Discharge.	Day.	Discharge.
	Sec. feet.		*Sec. feet.*
Jan. 13	16,900	Apr. 23	8,600
14	11,500	24	7,650
15	18,900	25	6,800
16	18,900	26	7,050
17	16,900	27	7,000
18	48,000	28	6,450
19	33,000	29	7,350
20	13,000	30	7,800
21	9,000	May 1	9,000
22	6,810	2	10,500
23	5,550	3	12,400
		4	11,600
Feb. 15	10,200	5	13,000
		6	12,500
19	11,100	7	12,500
20	5,550	8	12,500
21	10,700	9	13,600
22	6,810	10	13,200
23	7,850	11	14,400
24	7,850	12	11,400
25	8,230	13	8,600
26	6,810	14	9,300
27	11,100	15	10,000
28	9,000	16	6,950
Mar. 1	6,810	17	6,700
2	5,550	18	6,500
3	7,150	19	6,800
4	6,480	20	7,200
		21	7,150
11	5,550	22	7,000
12	28,400	23	6,500
13	12,500	24	5,750
14	12,500	25	8,900
15	9,400	26	18,700
16	7,150	27	18,200
17	6,160	28	20,100
		29	13,700
21	5,850	30	10,000
22	16,400	31	8,800
23	18,400	June 1	8,900
24	29,400	2	9,350
25	26,400	3	10,500
26	30,400	4	25,600
27	15,900	5	16,500
28	11,600	6	12,200
29	9,000	7	10,400
30	15,400	8	9,200
31	40,600	9	10,100
Apr. 1	18,100	10	11,700
2	13,500	11	13,100
3	11,700	12	18,000
4	9,100	13	11,700
5	8,600	14	8,700
6	8,300	15	8,800
7	8,350	16	14,100
8	8,700	17	9,450
9	8,700	18	7,200
10	8,600	19	11,700
11	8,000	20	10,300
12	7,700	21	8,400
13	7,950	22	8,200
14	7,500	23	8,100
15	8,100	24	6,100
16	8,100	25	6,000
17	8,500	26	5,700
18	8,500		
19	8,900	July 2	6,000
20	9,200	3	6,600
21	9,200	4	6,000
22	9,200	5	5,800

[a] See U. S. Geol. Survey Water-Supply Paper 213, pp. 142-143, 1907.

The flood channel in the vicinity of the barrier is 800 to 1,500 feet wide and is floored by gravel. Through the floor run minor channels, and at most points one of the minor channels is deeper and broader than the others, so as to carry all the water at low stages. At low stages such movement of gravel as takes place is purely local, tending toward but never accomplishing the filling of the deeper pools of the minor channel. As the discharge increases and the water first spreads over the broad gravel plateau and then deepens on it, through transportation is substituted for local, and the amount of through transportation (of bed load) then increases rapidly with increase of depth and velocity. We are at present concerned with the relation of the amount of through transportation to the discharge, and for the discussion of this I assume (1) that through transportation begins when the discharge reaches 5,000 second-feet, and (2) that the amount of through transportation, or the bed load, varies with the 1.3 power of the excess of discharge above 5,000 second-feet. The first of these assumptions is arbitrary; the second is founded on the discussion of laboratory data.[1] The result of a computation on this basis is that the bed load for the entire season from the autumnal low stage of 1905 to that of 1906 was proportioned to that of the flood of January, 1906, as 100 to 23. During all higher stages the bed load includes the grade classed as gravel in the analysis of the deposit above the barrier.

Data for the estimation of the suspended load also were acquired at the Smartsville gaging station. During the year 1906 a sample of the water was collected daily at this station. The samples of 10 consecutive days were combined in a composited sample, and for each composite the solid contents were separated and weighed. By the combination of these determinations with the discharges of water for the same periods the total suspended load was computed.

Table 12 gives the data for the first nine months of the year. As the river discharge varied greatly during some of the 10-day periods, and as the proportion of suspended matter was in general greater during high stages than during low stages, the computa-

[1] Gilbert, G. K., The transportation of débris by running water: U. S. Geol. Survey Prof. Paper 86, 1914.

tion of suspended load based on the composites does not give the same result that would have been obtained had the corresponding data for the individual days been used. Analysis of the record led to the conclusion that the tabulated total is much too small and should be increased about 20 per cent. On the basis of the same analysis, combined with the recorded discharges for the closing months of 1905, an allowance was made for the suspended load of those months—which fell outside the period of sampling—and an estimate was thus completed for the year included between the dates of survey.

TABLE 12.—*Suspended matter in Yuba River at Smartsville gaging station for 10-day periods in 1906.*

Month.	Observed suspended matter (parts per million of water).	Discharge of water (acre-feet).	Total load suspended matter (cubic yards).
January	80	10,000	910
	1,700	360,000	693,200
	260	90,000	26,510
February	220	45,000	11,210
	300	97,500	33,130
	360	137,500	56,080
March	320	112,500	40,780
	350	192,500	76,330
	700	437,500	346,900
April	260	205,000	60,390
	230	165,000	42,990
	350	152,500	60,460
May	290	242,500	79,680
	190	175,000	37,670
	240	250,000	67,970
June	350	250,000	99,130
	230	227,500	59,190
	140	127,500	20,220
July	120	107,500	14,620
	160	65,000	11,790
	270	37,500	11,480
August	90	18,000	1,830
	70	14,500	1,150
	85	14,500	1,400
September	45	10,000	510
	35	10,000	390
	35	9,700	380
Uncorrected total for January to September, 1906			1,856,300
Allowance for difference between daily samples and 10-day composites			371,300
Estimate for October to December, 1905			14,400
Total suspended load for flood season, 1905–6			2,242,000

On a single day during the flood of January, 1906, the suspended load was determined with much care at the Marysville carriage bridge, close to the mouth of Yuba River, and the details and result of this determination are shown in the following table:

TABLE 13.—*Suspended matter (parts per million) in samples of water collected from Yuba River under D Street Bridge, Marysville, Jan. 19, 1906.*

[Collection and analysis by C. H. Stone.]

Location.	Depth.[a]	Silt.	Coarser material.[b]	Total.
	Ft. in.			
South end of bridge	11 1	606	309	615
Do	9 0	634	250	884
Do	5 0	614	150	764
Do	2 4	668	55	719
Do	3	626	28	654
Near middle of bridge	10 0	798	225	1,023
Do	7 0	778	190	968
Do	4 0	782	202	984
Do	3	792	249	1,041
Deepest part, near north shore	14 0	614	377	991
Do	12 0	626	147	773
Do	7 0	560	46	606
Do	4 4	464	35	599
Do	6	554	36	590
Averages		658.7	[c] 164.5	822.9

[a] The lowest depth in each series was within 1 foot of the bottom.
[b] The "coarser material" includes all particles exceeding in diameter 0.0013 millimeter (0.00005 inch).
[c] In the 164.5 parts of coarse material are included 8.1 parts of organic matter.

The reported discharge of the river on the day on which these determinations were made was 33,000 second-feet, and a rough computation based on the Marysville observations indicated an annual load of suspended matter only one-half as great as that derived from the observations at the Smartsville gaging station. Little weight, however, should be given to the condition of the water on a single day, and the discrepancy may be due wholly to unexplained irregularity. On the other hand, it may be due in part to the difference in velocity at the two stations. The current was much stronger in the Smartsville narrows than at Marysville, and the stronger current, by maintaining in suspension coarser detritus than was thus carried by the weaker, also carried a larger quantity. The Smartsville result better represents the conditions at the barrier, and the Marysville observations are placed on record chiefly as an illustration of the fact that the suspended load may be so impartially distributed through the body of the current as not to be grossly misrepresented by samples taken at the surface.

The average content of three samples collected at the surface is about 7 per cent less than the average for all samples. It is noteworthy, moreover, that the variation with depth is shown only in the distribution of the coarser particles, not at all in that of the finer. During higher flood stages the suspended load at Smartsville narrows must have included much sand, for the current there was violent, but, in the absence of a mechanical analysis, I regard it as improbable that a notable amount of this sand was caught in taking the samples. If allowance were made for it the estimate of suspended load would be somewhat increased. We are specially concerned, however, with the evaluation of the load at the barrier, where, it is thought, most of the sand followed the bottom, and the estimate as it stands may be taken to represent the entire suspended load at that point as well as the silt factor of the suspended load at the narrows. The estimates contained in the following table take account of the data discussed in the preceding paragraphs and also of various minor factors the mention of which seems unnecessary in view of the unavoidably large uncertainty of the general result.

TABLE 14.—*Material passing over barrier No. 1, Yuba River, between October, 1905, and October, 1906, in thousands of cubic yards.*

Period.	Silt.	Sand.	Gravel.	Total.
During the flood of January, 1906	475	200	100	775
During the remainder of the year	1,715	1,430	1,650	4,695
	2,190	1,630	1,750	5,470

The combination of Tables 12 and 14 gives the following estimate and classification of the detrital load of the river from October, 1905, to October, 1906:

	Cubic yards.
Silt	2,200,000
Sand	1,900,000
Gravel	3,100,000
	7,200,000

The grouping as silt, sand, and gravel is that found convenient in classifying the deposits above the barrier. It recognizes the readily discriminated aggregates and is not analytic. What is called sand is not a pure sand, but includes in intimate mixture much fine material that by itself would be classed as silt, and, similarly, that which is called gravel has much sand in its composition. A few samples of the "gravel" were subjected to mechanical analysis, and the results indicated that the finer gravel contained about 45 per cent of sand and the coarser 15 per cent. If the material of the year's detrital load were separated into three parts mutually exclusive as to size of grains, the proportions would be about 31 per cent silt, 37 per cent sand, and 32 per cent gravel.

It is proper to inquire whether the movement of detritus in the season of 1905–6 was normal or exceptional. The data available for the discussion of the question are the daily discharge records at the Smartsville station and the precipitation records at neighboring mountain stations. The discharge records have been practically continuous since 1903 and the precipitation records at Colfax and Summit since 1871. From the daily discharge the relative capacity of the river for transportation was computed for nine flood seasons—October 1 to September 30—and the capacity in the season of measurement, 1905–6, was thereby compared with capacities in eight other seasons. Then the nine capacities were plotted in relation to the corresponding precipitations, a curve was drawn to express the law of relationship, and from this curve was inferred the capacity corresponding to normal precipitation. The discussion, the details of which are omitted, assumed (1) that the river's capacity for transportation varies with the 1.3 power of the discharge less 5,000 cubic feet per second, (2) that the discharge of a season is in the long run proportional to the seasonal run-off of the river basin, and (3) that the run-off varies with the precipitation, but more rapidly;[1] and it resulted in the conclusion that the normal load of Yuba River is about four-tenths of the load in 1905–6, or 880,000 cubic yards of silt, 760,000 cubic yards

[1] See discussion by C. E. Grunsky in Am. Soc. Civil Eng. Trans., vol. 61, pp. 496–515, 1908.

of sand, 1,240,000 cubic yards of gravel, a total of 2,880,000 cubic yards.

The use of the phrase "normal load" in this connection requires qualification. It should be understood to mean the load that would have been carried by the Yuba at this point in the season of 1905–6 if the precipitation for the season had been normal in amount and distribution. The characterization would not apply to another point on the river, nor to this point a decade earlier or later. The supply of coarse débris from the mountains, as shown by the changes at the Smartsville gaging station (see p. 28), had been waning for about five years and its waning has continued. The supply of fine débris, which had begun to lessen 20 years before, is probably still growing less, and its rate of change in 1905–6 may have been greater than that of the coarse débris. So the estimate given as normal for 1905–6 is below the local normal for a preceding period (not less than a decade) and above the normal for all later years.

RELATION OF THE YUBA'S LOAD TO OTHER ESTIMATES.

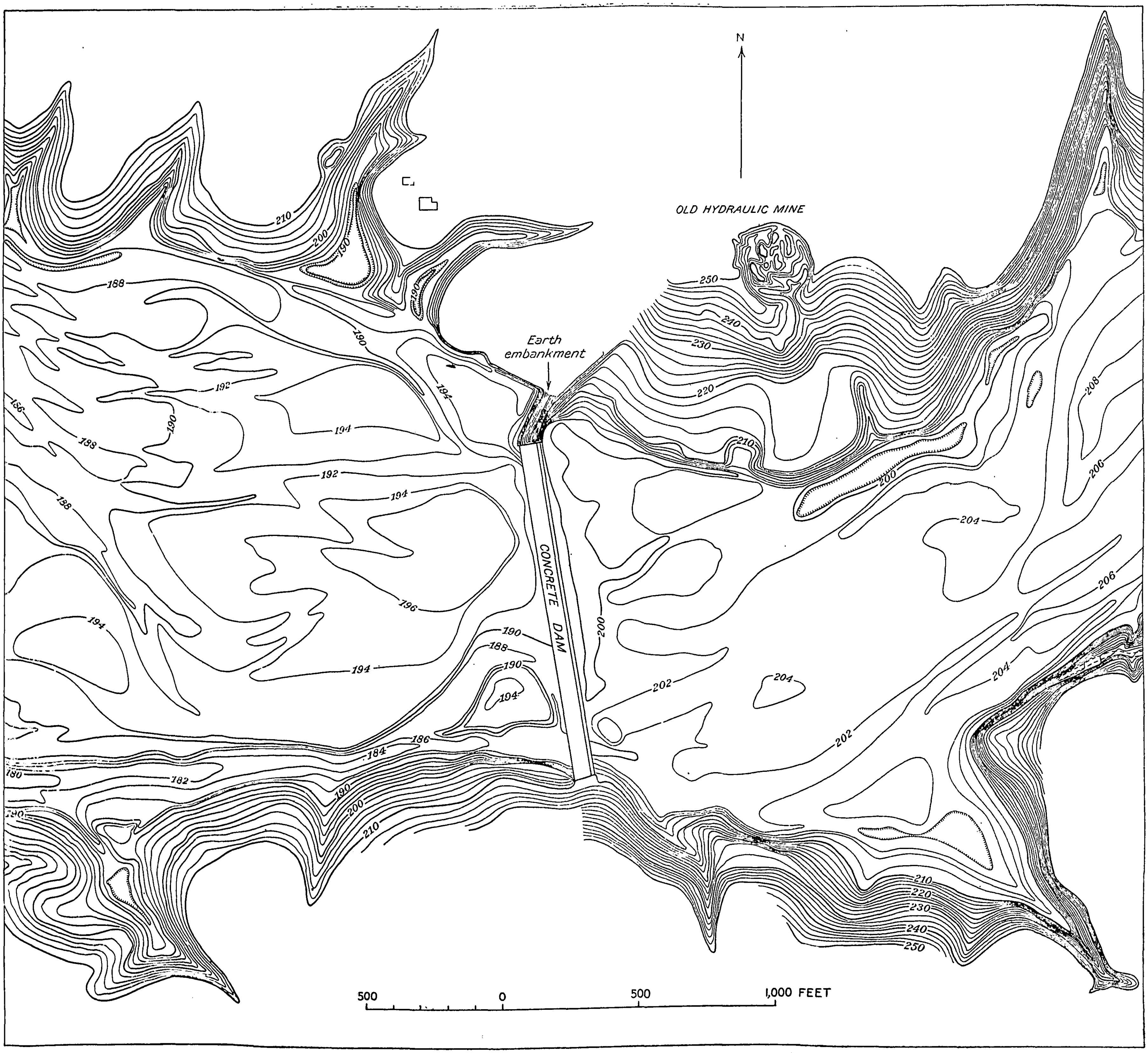
As already stated (p. 39), the estimate of the Yuba's load has been used in estimating the volume of mining débris remaining in the mountain portion of the Yuba River basin in 1914. Of the normal load of the Yuba at barrier No. 1 in 1905–6 the chief part was mining débris. The volume ascribed to the nonmining débris for a period of 65 years (p. 46) indicates for the season 1905–6 a volume of 600,000 cubic yards and leaves for the normal annual load of mining débris at that date 2,300,000 yards. This gives a point on a curve representing the variation of the rate of flow of mining débris from the mountains by way of the Yuba.

Other data affecting the curve are contained in the history of the development and restriction of hydraulic mining. The outflow increased with the increase of mining, and its rate of increase was, on the whole, more and more rapid until the restriction of mining, which began in 1884. The outflow of fine débris was then abruptly lessened, but the maximum discharge of coarser débris was not reached for several years. After the outflow of débris came to depend chiefly on the wasting of the temporary deposits of the mountains the rate of outflow was a diminishing rate, a rate destined to become very small when the deposits shall be nearly exhausted. The total outflow from the mountains is equal to the total volume of mining tailings less the volume of tailings so placed as to constitute permanent deposits. To supplement these data, two assumptions were made—first, that the rate of outflow in 1956 will be one-tenth the rate in 1906 and, second, that the volume of tailings remaining in the mountains in 1956 will be 25,000,000 cubic yards, and a curve of the variation of rate of outflow was then drawn to fit the data and conditions. That curve yielded the following estimates: Mining débris still remaining in the mountain deposits of the Yuba River basin in 1914, 65,000,000 yards; mining débris to be removed from the mountains by Yuba River in the 50 years following 1914, 42,000,000 yards. The first of these estimates has already been used in discussing the present distribution of the mining débris, and the second will be used in the consideration of its ultimate distribution.

SCOURING BELOW THE BARRIER.

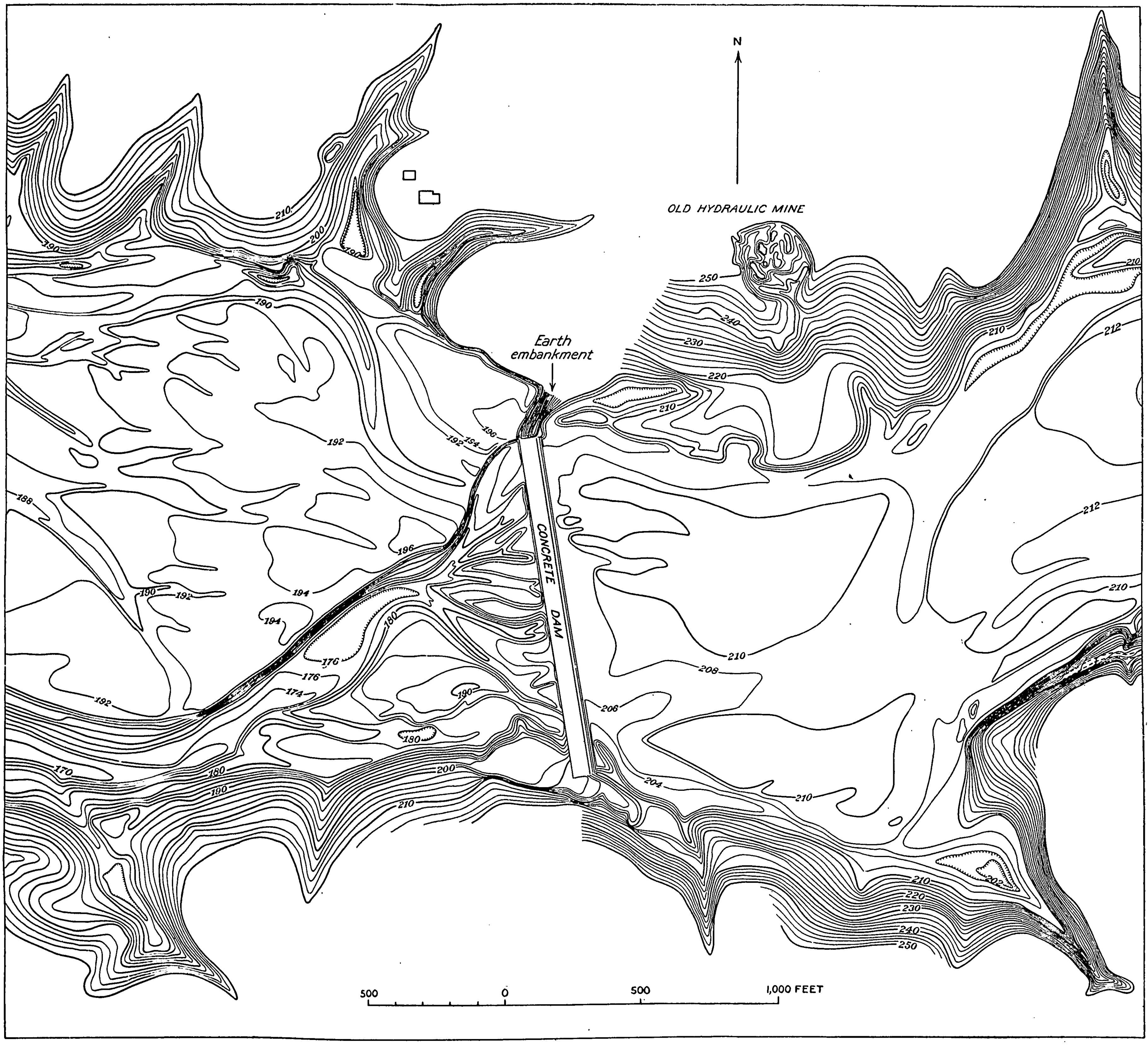
A stream flowing over a detrital bed adjusts the general slope of its bed, making it as steep as is necessary for the transportation of its bed load and no steeper. The adjustment of slope to load is accomplished, paradoxically, by means of a local adjustment of load to slope. Wherever the slope is too gentle for the load a part of the load is dropped, and the grade is thereby built up. Wherever the slope is steep enough to carry more load than the stream brings to it the stream increases its load by scouring the bed, and the slope is thereby pared down. Before the erection of the barrier the Yuba channel at that point was adjusted to the transportation of the bed load brought from the mountains in time of flood.[1] The barrier disturbed that adjustment by creating slack water and arresting the bottom load. The river passed from the crest of the barrier to the channel bed below without any load, but it could not flow without load on a slope of débris suited for the transportation of a large load. It therefore took up load and

[1] A few years earlier the piedmont deposit ceased to grow at this point, and its degradation probably began a little before the building of the barrier. The adjustment of slope to load may therefore have been approximate only, but any defect of adjustment was so slight that the statement in the text is practically warranted.



MAP OF THE BED OF YUBA RIVER ABOVE AND BELOW BARRIER NO. 1, IN OCTOBER, 1905.

By S. K. Baker. Contour interval 2 feet. The same configuration of bed is shown in Plate XXI, *A*.



MAP OF THE BED OF YUBA RIVER ABOVE AND BELOW BARRIER NO. 1, IN OCTOBER, 1906.

By C. L. Nelson. Contour interval 2 feet. The same configuration of bed is shown in Plate XXII, *B*, and in Plate XXV, *A* and *B*.

thereby scoured the old bed and reduced the slope. (See fig. 7.) The scouring continued below the barrier as long as deposition continued above it, and the rate of cutting below must have been approximately equal to the rate of filling above during the whole history of the barrier. So, although the barrier probably arrested in its first year one-half the bed load of the river and in its second year one-fifth, there is no reason to suppose that it diminished the river's load a few miles downstream.

It was in anticipation of this scour and to procure quantitative data concerning it that the survey of the river bed was extended half a mile below the barrier.

Prior to the construction of the barrier the river bed at that point had a width of about 1,500 feet and consisted of a platform of gravel,

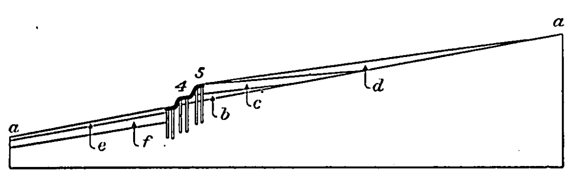


FIGURE 7.—Diagrammatic longitudinal section at barrier No. 1, Yuba River, illustrating the relation between fill above the barrier and scour below it. The straight line *a–a* represents the profile of the river bed before the placing of the barrier. The barrier was completed to the level marked "4" in 1904. Floods then made the deposit *b* and effected the scour *e*. The upper part of the barrier, 5, was added in 1905. The next flood made the deposit *c* and other floods the deposit *d*, and while these bodies were being added the volume *f* was removed by scour.

traversed near the left bank by a summer channel, 6 or 8 feet deep, in which the water level was only 3 or 4 feet below the level of the platform. The apron of the dam was sunk into this platform so that its upper surface was at approximately the same level.[1] After the completion of the first unit of the dam and after the basin thus created had been filled by débris brought down by the floods of one season the tract of channel immediately below the barrier showed evidence of moderate erosion. Minor channels a few feet in depth traversed the platform on several lines, and the main channel was probably deepened a few feet but without notable widening. The general degradation of the river bed perhaps amounted to an average of 2 or 3 feet. (See Pl. XXI, *A*.) It was at this time that the first contour map was made (Pl. XXIII). In the ensuing 12 months the second unit of the barrier was added, making its total height 14 feet. The basin thereby created was filled by the detritus brought down by the season's flood, and the second map (Pl. XXIV) was then made. A comparison of the maps shows that the floods of 1906 reduced the gravel platform through the greater part of its area, the average cut being 2.5 feet. It also greatly broadened and deepened the inner channel, the excavation in that region amounting to an average of 9 feet. The deepest line of channel in 1906 was on the average 19.5 feet lower than the deepest line in 1905. The appearance of the bed after these changes is shown by photographs reproduced as Plates XXV, *A* and *B*, and XXII, *B*.

The area of the river bed surveyed below the barrier was about one-third as large as the area above the barrier in which the surveys showed deposition to have taken place. From the former area 532,000 cubic yards were removed. If the area of deposition is divided into three tracts, each approximately equivalent to that below the barrier, the volume deposited on the lower tract was 883,000 cubic yards; on the middle tract, 545,000 cubic yards; on the upper tract, 261,000 cubic yards.

When the water of a stream falling from a ledge plunges down onto a bed occupied by detritus, it produces and maintains at the foot of the cataract a deep hollow occupied by a pool, and the thalweg rises in leading from this pool to the channel beyond. If there was any tendency of the water that passed over the barrier to produce a pool of this sort it was successfully combated by the quarry rock inserted as a riprap at the toe of the dam, and the result of the excavation was a general profile with continuous descent downstream from the edge of the barrier. This feature of descent, as well as the fact that the reduction of surface below the dam included the whole width of the river bed, leaves no reasonable doubt that the reduction was caused by the application to the river bed of a flood discharge that was free or nearly free from bottom load and therefore competent to excavate the loose material over which it passed.

The great depth to which excavation below the barrier was carried suggests that the eventual breaching of the structure may have been due to the eddy reaction called tail erosion rather than to the erosion and piercing of the

[1] This description pertains to a period before the locality was visited by the author and is based on oral and published statements of the engineers in charge of the work. See Am. Soc. Civil Eng. Proc., vol. 32, pl. 6, 1906.

concrete facing. During the earlier part of the great flood of March, 1907, the channel below the barrier may have been excavated still deeper, enabling the tail erosion to overpower the protecting riprap and undermine the system of piles and cables constituting the framework of the barrier. On the other hand, it is possible that the gradually increasing stream of detritus pouring over the barrier checked the excavation on the downstream side and determined a change from cutting to filling. However that may be, it is abundantly evident that a dam founded on a river bed of movable material will promote erosion on the downstream side in the same measure that it promotes deposition on the upstream side, and that such erosion is a factor to be reckoned with by the engineer.

The principle has various other applications and may be employed where erosion on the downstream side is a result to be sought as well as where its consequences are undesirable.

SEEPAGE.

In the autumn of 1905, after the basin created by the first unit of the barrier had been filled by detritus, and again in the autumn of 1906, after the filling of the basin created by the second unit, seepage water was observed under the toe of the dam. In 1905, when the seepage was delivered all along the toe of the dam at levels from 10 to 13 feet lower than the water surface above the dam, the discharge was measured and found to be 10 second-feet. This water contained no suspended matter but, having filtered through the deposit, was clearer than the water of the surface stream. Its freedom from detrital load showed that it was performing no work of erosion at the time of observation and that the deposit in the basin above, although it had not completely sealed the basin, had so retarded and regulated the flow of underground water that the movement of such water did not endanger the dam.

REMODELING OF CHANNEL.

The maps prepared for the purpose of studying the influence of the dam included a river tract about 5 miles long, but less than half of this tract was actually influenced by the obstruction in the year that elapsed between surveys. Nevertheless the whole tract was remodeled by the river. The flood channel in this portion of the Yuba is definitely limited by permanent walls, and its bed is a floor of gravel from 500 to 1,500 feet wide. This floor is traversed by one or more minor channels, which for half the year carry all the water and which are much more than sufficient for the flow of late summer and autumn. The remodeling of the bed of the flood channel included a rearrangement of the minor channels, and its scope is fairly illustrated by comparing the minor channels of 1906 with those of 1905. Similar rearrangement occurred in other seasons, as is shown by extending the comparison to the Débris Commission map of 1898 and to a map made by the Geological Survey in 1908. The channel outlines of the four maps are assembled in figure 8, but the reproductions include only that part of the river between the narrows and Parks Bar Bridge, a part not affected by the artificial changes at the barrier.

The species of channel shifting thus illustrated appears not to belong to either of the two types to which the attention of the physical geographer has been directed, although it is covered by the experience of the hydraulic engineer. In the shifting associated with meanders the main channel of the stream is affected. Its position is gradually changed by the eating back of one bank and the building out of the other, and the whole series of changes constitutes an orderly, predictable development or evolution. The shifting associated with a system of anastomosing or "braided" channels is conditioned by rapid deposition, whereby a delta or alluvial fan is built up. A channel is clogged by a local deposit that acts as a dam, causing part of the water to overtop the channel wall, and the overflow excavates a new channel. The distribution of detritus over the plain is thus accomplished by the frequent diversion of the streams of the plexus, and the deposition of detritus is the occasion of the diversion. In the Yuba near Parks Bar Bridge the main or flood channel is not shifted, its position being fixed by the walls of the valley, but the minor or low-water channels, which are features of the bottom of the main channel, shift from season to season. The changes take place during floods and their results are revealed at low stages.

The explanation I suggest is that the system of component currents within the flood torrent, as well as the associated system of diverse

A. DOWNSTREAM FACE OF THE COMPLETED BARRIER AFTER THE PASSAGE OF FLOODS THAT FILLED THE RESERVOIR WITH DÉBRIS.

Photographed September 19, 1906.

B. A NEARER VIEW.

The lowest of the three benches of the structure is the concrete apron. (See Pl. XXI.) The river bed was originally at this level, and its lowered position was caused by erosion. The angular stones seen at the left were placed below the apron after the erosion which followed the completion of the first unit, as riprap to protect against scour and back lash. A heavier body of riprap was being placed at the date of this view, and some of it appears at the right.

EROSION BELOW BARRIER NO. 1, YUBA RIVER, RESULTING FROM DEPOSITION ABOVE THE BARRIER.

velocities, varies with the magnitude of the flood. Each particular discharge, conditioned in its action by the fixed resistance of the outer banks, tends to develop a particular configuration of the bottom and if continued long

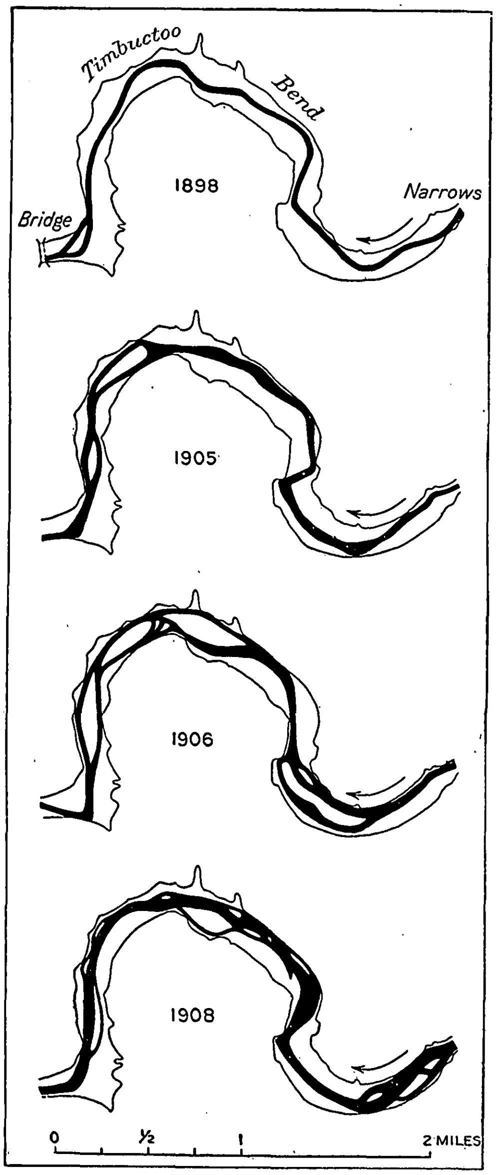


FIGURE 8.—Position and form of the low-water channel of Yuba River from Smartsville narrows to Parks Bar Bridge in different years. The outer lines show the high banks limiting the flood channel. The shiftings of the débris bed which modified the low-water channel were effected by the flood currents.

enough will establish that configuration. As a flood waxes and wanes, or perhaps oscillates in height, there is a sequence of such influences, and this sequence has individual characteristics with each flood. The resulting configuration, uncovered at the end of the flood, is thus a function of a complex of conditions, and the configurations wrought by different floods reflect in their diversity the diversity of the flood histories.

DAGUERRE POINT DAM AND TRAINING WALLS.

The general project adopted by the California Débris Commission for the control of the mining débris in Yuba River included several structures besides barrier No. 1, and two groups of structures have been successfully installed and are now effective. To understand how and why they modify the regimen of the river it is necessary to take account of what may be called the natural history of the piedmont deposit, and the following paragraphs attempt to outline that history.

The channel of the river from the mouth of its mountain canyon to its junction with the Feather was originally of gentle slope and moderate width. The banks were of resistant material, so that the channel could not shift. The channel bed was mainly of gravel. The stream was able to transport gravel on a bed of gentle slope because the quantity of débris supplied to it was small. When hydraulic mining greatly increased the stream's load, the slope was automatically increased by building up the bed, the amount of filling being greatest at the mouth of the canyon. One effect of the upbuilding was to broaden the waterway. A flood plain was created, over which flood waters were spread and on which channels were continually shifted and otherwise modified. The broadening of the stream at time of flood tended to reduce its transporting power and made the slope required for transportation steeper than it would have been with a narrower channel. The first mining débris to arrive was fine silt; afterward came sand also, and later gravel. At each stage of the invasion deposition was selective, coarser material lodging near the head of the piedmont deposit and finer material near its foot at the mouth of the river. At an early stage the visible deposit was mud at the mouth and sand near the mountain canyon. At a later stage the visible materials were sand below and gravel above. At the head of the deposit the slope was suitable to transport the coarser débris there constituting the bed, but farther down the slope was adjusted to the transportation of finer material only.

At the culminating stage of the deposit its head lay within the mountain canyon, and the slope of the channel was there comparatively gentle, 5 or 6 feet to the mile; that slope sufficed for the transportation of coarse gravel because the channel was narrow. In the next few miles downstream the quality of the load remained nearly the same, but the bed grew broader, and the slope, responding to the change in width, became steeper, a maximum of about 20 feet to the mile being reached. Farther down, although there was still for some miles an increase of width, the change in the material of the load became the controlling factor, and the slope diminished as the débris became finer. At the mouth of the river the surface of the deposit was sand and the forward slope of the bed was about 5 feet to the mile.

Up to this epoch, which was reached some time between the years 1895 and 1900, the whole history of the deposit had been one of growth. The supply of débris from upstream, gradually lessening for many years, now became so small that further increase of the slope near the head of the deposit was not demanded by the river's load, and growth ceased there, although continuing farther down. Then, with further reduction of débris supply, erosion began at the head of the deposit, but there only. The coarse material eroded was deposited farther down and all the downstream parts of the deposit continued to grow.

It was at this stage that the natural course of events was interrupted by permanent artificial constructions. The natural course would have been substantially as follows: The erosion at the head of the deposit would affect the entire width of the deposit within the canyon, but outside of the canyon a trench would be made. This trench would afterward be deepened and broadened. It would be extended downstream slowly and would not approach the mouth of the river for a number of years. Meantime the gravel eroded from the trench would be joined to the débris from the mountains and would help to build up the lower slopes of the piedmont deposit, and the plain of sand near the mouth of the river would be gradually converted to a plain of gravel. Eventually this plain also would be trenched and the flood plane of the river permanently lowered, but for several years, and perhaps for many years, the flood plane at the mouth would continue to rise, with attendant injury to the city of Marysville and neighboring districts. In the development of the trench through the deposit there would be much lateral erosion, and the ultimate result would be a valley bordered by terraces of gravel. The original slope of the channel bed would be approached, but not reached, because the river's load of débris will not again be so small as before the advent of the whites.

Daguerre Point (see fig. 6) is 4.5 miles below barrier No. 1 and about 10 miles above the mouth of the river. The general width of the débris plain near the point is 8,000 to 9,000 feet. At the point it is 1 mile. The point is a small hill connected with the low upland north of the plain by a narrow neck. An artificial channel has been excavated through this neck, and the floor of the channel, which is not of strong material, has been protected by a sill or low dam of concrete. To turn the stream to this channel a barrier or embankment has been built from the hill of Daguerre Point to the south edge of the gravel plain. In order to connect with a suitable upland, it has been run upstream as well as across the plain. The southeast end rests against Hallett Point, about 1.8 miles from Daguerre Point. The crest of the concrete sill at the cut is a few feet above the level of neighboring parts of the gravel plain.

These works were completed in 1910, so that the flood waters of the following season flowed through the cut and had their level determined by the sill. An immediate effect was the filling of the shallow basin above the sill with débris, and after that the cut became a thoroughfare for the transportation of the river's load of débris. A permanent effect is the limitation of the possible degradation of the gravel deposit above Daguerre Point. A large body of débris will be removed by the river before the ultimate profile of the river bed is attained, but another large body will be permanently stored below the plane of that profile.

Closely associated with these works are two training walls, which extend down the débris plain from the sides of the Daguerre cut for a distance of about 2 miles and confine the river to a channel width of 2,000 feet. An effect of the confinement is to increase the efficiency of the current for the transportation of débris and enable the river to carry its load on a lower slope than would otherwise be necessary.

In combination with the reduction of débris load that followed the establishment of the sill, it has induced erosion of the channel bed below Daguerre Point and has restrained the normal tendency toward continued building up of the deposit in the neighborhood of the river mouth. The deposit near the mouth reached and passed its maximum phase earlier than it would otherwise be reached, and the maximum was less high. The training walls also protect considerable areas of the débris deposit outside them from attack by the current, and these portions of the deposit are probably to be regarded as permanently fixed. Before the establishment of the Daguerre barrier and the training walls the coarsest material of the débris plain near the river mouth was coarse sand. Soon afterward, and as a direct consequence of those works, gravel was carried along the main channel to the river mouth.

The hydraulic principle most emphatically illustrated by these results is that the efficiency of a current may be increased by confining it laterally, so as to make the ratio of the depth to width greater than it is under natural conditions on an alluvial plain; and it is thus possible to make a stream carry its débris load on a gentler slope than would naturally be assumed.

An important factor in the construction of the Daguerre Point works was the gold-mining dredge. That engine, advancing across a débris plain, digs a deep, wide trench and immediately fills it again with the same material. The digging takes place at the front of the dredge and the chief filling at the rear. The open trench between contains a pool of water on which the dredge floats. Within the dredge the débris is separated by a screen into coarse and fine. The fine, after treatment for the extraction of gold, is discharged into the pool. The coarse is discharged at the rear. As a result of this handling the site of the trench comes to be occupied by two distinct deposits, of which the upper is gravel without any admixture of clay or sand. The removal of the clay, sand, and very fine gravel which had previously occupied the interstices between pebbles of the coarser gravel does not greatly reduce the volume of that gravel, and consequently the total volume of the two new formations is greater than the volume of the same material as naturally combined, the increase of volume being nearly equal to the volume of the underlying finer formation. The course of the dredge is therefore marked by a ridge of gravel, and this ridge may rise 10, 20, or even 30 feet above the plain.

Before the completion of the Daguerre Point works gold dredges had been introduced on the débris plain of the Yuba; and their work was so directed as to construct the Daguerre embankment as a by-product of gold mining. That embankment, instead of being a single ridge, is a plateau of gravel. It is not impervious, but the water seeping through it does not affect its stability, and it is adequate for its purpose of turning the flood waters to the Daguerre cut.

The training walls also are embankments made by the gold dredges, after a futile attempt to construct them of the sand and fine gravel which there constitute the surface material. The chief source of gold in this vicinity is an ancient coarse gravel underlying the recently deposited tailings from hydraulic mining. By working a gold dredge along the line selected for a training wall the positions of the two formations were practically reversed, and the bouldery gravel which was lifted to the surface and constitutes the training wall is said to succeed in resisting the attack of flood currents. Some of its finer components were washed away at first, but there remains a facing of boulders which is adequate for the purpose.

The preceding paragraphs were written in 1914. In the following year the sill at Daguerre Point was raised 1.5 feet, the training walls below the cut were extended, and other training walls were constructed above the cut, thus increasing the protection against erosion.

Chapter VIII.—LOOKING FORWARD.

RIVER DÉBRIS FROM SOURCES OTHER THAN MINING.

In considering the future movements of water-borne débris in this region and their results, it is necessary to take account of the non-mining as well as the mining portion. The non-mining waste assumed importance at the same time with the mining waste. Its annual volume in the entire Sacramento-San Joaquin valley is now nearly as great as that of the mining waste, and its origin is connected with so many and so vital industries that restriction is impracticable. Agriculture and the use of roads are increasing and will continue to increase. The soil waste occasioned by them and by grazing is not likely to diminish, although the effect of expanding industries may in time be largely offset by the effect of improved methods. Although we can not now make a direct comparison between the soil waste under natural conditions and the soil waste as stimulated by non-mining industries, we may feel confident that the contrast is strong and that the streams, quite independently of mining conditions, are permanently charged with the transportation of loads greatly exceeding those furnished by purely natural agencies.

The additions to the débris output made by industries other than mining consist largely of soil waste, which is dominantly of fine grain. The mining débris likewise contributes more to the suspended load of streams than to the bed load, but its proportion of fine material is less than that of the soil waste. Much of the finer material from mining went immediately to the bays and inundated lands, and that which rested by the way and is still in transit is dominantly coarse. As the stores of mining débris are gradually depleted the supply of coarse débris to the Sierra rivers will diminish, but there will be less change in the supply of fine débris.

In considering the future movements of débris it is necessary to take account also of plans which have been adopted for engineering works to restrain débris on Yuba River and to control flood waters of Sacramento and Feather rivers.

RESTRAINT OF DÉBRIS ON THE YUBA.

The existing works on the Yuba—the Daguerre Point barrier and spillway and the associated training walls—are described on page 62. If no further measures are taken to restrain the river the slope of its bed will gradually be reduced both above and below the spillway, until a stable slope of about 5 feet to the mile is reached. The channel bed at the mouth will be lowered, along with that of Feather River, until the ante-mining level is approached or possibly reached. Along with the lowering there will be broadening of the river's trench, and the broadening will be carried in many places to the slopes of the ante-mining valley. The excavation will remove a large part of the piedmont deposit, but there will remain, first, the basal portion protected by the Daguerre Point sill; second, the portions lying north and south of the training walls; and, third, a system of lateral remnants, constituting terraces on the sides of the reopened valley. I estimate the quantity of débris which may thus be removed at 190,000,000 cubic yards, and the quantity fully protected by existing works at 140,000,000 cubic yards.

There is good reason, however, to believe that the river will not be permitted to accomplish this excavation without interference. By change in the river's work from deposition to excavation the problem of river control is simplified, for a tendency toward automatic intrenchment will cooperate with any works that may be erected to limit its wandering. All of the débris plain below Daguerre Point which has not been traversed by gold dredges is available for agriculture if it can be protected from the ravages of the river, and its agricultural value constitutes an incentive for the erection of levees or other protective works. Above Daguerre Point the débris plain is less available for agriculture, but the deposits beneath the plain are more available for gold dredging, and the operations of the dredge may be depended on to obstruct and restrict the river's work of excavation. It is not improbable that the dredging work will be so conducted as to practically fix the river channel by training walls of boulders. Finally, to the incentive of private interests is to be added the cooperative and regulative work of the California Débris Commission, which represents the interests of the general public.

Should engineering works restrict the river to a channel width of 2,000 feet the body of débris excavated from the Piedmont deposit will be only about 110,000,000 cubic yards instead of 190,000,000. The actual quantity to be swept into Feather River will probably fall between these limits.

FLOOD CONTROL IN THE SACRAMENTO VALLEY.

The area of periodically inundated lands in the Sacramento Valley is large. In 1894 the part directly associated with Sacramento River was estimated by Manson and Grunsky[1] at 1,254 square miles. In the reclamation of this land for agriculture one tract after another is surrounded by levees, and the natural facilities for the storage of flood waters are thus restricted. In consequence of the restriction the flood levels are raised, and lands are inundated that had previously not been covered. With the progress of reclamation up to the present time the total extent of inundation has not been greatly reduced, because the areas newly invaded by the water have been nearly as large as the areas from which the water has been excluded. The raising of the flood plane had the effect also of making the levees constructed earlier, too low, and it became evident that it would be impossible to reclaim the entire area unless provision was made for the freer escape of the flood water. To accomplish this a comprehensive plan would have to be adopted, and to this plan all future levee construction would have to be conformed. The subject was investigated by several boards of engineers, and a number of plans were formulated. The plan finally adopted by the State, in 1911, was that recommended by the California Débris Commission, and it included most of the features of a plan proposed by Marsden Manson and C. E. Grunsky in 1894.[2] Under this plan the State, through a special board, regulates the construction of private levees, and the United States, through the Débris Commission, executes all public engineering work; the cost of the public work is divided between the State and the Government. In the following outline the plan is developed only so far as is necessary to show its relations to the movement of débris.

Along those portions of Sacramento River that are bordered by lateral basins the channels are to be straightened in places but not so enlarged as to carry the entire flood discharge. The excess of flood discharge above the capacity of the channel is to be conveyed by wide accessory channels called by-passes. The first by-pass will be east of the permanent channel and will traverse Butte and Sutter basins. Weirs will be so arranged in the bank of the permanent channel that water will escape to the by-pass only during floods. At the south end of Sutter Basin the diverted water will be returned to the permanent channel and immediately rediverted on the opposite side, entering there a second by-pass to be separated by levees from Yolo Basin. At the south end of that basin the water will again be returned to the main channel. Along Feather River the same object will be attained by limiting flood waters to a belt wider than the channel proper but including that channel. From the south end of Yolo Basin to the mouth of Sacramento River the river channel will be enlarged so as to carry the entire flood discharge. These elements of the plan are shown in figure 9. The minor drainage now received by the lateral basins from both sides of the valley will be intercepted by suitable canals and guided to the by-passes, but the designs for these canals have not yet been prepared.

The execution of the plan will require a number of years. An immediate effect of its adoption was to stimulate the work of reclamation by landowners, and large additions to the leveed area are being made. The first of the public works to be undertaken, the enlargement of the lower river, has been begun. In the future conduct of operations some details of the plan

[1] California Comm. Pub. Works Rept., 1894, p. 28.

[2] The report of the commission, which includes statements of other plans, is published as H. Doc. 81, 62d Cong., 1st sess.

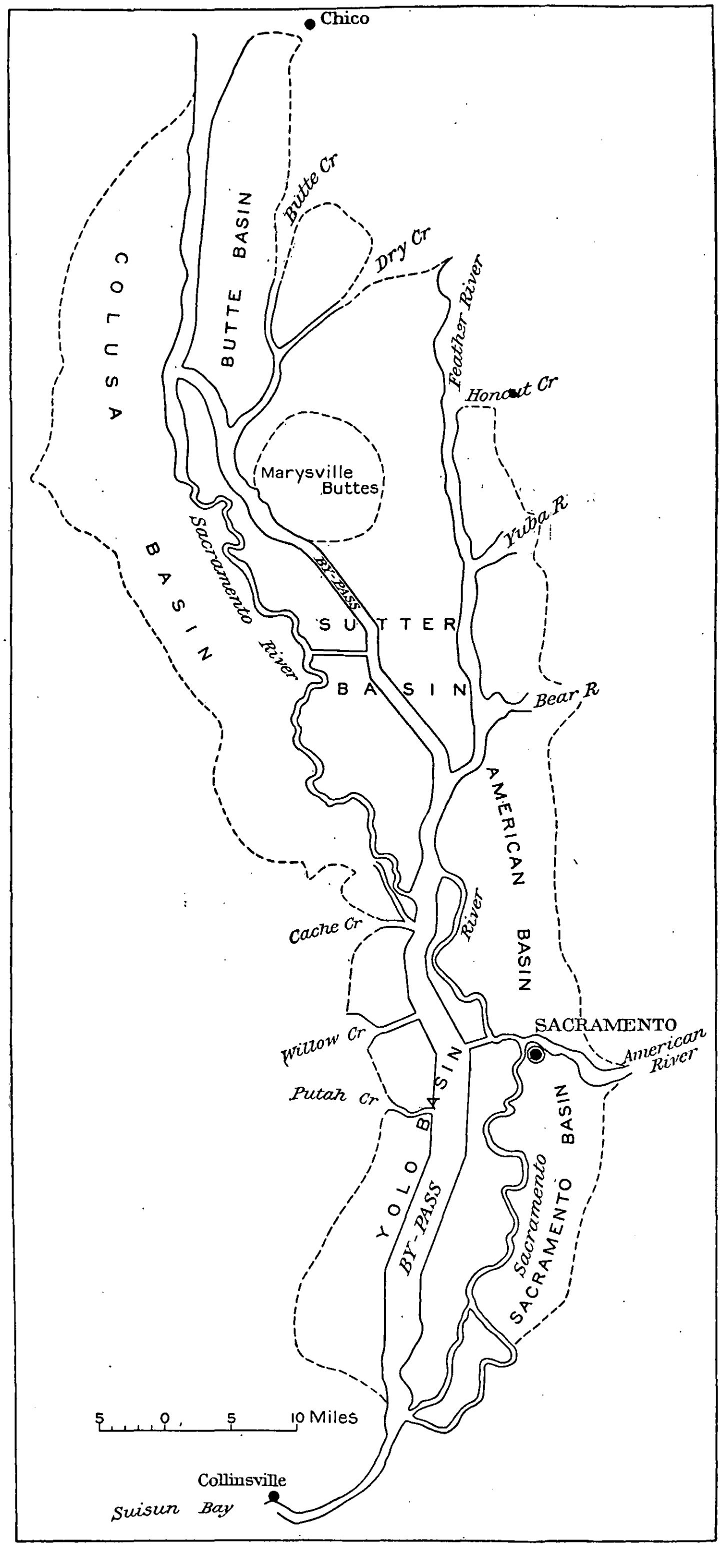
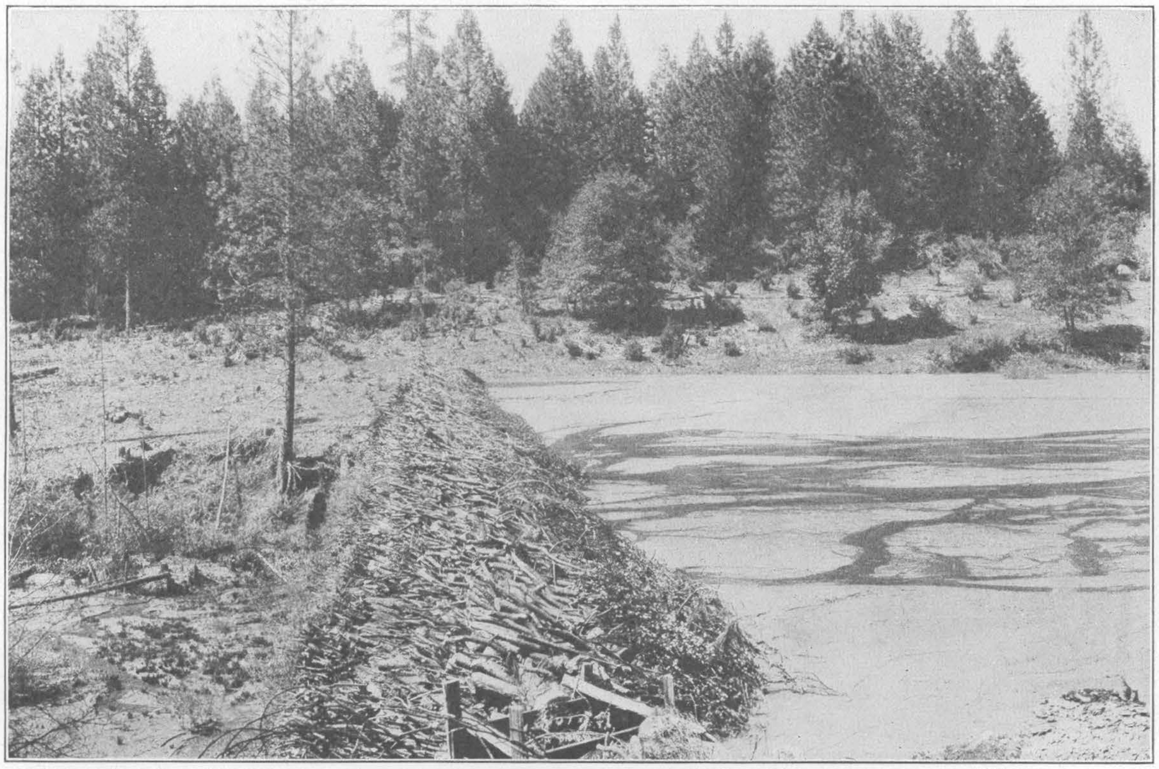


FIGURE 9.—Outline of the major levee system adopted for control of floods in Sacramento Valley. The full lines show levees; the broken lines show boundaries of the areas which will require protection because lying below the flood plane in neighboring river channels and by-passes.

will doubtless be modified, but it is hardly to be questioned that its main features will be realized.

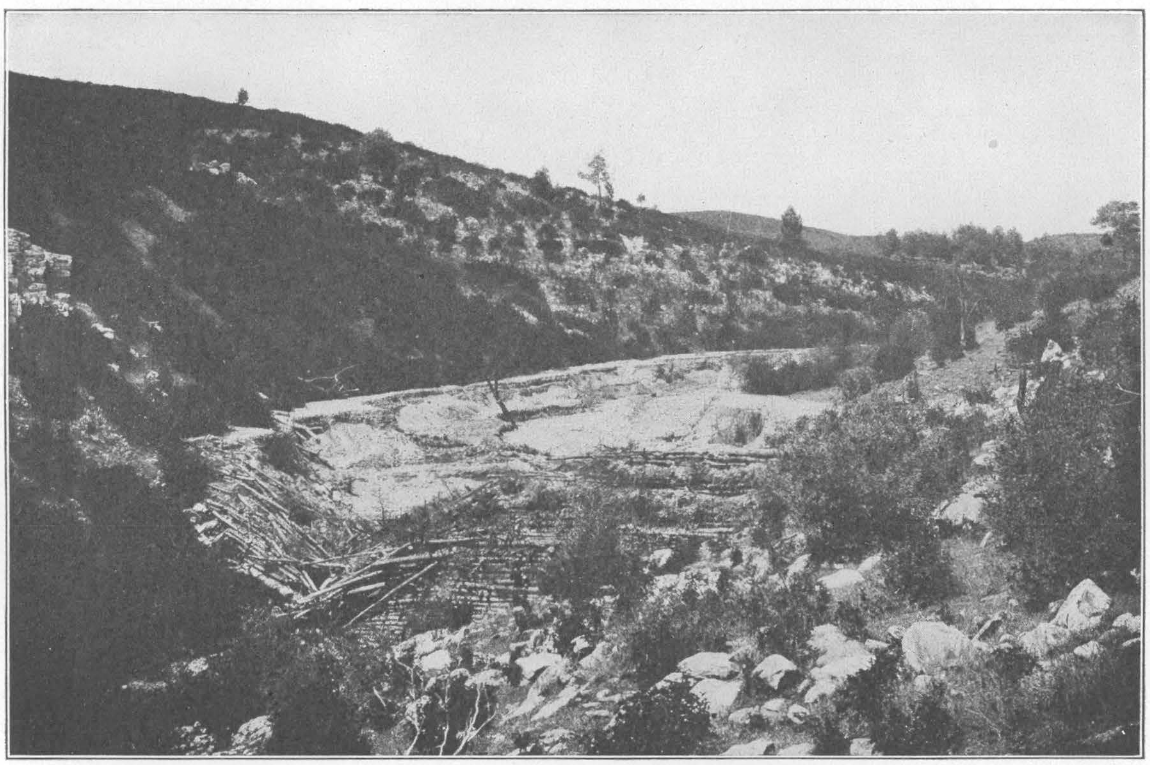
One of the consequences of the projected changes will be the exclusion of the river-borne débris from the lands now inundated. At the present time, as in past times, a considerable fraction of the fine débris carried by the flood waters is deposited on the inundated lands. The substitution of by-passes for flood basins is the substitution of channels for reservoirs. In these by-channels the velocities of flood waters will be sufficient to prevent permanent deposition. The routes of the intercepting canals have not yet been determined, but one of the prime conditions to be satisfied in their planning is that the canals have sufficient fall to prevent clogging by sediment. So they will not be receptacles of débris; and when the system shall have been completed all the fine débris will be carried to the bays.

Another result of the projected changes will be the strengthening of the current in the main channels of the rivers. Except in the immediate vicinity of the bay the flood plane will be raised and its slopes steepened, and these two changes, in combination, will quicken the flow in the channels. As a result of that quickening the transportation of bed load will be promoted and the channel beds will be scoured. The removal of the sand deposits caused by hydraulic mining, which has already commenced, will be accelerated. But for the enlarged output of non-mining waste the bed profiles of the rivers would eventually be reduced below their original positions, and it is not improbable that that result will be attained in a considerable portion of Sacramento River. The material thus scoured out will be carried to the bays.



A. MODE OF CONSTRUCTION.

Logs placed transverse to the direction of the stream alternate with layers of branches placed with the butts downstream, and a tangle of twigs helps to arrest the débris. The initial dam is low, and as débris accumulates against it additions are made. Photographed in May, 1908.



B. ANOTHER DAM, ILLUSTRATING A LATER STAGE.

After the filling of such a dam by débris a breach eventually occurs, unless the entire stream has been diverted to another course. The removal of the débris then begins and nearly all of it finally escapes. Photographed in 1905.

BRUSH AND LOG DAMS FOR STORAGE OF HYDRAULIC MINING DÉBRIS.

A. NOVEMBER 3, 1905.

First construction in 1901; height increased 10 feet in 1903. The crib work was filled with gravel, except a surface facing of quarry rock.

B. OCTOBER 27, 1908.

The dam had failed in 1907, four years after its completion. With better filling it might have lasted until the timbers began to decay, but its storage of débris was in any case temporary.

CRIB DAM FOR STORAGE OF HYDRAULIC MINING DÉBRIS.

The reclamation of extensive inundated lands bordering San Joaquin River is also in progress, and its effect on the movement of débris will be the same—the delivery of the entire output to the bays.

MINING DÉBRIS NOW STORED IN THE MOUNTAIN AND PIEDMONT DEPOSITS.

The deposits on the hydraulic dumps and in the valleys of upland creeks have been estimated at 265,000,000 cubic yards. The annual wasting of these has decreased in the past and will continue to decrease. The piedmont deposits have been estimated at 520,000,000 yards, and the annual wasting of these is perhaps not yet decreasing. The wasting of the Yuba deposit has barely begun, and the augmentation of its rate probably offsets the reduction in rate at other localities. After the lapse of, say, 50 years the annual tribute to the streams from both classes of deposits will have become so small that what then remains may be regarded as permanent. Guided chiefly by observations on the Yuba, I estimate the permanent deposits in the mountains at 100,000,000 yards and the permanent piedmont deposits at 335,000,000 yards. These estimates are necessarily arbitrary and rough. They leave as an estimate of total future waste from existing mountain and piedmont deposits 350,000,000 cubic yards.

In making these and other estimates of the volume of hydraulic tailings temporarily or permanently lodged in the mountains I have included, without specific mention, the tailings arrested by restraining dams constructed under permits issued by the California Débris Commission. In the early years of the commission's control its requirements were satisfied by dams of brush or of wooden cribs loaded with stone or gravel, and it is only in recent years that concrete dams have been prescribed. In a few projects separate spillways were provided for the streams on which brush and crib dams were built, but usually the streams were allowed to cross the crests of the dams, and in all such places the storage was not permanent. After the wood of brush and cribs has decayed, and often sooner, the dams are breached and the stored débris is exposed to wash. (See Pls. XXVI and XXVII.)

In considering what part of the mining débris now on the dumps should be regarded as permanently lodged and what part as merely delayed in transit, account was taken also of waste from the steep and bare walls of old hydraulic mines. (See p. 50.)

FUTURE DISTRIBUTION OF DÉBRIS.

From this time onward the valley rivers are not accumulators of débris, but the deposits they have previously acquired are to be gradually removed. Their work as carriers, always their chief work, will then remain. Their load, destined to diminish for some decades, will then have become practically constant but will be much larger than it was before the settlement of the country. Having formerly amounted, perhaps, to 2,000,000 yards annually, it will have a future average of not less than 8,000,000 yards. Assuming that a period of 50 years will close, for the rivers, the history of the hydraulic mining débris of the last century, we may now estimate for that period the rivers' entire work of transportation. From the débris deposits of the mountains and the piedmont they are to receive 350,000,000 cubic yards; from their own beds they will excavate 100,000,000 yards; and the soil waste brought to them will add about 400,000,000 yards, giving a grand total of 850,000,000 yards of débris.

Of the material to be contributed from mountain and piedmont deposits two-thirds is coarser than silt; the deposits now in the river channels are almost wholly of sand; of the soil waste seven-eighths is silt. Of the grand total 475,000,000 cubic yards may be classed as silt and 375,000,000 yards as sand and gravel, chiefly sand.

The inundated lands, from which the floods will be gradually excluded, probably during the first half or first third of the 50-year period, may be assumed to receive 10 per cent of the silt, or 50,000,000 yards. The remaining 425,000,000 yards will be delivered to the bays, and part of it will pass from the bays to the ocean. The coarser débris also will be delivered to the bays, but not in its present condition, for it will have been worn down in its long journey. Much of the sand will reach the bays as silt, and much of the gravel as silt and sand. It is possible that none of the gravel now in transit will reach the bays as gravel, but it may be assumed that as the pre-mining slopes of the river channel are approached the character of the pre-mining channel bed will also be approached. In a general way the mining débris now journeying along the beds of the valley rivers is of finer grain than the débris it overlies, and when that older and coarser débris shall again be exposed to the current the conditions may be suitable for its transportation. The conditions will not be the same as in the earlier period because the load of soil waste will be greater and because the flood discharge following the channels will be greater.

From the character of the channel deposit in San Pablo Bay (see p. 92) it is inferred that nearly the whole of the débris delivered to the bays, 800,000,000 cubic yards, will have been so comminuted before it comes to rest that it should not be classed as sand. The greater part of this material will be retained on the shoals of the bays, and a minor part, arbitrarily estimated at 40,000,000 cubic yards, will reach the ocean.

In completing a series of estimates in which personal judgment plays so important a part, I wish to repeat that my excuse for presenting them lies in the leaven of definite measurement they contain. The measurements of mining excavations in the Yuba River basin help to gage the largest body of débris at its source. The measurements of changes in the bays help to gage the transported débris at its chief point of deposition. The measurement of the Yuba's detrital load for a single season aids judgment as to rates of transportation. There is further aid in measurements of the greatest of the piedmont deposits and in numerous eye estimates by myself and others. In the use of the imagination by which these quantitative elements have been supplemented the attempt has been made to utilize all available laws of interdependence so as to organize the estimates into a consistent system.

Of the injurious effects of the mining débris only two have future importance, provided hydraulic mining continues to be regulated as at present. The encroachment of the débris on agricultural lands has ceased, and future developments in the areas of the piedmont deposits will be in the direction of their return to agricultural service. The influence of the débris on valley floods is steadily diminishing, is now less than the influence of the reclamation of lowlands by levee building, and in a few years will be so overshadowed by the greater results of reclamation as to be properly regarded as negligible. The conditions for navigation in the rivers are steadily improving and will soon equal those which existed before the débris invasion. But deposition in the bays will continue, with increasing obstruction to navigation and additional encroachment on the tidal prism.

Chapter IX.—RELATIONS OF DÉBRIS MOVEMENT TO THE GOLDEN GATE BAR.

PROCESSES AND CONDITIONS.

The depth of water on the bar outside the Golden Gate is a matter of prime importance to the port of San Francisco. That depth is believed to depend chiefly on two factors—the supply of sand brought to the bar and the velocity of the tidal currents by which it is distributed. Through these factors it may be affected by the flow of mining débris, by the increase of soil waste incident to the development of agriculture and other rural industries, and by the reclamation of marsh lands. It is proposed in the present chapter to discuss these influences, and in order to do so intelligently it is necessary to understand, at least in a general way, the natural processes by which the bar has been shaped and by which its form is maintained.

The bar is composed of sand. The sand has three sources—cliffs of the outer coast, cliffs of the inner coast, and streams tributary to the bays.

For 7 miles north of the Golden Gate the coast presents a series of cliffs, and it is evident that these are sapped and eaten back by the beating of the waves. The coarser waste from that erosion is drifted by shifting currents in two directions. Part of it reaches Bolinas Lagoon, where it is built into a bar across the entrance, and another part goes past Point Bonita to the entrance of the Golden Gate. Thirteen miles south of the Gate, at San Pedro Point, begins another line of cliffs from which the waste is swept in two directions. The larger part goes northward, is reinforced by other waste at and near Mussel Rock, and maintains the great beach (Ocean Beach) south of Point Lobos. A portion of its sand escapes from the sea and is blown inland, where it travels in dunes; another portion finds its way, either directly or indirectly, to the Golden Gate bar. Some of these geographic relations are shown in figure 15; they are more fully shown on United States Coast and Geodetic Survey chart 5500.

The mode of progression of the cliff-born sand involves the cooperation of waves and currents. Each wave disturbs the sand of the beach, momentarily lifting a portion, and while the grains are free from the bottom they drift with the current. Even a gentle current thus determines the direction of sand movement. On this part of the coast the normal direction of the shore current is northward. There is a slow northward drift known as the Davidson inshore eddy,[1] and this determines the dominant movement of sand; but strong northwest winds may temporarily reverse the current and sweep the sand in the opposite direction. The travel of sand is not confined to the immediate vicinity of the beach but may be induced by storm waves at considerable depths, and there can be no question that the crest of the bar is well within the range of such action, for large storm waves break in passing the bar, and the reaction of the bottom on the waves is the counterpart and index of the reaction of the waves on the bottom.

The shores of the strait and of the bays are washed by waves, and though the attack is less vigorous than on the outer coast it causes erosion and creates cliffs. Part of the débris from this erosion finds its way as sand to the channels and is swept to and fro by tidal currents, with a net movement toward the bar. The débris brought to the bays by rivers and creeks consists in part of sand and is carried forward in the same manner by the tidal currents.

In the map of the bar and strait (fig. 10) the configuration of the bottom is shown by contours with equal intervals of 10 fathoms. The headlands at the entrance to the strait, Point Bonita and Point Lobos, are separated by a space of 2.3 miles, but the bar has a length of about 13 miles, swinging seaward in a great arc. It is not closely united to the shore at either end, but is separated by chan-

[1] U. S. Coast Pilot: Pacific coast; California, Oregon, and Washington, 2d ed., p. 11, 1909; Coast Pilot of California, Oregon, and Washington, 4th ed., p. 227, 1889.

nels. The bar is wholly submerged, its crest lying from 5 to 6 fathoms below low-water level except at the north, where it has a minimum submergence of about 4 fathoms. But for the tidal currents the bar would extend in a direct line from Point Lobos to Point Bonita, and its crest, a continuation of Ocean Beach, would be above the level of high tide. Its great distance from the shore and its deep submergence are due entirely to the speed and volume of the ebb tides. Any modification of the bays which has the effect of reducing the volume of the tides tends to cause the crest of the bar to move landward and to rise nearer to the surface of the water.

The magnitude of the bar is affected also by the supply of sand. As the sand of its surface is agitated by currents and by the passage of storm waves, the grains are struck and rubbed against one another and are thereby broken and worn. The wearing process is slow, but its result is to reduce the grains until they are so small as to be carried far away in suspension. If there were no fresh supply of sand, the bar would waste away, and its magnitude at any particular time represents a resultant between supply and waste of sand. Any modification of natural conditions which has the effect of increasing the supply of sand will cause the bar to grow and will bring its

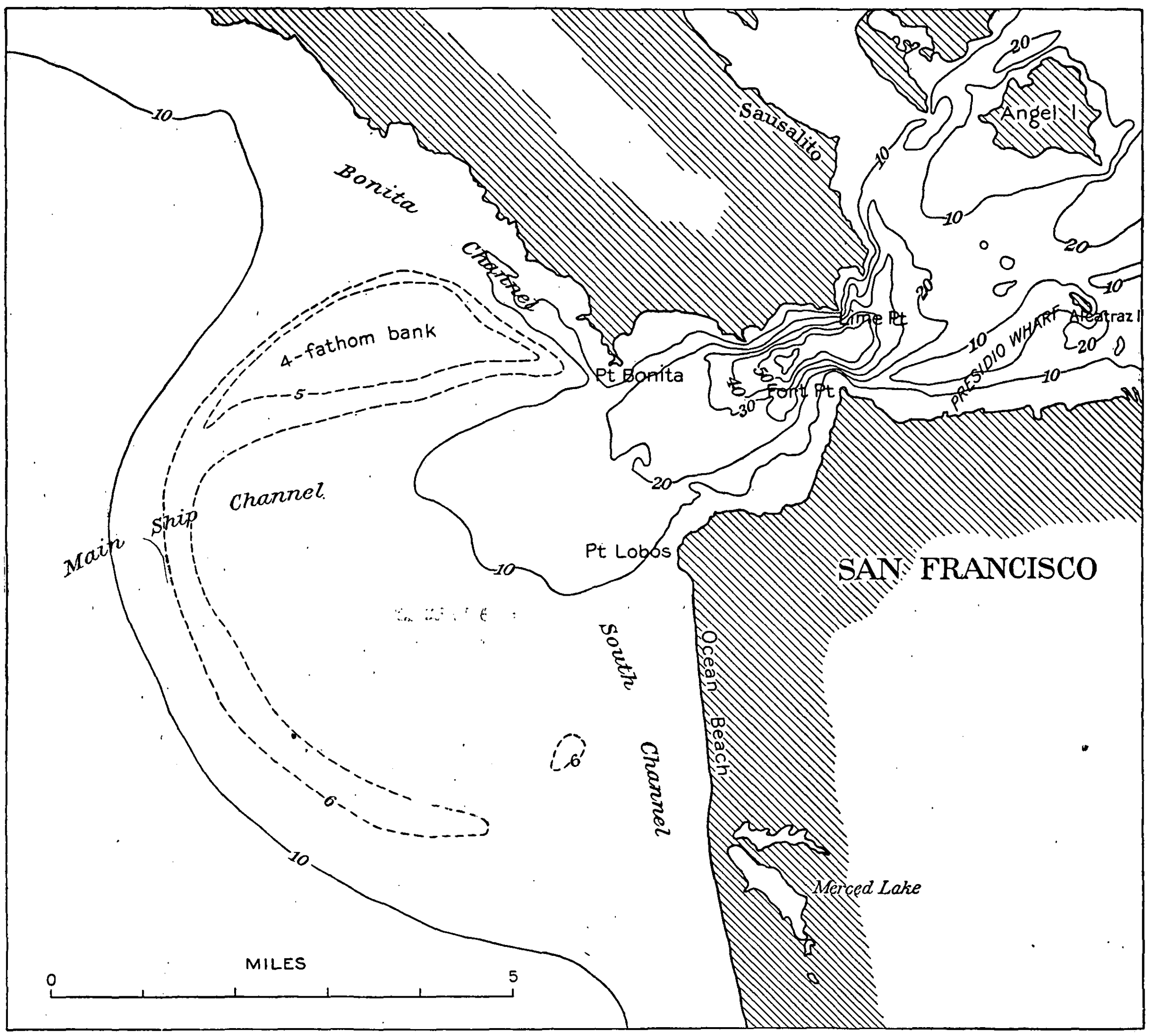


FIGURE 10.—Configuration of the bottom in the Golden Gate and on the Golden Gate bar. Based on chart 5532 of the United States Coast and Geodetic Survey, with additional details from original plats of survey. Contour interval, 10 fathoms. The 6-fathom and 5-fathom curves are shown on and near the bar by dotted lines. The dates of survey were, for the bar, 1900; for the strait west of Fort Point, 1894-1897; east of Fort Point, 1871-1873.

crest nearer the water surface. Some of the statements in this paragraph and the one preceding it admit of qualification, but it has not seemed best to expand this preliminary outline of theoretic relations. The subject will be resumed near the end of the chapter.

Where the strait is narrowest, in the vicinity of Fort Point, the tidal currents have their greatest velocity and maintain a very deep channel. There is one sounding of 63 fathoms; thence in both directions the channel shoals as it broadens. Outside the headlands the bar incloses a funnel-shaped basin, deepening toward the strait, as shown in figure 30 (p. 140).

When the tide rises outside the bar, it tends to flow into the basin from all sides but is opposed in part by the momentum of the still-flowing ebb tide, which is directed westward. It results that for a time the currents set outward across most of the bar but inward through Bonita and South channels.[1] During the period when the ebb tide is strong its courses outside the strait are much influenced by the momentum acquired within the strait. It spreads to all parts of the bar, but its strongest set is toward the west and southwest. It does not send a strong current through South Channel, and it is said to create an eddy current southwestward in Bonita Channel. Thus in Bonita and South channels the principal currents are toward the entrance to the strait, while those away from the strait are feeble. It can hardly be questioned that all the sand which drifts southward from the cliffs north of Point Bonita is carried by the flood-tide currents of Bonita Channel to the entrance of the Golden Gate and is then borne by the currents of ebb tide outward to the bar. South of the entrance the evidence is less clear, but I regard it as probable that the chief route of the sand which has followed the coast from San Pedro Point and Mussel Rock is northward with the flood tide through South Channel until it reaches a position where it may be controlled by the ebb-tide current from the strait. Along a zone which is common ground for the two currents the sand is probably drifted to and fro, but, inasmuch as the directions of the currents intersect at an angle, the course of each grain is a zigzag, and the resultant effect is a drifting southwestward in the direction of the axis of the bar.

[1] Coast Pilot of California, Oregon, and Washington, 4th ed., p. 227, 1889.

The direction of sand movement along the bar crest in its medial or western portion probably depends on the general movement of water parallel to the coast. According to Davidson, that movement is northward, but the evidence he cites pertains almost wholly to more northerly portions of the coast. At the lightship moored 4 miles outside the bar the surface current is found to vary with the direction of the wind. If Davidson's view is correct, the sand drifted along the bar crest helps to maintain the 4-fathom bank. In any case, an important factor in determining the existence of the bank is the relative weakness in that direction of the ebb current from the strait.

THE EFFECTIVE TIDAL PRISM.

During the rising of the tide water flows from the ocean to the bay; while the tide is falling the flow is toward the ocean. The general measure of the volume which thus passes through the strait is the space between the

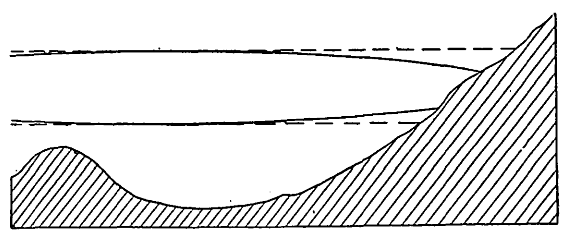


FIGURE 11.—Ideal section of effective tidal prism in a large bay.

plane of high tide and the plane of low tide within the bay, a space known as the tidal prism. For a small bay, in which high tide occurs everywhere at nearly the same time, this general definition suffices, but the San Francisco Bay system is so extensive that high tide reaches different parts at very different times, and it is necessary to take account of these differences in estimating the tidal discharge. In seeking a more specific definition there is advantage also in substituting for the times of high tide and low tide the two times of slack water which follow the times of high and low. The volume of water which flows through the bay between any time of slack and the time of the following slack is equal to the volume of the space between the "water plane," or position of the water surface, at the first time and the water plane at the second. In the diagrammatic section of a bay in figure 11 the full lines represent the water planes of two slack-water times. The broken lines represent the levels reached by the high water and low water of the tidal wave as it travels through the bay, and these levels, although neither of them is occupied simultaneously through its whole extent by water surface, are usually called the high-water and low-water planes. The space between the slack-water planes, or the effective tidal prism, is less than that between the "planes" of high tide and low tide.

In an estuary so long that the passage of the tidal wave occupies several hours the planes of the two slack-water times may intersect, and they may even cross more than once. Figure 12 represents a hypothetic case in which there are two intersections, the plane of one slack-water time being represented in profile by the line *AEHGB* and the plane of the other by the line *CEFGD*. It is evident that the effective tidal prism is equal to the volume of the space represented in section by the area *AEC*, minus the space represented in section by the area *EFGH*, plus the space represented in section

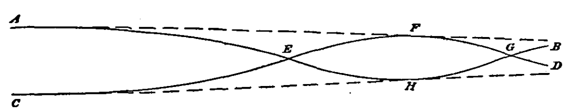


FIGURE 12.—Ideal section of effective tidal prism in a long estuary.

by the area *BGD*. The tidal oscillation between *E* and *G* reduces instead of augmenting the tidal discharge and therefore reduces the force of the tidal currents at the mouth of the estuary, and this general fact is of special interest in the present connection because it is illustrated by the tidal phenomena of the San Francisco Bay system.

The position *AC* in figure 12 may represent any cross section of an estuary, and for each section there is a separate and different effective tidal prism determining the tidal volume at that section. For the discussion of conditions in the San Francisco Bay system we need to consider the volume at several points, but especially at the bar outside the Golden Gate. It happens, however, that the available data apply much better to the determination of the volume flowing through the narrowest part of the strait—at Fort Point—than to the determination of that flowing across the bar, and computations will for that reason be made for the Fort Point section. The velocities at bar and strait are so intimately related that, for the purposes of this investigation, the difference in locality is unimportant.

MEAN TIDAL VOLUME AT THE GOLDEN GATE.

THE OPEN-WATER EFFECTIVE PRISM.

The tidal volume is greater for some tides than for others. Computation will first be made of the volume corresponding to a tide of average range. It is convenient to consider separately, first, the effective tidal prism of the open water of the bays, and second, the additional storage of tidal water on marshes.

The chief body of data required for the computation of the effective tidal prism is re-

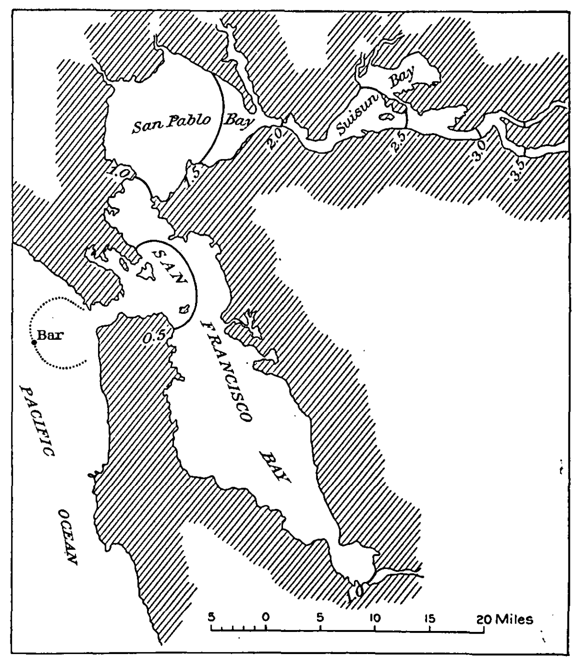


FIGURE 13.—Cotidal lines in the San Francisco Bay system.

corded by the United States Coast and Geodetic Survey in the Tide Tables. Those data include, for many stations about the shores of the bay, (1) the mean range of tide, (2) the average difference in time between high water at the station and high water at Fort Point, and (3) the average difference in time between low water at the station and low water at Fort Point. To complement these data it is necessary to know also the time interval at the Golden Gate between high water and the following slack water, and the interval between low water and the following slack water; and to obtain this information special series of observations were undertaken in September, 1914. A record and discussion of the observations is contained in Appendix A (pp. 108–120). The resulting estimates of average slack-water intervals are, after high water, 57 minutes; after low water, 114 minutes.

The cotidal lines in figure 13 show by half-hour intervals the successive positions of the tide wave (high water) as it moves through the bays.[1]

tervals between slack water at Fort Point and the extremes of tide at the stations, the slacks which severally follow high tide and low tide at Fort Point being distinguished as high-water slack and low-water slack. The fifth column gives for each station the mean range of tide. The numbers in the sixth column were computed from those in the third, fourth,

TABLE 15.—*Data for mean effective tidal prism of San Francisco Bay system as affecting the discharge at the Golden Gate.*

Station.	Distance.	High water at station follows high-water slack at Golden Gate by—	Low water at station follows low-water slack at Golden Gate by—	Mean range of tide.	Range effective for current at Golden Gate.
	Miles.	*Minutes.*	*Minutes.*	*Feet.*	*Feet.*
Fort Point, Golden Gate	0	− 66	−107	3.9	2.9
San Francisco Bay:					
Mission Street wharf	6	− 38	− 76	4.2	3.7
Goat Island Light	6	− 38	− 74	4.0	3.5
Avisadero Point	11	− 34	− 67	4.6	4.1
San Mateo Point	21	− 21	− 51	5.1	4.8
Guano Island	24	− 18	− 37	5.7	5.5
Coyote Hill Creek entrance	27	− 6	− 31	5.7	5.6
Redwood Creek entrance	28	− 10	− 36	6.1	5.9
Ravenswood	30	− 9	− 25	6.0	5.9
Alcatraz Island Light	3	− 55	− 94	3.6	2.9
Sausalito	3	− 61	− 88	3.7	3.0
Angel Island	4	− 57	− 80	3.8	3.2
West Berkeley	10	− 21	− 56	4.3	4.0
San Quentin Point	13	− 8	− 44	4.1	3.95
Brothers Light	14	− 5	− 41	4.2	4.0
San Pablo Bay:					
McNear's Landing	15	− 4	− 43	4.0	3.85
Point Wilson	22	34	12	4.7	4.6
Petaluma Point	24	0	− 15	4.5	4.5
Sonoma Creek entrance	26	16	1	4.5	4.5
Carquinez Strait:					
Mare Island Light	27	39	18	4.8	4.6
Wheatport	28	49	32	4.7	4.4
Benicia	31	74	57	4.7	4.0
Suisun Bay:					
Seal Bluff	38	81	78	4.9	3.8
Suisun Creek entrance	39	93	90	4.7	3.3
Sacramento River:					
Collinsville	49	135	148	3.9	1.4
Sacramento	113	417	517	1.5	−1.0
San Joaquin River:					
Antioch	53	168	186	3.9	0
Stockton [a]	94	414	493	2.5	−1.4

[a] The intervals and mean range for Stockton were furnished by an officer of the Engineer Corps, U. S. Army, with the statement that they are approximate only.

In Table 15 the first column contains the names of stations at which tidal constants available for the discussion of the prism have been determined. In the second column are distances along the lines of tidal propagation. In the third and fourth columns are time intervals between slack water at Fort Point and the extremes of tide at the stations, the slacks which severally follow high tide and low tide at Fort Point being distinguished as high-water slack and low-water slack. The fifth column gives for each station the mean range of tide. The numbers in the sixth column were computed from those in the third, fourth, and fifth (with the aid of certain other tidal elements not here stated) and show for each station the change in water level occurring between two consecutive times of slack water at Fort Point. All quantities are annual means.

The heights of the effective tidal prism (sixth column), or the effective ranges of tide for the stations, were plotted on a map and by their

[1] The time unit is the lunar hour, 3.5 per cent larger than the mean-time hour. A similar plot for low tide would be somewhat different, as the low tide travels more slowly. The distance covered by high tide in 3 hours requires for low tide about 3.8 hours.

aid the average height of the effective prism was estimated for each of several divisions of the bay system. These averages are contained in Table 16 (p. 75).

Certain of the ranges were used also in the construction of figure 14, where they are plotted on a scale of distances which represents the route of the tide from the Golden Gate, through the northern part of San Francisco Bay, San Pablo Bay, Carquinez Strait, Suisun Bay, and Sacramento River, to the city of Sacramento. The plot does not include data for the southern arm of San Francisco Bay nor for San Joaquin River. The horizontal line marked 0 is the zero of tidal range. The circles represent local mean ranges, and their irregularities are related to the fact that the stations do not stand in line but are scattered about the shores of the bays. The curve *AB*, associated with them, is intended to show the variation of mean range along the line of the main channel. The range at Sacramento was determined in 1857, before the river channel had been greatly modified by mining débris. The ranges effective for the times of slack water at the Golden Gate are indicated by crosses, and only those for stations near the main line of channel are plotted. The corresponding curve, *CD*, is close to the mean range curve in the part corresponding to San Pablo Bay and beyond that part descends. The effective range changes from positive to negative a few miles above the mouth of Sacramento River and should become again positive a few miles above Sacramento. Between Collinsville and Sacramento accurate observations are lacking, but somewhere in this tract the negative effective range has a maximum.

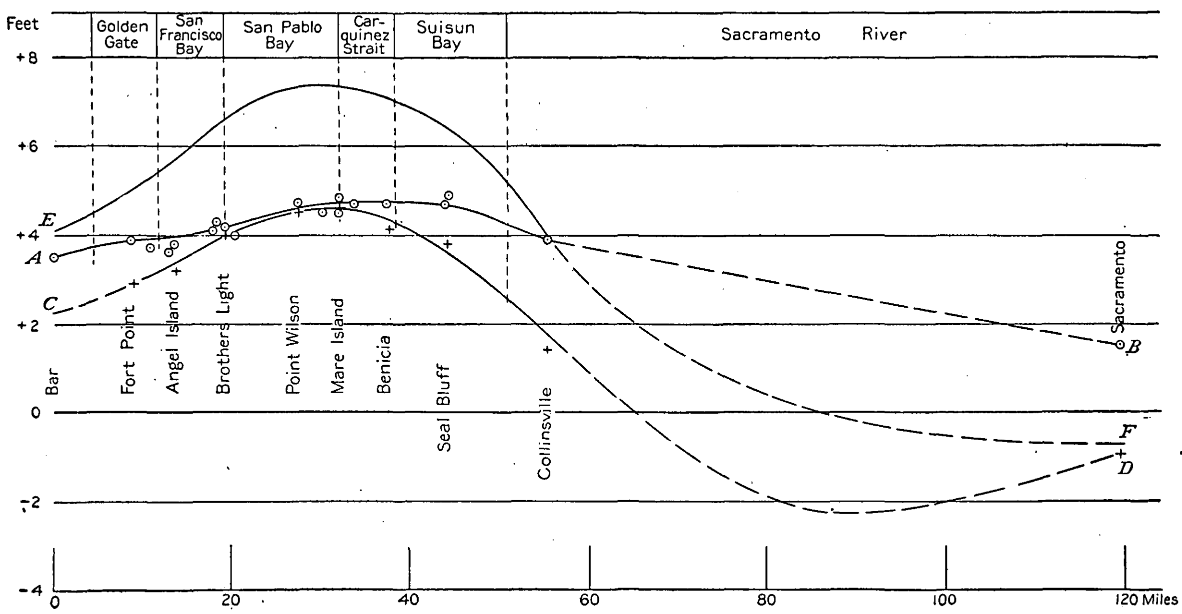


FIGURE 14.—Profiles of tidal range along the line of the main channel from the Golden Gate bar to Sacramento. *AB*, Mean range of tide = average local high water above average local low water; *CD*, effective mean range, computed with reference to tidal volume at the Golden Gate; *EF*, effective tropic range.

The facts illustrated by this curve are (1) that the volume of tidal current through the Golden Gate which corresponds to mean range of tide realizes a large fraction of the full effect in San Francisco Bay, (2) that it realizes nearly the full effect in San Pablo Bay, (3) that it realizes a rapidly diminishing fraction of the full effect for Suisun Bay and the lower reaches of Sacramento River, and (4) that the discharge is reduced by tidal volume for higher reaches of Sacramento River. So far as tides of mean range are concerned, the abridgment of tidal storage by artificial means may weaken the currents at the Golden Gate and the bar, may strengthen them, or may not affect them, its relation to the currents depending on locality.

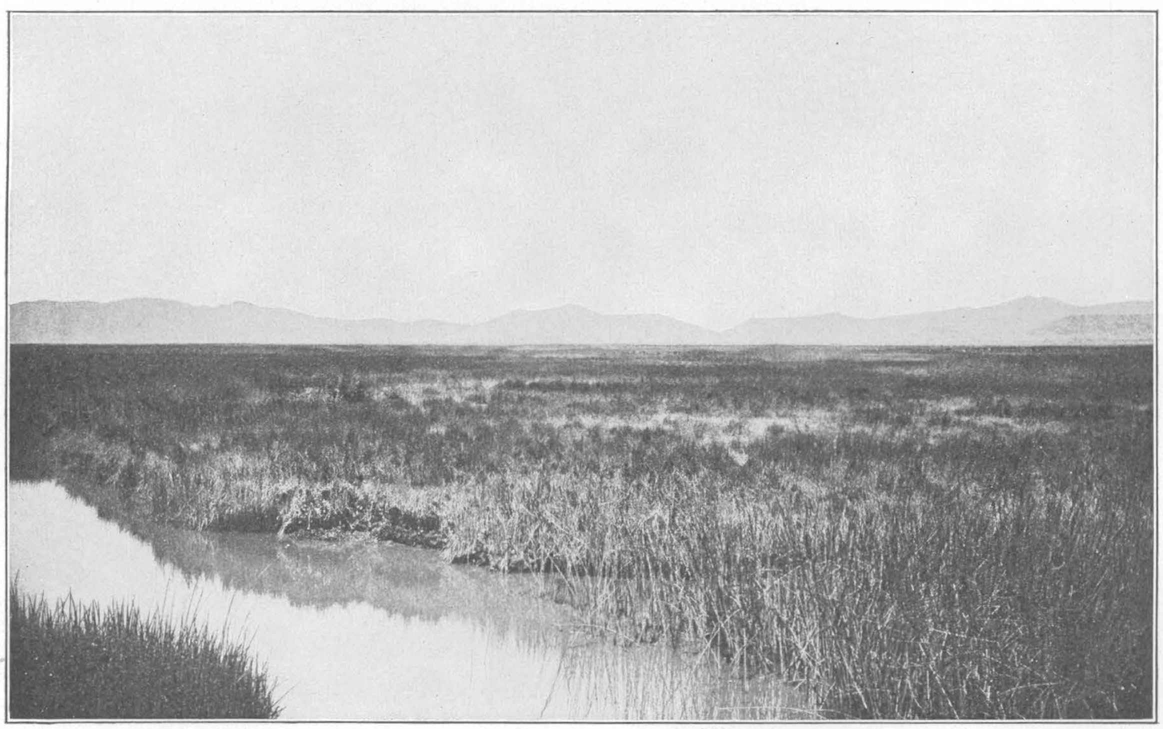
In computing the tidal volume through the Golden Gate account is taken of the effective ranges and the associated areas. So far as practicable the areas of the water bodies were measured on charts made before the invasion

A DELTA MARSH BORDERING SAN JOAQUIN RIVER.

The foreground shows the dominant vegetation of the tidal marshes where the water is fresh or nearly fresh. The bushes mark the position of the natural levee, here low. An artificial levee may be faintly seen above the rushes. The work of reclamation was in progress at the date of the view, August 31, 1905.

A. A RECLAIMED DELTA MARSH, BORDERING SACRAMENTO RIVER.

In the center is the artificial levee, which stands on the natural levee. The river is above mean stage and its surface is several feet higher than the land seen at left. The orchard stands on the inner slope of the natural levee. (Compare Pl. XXVIII.)



B. TIDAL MARSH NORTH OF SUISUN BAY, WITH TIDAL SLOUGH IN FOREGROUND.

Photographed in June, 1905.

TIDAL MARSHES.

of the bays by mining débris, but that was not possible for every body of water. The dates of the surveys are recorded along with the areas in Table 16. Each tabulated area of a bay is the arithmetic mean of the high-water area and the low-water area as charted. The high-water line of the charts represents the water margin at approximately mean high-water stage, but the low-water line does not represent the margin at the coordinate mean low-water stage. It is the contour of the "plane of reference" and represents the margin at the mean of lower low-water stages. The depression of mean lower low water below mean low water is about one-fourth of the mean range of tide. In consequence of this discrepancy the low-water area obtained from the charts is too small and so is the computed half-tide area. If a correction were to be applied it would increase the estimate of total area by about 1.5 per cent and would correspondingly increase the estimate of tidal volume.

The river areas given in the table include some of the more important sloughs.

TABLE 16.—*Computation of the mean tidal volume at the Golden Gate, so far as given by the effective tidal prisms of the bays and other bodies of open water.*

Body of water.	Year or years of survey.	Area at half tide.	Mean depth of effective prism.	Volume of effective prism.
		Sq. miles.	*Feet.*	*Cubic feet.*
San Francisco Bay:				
Southern part	1857–58	188.3	4.7	25,660,000,000
Northern part	1855	77.4	3.7	7,980,000,000
San Pablo Bay	1856	106.8	4.45	13,250,000,000
Napa Creek	1856, 1860	5.0	4.3	680,000,000
Carquinez Strait	1857, 1866	8.0	4.25	950,000,000
Suisun Bay	1866–67	[a] 47.9	3.1	4,140,000,000
Sacramento River	1886, 1906–1908	8.8	−.27	− 64,000,000
San Joaquin River	1886, 1907–1912	16.8	−1.80	− 843,000,000
		459.0	....	51,753,000,000

[a] This area includes Sacramento River to Collinsville and San Joaquin River to Antioch.

WATER STORAGE ON MARSHES.

The marsh lands that border the bays (see fig. 15 and Pls. XXVIII and XXIX) are subject to overflow by the tides. They receive water while the tide is rising and return it while the tide is falling, and the storage thus accomplished is additional to the storage measured by the tidal prism of the open water. Each marsh tract has in fact a tidal prism, and a part of that prism is effective, in the same sense as the effective prism of the open water; but because of peculiarities in the configuration of marsh land the relation of the effective prism to the entire prism is not the same for marsh land as for open water. A special investigation was made of the natural laws affecting the storage of tide water by marsh lands.

The typical tide marsh of the region is a plain traversed by a branching system of sloughs. At low stages of tide the plain is uncovered and only the trunk sloughs contain water. These communicate with the adjacent bay. As the tide rises in the bay there is a flow inward through the sloughs, and as it falls there is a flow outward. If the tidal oscillation is relatively small the entire movement is confined to the sloughs; if it is relatively large the plain is flooded. In the special investigation just mentioned a station was established in a trunk slough near its mouth, a record was made of the rise and fall of the tide, the inflow and outflow were measured, and the observations were made in continuous series to cover tides of several types. As the record and discussion of the observations occupy considerable space they have been relegated to an appendix (pp. 123–138), and only the generalizations will be given here.

The marsh specially studied is that served by Ravenswood Slough and borders the south arm of San Francisco Bay. The mean range of tide in the adjacent part of the bay is 6.0 feet, and the great tropic range is 9.3 feet. The average tidal storage by marsh and slough, equivalent to the mean tidal prism of the tract, equals a layer of water 0.60 foot deep over the entire tract. It is convenient to speak of this as the depth of storage. For the great tropic tides, which in these bays are ebb tides, the average depth of storage is 1.27 feet; for the flood tides preceding the great tropic ebbs it is 0.87 foot.

The observations were made in a place where the open-water tidal range is exceptionally large. It is assumed with confidence that in regions where the range is less the depth of storage on marsh lands is also less; but the reduction in storage is not necessarily proportional to the reduction in range. Vegetation has much to do with the physiography of a tide marsh, and it is possible that its control

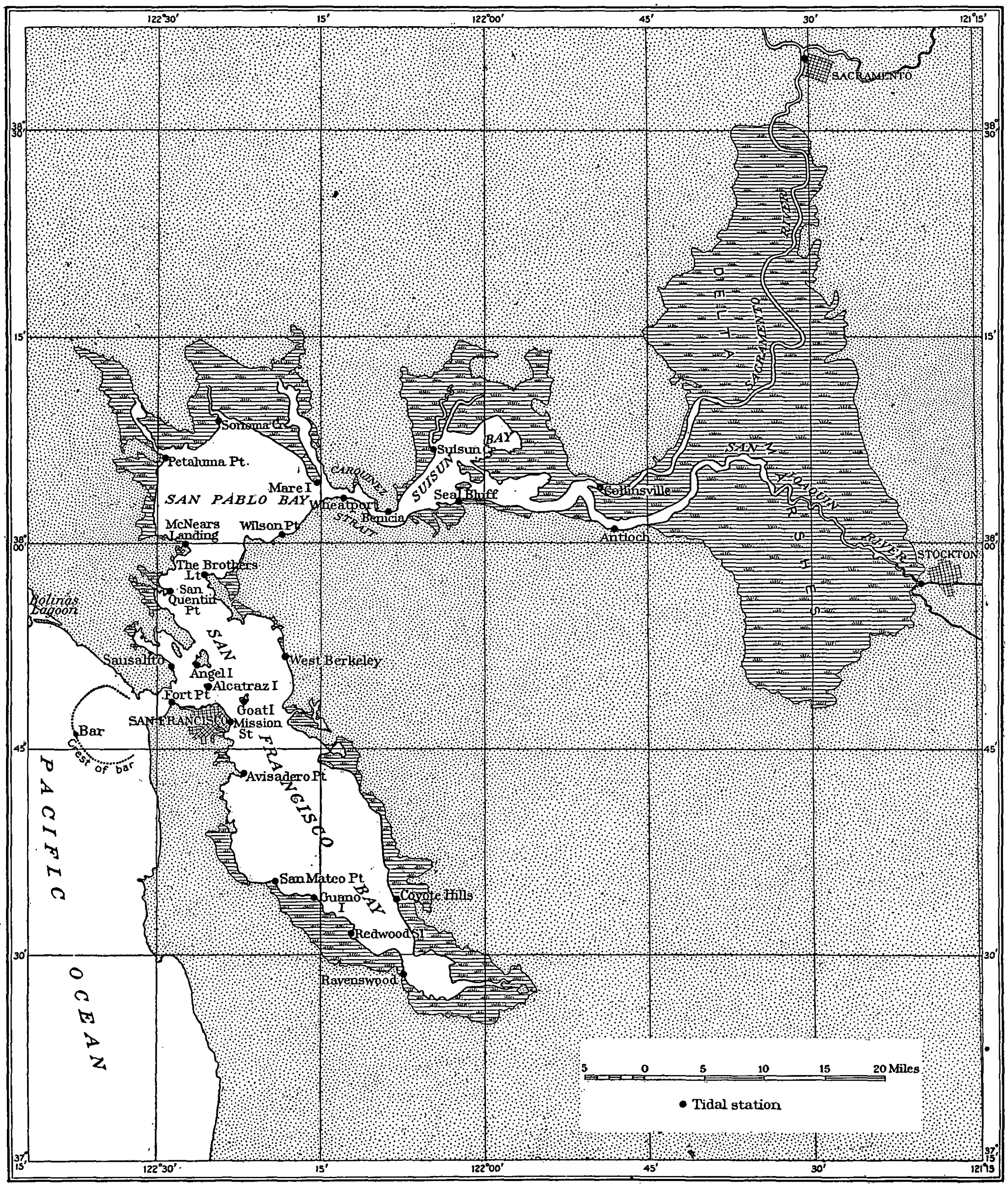


FIGURE 15.—Marsh lands and bodies of open water affecting the tidal volume at Golden Gate bar.

tends toward uniformity of high-water depth on the marsh plain, in which case the variation in depth of storage would be less rapid than the variation in open-water range. The subject is further complicated by the fact that the marsh vegetation is not everywhere the same. The higher levels of all the marshes are marked by samphire (*Salicornia*) and alkali grass (*Distichlis*), but the flora of the lower and broader parts varies with the salinity of the water. About San Francisco Bay the dominant plant is creek sedge (*Spartina*); about Suisun Bay and on the river deltas the dominant plants are cat-tail rush (*Typha*) and tule (*Scirpus*). In the lack of definite information as to the influence of these factors, the computations have in general assumed that the storage constants for the various marshes are proportional to the tidal ranges of adjacent bodies of open water, but in computing the storage volumes of the larger marshes an allowance was made for the fact that the tidal range is less at a distance from the open water than near it.

Where the tide enters a deep bay through a deep, broad strait, the sequence of discharges in the strait follows a simple law. If the discharges are plotted with reference to time, the resulting curve is symmetric and is approximately a sine curve. Such a curve is shown in the upper part of figure 16, where flood discharges are reckoned downward from a base line and ebb discharges upward.[1] Departures from the type form are unimportant. The other three curves of the figure show sequences of discharges for tidal marshes and are based on the Ravenswood observations. It will be seen that they depart widely from the sine-curve type. Their most striking peculiarity is that the maximum discharge for both flood and ebb occurs near the change from flood to ebb—that is, it occurs when the water stage is high. This is connected with two facts—first, that the section of the current in the slough is much larger at high water than at low; second, that the water area in the marsh tract (the area receiving or delivering water) is much larger at high water than at low. A relatively small volume of water is moved in filling or emptying the sloughs, but a relatively large volume is moved in flooding or draining the marsh plain.

The curves pertain severally to tides giving the average amount of marsh storage, to tropic tides, and to very large tides. Their use will be illustrated by an example. It is to be premised that as the ordinates of the curves represent discharge, or the rate of passage of volume of water, the space between any curve and its base line represents the total volume of water passed, and the space between a portion of a curve and the corresponding portion of its base line represents the volume of water passed in the corresponding time.

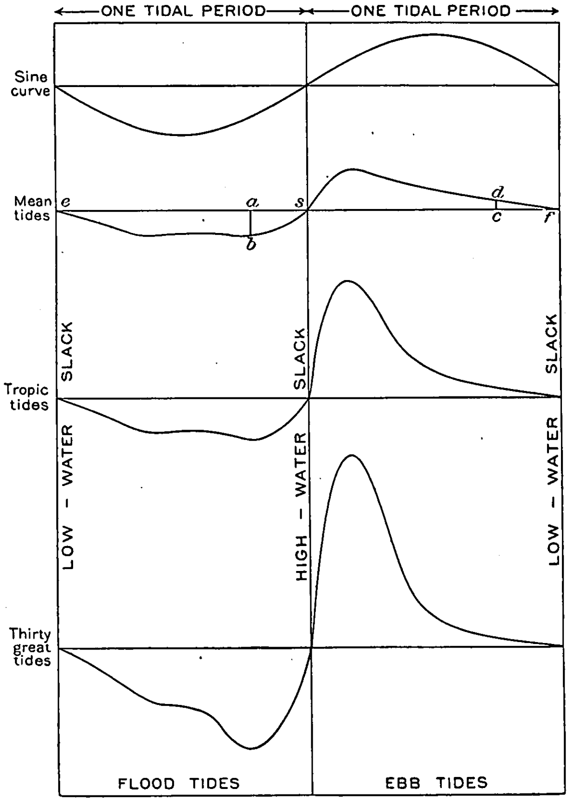


FIGURE 16.—Curves showing progressive variations of discharge in a channel serving a tidal marsh. Vertical distances represent discharge, ebb discharges being reckoned as positive, flood discharges as negative. Horizontal distances represent time, the unit of time being the period of a flood or ebb tide. The lower three curves are copied, with change of scale, from curves XII, XIV, and XIII of figure 27 and curves IX, VIII, and X of figure 26. The unit of the time scale is the tidal period. Measured in hours and minutes the ebb periods are longer than the flood, and this difference is greater for large tides than for small. It is also relatively great for marshes at a distance from the Golden Gate.

[1] Flood and ebb, implying motion in opposite directions, are usually characterized by opposite signs, but there is no fundamental reason why one rather than the other should be regarded as positive. As a matter of convenience ebb discharges are here treated as positive; and, equally as a matter of convenience, flood velocities and discharges are treated as positive in Appendixes A and B. In the appendixes currents are discussed in relation to the tidal oscillations which cause them, and flood currents are made positive because they are caused by positive (rising) tides. In the present connection we are concerned especially with the transporting power of the ebb current in the Golden Gate, and with reference to that current ebb discharges in the marsh sloughs are positive.

The average depth of tidal storage for the marsh served by Suisun Slough is 0.47 foot. It is desired to find what portion of this is effective with reference to ebb discharge at the Golden Gate. When the ebb begins at the Golden Gate, the flood is still running at the entrance to Suisun Slough, and it will continue to run for a time represented, on the second curve of figure 16, by the distance *as*. After the ebb ends at the Golden Gate it will continue to run at the slough entrance for a time represented by the distance *cf*. The verticals *ab* and *cd* having been drawn, the area *sdc* represents the volume delivered by the slough during the ebb period at Golden Gate, and

$$\frac{\text{area } sdc}{\text{area } sdfc}\times 0.47 \text{ foot}$$

represents the corresponding depth of storage. Similarly the area *sab* represents the volume received by the slough during the ebb period at the Golden Gate, and

$$\frac{\text{area } sab}{\text{area } sbea}\times 0.47 \text{ foot}$$

represents the corresponding depth of storage. The depth of storage measuring the net contribution of Suisun Marsh to the discharge at the Golden Gate is

$$\left(\frac{\text{area } sdc}{\text{area } sdfc}-\frac{\text{area } sab}{\text{area } sbea}\right)\times 0.47 \text{ foot.}$$

The product of this depth by the area of the Suisun Marsh tract is the effective volume of tidal storage by the tract.[1]

The computations involved other factors, to which due attention was given, but only their general character will here be indicated. The Tide Tables deal with the rise and fall of the water surface and define four epochs—high water at the Golden Gate, low water at the Golden Gate, high water at a slough mouth (Suisun, for example), low water at the slough mouth. The flood and ebb curves of figure 16 begin and end with epochs of slack water, and the use of the data contained in the curves requires the time differences between each of the high-water and low-water epochs and the associated (following) slack-water epochs. The time differences at the Golden Gate are discussed in Appendix A; the time differences at slough mouths in Appendix B.

TABLE 17.—*Average tidal storage on marsh tracts of San Francisco Bay system, as affecting tidal discharge at the Golden Gate; computed for conditions before encroachment by levees.*

Marsh tract.	Area.	Effective depth of storage.	Effective volume of storage.
Bordering San Francisco Bay:	*Square miles.*	*Feet.*	*Cubic feet.*
South of Newark and Ravenswood	26. 8	0. 56	418, 000, 000
East side, Newark to Berkeley	33. 4	. 53	493, 000, 000
West side, Ravenswood to San Mateo	26. 4	. 52	383, 000, 000
West side, San Mateo to San Francisco	7. 1	. 40	79, 000, 000
North of Goat Island	8. 0	. 38	85, 000, 000
Bordering San Pablo Bay:			
Served by Gallinas, Novato, Petaluma, and Tolay creeks	41. 0	. 39	446, 000, 000
Served by Sonoma Creek	28. 0	. 38	297, 000, 000
South shore	2. 0	. 44	25, 000, 000
Served by Napa River	31. 8	. 29	257, 000, 000
Bordering Suisun Bay:			
Served by Suisun Creek	35. 0	. 22	171, 000, 000
Served by Montezuma Creek; main part	31. 7	. 19	168, 000, 000
Island region and south shore	36. 0	. 28	281, 000, 000
			3, 103, 000, 000
River deltas:			
Sacramento	168. 0	−. 116	− 544, 000, 000
San Joaquin	365. 0	−. 173	−1, 760, 000, 000
	840. 2	....	−2, 304, 000, 000
			799, 000, 000

[1] The statement of this example is intended to show the essential relation of the curves to effective volume of storage. For the actual work of computation the data embodied in the curves were put in more convenient form.

The results of the computations are presented in Table 17. The areas there given—the areas used in computing the volumes of tidal storage—are areas of original marsh land, including associated sloughs, and differ materially from the areas now flooded by the tides. Most of the tracts have been more or less abridged by the work of reclamation, and the abridgment has been especially great in the delta tracts, which are largest of all. Wherever two of the indicated marsh tracts adjoin there is more or less interchange of waters, so that their common boundary has not a fixed position, and in such places a position was arbitrarily assigned to it.

The computations for the deltas involved much interpolation, because the data are imperfect. There were few trustworthy tide observations and the system of arteries for the flow and ebb of tide water was not mapped until after its modification by levees.

In Table 18 the storage volumes for bays, rivers, and marshes are assembled from Tables 16 and 17 and are compared by means of percentages. Although the area of the marsh lands is 83 per cent greater than the area of open water, their effective storage, with reference to the Golden Gate discharge, is much smaller. Considered without respect to sign, it is one-tenth that of the open water.

TABLE 18.—*Average volume flowing through the Golden Gate during a flood or ebb tide, with indication of the chief associated units of storage.*

[Based on data of Tables 16 and 17.]

Division of San Francisco Bay system.	Volume of storage. Millions of cubic feet. Open water.	Millions of cubic feet. Marsh.	Per cent. Open water.	Per cent. Marsh.
San Francisco Bay:				
Southern part	25,660	1,373	48.82	2.61
Northern part	7,980	85	15.18	.16
San Pablo Bay	13,250	768	25.24	1.46
Napa River	680	257	1.29	.49
Carquinez Strait	950	....	1.80	....
Suisun Bay	4,140	620	7.88	1.18
	52,660	3,103	100.21	5.90
Sacramento Delta	−64	−544	−.12	−1.04
San Joaquin Delta	−843	−1,760	−1.60	−3.35
	−907	−2,304	−1.72	−4.39
	51,753	799	98.49	1.51
	52,552		100.00	

TROPIC TIDAL VOLUME AT THE GOLDEN GATE.

To the results obtained by the preceding computations and estimates there is an important qualification. They are based in chief part on the constants of a tide of average size, but the work of a large tide differs materially from the work of a small one, and the mean of effects of all tides is not the same as the effect of a tide of mean size. The particular effect which concerns us in this discussion is the modeling of the bar, and that depends on velocities of currents. The relative efficiency of large and small tides is partly illustrated by figure 17, where horizontal spaces represent time and vertical spaces velocity. Each curve shows the sequence of velocities during an ebb tide, the middle curve corresponding to an

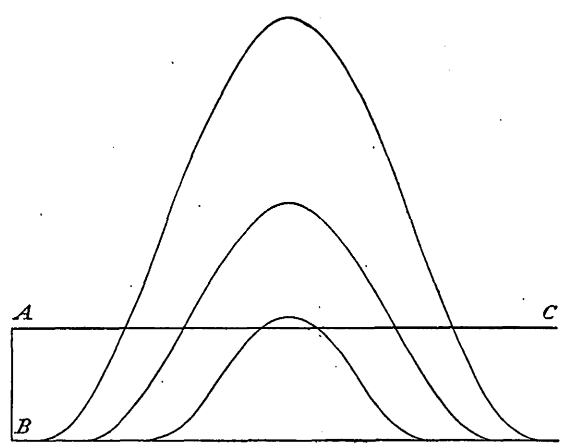


FIGURE 17.—Diagram illustrating the relative efficiency of large and small tides for the transportation of débris. Horizontal distances represent time; vertical distances represent velocity of tidal current.

average tide and the others severally to a very large and a very small tide—the data being taken from the prediction tables for Fort Point. If the ordinate *AB* represents the velocity that is barely competent to move sand on the inner slope of the bar, the portions of the horizontal line *AC* intercepted by the curves show the relative periods during which currents of the three tides work on the bar. The amount of work accomplished by either in a unit of time is proportional to a power of its velocity not less than the third.[1] So the potency of the large tide exceeds that of the average tide in a ratio which is far greater than the ratio between the areas embraced by their respective velocity curves. For this reason it is desirable to learn the volumes of large tides as they pass

[1] See U. S. Geol. Survey Prof. Paper 86, pp. 160-161, 1914.

the bar and also the characteristics of the effective prisms associated with them.

The more important factors determining large tides in the San Francisco bays are, first, the reinforcement of the lunar attraction by the solar (giving spring tides); second, the nearest approach of the moon to the earth (giving perigee tides); and third, the greatest departure of the moon from the plane of the earth's equator (giving tropic tides). The third factor is the chief cause of the inequality of the two tide oscillations occurring on the same day. The first and second affect the volume of water crossing the bar, but do not materially affect the percentages of that volume which are contributed by the effective prisms of individual bays and tracts of marsh land. The third affects both volume and percentages, and its influence on volume is greater than the joint influence of the other two factors.

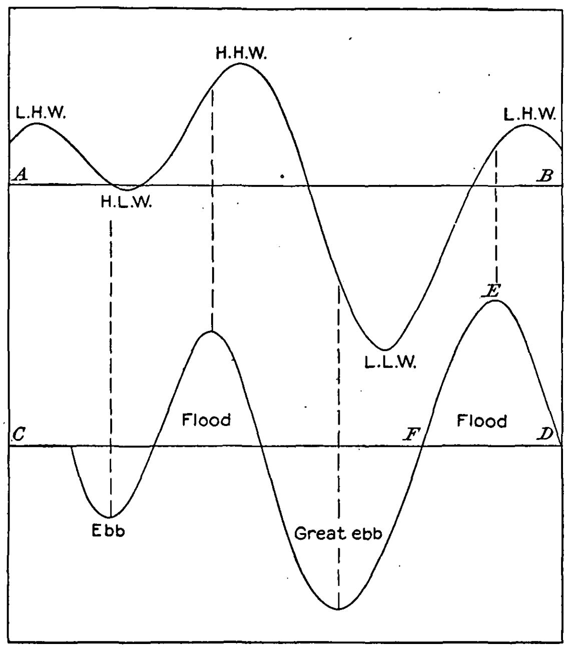


FIGURE 18.—Sequence and relation of tides and currents in San Francisco Bay when the moon is far above or below the plane of the earth's equator. The upper curve gives water stage (vertical) in relation to time; the lower gives discharge in relation to time. L.H.W., lower high water; H.L.W., higher low water; H.H.W., higher high water; L.L.W., lower low water. Flood discharges are laid off upward from *CD;* ebb discharges downward.

In figure 18 the horizontal scale represents time and is the same for both curves. The upper curve shows the tropic sequence of tides in San Francisco Bay, the cycle of four tides filling one lunar day (24.8 hours). Beginning with the lesser of the two high waters—the "lower high water"—we have first a fall of moderate amount, then a rise of greater amount (to higher high water), and then a fall through the extreme range of the tide (to lower low water), followed by a second rise which completes the cycle. Each rise is associated with an inflow from the ocean, or flood current, and each fall with an outflow, or ebb current. The order in which the tides occur, the lower low water coming immediately after the higher high water, causes one of the ebb currents to have greater volume than either of the flood currents. The lower curve of the figure shows the sequence of currents, the zero of current, or slack water, being represented by the line *CD*. Vertical distances represent discharge, or the volume of water passing through a given cross section of channel in a unit of time; the flood discharges are laid off above the zero line, and ebb discharges below. The sum of discharges during the period of one of the currents, or the total volume of that current, is represented by the area between the corresponding part of the curve and the zero line; for example, the volume of the final flood current is shown by the area between *DEF* and *DF*. Because, on the average, tidal inflow and outflow are equal, the curves have been so drawn that the sum of the two flood areas equals the sum of the two ebb areas.

The great ebb current, associated with the fall from higher high water to lower low water, is the greatest of the currents; and next to it in magnitude is the flood current which follows it, corresponding to the rise of the tide from lower low water to lower high water.

The curve of velocities is similar to the curve of discharges but is not identical in form. Velocity would be strictly proportional to discharge if the sectional area of the channel were constant, but that varies with the stage of tide. When the tide is high the sectional area is relatively large, and a relatively low velocity suffices to produce the discharge. The times of the tides and currents are so related (see fig. 18) that the maximum flood discharges occur when the water stage is above its mean position, and the maximum ebb discharges occur when the water stage is below its mean position; and as a result the greatest ebb velocity exceeds the greatest flood velocity by a ratio which is larger than that of the greatest ebb discharge to the greatest flood discharge.

It is estimated that the maximum discharge during the great ebb is about 10 per cent greater than the maximum discharge of the following flood. The extent to which the contrast of velocities is enhanced by the factor connected with water stage varies with locality, being affected largely by depth of channel. In the Golden Gate, where the channel is deep, it may amount to 1 or 2 per cent; over the Pinole Shoal in San Pablo Bay it probably exceeds 25 per cent. Thus there is a notable difference between the speeds of the strongest tropic ebb current and the strongest tropic flood current.

When the tides lack the tropic characters, and the four currents of the day have approximately the same volume, the ebb velocities are still somewhat greater than the flood, but the difference is then comparatively small.

The superior strength of ebb currents determines the direction of transportation of débris along the bed of the channel. At most points the currents in each direction are sometimes strong enough to move débris, so that it is dragged both seaward and landward, but the ebb currents accomplish most, and the net result is a progress toward the ocean. So the tropic tides are of special importance in connection with the harbor entrance, not only because the volume of the great ebb current gives to it peculiar power for the control of the position of the bar, but also because the inequalities of their alternating currents make them peculiarly efficient as conveyors of débris to the bar.

For these reasons I have made a separate computation of the average effective tidal prism which determines the volume of the great tropic ebb current. The computation and estimation, of which the results appear in Table 19, followed the lines already indicated for the mean tidal volume.

The curve of effective range for the route of the tide from Golden Gate to Sacramento appears in figure 14 (p. 74) as the line *EF* and is well controlled by the data as far as Collinsville. The interpolated portion between Collinsville and Sacramento is largely hypothetic, but there is no reason to question its indication that the point at which the tropic effective range becomes negative is farther upstream than the corresponding point for the mean-tide effective range.

TABLE 19.—*Estimate of the average volume of great tropic ebb currents at the Golden Gate as dependent on the effective tidal prisms of bays, other bodies of open water, and marsh tracts.*

Division of San Francisco Bay system.	Effective range of tide, in feet.		Volume of storage, in millions of cubic feet.[a]		Relative volume of storage, in per cent.	
	Open water.	Marsh.	Open water.	Marsh.	Open water.	Marsh.
San Francisco Bay:						
Southern part	7.7	1.03	40,402	2,690	43.94	2.92
Northern part	6.05	.87	13,050	194	14.19	.21
San Pablo Bay	7.15	.72	21,280	1,425	23.15	1.55
Napa River	7.0	.55	1,064	487	1.16	.53
Carquinez Strait	7.0	....	1,560	....	1.69	....
Suisun Bay	5.6	.52	7,480	1,488	8.14	1.62
River deltas:						
Sacramento	.95	.108	225	506	.24	.55
San Joaquin	.49	−.013	229	−132		−.14
			85,290	6,658	92.76	7.24

[a] Volume at the Golden Gate, 91,948,000,000 cubic feet.

The estimates for marsh lands are less trustworthy than those contained in preceding tables. Certain assumptions made (in Appendix B) as to the lag of slack water affect only moderately the computations of mean-tide storage on marsh lands, but they affect more seriously the computations of tropic-tide storage. This qualification is, however, only a single phase of a more general qualification. The empiric methods employed in the discussion fail to take proper account of the kinetic elements of tidal phenomena, and the consequences of this failure are peculiarly apparent in the treatment of the invasion of marsh lands by tropic tides.

Despite this qualification it is my belief that the system of percentages (Table 19) based on the tropic-tide data is preferable to that based on mean-tide data (Table 18) for the discussion of the effect on the bar of local restrictions of tidal storage.

CHECK COMPUTATIONS OF VOLUME.

The preceding estimates of tidal volume in the Golden Gate rest chiefly on measurements by the United States Coast and Geodetic Survey of the range of tide in different parts of the bay system and of the rates of propagation of tide waves in the bays. Their method is that of the tidal prism. Another group of estimates, given in Appendix A, rests on measurements of the velocity, section, and duration of certain ebb and flood currents in the Golden Gate. In method and data they are independent of the estimates by tidal prism, so that each group of results may serve to check the other. The comparison can not be made directly, because the estimates by tidal prism are general averages, whereas the estimates from current observations pertain to individual ebb or flood currents, but a relation may be established through the factor of tidal range in the Golden Gate. The estimates by tidal prism correspond to certain average tidal ranges in the strait. The estimates from current observations correspond to ranges observed at Presidio wharf while the currents were being measured.

The bay tides are caused by the tides of the ocean outside. Waves generated in the ocean traverse the bays, and the horizontal movements of water involved in their propagation are the chief elements of the tidal currents. It is therefore true, in a general way, that the greater the amplitude of the tide wave as it traverses the strait the greater the volume of the associated transfer of water. There is a general correlation between range of tide and magnitude of current. The correlation is probably perfect so far as general averages are concerned, but it is only approximate with respect to individual tides, because the volume of current depends in part on other factors. The current is especially influenced by the surface slope—the relative height of water surfaces inside and outside the strait—and that varies in a complicated way with the varied sequence of tide waves of different magnitude.

TABLE 20.—*Relations between general means of tidal range in Golden Gate and mean tidal volumes estimated by the prism method.*

	Range, in feet.	Volume, in cubic feet.
Mean of all tides	3.9	52,552,000,000
Mean of great tropic ebb tides	6.2	91,948,000,000

The great tropic volume is somewhat greater than it would be if the volumes were strictly proportional to the ranges, so that the law of relation is not that of simple proportion. A convenient assumption as to the law is that the volumes are proportional to some power of the ranges, and this assumption yields

$$\text{Volume} = 10{,}150{,}000{,}000 \times \text{range}^{1.207}$$

The observations of range associated with the observations of current were made at the Presidio wharf, where the mean range is 3 per cent greater than at Fort Point, the station to which the other data pertain, and a correction of -3 per cent was therefore applied to the measured ranges. They were then entered, severally, in the preceding equation, and the computed results constitute estimates of the volumes of individual tides based on the discussion of the tidal prism. These appear in Table 21, and with them are the corresponding estimates from current measurements.

As shown by the tabulated differences and ratios, the discrepancies between the estimates by the two methods are both large and varied. On the whole, the results from the tidal prisms appear to be smaller than those from current observations, but even this generalization is not secure, and the comparisons show chiefly that the variation among individual tidal volumes does not follow closely the variation of associated amplitudes of tidal waves. Considered as a check, the comparisons indicate only that results by the two methods have the same order of magnitude, and that the general estimates by the method of prisms are not necessarily inconsistent with the information afforded by a few specific measurements of currents.

TABLE 21.—*Comparison of estimates of tidal volume at the Golden Gate based on data of the tidal prism in the bays with estimates based on current observations in the strait.*

Date, 1914	Sept. 12	Sept. 13	Sept. 19	Sept. 19
Type of tide [a]	Ebb.	Flood.	Ebb.	Flood.
Range reduced to Fort Point, in feet	4.534	3.534	4.457	4.554
Volume, in millions of cubic feet:				
(A) Computed from current observations	74,390	41,030	68,950	64,570
(B) Computed from data of tidal prism	63,030	46,690	61,720	63,230
Difference: (B)−(A)	−11,360	+5,660	−7,230	−1,340
Ratio of (B) to (A)	0.85	1.14	0.90	0.98
Mean of ratios	0.97			

[a] Further information as to character of these tides may be found in Appendix A (p. 109).

TIDAL VOLUMES AT OTHER POINTS.

This inquiry is concerned with the velocity of tidal currents and, therefore, with tidal volumes all along the route of débris transportation from the head of Suisun Bay to the Golden Gate bar. Computations have been made of the volume of the average great tropic ebb current in Carquinez Strait, in San Pablo Narrows, and on Pinole Shoal, as shown in Table 22.

TABLE 22.—*Estimates of the average volume of great tropic ebb currents at San Pablo Narrows, Pinole Shoal, and Carquinez Strait as dependent on the effective tidal prisms of bays, strait, rivers, and marsh tracts.*

San Pablo Narrows (whole volume, 39,800,000,000 cubic feet).

Division.	Effective range of tide, in feet.		Volume of storage, in millions of cubic feet.		Relative volume of storage, in per cent.	
	Open water.	Marsh.	Open water.	Marsh.	Open water.	Marsh.
San Pablo Bay	6.2	0.85	18,460	1,680	46.4	4.2
Napa River	6.7	.71	920	630	2.3	1.6
Carquinez Strait	7.2	....	1,600	....	4.0	....
Suisun Bay	7.3	.71	9,750	2,030	24.5	5.1
Sacramento River	3.0	.25	710	1,170	1.8	2.9
San Joaquin River	2.6	.16	1,220	1,630	3.1	4.1
	....	....	32,660	7,140	82.1	17.9

Pinole Shoal (whole volume, 23,940,000,000 cubic feet).

Division.	Effective range of tide, open water	Marsh	Volume of storage, open water	Marsh	Relative volume, open water	Marsh
San Pablo Bay	6.2	....	1,850	....	7.7	....
Napa River	6.8	0.71	950	630	3.9	2.6
Carquinez Strait	7.0	....	1,560	....	6.5	....
Suisun Bay	7.2	.85	9,610	2,430	40.2	10.2
Sacramento River	3.6	.39	850	1,830	3.6	7.6
San Joaquin River	3.4	.26	1,590	2,640	6.7	11.0
	....	....	16,420	7,530	68.6	31.4

Carquinez Strait (whole volume, 20,580,000,000 cubic feet).

Division.	Effective range of tide, open water	Marsh	Volume of storage, open water	Marsh	Relative volume, open water	Marsh
Strait above Point Dillon	6.4	....	890	....	4.3	....
Suisun Bay	7.1	0.90	9,350	2,580	45.4	12.5
Sacramento River	3.8	.44	900	2,060	4.4	10.0
San Joaquin River	3.7	.30	1,750	3,050	8.5	14.9
	....	....	12,890	7,690	62.6	37.4

The ebb volume through San Pablo Narrows, at the junction of San Pablo and San Francisco bays (see fig. 15), is 39,800,000,000 cubic feet and is about 43 per cent of that through the Golden Gate. The flow through Carquinez Strait, estimated for the narrow constriction at Point Dillon, is about half as great, 20,580,000,000 cubic feet. Pinole Shoal, which merits special consideration because of the difficulty of maintaining a navigable depth there, affords less definite data for the computation of volume. It is part of the bed of the main channel traversing the bay and has a length of several miles. The ebb current, as it follows the channel, is continuously augmented by water from a broad shoal north of the channel, so that no single estimate of volume can apply to the whole of Pinole Shoal. The quantity given in Table 22—23,940,000,000 cubic feet—was computed for the section opposite Point Wilson, where the channel is shoalest, and the computation assumed, somewhat arbitrarily, that the current at that place includes a contribution from the tidal prism of San Pablo Bay equivalent to one-tenth of the entire prism of the bay.

The volume of the tropic ebb on the bar outside the Golden Gate (see fig. 10, p. 70) may be nearly the same as in the narrows of the strait or it may differ materially. Its measure includes a large block of tidal prism lying outside the narrows, but there is a compensatory exclusion in the region of Suisun Bay and the river deltas. The excluded volume can not now be determined, even approximately, because certain data essential to the computation (the times at which the currents on the bar change from flood to ebb and from ebb to flood) are unknown.

One of the striking facts illustrated by the details assembled in Tables 19 and 22 is that the quantity of water contributed by any unit of open water or marsh land to the volume of current through a channel depends in part on the distance of the channel from the contributing unit. The explanation of this has already been given on pages 71–72. To aid the reader in making the comparison some of the details are rearranged in Table 23.

The eastern units of the tidal prism contribute a relatively small amount to the current through the Golden Gate and relatively large amounts to the currents at points nearer by; and, with a single exception, the order of magnitude of the contributions is the inverse of the order of distance. It is further to be observed that although these contributions constitute the greater part of the entire volume of the current in Carquinez Strait, they form relatively small fractions of the currents at points farther west. The great marshes of the river deltas give to the current in Carquinez Strait 25 per cent of its volume, to that on Pinole Shoal 19 per cent, to that through San Pablo Narrows 7 per cent, and to that through the Golden Gate only 0.4 per cent.

It has been convenient to phrase the preceding paragraphs in the present tense, and, to avoid a possible misapprehension, it is well to recall to the reader's attention the fact that the computations and their results pertain to a condition which no longer exists. Many of the tidal constants employed were derived from observations made during early surveys

TABLE 23.—*Comparison of the volumes of tide water contributed, in early years, by certain bodies of water and marsh to the tropic ebb currents of different straits and channels.*

Contributory body of open water or marsh.	Volume, in millions of cubic feet, contributed to the current at—			
	Golden Gate.	San Pablo Narrows.	Pinole Shoal.	Carquinez Strait.
Suisun Bay	7,480	9,750	9,610	9,350
Associated marshes	1,488	2,030	2,430	2,580
Sacramento River	225	710	850	900
Associated marshes	506	1,170	1,830	2,060
San Joaquin River	229	1,220	1,590	1,750
Associated marshes	−132	1,630	2,640	3,050
	9,796	16,510	18,950	19,690

of the bays, and the areas ascribed to bays and marsh tracts are those of the earliest accurate charts and maps available. The attempt has been made to determine, as nearly as practicable, the strength of tidal currents before they were modified by the activities of the white man. The shoaling and contraction of the upper bays and the great abridgment of the marshes which have since been brought about have changed and in the main reduced the volume of currents and have doubtless changed the range of the tides as well as the times of high water and low water.

REDUCTION OF TIDAL VOLUME IN THE GOLDEN GATE BY ENCROACHMENTS ON THE TIDAL PRISM.

It is proposed now to consider in a quantitative way the modification of the volume of tidal currents in the Golden Gate by the restriction of the area through which tidewaters expand. Most of the quantities to be indicated pertain to the great tropic ebb tide and

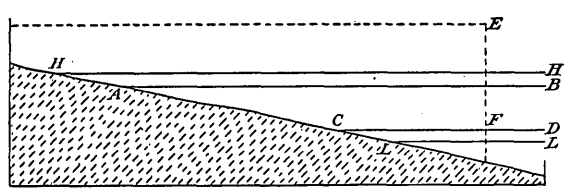


FIGURE 19.—Diagrammatic section of a shore in San Francisco Bay, to illustrate the relation which structures that invade the water bear to the effective tidal prism.

are derived from the same data as the quantities in Table 19.

Figure 19 represents in section a sloping shore of a bay. *HH* is the level of high water, *LL* of low water. *AB* is the position of the water surface when the current in the Golden Gate changes from flood to ebb; *CD* its position when the current changes from ebb to flood. The height of *HH* above *LL* is the range of tide. The height of *AB* above *CD* is the effective range, or the thickness of the effective tidal prism at the locality. Encroachments on the space between *AB* and *CD*, as by the building of piers or the reclamation of tide flats, reduce the volume of current through the Golden Gate. The current is not affected by encroachments above the level *AB*. It is not directly affected by encroachments below the level *CD* but may be affected indirectly if such encroachments interfere with the circulation of tide-water through the bays. It is evident that if an embankment is extended from the land to *EF*, the part between *C* and *F* will reduce the effective prism by the full depth of the prism, while the part between *C* and *A* will reduce it by a less amount. The figures in the second column of Table 24 refer to encroachments cutting out the entire depth of the prism.

The case of tide marshes can not be stated with equal simplicity. They are flooded and drained through long channels, and the process consumes time. The estimates of their capacity to store tidal water depend on measurements of current in the channels (see p. 75 and Appendix B), and their statement in depth of effective prism does not imply any direct measurement of the prism. The tabulated depth of effective prism (third column of Table 24) indicates, when multiplied by the area of the marsh tract, the loss to the Golden Gate current from the reclamation of the tract by levees. It is implied that the reclamation excludes the tide from the sloughs as well as the marsh lands themselves; if the marsh lands only are leveed the loss to the Golden Gate current, per unit of marsh area, is less.

If the depth of effective prism at a given locality is multiplied by the area of bay or marsh from which the tide is excluded, the product will be the volume of water by which the tidal current in the Golden Gate is reduced; and the significance of the reduction may then be learned by comparing the volume of reduction with the total volume of the current, 92,000,000,000 cubic feet. As this procedure is inconveniently long, I have given the estimates another form by indicating, in separate columns, from how many acres of water or of marsh in each region the tide may be excluded at a cost to the Golden Gate current of its one-thousandth part, or the tenth of 1 per cent.

As regards the open water of the bays, the effects of encroachment vary in amount to only a moderate extent. It is to be observed, however, that mere remoteness from the Golden Gate does not make the effects of encroachment unimportant. They are more important for the extreme southern part of San Francisco Bay than for any other district, and more important for the waters between San Pablo Strait and Benicia than for the waters about the water front of San Francisco and Oakland. There is a rapid change in conditions in Suisun Bay and in the rivers. For the eastern part of Suisun Bay the effect of encroachment is less than at San Francisco, and for the remoter parts of the tidal rivers the effect is negative, encroachment tending to increase the volume in the Golden Gate. (See fig. 14, p. 74.)

As regards the marshes, all the figures given are rough averages, the depth of the effective prism varying greatly with details of local condition. It may be said in a general way that the tabulated estimates of prism depth should be increased for marsh tracts that communicate directly with open water and should be diminished for tracts that communicate only through long sloughs. The variation is greatest for the delta marshes, those near the mouths of the rivers having effective prisms comparable with the prisms of the Suisun marshes, while large areas that communicate with the rivers at higher points have negative effective prisms.

I regard it as entirely possible that the net effect of tidal storage in the delta marshes is negative instead of being positive, as it appears in the table. The meagerness of observational data in that region, as well as the recognized imperfection of the methods by which the marsh prisms were computed, leave much room for doubt on this point. On the other hand I am confident that the total influence of the delta marshes on the Golden Gate current, whatever its sign, is small, or rather that it was formerly small, for little of this area is now accessible to the tides.

The extent of actual encroachments due to deposits of mining and other débris is indicated by charts of different dates, showing changes in the positions of the outlines of high water and low water. As a rule the water areas inclosed by these outlines were greater when the early surveys were made than at the dates of the later surveys. Changes of the high-water line have been of appreciable amount only where the shore is marshy, and in such localities the notation of the charts is not entirely consistent. The marsh edge in nature usually has as one of its features a low beach ridge, or else an abrupt change of slope, these features being shaped in part by the waves; but there are places also where the slope of the ground is gradual and uninterrupted, and in those the visible limit of the marsh is the outer edge of the tract of marsh vegetation. Where the beach is present the vegetation may stop at the beach or it may follow for a distance down the gently sloping strand. It results that the high-water line of the charts represents in part a beach and in part a limit of vegetation. On some of the later charts both phases are indicated, with distinctive notation, but the distinction is not recognized on the earlier charts. The matter is further complicated by the fact that some of the fringing plants die down in winter, so that the visible extent of the fringe has a seasonal variation.

The low-water line, the line of mean lower low water, is not surveyed at low water by direct observation. Its position is inferred from plotted soundings after the soundings have been reduced to a common datum by cor-

TABLE 24.—*Data illustrating, for different parts of the San Francisco Bay system, the relation which encroachments on the tidal prism bear to the volume of tidal currents in the Golden Gate.*

Locality.	Depth of effective tidal prism, in feet.		Area, in acres, corresponding to one-tenth of 1 per cent of the tidal volume in the Golden Gate.	
	Open water.	Marsh land.	Open water.	Marsh land.
Southern part of San Francisco Bay	7.7	1.03	270	2,000
San Francisco and vicinity	6.2	1.00	350	2,100
Northern part of San Francisco Bay	6.05	.87	360	2,400
San Pablo Bay	7.15	.72	290	2,900
Napa River	7.0	.55	300	3,800
Carquinez Strait	7.0	.80	300	2,600
Suisun Bay	5.6	.52	370	4,000
Deltas of Sacramento and San Joaquin rivers	.6	.02	3,600	100,000

rections for stage of tide. It represents the intersection of the "plane of reference" with the slope of the bottom, and as that slope is gentle in the principal regions of deposition large errors in the position of the charted line may be occasioned by small errors in the plane of reference. There is circumstantial evidence that errors of this sort exist (see p. 34), but an attempt to investigate them encountered difficulty because of imperfection in the record of methods of reducing soundings. On the whole the precision of the charted positions of the low-water line is believed to be lower than that of the position of high water.

Although these considerations seriously qualify the numerical results that follow they do not affect the general inference that the deposits have wrought an appreciable and noteworthy reduction of the tidal prism.

In a general way the areal change in the tidal prism is equivalent to the mean between the change in the high-water area and the change in the low-water area, but some exceptional conditions are locally so important as to deserve mention. A shoal tract that appears at low water as an island but is submerged by a small rise of the tide may change its area greatly and yet affect the tidal prism but little. Such tracts occur in all the bays, and they are especially abundant in the southern part of San Francisco Bay. By way of allowing for these, and at the same time taking account of the lower precision of the records of low-water outline, I have computed the change in tidal prism as a weighted mean of the changes in high-water and low-water area, assigning to the high-water data a weight twice that of the low-water data.

Table 25 contains a summary of data and estimates of the encroachments on the tidal prisms of the several bays. From the amounts of change indicated by the charts for the periods between surveys the amounts corresponding to the longer period 1849–1914 were computed by means of the curve reproduced in figure 5 (p. 36). The factors for the conversion of acres of encroachment into per cent of tidal volume are taken from Table 24.

It will be noted that for a small division of San Pablo Bay and for both divisions of San Francisco Bay the charts indicate changes of opposite sign for the high-water and low-water boundaries. They declare that the marshes have encroached on the open water but that the low-water lines have retreated from the open water. Now, if the cause of the changes were either deposition, or erosion, or subsidence, or elevation, the probable character of change would be the same for both boundaries—that is, the high-water and low-water lines would both be made to advance or else would both be made to retreat. Therefore, as these four categories include all the sources of change that we need to consider, I am prone to believe that the apparent association of advancing high-water lines with retreating low-water lines is not actual and that the inconsistency of the results has been

TABLE 25.—*Estimates of reduction of tidal currents in the Golden Gate caused by deposition of mining and other débris on the shoals of the bays.*

Bay or division.	Period to which record pertains.	Encroachment on water area shown by charts.		Encroachment on tidal prism (weighted mean of preceding).	Encroachment on tidal prism for period 1849–1914.	Area corresponding to 0.1 per cent of tidal volume in Golden Gate.	Reduction of tidal volume in Golden Gate.
		High water.	Lower low water.				
		Acres.	*Acres.*	*Acres.*	*Acres.*	*Acres.*	*Per cent.*
Suisun Bay	1867–1886	2, 860	2, 280	2, 670	8, 330	370	2. 25
San Pablo Bay:							
Main body	1857–1897	2, 160	3, 380	2, 530	3, 870	290	1. 33
Southwest of Pinole Point	1857–1900	75	−790	−180	−275	310	−. 89
San Francisco Bay:							
Northern part	1855–1896	40	−500	−140	−220	360	−. 61
Southern part	1858–1898	1, 960	−1, 920	670	1, 110	270	. 41
							2. 49

occasioned by differences in method between the earlier and later surveys.

I regard it as probable that on all the shoals with which the apparent retreat of the low-water line is associated there was growth by deposition between the surveys of 1855–1858 and the surveys of 1896–1900, that such subsidence as occurred in the same period had a smaller mean amount than the mean depth of deposition, and that the negative signs in the table represent chiefly errors in the determination of local planes of reference for the reduction of soundings. If this opinion is warranted the quantitative results for San Francisco and San Pablo bays are without value. The result for Suisun Bay, however, has a much better status, for the reason that its two surveys agreed closely in method, and also because their methods were better than the methods used in the earlier surveys of the lower bays. If the result for Suisun Bay (2.25 per cent) is substantially correct, the estimate of 2.5 per cent as the total loss of tidal current occasioned by débris deposits is more likely to fall below the fact than above.

The extent of tide-marsh reclamation is shown in part only by the charts of the Coast Survey and the atlas sheets of the Geological Survey. From their definite records it appears that previous to the year 1912 the marshes adjoining San Pablo Bay and Napa River were leveed to the extent of 42,000 acres, and that previous to 1901 those adjoining San Francisco Bay lost 9,600 acres. These abridgments of tidal storage are estimated to have reduced the tidal volume in the Golden Gate by 0.8 and 0.5 per cent, respectively. A much greater acreage has been reclaimed in the delta marshes, but the effect on tidal volume is believed to be negligible. In recent years the reclaimed area south of San Francisco has been increased somewhat and there has been much activity in the reclamation of the Suisun marshes, but as to these works I have no statistics. The order of magnitude of the effect of tide-marsh reclamation may be indicated by saying that it has reduced the volume and velocity of tropic ebb tides in the Golden Gate by 1.5 per cent.

The estimated effect of all débris deposition and all marsh-land reclamation, namely, the reduction of tidal volume by 4 per cent, is equivalent to the effect of so extending the water fronts of San Francisco and Oakland as to take 14,000 acres, or 22 square miles, from the tidal area.

VELOCITIES.

The velocity of the current by which débris is moved along the channel depends chiefly on the tidal volume. In strictness the effective velocity is that of the strand of current in contact with the channel bed, but it is more convenient to deal with the mean velocity of the whole current. Velocity at contact is so difficult of measurement that we have little knowledge of it, and the statements sometimes made of its relation to mean velocity are misleading. On the other hand, there is a certain amount of information as to the relation of mean velocity to the movement of débris.

The term "mean velocity," as used above, denotes the average of velocities in a cross section of a current. Its measure is the discharge divided by the area of the section. It is a mean with respect to space. The term may be used also to denote a mean with respect to time. In the movement of tide water through a particular section during the period from one slack to the next, the velocity is variable, first increasing from zero to "strength" and then diminishing from strength to zero. The mean velocity for the tidal period is less than the velocity "at strength," and the approximate ratio between the two is that of 2 to π.[1] The measure of the mean mean velocity, or the mean velocity with respect to both time and space, at any section is the tidal volume divided by the area of the section and by the length of the tidal period. The velocity to be considered in relation to movement of debris is the mean as regards space and the maximum as regards time and is computed by multiplying the mean mean velocity by $\pi/2$.

The velocities in the Golden Gate associated with mean tide and with the great tropic ebb tide have been computed and are reported in Table 26. In the same table are velocities attributed to a very large tide, the great ebb of December 16, 1914. The predicted range of that tide was 8.5 feet, and it was a matter of observation that the water rose higher on that day than on any other day of the year. The tidal volume corresponding to that range,

[1] This is the theoretic ratio of mean to strength under mean-tide conditions, when the velocity curve is a sine curve and symmetric. It is only approximate for the velocities associated with tropic tides.

computed by the formula on page 82, is 134,400,000,000 cubic feet.

In addition to the computed values of mean velocity "at strength," the table contains a few estimates of the midstream surface velocity. This is greater than the mean for the section, the ratio between the two depending on the character of the bed and walls of the channel. For the narrowest part of the Golden Gate the ratio assumed is 133 to 100.

Clapp, Murphy, and Martin,[1] who studied a great flood in 1907, estimated that if its waters had gone unimpeded to the bays the mean rate of delivery for four days would have been about 782,000 cubic feet per second; and a closely related estimate has been made from the same data by the California Débris Commission, which is charged with the construction of works for control. All authorities are agreed, however, that such a rate of delivery has not been realized in the past, and before the construction of levees it was not even approached. So much flood water was stored in the lateral basins of Sacramento Valley and on the delta marshes that the delivery to the bays was regulated as by a reservoir. Its rate may never have exceeded 300,000 cubic feet per second, and 400,000 cubic feet can be accepted as an outside estimate.

TABLE 26.—*Velocities of ebb currents at the time of greatest strength, with associated data.*

Place.	Year.	Designation of current.	Volume of current.	Duration of ebb.	Area of section.	Velocity.	
						Mean for section.	Maximum surface.
			Cu. ft.×10⁶	*Seconds.*	*Square feet.*	*Ft./sec.*	*Ft./sec.*
Golden Gate at Fort Point	1856	Mean tide	52, 552	24, 360	912, 400	3. 7	5. 0
Do	1856	Great tropic	91, 948	30, 600	909, 800	5. 2	6. 9
Do	1914	Dec. 16	134, 400	32, 220	907, 600	7. 2	9. 6
Midslope (inside) of bar	1900	Great tropic	[93, 000]	[30, 360]	1, 514, 000	3. 2	....
Crest of bar	1900	.....do	[94, 000]	[30, 120]	2, 380, 000	2. 1	....
San Pablo Strait	1856	.....do	40, 800	25, 680	497, 000	5. 0	....
Do	1879	.....do	29, 200	25, 680	494, 000	4. 9	....
Pinole Shoal	1856	.....do	23, 940	26, 130	340, 000	3. 9	....
Do	1897	.....do	[19, 200]	26, 130	283, 000	4. 1	....
Carquinez Strait at Point Dillon	1856	.....do	20, 580	26, 580	234, 000	5. 2	....
Do	1886	.....do	[18, 400]	26, 580	198, 000	5. 5	....

The water that enters the bays from streams and falls on their surface as rain escapes by way of the Golden Gate, except for a fraction absorbed by the air. Flowing outward through the strait, it increases the ebb velocities and diminishes the flood velocities. The mean volume of river water is so small compared to the tidal volumes that its influence on velocities is negligible, but the volume from flooded streams is of importance.

There are no adequate measurements of the rate of delivery of flood water to Suisun Bay by the rivers, either at the present time or in the earlier times when the movements of river waters were not obstructed by levees. Continuous measurements, however, are made of the discharge of streams near the points where they enter the Great Valley, and the data from these measurements have been used in estimating the maximum flood discharge to the bays after the completion of the system of works under construction for flood control.

A discharge through Golden Gate of 400,000 cubic feet per second corresponds to a mean velocity, at the point where the section is least, of 0.435 foot per second and to a midstream surface velocity of 0.58 foot per second. This is not a large fraction even of 5 feet per second, the average midstream velocity for all tides, but is nevertheless of importance because of the great addition to power of transportation which accompanies a moderate increase of velocity.

An estimate of maximum midstream ebb velocity in the strait may be obtained by adding

[1] Am. Soc. Civil Eng. Trans., vol. 61, pp. 281-330, 373-376, 1908.

the estimated maximum velocity from river flood to the estimated velocity on December 16, 1914. The sum is 10.2 feet per second, which equals 6.9 miles per hour. The late Prof. George Davidson[1] says: "Between Fort Point and Lime Point we have measured the ebb surface current running with a velocity of 6.6 miles per hour, whilst the subsurface currents have been measured running over 8 miles per hour."

Velocities on the bar—mean velocities at strength of current for tropic ebb tides—have been computed for the inner slope, halfway from the headlands to the outer crest (see fig. 10, p. 70), and for the crest itself. In making the computations the tidal volume and tidal period, which are not accurately known, were assumed to be the same as at Fort Point, and assumptions were involved also in the determination of sectional areas. The section lines selected were curves, resting at the south against Ocean Beach and stopping northward at the outer edge of the Bonita Channel, which is said to carry little or none of the ebb current; and no allowance was made for the fact that the probable direction of the current is not everywhere normal to either assumed line of section. On the whole the estimates of mean velocity are more likely to be too small than too large.

COMPARISON OF VELOCITIES WITH THE CHARACTER OF THE DÉBRIS IN TRANSIT.

The velocity with which a current sweeps its bed varies from point to point of the bed. It is controlled not only by those conditions which determine mean velocity but by bends and other details of the shape of the channel. The débris transported by a current usually includes particles of diverse size, the range from largest to smallest being great, and usually a portion of the load—the finer portion—is borne in suspension, while the remainder is dragged along the bed. The line of separation between suspended load and bed load is drawn by velocity, the suspended load being larger and including coarser débris as the velocity is greater, so that the constitution of suspended load and of bed load changes with changes of velocity. The débris which composes the bed at any point belongs to the bed load (except as finer stuff may lodge in its interstices), and so the characteristic material of the bed at any point is an index of the local velocity of the current.

Because of this general correlation between velocity and the texture of bed material, I have been led to compare certain of the velocities listed in Table 24 with samples from the channel bed at the same places. Each of the velocities used in the comparison is the mean velocity, within a particular section of channel, at the time of the greatest strength of an average tropic ebb current. The mode of comparison assumes a constant ratio between this mean velocity and the greatest velocity on the bed in the same section, and the result of the comparison is qualified by the inaccuracy of this assumption.

Most of the available specimens of bed material from the localities for which velocities have been determined are samples brought up by the sounding lead. They were obtained by the United States Coast and Geodetic Survey in connection with its hydrographic work and are now preserved in the United States National Museum. For some of the velocity stations the collection includes several samples, and from each such set of samples the coarsest was chosen for the comparison. Each selected sample was divided by means of sieves into a series of grades, and the grade found to contain the largest fraction of the sample was taken to represent the sample. The corresponding mean diameter of débris particle was then obtained from a table prepared in connection with the Berkeley experiments on débris transportation.[1]

The mean diameters, representing the grade of bottom material in respect to coarseness were then plotted in relation to the associated mean velocities, the plot being made on logarithmic section paper. The data gave five plotted points, and it was found that four of these lay nearly in line, the fifth being rather aberrant. The equation given by the four points is

$$D = 0.093\, V^{1.6}$$

in which D is mean diameter, in millimeters, and V is mean velocity, in feet per second. By means of this equation a value of D was computed for each velocity; and in Table 27 the computed and observed values are assembled for comparison.

[1] Pacific Coast Pilot, 1889 ed., p. 227. As the Coast Pilot is written for navigators, it is possible that the "miles" referred to are nautical. A velocity of 10.2 feet per second equals 5.9 nautical miles per hour.

[1] See U. S. Geol. Survey Prof. Paper 86, p. 21, 1914.

TABLE 27.—*Comparison of velocities of tropic ebb current, at strength, with coarseness of débris constituting channel bed, the coarseness being represented by the average diameter of particle in the characteristic portion of the débris.*

Locality.	Velocity.	Average diameter of particle.	
		Computed.	Observed.
	Feet per second.	*Millimeters.*	*Millimeters.*
Crest of bar, San Francisco entrance	2.1	0.30	0.2
Midslope (inside) of bar	3.2	.56	.65
Golden Gate at Fort Point	5.2	1.30	1.3
San Pablo Strait	4.6	1.07	[0.6–0.8]
Pinole Shoal	3.6	.72	.2
Carquinez Strait	5.2	1.30	1.3

The more accordant diameters are those for the inner slope of the bar, for the Golden Gate, and for Carquinez Strait. For San Pablo Strait the tabulated diameter was not determined from a preserved sample, but its value was inferred from descriptions of samples recorded by the surveyor. The value is materially less than that appropriate to the velocity.

It is not surprising that there should be discordance for the crest of the bar, because there the conditions are peculiar. Wave agitation is added to current action as a sorting agency; and the sand that reaches the crest by rolling and tumbling along the bottom can escape from it only when trituration has fitted it for suspension.

For Pinole Shoal the discordance is great. It is in fact much greater than appears from the contrast of the tabulated diameters—0.72 millimeter as computed and 0.2 millimeter as observed—for on the bed of the channel at that point the characteristic material is an impalpable mud, and the sand affording the measurement of diameter is only a minor constituent. Not only the mud but the greater part of the sand is so fine as to be carried in suspension by the stronger currents of the locality, and the fact that such material occupies the entire bed of the channel is one requiring explanation. It appears to me probable that the peculiar condition is occasioned by flocculation. Where muddy river water meets and mingles with sea water the salt usually causes the suspended particles to gather together in fleecy bunches, or floccules, and these sink through the water more rapidly than individual particles, so that their formation tends to carry the suspended matter to the bottom. At ordinary stages of Sacramento and San Joaquin rivers their waters meet the sea salt near their mouths [1] and the resulting precipitation may affect chiefly the shoals of Suisun Bay, but at times of great flood, which are also the times of greatest suspended load, the chief mingling of waters is probably in the upper end of San Pablo Bay, and it may be supposed that the resulting flocculation enables a large amount of suspended mud to reach the bottom. Accordant with this supposition is the fact that the layer of mud which was spread over the great northern shoal of San Pablo Bay between 1856 and 1896 was much thicker near Carquinez Strait than farther west. If this view is well founded, the line of separation of transported débris into suspended load and bed load is not here a simple function of coarseness of débris particles and velocity of current but is materially influenced by the tendency of the particles to adhere. It is conceivable that the floccules on reaching the bottom become units of the bed load and are rolled by the current, but it appears to me more probable that the same property of surface tension which determines flocculation serves also to weld the particles of the channel bed into a coherent mass which resists the scouring force of the current.

SOURCES OF BAR MATERIAL.

There is no question that a large part of the débris constituting the bar has been quarried by the waves from the cliffs of the outer coast. A smaller part must have been derived from shore cliffs bordering the Golden Gate. Some may have been furnished by the few cliffs of the bay shores, but the contribution from these would in any case be inconsiderable. Finally, a portion may have come from Sacramento and San Joaquin rivers. The body of sand delivered to Suisun Bay by the rivers has been great, and the present annual contribution is evidently large, but there is room for doubt as to the delivery of river sand on the bar. The present section is concerned with the question

[1] At low stages of San Joaquin River the flood tide is said to carry brackish water several miles above its mouth. In Carquinez Strait the ordinary salinity, according to the *Albatross* observations, is about one half that of the ocean.

whether or in what quantity river sand finds its way to the bar, and the discussion deals particularly with the evidence afforded by samples of sand from various localities. Sand from the surface of the bar is compared with sand from neighboring beaches of the outer coast and the Golden Gate and with river sand.

In connection with an elaborate mapping of the bar in 1873 a series of bottom samples were obtained by the United States Coast and Geodetic Survey. They came from more than 100 points and represent the whole surface of the bar. They range from fine sand to small gravel, and with some of them are broken shells as well as a few entire shells. The sands are clean, in the sense that they hold no mud, and the range of size in each sample is less than is usually found in river sand. The characteristic or dominant diameter of grain on the crest of the bar is in some places as low as 0.13 millimeter, in others as high as 0.25 millimeter; the average is 0.20 millimeter. The sand of the outer slope, sampled only to a depth of 10 fathoms, appears similar to that of the crest. On the inner slope there is a general increase in coarseness with increase of depth, the characteristic diameter at 20 fathoms being about 1 millimeter.

The sand samples to represent the supply from local sources were obtained from Tennessee Cove and Rodeo Beach, north of Point Bonita, from Ocean Beach, and from a beach between Point Lobos and Fort Point.

The river sands selected for comparison were not taken from the river beds but from the bed of the main tide channel through Suisun Bay, Carquinez Strait, and San Pablo Bay. That channel, which was remodeled and contracted by the invading débris from the mines, is unquestionably lined by sand and gravel from the rivers, and the material of its bed epitomizes the composition of sands from the two rivers and their tributaries. The Suisun and Carquinez samples were obtained by the Coast Survey during the hydrographic surveys of the year 1886, being brought from the bottom by the sounding lead. The San Pablo samples were collected in 1913 by the United States Bureau of Fisheries, in connection with a biologic survey of the waters of the bays that was undertaken in cooperation with the University of California.[1] In that work the steamer *Albatross* was employed, and samples of the bottom were taken by means of a special apparatus which penetrated the deposits to a depth of several feet, bringing up a core. Two such cores were obtained from the same station in San Pablo Channel, at a locality within the tract known to navigators as Pinole Shoal. From one of the cores three samples were taken—the top, middle, and bottom parts—and were examined under the direction of Prof. George D. Louderback. Three similar samples from the other or duplicate core were lent to me for examination. Louderback's report[2] includes the following information:

The core obtained January 13, 1913, at hydrographic station 5288 had a length of 117 centimeters (3.8 feet). The inorganic material of the three samples was composed as follows:

Diameter of grains.	Top.	Middle.	Bottom.
	Per cent.	*Per cent.*	*Per cent.*
Less than 0.02 millimeter	93.70	70.61	56.27
From 0.02 millimeter to 2.0 millimeters	6.30	29.28	43.73
From 2.0 to 5.0 millimeters	....	.11	....
	100.00	100.00	100.00

A mechanical analysis of samples from the duplicate core gave:

Diameter of grains.	Top.	Middle.	Bottom.
	Per cent.	*Per cent.*	*Per cent.*
Less than 0.02 millimeter	88.5	65.6	57.1
From 0.02 to 0.06 millimeter	5.5	8.7	4.5
From 0.06 to 0.15 millimeter	.9	1.9	2.6
From 0.15 to 0.2 millimeter	2.4	8.2	13.4
From 0.2 to 0.3 millimeter	1.6	8.0	14.5
From 0.3 to 0.4 millimeter	1.1	7.0	7.1
More than 0.4 millimeter	....	.6	.8
	100.0	100.0	100.0

The results of the two analyses are in substantial agreement. The material which the analysis of the first core reports as larger than 2 millimeters consists of thin flakes of shell and

[1] The first publication resulting from the work of this survey is "A report upon the physical conditions in San Francisco Bay, based upon the operations of the U. S. Bureau of Fisheries steamer *Albatross* during the years 1912 and 1913," and constitutes vol. 14, No. 1, of University of California Publications in Zoology, 1914.

[2] Idem, pp. 14-19, 175-192.

mica, as easily transported as the coarser material of the duplicate core.

The greater detail of the second analysis brings out the fact that the curve of size for the débris has two maxima, and this feature, by indicating that the deposit is a mixture of two materials of very different coarseness, supports the hypothesis of flocculation. One material, of which the characteristic diameter lies between 0.15 and 0.3 millimeter reached the place as bed load, drifting along the bottom of the channel. The other, of which the characteristic diameter is less than 0.02 millimeter, was deposited by flocculation from the suspended load.

[Since the preceding paragraph was written I have had further opportunity to examine the *Albatross* samples and have learned that the Pinole shoal deposits are distinctly laminated. Alternating thin layers are characterized by coarser and finer materials, corresponding to the two grades revealed by the analysis. The layers containing the coarser grains carry also some of the finer and may be called fine, muddy sand; the intervening layers are of pure mud.]

The position of the *Albatross* when the cores were taken is recorded by bearings and when plotted appears to be at the edge of the artificial channel maintained by dredging across Pinole Shoal. (See p. 102, footnote.) The recorded depth of water indicates that it is within the area of excavation. A comparison of the records of sounding at various dates with the record of dredging operations has made it seem highly probable that the lower parts of the cores are from a deposit of earlier date than 1856, in which case they represent the alluvium traversing the channel before the flow of mining débris. This inference finds support in the fact that the sandy portion of the core material is notably distinct from the sand occurring in Carquinez Strait in 1886, which represents post-mining débris. The material of the upper parts of the cores may be a fresh deposit washed from the side of the excavated channel, but it is distinguished from the material of the lower parts only by the relatively large proportion of mud.

In a preliminary examination of the sands with reference to composition it was found that the proportions of different components are not the same for the coarser and finer parts of the same sample, and because of this fact the portions to be subjected to fuller comparison were separated by sieves so as to have about the same mean diameter, 0.2 millimeter.

In general color the sands show certain differences. The following statement does not attempt to describe the colors but refers only to differences. All sands from the bar have about the same shade. Sands from beaches near the bar agree in color with bar sands but are slightly darker. When sands from Suisun and Carquinez channels (river sands, 1886) are compared with bar sands the former appear relatively orange and the latter relatively greenish. When the Suisun and Carquinez sands are compared with sand from the San Pablo channel (*Albatross* sample) the former appear relatively orange and the latter relatively green. When the San Pablo sand is compared with bar sand the former appears gray and the latter brownish.

In all the sands the most abundant material is quartz, and some of the quartz is clear and vitreous. Much of the quartz is colored, the coloring matter being either diffused [1] or in specks. The colors of the quartz produce most of the differences in the general colors of samples. Few grains of feldspar were recognized, but no serious attempt was made to discriminate feldspar from quartz. Among the dark grains only a few seem to be fragments of crystals, but such occurrences are rarer in the bar sands and beach sands than in the river sands. In all the sands the dark grains are chiefly rock fragments, each being an aggregate of two or more minerals, and the dominant mode of aggregation is that of holocrystalline igneous rocks.

The inquiry was directed especially to the discovery of some material at the same time fairly abundant in the river sands and very rare in beach sands of the coast, so that its occurrence in or absence from the bar sand might lead to inference as to the presence or absence of river sand in the bar, but no such material was found. All the chief components of the river sands occur also in the beach sands. On the other hand, there is a prominent component of the beach sands which was not found in the river sands. This is quartz from the radiolarian cherts of the Franciscan formation. Much of it is strongly colored, reddish brown or

[1] This appearance was observed with a microscope of low power; high power was not applied.

green, and it has a distinctive structure. It is conspicuous not only in the beach sands but also in the bar sands, but its presence on the bar serves only to confirm the inference from the physiography that the bar is built chiefly of the waste from coastal cliffs.

The sand from the San Pablo channel is distinguished from all the other sands, including the river sand of Carquinez Strait and Suisun Bay, by the fact that it contains almost no yellow quartz grains or quartz grains with yellow specks. This peculiarity conforms to the inference, drawn from other data, that the core samples represent débris brought to the bays by the rivers before the time of hydraulic mining.

In all the sands large grains are, as a class, better rounded than small, and dark grains are better rounded than pale. Of the small grains, 0.1 to 0.3 millimeter in diameter, very few are worn to pebble form except in the bar sands. The edges of angular grains show more rounding in the bar samples than in any other. Edges that show no evidence of wear are rarely seen except on grains of transparent quartz. They occur on such grains in all the samples, but least commonly in the samples from the bar.

The evidence of the sand samples is supplemented by data from the dredging operations on Pinole Shoal. On the line of the artificial channel the dredge has removed all the débris deposited in the natural channel since the year of the first general survey, 1856, and has penetrated several feet into the earlier or premining deposit. I am informed by Capt. H. L. Demeritt, the engineer in immediate charge of the work, that all the dredged material would be classed by dredgers as blue mud—it is so coherent as to "stand up" on the dredge bucket like stiff mud or clay—but that a magnifying glass shows that it contains much fine gray sand. This description applies perfectly to the material of the core samples and gives generality to certain inferences from the samples. The coarser river-borne material finds the limit of its journey where the current slackens between Carquinez Strait and Pinole Shoal, and the same limit existed in pre-mining times. Nothing coarser than fine sand gets beyond Pinole Shoal. The coarse sand and fine gravel moving down Sacramento River is reduced by attrition before it reaches San Pablo Bay.

It does not necessarily follow that the river débris makes no contribution to the bar, for the sand found in the core samples from Pinole Shoal is not too fine to come to rest on the bar and it is constituted of grains which by surviving have demonstrated great ability to stand buffeting. The comminution of débris by rolling and jostling on a stream bed is a process which becomes less rapid as coarseness is reduced. The weaker grains tend to disappear, being ground so fine as to join the suspended load, and the surviving resistant small grains suffer little from the feeble blows they give one another. So the rate of wear from Pinole Shoal to the bar is less than the rate from the river mouths to Pinole Shoal. There must, however, be some wearing, and as the sand grains at the shoal are already about as small as those on the crest of the bar only a little wearing is needed to unfit them for deposition on the bar. About 92 per cent of the grains on Pinole Shoal are either rounded or else have edges blunted by attrition, and as they are shown by that fact to be destructible it seems fair to assume that they will not survive the long journey. Of the remaining 8 per cent, grains of vitreous quartz with sharp edges, a portion may reach the bar. As the sand of Pinole Shoal is itself but a remnant of the bed load of the rivers, it would appear that the possible contribution, past or present, made by the rivers to the bar is but a minute fraction of the great body of mining débris and soil waste, while the probable contribution is of no practical importance as a factor affecting the history of the bar.

OBSERVED CHANGES IN THE BAR.

In 1881 Lieut. Col. G. H. Mendell[1] made a report to the Chief of Engineers, United States Army, on causes tending to decrease the depth of water on the bar. The report contains an admirable statement of the general situation at that time, draws such conclusions as were warranted by the data then available, and points out the lines of investigation which would lead to more definite and satisfactory conclusions. From a comparison of the charted results of two surveys, made by the Coast Survey in 1855 and 1873, he infers that the changes which took place in the intervening 18 years were not great and that the depth of water on

[1] Chief Eng. U. S. Army Ann. Rept. for 1881, pp. 2515-2524.

the crest of the bar was, if anything, greater at the time of the second survey, but he also states that the first survey was not sufficiently elaborate to make the comparison entirely satisfactory. Three years later Prof. George Davidson [1] addressed the Geographical Society of the Pacific on the same subject, and he also presented the results of a comparison of charts, his conclusions agreeing with those of Col. Mendell. More recently a graphic discussion by Nautical Expert J. T. Wilkins, of the Coast Survey (see Appendix C), took account of a change which had been made in the "plane of reference," or zero of soundings, between the dates of the two surveys, and it appeared that when the proper correction for this change had been applied the earlier conclusions as to depth were not sustained; the average depth on the crest of the bar was notably less in 1873 than in 1855. Both Mendell and Davidson recommended that a new survey be made, the data from which could be compared with those from the survey of 1873, and that yet other surveys be made from time to time. In 1884 a few lines of soundings were run, and in 1900 there was a complete resurvey, coordinate with that of 1873.

I have carefully compared the sounding records of 1900 with those of 1873, making use of the large-scale manuscript charts in the archives of the Coast Survey, which contain much fuller data than the published charts, and receiving, through the courtesy of that Survey, the advice and assistance of certain of its experts. As the full record of the comparison involves many details it has been relegated to an appendix (pp. 139–148) and only the general results will here be given.

Between 1873 and 1900 the crest of the bar was lowered through most of its length, the average amount being 0.9 foot. This change was least in the medial or western third of the bar and greatest in the southern third, where the bar summit is expanded into a broad, plateau-like shoal. There was a loss of several feet from the outer slope of the bar, a change which may be otherwise stated by saying that the outer slope moved landward through a distance of several hundred feet. There was also a loss from the inner slope, relatively small near the crest but increasing with depth until at the 16-fathom contour it amounted to 8 feet. In the vicinity of that contour the inner slope moved oceanward through a space of more than 1,000 feet. So the great body of sand to which the name bar, in its larger sense, is applied became notably narrower near its base. The charts do not cover the entire body but perhaps nine-tenths of it—a tract of about 44 square miles. From that tract the average vertical loss was 1.7 feet, corresponding to a volume loss of 77,000,000 cubic yards.

These changes were accompanied by a change in the position of the crest line. In the medial region, where the summit is narrowest and the crest best defined, its migration was measured from 1855 to 1873 and from 1873 to 1900. In each interval the migration was toward the land. The distance traversed during the first interval of 18 years is not very definitely shown but falls between 400 and 700 feet; during the second interval, of 27 years, it falls between 400 and 500 feet. The average annual rate, which was greater for the first interval than for the second, was 20 to 25 feet for the whole period of 45 years. The total change in that period was from 3 to 3.5 per cent of the whole distance of that portion of the bar crest from the general line of the coast.

The correction that Watkins applied in his discussion of the relative crest heights in 1855 and 1873 is equally applicable to other parts of the bar. The combination of his results with those of Mendell and Davidson yields as its broadest generalization a general growth of the bar between those dates. So the conclusions that appear to follow from the data given by the three surveys are (1) that the volume of the bar increased between 1855 and 1873; (2) that the volume of the bar diminished between 1873 and 1900; and (3) that the crest of the bar moved toward the land during both of these periods.

As to the validity of these results, it may be said that those involving data from the survey of 1855 are less secure than those dependent only on the later surveys. It is my judgment also that those relating to the migration of the crest are more secure than those relating to the volume or general height of the bar.

INTERPRETATION OF OBSERVED CHANGES.

The San Francisco bar is so unlike other harbor bars that a comparative study throws little light on its hydraulics. With the aid of the United States Hydrographic Office I have

[1] The shoaling of the bar at the entrance to San Francisco Harbor: Geog. Soc. Pacific Proc., meeting of May 20, 1884, pp. 2–23.

sought its nearest relatives, finding them in the submerged delta of the Tagus, outside Lisbon Harbor, and in the tide-built bar outside Manukau Harbor, New Zealand; but I have failed to correlate the differences of form with recognized differences in local conditions.

On the shore of Evolution Lake, an alpine lake in the Sierra Nevada, I once saw miniature bars that copied the outline of the bar at San Francisco. The shore there was straight and bore at the water's edge a steep, narrow parapet of sand that had been crowded up by the ice in winter. The water from a recent storm gathering behind the parapet had breached it at several points, and at each point the sand washed from the parapet had been deposited in the lake as a semicircular bar. (See fig. 20.) The outrush of water was strong and brief and the supply of sand was local and small. The phenomenon serves to indicate that the semicircular form is normal where the depositing agent is a strong current reaching still water through a narrow passage. It is probable, therefore, that the general form of the San Francisco bar has been given by the tidal currents and that the cooperation of the waves is not essential to its production.

It is a generalization from the features of many coasts that the waves, when acting on an inshore bottom of loose material, give to it a gentle inclination seaward. They grade the surface by removing prominences and filling hollows. In what might be called the Franciscan Bight, from Duxbury Point to San Pedro Point, the general slope is at the rate of 1 in 700 but becomes steeper as the beach is approached. The bar, which has outward slopes of 1 in 150 to 1 in 100, rises above this platform as if built on it and constitutes a prominence such as the normal action of the waves would remove. It would be a mistake, however, to think of the bar as resting on the platform. Bar and platform have been developed together, the waves molding the outer face of the bar at the same time that they molded the platform.

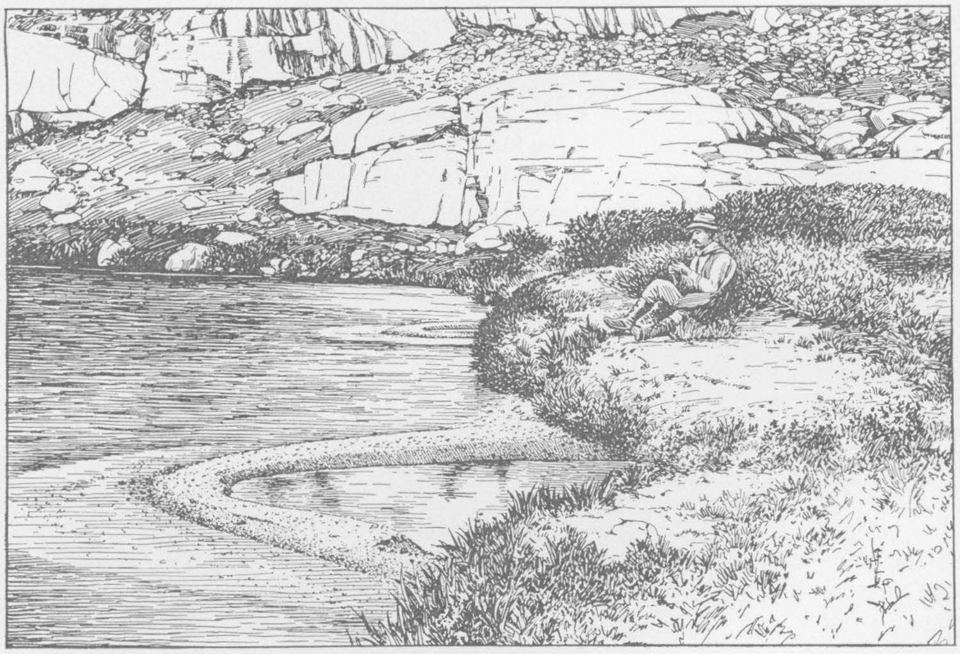


FIGURE 20.—Miniature sand bar in Evolution Lake, Sierra Nevada, illustrating the mode of origin of the Golden Gate bar. From a photograph by W. D. Johnson.

Three principal factors go to the determination of the form of the bar—the tidal currents, the waves, and the supply of sand.

In the Golden Gate, as in the bays, the ebb currents develop higher velocities than the flood currents and thereby determine the movement of débris outward. The chief conditions on which this dominance of the ebb depends do not necessarily continue to the bar, but another condition is there added. Bonita Channel carries very little of the outgoing tide but carries a large volume of the incoming tide, and by consequence the average ebb volume crossing the bar is greater than the average flood volume. It is therefore probable that the tidal currents move sand outward all the way to the bar crest and would if unopposed deposit it just outside the crest. After passing the crest the ebb current slackens because its depth increases, and it slackens especially at the bottom because of its tendency to leave the bottom and pass oceanward as a surface current.

Wave work as an agency for molding the bottom results from a to-and-fro motion of the water in contact with the bottom, in conjunction with whatever motion the same water may have as part of a current. The to-and-fro motion may of itself be relatively swift in one direction and thereby transport sand; and by lifting sand momentarily from the bottom it enables currents, even very feeble currents, to perform the work of transportation. It is through such action as this that the outer slope of the bar receives its profile, a profile slightly concave except near the crest. I have no knowledge of the interactions by which this profile is determined but am confident that it is in fact a profile of equilibrium, so that when any part of it is disturbed by some extraneous cause the reestablishment of equilibrium involves the reconstruction of the whole profile. When the crest of the bar was moved landward, as shown by the surveys of 1873 and 1900, the whole outer profile (down to the 10-fathom contour, which limits the area of comparative data) moved in the same direction.

The magnitude of the to-and-fro motion and the consequent strength of wave action vary inversely with depth. On the outer face of the bar the action is so feeble at 12 fathoms as to allow mud to come to rest, but at all soundings in less depth the material of the bed is reported to be sand. The action reaches its maximum at the bar crest, where the reaction is so strong that the largest waves are made to break at the surface. In the act of breaking they are changed wholly or partly to waves of another type, and as these move on landward they have less energy.

Despite the incompleteness of this analysis, it serves to show that of the two molding agencies the tidal currents dominate inside the crest and the waves outside. The region of the crest is their common ground, and I believe it to be their field of conflict. As the ebb current has caused the advanced position of the bar, I think of it as striving ever to push the crest farther out. As the waves have, within the period of observation, pushed back the central part of the bar, I think of them as striving ever to force it toward the land.

Postulating that the strength of the wind-made waves, though highly variable in detail, is in long averages constant, and knowing the average strength of tidal currents to be dependent on the volume of the tidal prism, I infer that the position of the bar may be changed by any influence affecting the tidal prism.

Tidal discharge (proportional to tidal volume) is measured by the product of width of channel by mean depth of channel by mean velocity. Adapting this formula to the matter under consideration, we may say that tidal volume is approximately proportional to the length of the bar (corresponding to width of channel), to the depth of water on the bar, and to ebb velocity across the bar. A reduction of tidal volume first affects velocity; reduction of velocity causes the bar crest to retreat landward; the retreat shortens the bar; and the shortening of the bar, by diminishing the channel space, tends to restore the velocity. In the final readjustment to equilibrium with wave action the bar is shorter and nearer shore.

This statement, however, is incomplete because the shortening of the bar affects other dimensions of the bar and affects also the relation of sand supply to sand waste. To appreciate the importance of these additional reactions it is necessary to give attention to the process of sand wasting, which is a factor coordinate with wave molding and current molding in the control of the bar.

The sand that is fed to the bar through the erosion of coastal cliffs would steadily augment the volume of the bar if there were no process of removal. The removal is accomplished by trituration and suspension. Moved by waves and currents, the grains strike one another and are worn smaller, and the currents finally bear away in suspension not only the minute chips stricken off but the reduced grains. The work is probably most active in the region of the bar crest, where the wave effect is strongest, and the quantity of sand thus worn out and removed is, other things being equal, proportional to the length of the bar. The quantity is also related to the velocity of the ebb current, which is the vehicle of the deported grains, for that velocity determines the critical size that separates the grains to remain from the grains to float away. With a weaker current the grains remain longer in the field of trituration, and so the wasting is slower; with a stronger current the wasting is more rapid.

We return now to the subject of the shortening of the bar as a consequence of a reduction of the tidal prism. Let us assume, for the moment, that the shortening is accompanied by proportional reduction of all other horizontal dimensions but that the volume of the bar is unchanged. It follows that horizontal shrinkage is accompanied by vertical expansion, the fractional increase in height being equal to the fractional decrease in area, or (approximately) to twice the fractional reduction of the crest in length. If the length is reduced by 1 per cent, for example, the height is increased by 2 per cent. In the central part of the bar the height of the crest above the general plane of the sea bed is 55 feet, and 2 per cent of this is 1.1 feet. At the same place the depth of water (below the plane of reference) is 34 feet, and a reduction in depth of 1.1 feet is a reduction of 3.2 per cent. So, under the assumptions just made, a reduction of the bar length of 1 per cent is accompanied by a depth reduction (at an important locality) of 3.2 per cent. The computation has been made merely to show that the reduction of length tends to reduce the depth and that the tendency is important. It does not in fact greatly reduce the depth, because any reduction of depth increases velocity, and increase of velocity promotes wasting of sand, and this tends to reduce the volume of the bar—so the assumption of constant volume is untenable.

A shortening of the bar also has the effect of diminishing the crest area, on which bar material is worn out and wasted, and, provided the supply of new material is unchanged, this effect must be offset by a strengthening of the ebb velocity. The increase of velocity necessary to dispose of the excess of sand occasioned by the shrinking of the bar may be regarded as temporary, being no longer required after adjustment has been effected; but the increase necessary to maintain a rate of wasting equal to the rate of supply is permanent. Thus we have the somewhat paradoxical result, that a reduction of tidal volume, which initially reduces ebb velocity across the bar, sets in motion a sequence of changes of such character that when equilibrium has been again attained the ebb velocity is greater than before.

The entire space between the crest of the bar and the water surface may be regarded as a channel for the ebb discharge; it is so wide a channel that the mean velocity in it is not appreciably affected by the channel walls, and there is no error in saying that the mean velocity varies inversely with the mean depth. It follows that the increase of velocity inferred through the reasoning of the last paragraph implies the same ratio of decrease in depth.

Thus it appears that the physical results following such a reduction of tidal volume as is occasioned by encroachment on the tidal prism include (1) a retreat of the bar crest toward the shore, (2) a reduction of depth of water above the bar, and (3) an increase in the velocity of tidal currents as they cross the bar.

The quantitative relations of the several effects do not appear, and the available local data do not suffice for their discussion, but some inference is possible from the phenomena of other harbors. The harbors of the world furnish many examples in which the entrance bar lies in the line of the beach, holding that position because the tidal current is not strong enough to drive it from the line established by the waves; yet there may be great depth of water on the bar. In view of these examples we may infer that if the currents of the Golden Gate should so weaken as to permit the bar to retreat to the coast line the bar would still carry a fair depth of water. That is, the retreat of the bar through its whole distance from the land would not be accomplished by a loss of the entire depth of water but only by a moderate fraction of it. And so the ratio in which the depth of water on the bar is reduced by encroachment on the tidal prism is believed to be less than the ratio in which the bar's distance from the coast line is reduced.

It is desirable so to extend the analysis as to discover the ratio which change in depth of water on the bar bears to change in tidal discharge, but the way is not clear. If we turn again to the consideration of tideways which cross the sandy cordon of the coast without deflecting it, we see that where the discharge is relatively large the traversing channel is relatively wide and relatively deep and the current through it is relatively swift. Width, depth, and velocity are all direct functions of discharge. Width and depth are apparently similar functions, so that their rates of change are equal and the theoretic rate of change in depth is less than half the rate of change in discharge. Where the bar is arcuate, however, only width and depth are direct functions of discharge, and velocity is an inverse function. If width and depth are similar functions of discharge, so as to have the same rate of change, the rate of change in depth is more than half the rate of change in discharge, but the "if" is important, for we have no information as to the relative rates of variation of width and depth.

The preceding discussion of the effect of change in tidal volume assumes constancy in the supply of sand. Let us now assume constancy in the tidal volume and consider the effect of a change in the supply of sand. Evidently the immediate or initial effect of an increase in the supply of sand is to build up the bar and thus reduce the depth of water above it. With smaller depth the velocity is greater, and increase of velocity tends in two ways toward a readjustment in which the wasting of sand is equal to the supply. First, it permits larger grains of sand to be removed in suspension; and second, it gives greater power to tidal forces in their conflict with the waves, with the result that the bar is pushed farther from the land, its length is increased, and the field of intensive sand wasting is enlarged. When the new equilibrium has been established the bar crest will be farther from the land, the depth of water on the bar will be less, and the ebb current will have a higher velocity.

It is evident that a reduction of the supply of sand will result in changes of opposite character.

We are now ready to compare the observed changes in the bar with the changes which theoretically should follow either a reduction of tidal volume or an increase or reduction of the supply of sand. In the following tabulation (Table 28) no mention is made of velocities because observation has told us nothing of their changes.

The movement of the crest line toward the land that was determined by comparing the soundings of 1873 with those of 1855 is such as might be occasioned either by a reduction of the tidal prism or by a reduction of the rate at which sand was supplied to the bar. The simultaneous loss in depth inferred from a comparison of the same systems of soundings might be occasioned by a reduction of the tidal prism or by an increase in the rate of sand supply. Reduction of the tidal prism, the cause indicated by both the observed changes, is itself an observed fact, for it is known that during that period there were encroachments on the bays and also on the tidal marshes. As to change in the supply of sand—a change concerning which the theoretic indications are conflicting—we lack information.

TABLE 28.—*Comparison of observed changes of the Golden Gate bar with changes theoretically due to specific causes.*

	Character of changes theoretically caused by—		
	Reduction of tidal prism in the bays.	Reduction of sand supply.	Increase of sand supply.
Crest moved	Landward	Landward	Oceanward.
Depth of water on crest	Reduced	Increased	Reduced.
	Observed changes.[a]		
	1855–1873	1873–1900	1855–1900
Crest moved	Landward (425 feet).	Landward (465 feet).	Landward (1,125 feet).
Depth of water on crest.	Reduced (0.5 foot).	Increased (1.1 feet; 0.9 foot).	Increased (0.6 foot).

[a] The figures indicating amounts of change are taken from Appendix C (p. 145), to which the reader is referred. The measurements of crest movement were all made within the central third of the arc of the crest, but not in precisely the same tracts, which accounts for a discrepancy among the figures. The figures giving estimates of change in depth are averages for the entire crest. They are from a study by J. T. Watkins, except that the smaller estimate for the period 1873–1900 is by the writer.

The movement of the crest line between 1873 and 1900 was also toward the land, implying either a reduction of the tidal prism or a reduction of sand supply; but the change in depth for this later period was a gain instead of a loss, and gain implies either an enlargement of the tidal prism or a reduction of the sand supply. The two observed changes agree in indicating defect of sand supply as a cause but differ in their indications as to the tidal prism. As it is a matter of independent knowledge that the tidal prism was reduced in various ways during that period, no part of the gain in depth can be assigned to enlargement of prism and the whole should be ascribed to a defect of sand supply.

The view that the sand supply was exceptionally small during this period finds support in an observed change in the form of the bar. A simple landward migration, such as was considered in the theoretic discussion of the effect of reduced tidal volume, involves a landward shifting of the crest and of the outer and inner faces, but the change revealed by the resurvey in 1900 was somewhat different. The outer face and the crest moved toward the land, but the greater part of the inner face did not. There was a steepening of the inner slope, so that while the extreme upper part moved somewhat toward the land the lowest part moved more than 1,000 feet in the opposite direction. The broad base of the bar was narrowed to an extent that was proportionally greater than the reduction in length or the reduction in height, and there was a large reduction in the volume of the bar.

The fact that the bar crest was lowered so as to give more depth of water, notwithstanding the reduction of tidal prism, which tended to cause less depth, indicates that the influence of change in the prism was overpowered by the effect of change in sand supply. The rate of sand supply appears to be the preponderant factor in determining depth of water on the bar.

In the preceding discussion the endeavor has been to draw legitimate conclusions from the data afforded by three surveys of the bar, and the accuracy of the data has been assumed. It remains to consider difficulties. The result that I find hardest to accept is that during the period 1873–1900 there was a great defect in the supply of sand reaching the bar, a defect causing the bar to lose on the average 1.7 feet from its surface and to sustain a loss of volume of over 70,000,000 cubic yards. If it is admitted that the sand tribute from the rivers is negligible we must regard the wave-beaten cliffs and bluffs of the coast as the only important source of the bar's supply of sand, and the rate of erosion of the coast seems to depend on factors that afford little variation, when the average for 27 years is compared with the average for a preceding long period. Most of those factors are natural, and I know no reason to suppose they have suffered important change within the last century. Man has at a few points tried to retard the slumping of sandy cliffs toward the beach, but what he has accomplished is trivial and may be fully offset by the stimulus he has given to rain erosion by his plowing and road making on lands that drain directly to the coast.

If importance is ascribed to the tribute from the rivers the difficulty is not less, for the period from 1873 to 1900 includes not only the decade of greatest output of sand from hydraulic mining but also the following decade, in which the delivery to the bar would presumably be greatest.

The recognition of this difficulty led me to scrutinize the data from the surveys of 1873 and 1900 with special care, as described in Appendix C. Their details are such that certain probable errros are readily computed, and the probable error of the computed mean change in depth for the whole bar area, an increase of 1.7 feet, was found to be only ± 0.1 foot. That check applies, of course, only to accidental errors and has no bearing on the question of systematic errors. My search for systematic errors, however, revealed none that helped to remove the difficulty. The chief discovered reason for questioning the survey data, aside from the improbability of the results to which they lead, lies in the fact that the methods of reducing the measurements made with the sounding line at different stages of tide to a common reference plane were not the same in 1873 and in 1900.

SUMMARY.

There is a continuous channel from the mouths of Sacramento and San Joaquin rivers to the Golden Gate bar. This channel is maintained by tidal currents, and the tides are of such nature that the stronger ebb currents have higher velocity than the stronger flood currents. The ebb currents, moreover, are reinforced by the discharge from the rivers. It results that sand and other coarse débris delivered to Suisun Bay by the rivers and dragged forward and backward by the currents has a net movement toward the bar. While thus in transit it suffers attrition, and the greater part of it is ground so fine as to leave the channel bed and pass into suspension. At Pinole Shoal, in San Pablo Bay, a point midway between the river mouths and the bar, the coarsest material remaining in the channel bed is a fine sand, the grains being about as large as those of the sand which constitutes the crest of the bar. The course of the river sand has not been traced beyond this point, but it is believed that very little of it can survive the buffetings of the remaining journey and find lodgment on the bar.

The sand on the bar is stirred and jostled by storm waves, which agitate the water to considerable depths, and it also is worn out. The chief source of renewal, to compensate for the waste, is the erosion of the coast. The cliffs are quarries worked by the waves, and the output in sand and gravel drifts along the beaches to the tidal currents of the Golden Gate. In samples of sand from the bar it was found easy to recognize material that could have come only from the coast or from the Golden Gate, but attempts to identify material from the rivers were unsuccessful.

The depth of water on the bar depends partly on the rate at which sand is supplied to it and partly on the strength of tidal currents. The strength of currents depends in turn on the volume of the tidal prism. The effective tidal prism is the space between the position of the water surface in the bays when the outward flow begins at the Golden Gate and the position of the water surface when the outward flow ends. The volume of the prism has been reduced and is being reduced in three ways—by the filling of shoals and construction of piers, by the reclamation of tide marshes, and by the deposition on shoals in the bays of débris brought by rivers and creeks. It is estimated that the encroachment thus caused by mining débris and general soil waste has affected the tidal prism to the extent of 2 or 3 per cent, and the encroachment from marsh reclamation about 1.5 per cent.

Theoretically the reduction of the tidal prism should occasion two changes in the bar—a migration of the crest toward the land and an upward growth, reducing the depth of water on the crest. A comparison of charts made from surveys in 1855, 1873, and 1900 shows that in each interval between surveys the crest migrated toward the land, the entire change of position being nearly or quite 1,000 feet. The same charts indicate a loss in depth of 6 inches between 1855 and 1873, and a gain of 1 foot between 1873 and 1900, giving a net gain of 6 inches between 1855 and 1900, but the accuracy of these indications is questioned. The theoretic change in depth corresponding to a migration of 1,000 feet would be less than 6 inches, and would be a loss instead of a gain.

A falling off of the supply of sand is theoretically competent to increase depth of water on the bar and at the same time cause the crest to move toward the shore, but there is no independent evidence of defective sand supply during the period to which the survey data pertain. The discussion leaves open the question whether the apparent gain in depth was actual, the result of an unknown change in conditions determining sand supply, or was apparent only, the result of some undiscovered defect in methods of survey.

There is no reason to believe that mining débris by deposition on the bar has affected or might affect the depth of water on the bar to any appreciable extent. There is good reason to believe that mining débris and the soil waste promoted by agriculture and other industries have reduced and will reduce the depth of water by reducing the strength of tidal currents, their effects in this direction being combined with the similar effects of reclaiming tidal marshes on the borders of the bays.

Encroachments on the tidal prism of Suisun Bay have less influence on the currents in the Golden Gate than similar encroachments in the lower bays. The reclamation of marsh lands adjoining Suisun Bay and Napa River has about half as much influence on the Golden Gate currents as the reclamation of marsh lands adjoining the southern part of San Francisco Bay. The currents are little affected by the reclamation of marsh lands of the river deltas; reclamation near the river mouths tends to weaken the currents, and reclamation in the remoter parts of the deltas to strengthen them.

PINOLE SHOAL AND MARE ISLAND STRAIT.

The establishment and maintenance of a United States navy yard on Mare Island has given special importance to the shoaling of the San Pablo channel and to the formation of a shoal at the mouth of Napa River, for the maximum draft of vessels that can pass from the ocean to the navy yard is determined by the depth of water at these points. The commerce of the region about Carquinez Strait is also affected, though in less degree. Dredging has been resorted to at both points, and the maintenance of adequate depth has become both costly and precarious.[1]

It is to be observed, however, that the naval difficulty would have arisen even if there had been no shoaling, for war vessels of modern maximum draft could not have reached Mare Island at the time the locality was selected for a navy yard.

The channel through San Pablo Bay is bordered on both sides by broad shoals, and its banks and bed alike are composed of deposited débris. It is shaped by the tidal currents which traverse it, and its dimensions are determined partly by the volume of those currents, supplemented from time to time by river floods, and partly by the rate of influx of débris. Because of the reduced volume of tidal currents and because of the increased influx of débris, the bordering shoals have grown at the expense of the channel, and at the same time the channel depth has been reduced except for a central groove created by dredging. Between the years 1856 and 1897 the channel width at the 3-fathom contour was reduced from 10,870 to 8,300 feet. In an official report on channel improvement at Pinole Shoal the loss in depth between 1856 and 1899 has been estimated at 2 feet.

The reduction of tidal discharge was occasioned in part by deposits on the shoals of Suisun Bay, in part by the reclamation of marsh lands which had received tidewater from the Napa estuary, and in part by the reclamation of tide marshes of the Sacramento-San Joaquin delta. It is especially to be noted that the storage of tidewater on the delta, while of no importance with reference to currents in the Golden Gate, contributed much to the currents on Pinole Shoal. It has been estimated (see Table 22, p. 83) that when all the delta marshes shall have been reclaimed the great tropic ebb current across Pinole Shoal will have lost one-sixth of its volume and that an additional tenth of the volume may be cut off by the complete reclamation of the Suisun marshes.

The abridgment of tidal area occasioned by the silting up of Suisun Bay has been estimated to reduce the volume of tidal currents in the Golden Gate by more than 2 per cent. The corresponding estimate for Pinole Shoal is a reduction of tidal volume by more than 9 per cent.

By the engineering works for the control of Sacramento River floods the flood discharge of the river will be increased, and the increase will reinforce the ebb current on Pinole Shoal at a critical time, because then the water is most highly charged with sediment. This advantage will be partly or perhaps wholly offset by the fact that the bays will then receive all the débris that is now caught by the lateral basins of Sacramento Valley.

The lower part of Napa River is a tidal estuary and has an average width of 1 mile. Near its mouth, where it communicates with Carquinez Strait and San Pablo Bay, it is constricted into the narrows known as Mare Island Strait. On the north and west the estuary adjoins extensive marshes, and it receives the tidal sloughs of the marshes. The strait is the channel through which tidal waters flow to and from the estuary and marshes, and the original depth of water in the strait was determined by the tidal currents, conditioned by the small amount of débris which came with the river floods. In the early fifties, when the site for the navy yard was selected, the least depth of water in the strait was greater by a fathom than the least depth on Pinole Shoal. There were then no encroachments on the tidal storage of the marshes, and the influence of the mining débris had not been felt. In 1898, after the tide had been excluded from a portion of the marsh land and after the great influx of débris from mines and fields, the least depth was found to have diminished from 27 feet to 15 feet.[2] The shoaling has been ascribed to the change in débris conditions, and I am not aware that the influence of reclamation has been mentioned in this connection, but there need be no question that the impairment of the channel has been caused in part by the

[1] The first dredging on Pinole Shoal was in 1904–1906 and produced a trench about 5 miles long with a bottom width of 300 feet and side slopes of 1 in 3. Before the end of 1910 it had been filled and obliterated. In 1912–13 a new trench was dug, with a bottom width of 500 feet and side slopes of 1 in 5. Up to June 23, 1913, the appropriations for the work amounted to $1,153,168.41, and it had been estimated that the maintenance of that trench would cost $100,000 annually. In 1898–1900 Mare Island Strait was deepened by dredging. A plan for further improvements, recommended and approved in 1908, called for an initial expenditure of $1,007,000, to be followed by the annual expenditure of $70,000 for maintenance. In 1913 plans involving contract dredging were abandoned, and the first steps were taken for the construction of a Government-owned dredge to be used on Pinole Shoal and in Mare Island Strait.

[2] The history of change is given in the report of a board of Army and Navy officers "appointed to investigate the hydraulics of Mare Island Straits and approaches, with a view to improvement" (60th Cong., 2d sess., H. Doc. 1103, 1908).

weakening of the tidal currents. A close estimate of the extent to which the currents have been weakened is not practicable, because the marsh tract lying west of the estuary has not a definite boundary. It merges with a tract draining to Sonoma Creek, and the joint tract is traversed by a system of connecting sloughs. In preparing the data for Tables 17 and 22 I drew an arbitrary line of separation on the map, and the marsh lands thus assigned to Napa River had an area of 26 square miles; the area of the estuary is 5 square miles. On the basis of this classification the currents through the strait derived 60 per cent of their volume from the tidal prism of the estuary and 40 per cent from the tidal storage of the marshes. Prior to the first mapping of the region (Napa quadrangle) by the Geological Survey in 1899 about one-fourth of the marsh area had been reclaimed, so that 10 per cent may be used as an estimate of the loss in tidal volume in 1898. The amount of shoaling that would adjust the channel to this change and preserve the same velocity of tidal current is about 3 feet; and this is to be compared with an actual shoaling of 12 feet. These figures would doubtless be modified somewhat if the data as to the marsh lands were more exact, but their general indication may be accepted—that reclamation is responsible for an important fraction of the trouble from deposition in the strait.

The work of reclamation continues and bids fair to exclude the tides from all the marsh area except some of the larger sloughs. It will then have reduced the tidal discharge to about two-thirds of its original amount. Later mapping by the Geological Survey (Mare Island quadrangle) indicates that in 1914 more than half the marshes tributary to Napa River had been reclaimed, and that levees about still other tracts were then under construction.

CHAPTER X.—THE OUTLOOK FOR HYDRAULIC MINING.

The interests that suffered most acutely and consciously by reason of the great wave of mining débris from the Sierra were those of lowland farm lands and lowland towns. Some farms were buried, and for others the cost of protection from inundation was increased. Towns had to levee against sands and rising floods and were deprived of the advantages of river transportation. In respect to these interests the period of tension is now past. The piedmont rivers have intrenched themselves in the piedmont deposits, and their sands have ceased to spread. The valley rivers are lowering their beds, and the full resumption of river traffic is in sight. The débris in the river beds has lost prominence as a factor in the aggravation of floods, being now clearly subordinate to the reclamation factor.

The remoter effects of the débris invasion, though not neglected by the Government engineers in charge of rivers and harbors, received little attention from the general public, despite the fact that the integrity of the harbor is of higher importance to the community as a whole than the navigability of the rivers.

The building of the piedmont deposits gave to the channels of the piedmont rivers such slopes that they are now able to carry forward a much larger annual load of débris than in pre-mining years. The system of levees by which the valley floods are being controlled is giving to the valley rivers also an ability to transport a greater annual load. So far as riparian interests are concerned it would soon be possible to admit to the rivers a considerable annual load of mining tailings without a recurrence of the old-time tension. Such a modification of the existing system of regulation is inadmissible chiefly or wholly because the consequence would be prejudicial to navigation—because it would tend to diminish the depth of water in the rivers, on Pinole Shoal, and on the Golden Gate bar.

Back of this proposition lie certain postulates as to relative values. It is true that the present restrictions on mining were determined in chief part by considerations of justice between two local interests—the miners should not continue their work in a manner injurious to property in the valley—but San Francisco Harbor belongs to the whole community, and it is proper for the community to weigh its impairment, in such measure as it might be impaired, against the advantage to the community of having the gold extracted from the Sierra gravels. So too the community—or the custodians of its interests—may weigh the embarrassment of navigation in bays and rivers against the advantages from gold extraction. The regulations that restrain hydraulic mining should not be made less stringent unless the advantage from the mining is of greater moment to the community than the disadvantage to navigation that a change of policy might entail.

In this connection it is to be observed that the public and its representatives may properly consider to what extent the interests of agriculture and commerce are brought into antagonism by existing conditions in the bays. Now that the flow of mining débris is waning the flow of soil waste, whose effects are of the same character, is acquiring relative importance. Soil waste is mainly the tailings of agriculture, and through it agriculture is obstructive to navigation and commerce. Coordinate with the weakening of the Golden Gate currents by deposits of mining débris and soil waste is the weakening caused by the reclamation of tidal marshes, and nearly all that reclamation is for the purposes of agriculture. That agriculture in its entirety is the industry of first importance is recognized by all, but it does not follow that commerce should yield to it at every point of interference. Each particular case of conflicting interest involves an economic problem in relative values and should be adjudged on that basis.

As to soil waste there is no essential conflict of interest, for the conservation of soil is more important to agriculture than to commerce. The injury to commerce is occasioned only by the improvident and profligate methods of frontier farming. In time the methods will be reformed without regulative compulsion, and it is possible that this result may be achieved somewhat quickly through education, but if it must await for its motive a strong pressure of population on agricultural area much harm to navigation may first be caused.

In respect to reclamation the interests of agriculture and commerce are directly antagonistic. Every acre of reclaimed tide marsh (except in the upstream parts of the river deltas) implies a fractional reduction of the tidal current in the Golden Gate. For any individual acre the fraction is minute, but the acres of tide marsh are many, and if all shall be reclaimed the effect at the Golden Gate will not be minute. The question whether the community should make a large addition to its permanent agricultural wealth at the cost of a small permanent injury to its great harbor is a question of relative values.

Returning to the consideration of hydraulic mining, I shall assume that, in the future as now, the working of the auriferous gravels will be permitted only on condition that the tailings, coarse and fine, are kept from the rivers.

The history of mining under permit has served to bring out certain economic limitations. When the system of regulation was first established its rules were framed especially for the immediate arrest of the coarser débris. Much of the finer material was allowed to escape, and the types of impounding dams prescribed were not such as to make the débris storage permanent. Rules formulated later were more stringent, and the expense to the miner was increased, especially by the requirement that his dams have the quality of permanence. Partly because of the increasing stringency of regulation, and partly because of the exhaustion of the richer gravels and of the more available storage sites, the industry has slackened, and its magnitude is now relatively small. With minor exceptions, the gravels that remain in the Sierra can not be worked profitably so long as the cost of storage is added to the cost of washing.

With the lapse of time, also, the money value of water power has risen. Hydraulic mining must now compete with those valley industries which obtain power from the Sierra through electric transmission, and the restrictions thus imposed on mining increase with the development of the power-using industries. In the near future agriculture, which has postponed the full utilization of Sierra waters for irrigation, will be imperative in demanding a large share in the control of the streams, and the arrangements to meet the joint needs of irrigation and electric power are likely to so increase the storage of water in reservoirs that mining will have comparatively little opportunity for that use of surplus or otherwise unappropriated water which it now finds a resource.

As a result of the enlarged and growing cost of hydraulic mining the quantity of auriferous gravel that can be worked at a profit is less than it was 25 years ago. If the estimates made at that time were to be shorn of all exaggeration they would still need much paring to bring them into accord with present conditions.

In the memorial of the California Miners' Association (p. 12) asking for an investigation by the Geological Survey it was suggested that waste lands might be found in the foothills on which the mining débris could be deposited. The lands that are waste in the sense of having little or no value for agriculture are lands of steep slope, on which the débris could not be deposited without expensive dams. Deposition in the foothills could not in any case be accomplished without local control of the rivers, and such control would be more expensive than the control of streams near the mines.

Various schemes have been broached for the storage of mining débris in one of the lateral basins of the Sacramento. The cost would include engineering works for the control of large streams and also the purchase of the lands to be covered by the deposit, and such cost would be greater than the benefited mining industry could afford. Nevertheless, such projects are not necessarily visionary, because the mining interest is not necessarily the only one to receive benefit. A project of that kind might include the complete protection of a piedmont deposit of mining débris from further erosion and thus deserve consideration by the State as a measure for the conservation of San Francisco Harbor.

The reasons that have been given by engineers for the rejection of such schemes have included interference with vested rights, prohibitive cost, and inadequate fall or slope. While I do not question that the second reason is adequate, it seems to me desirable to point out that the third is fallacious. It is indeed true that a stream which carries a load of débris can not carry its load on a route giving less slope if other conditions remain the same, but it is also true that on most streams the ability to carry load may be greatly increased by reducing the width of channel. An unrestrained stream that has a load to carry shapes for itself a wide, shallow channel, whereas the channel form most efficient for the transportation of débris is narrow and deep. It results that a stream with a fixed load which has adjusted its slope to a wide channel can be made to do its work on a gentler slope by narrowing its channel.

As already mentioned (p. 63), this principle is illustrated by results from the training walls at Daguerre Point; and it is further illustrated at the narrows of Yuba River near Smartsville. In the narrows, where rock walls determine a width of 300 to 400 feet, the Yuba established a slope of 5 feet to the mile as appropriate to the transportation of its load of coarse gravel at a time when the movement of mining débris was near its maximum. Outside the narrows, where the width of the flood channel was 1,000 to 1,500 feet, the slope adjusted to the same load was about 18 feet to the mile. Had the rock walls at the narrows been smooth instead of uneven, a slope of less than 5 feet to the mile would have been established there. If the river were to be constrained by smooth training walls 400 feet apart all the way from the narrows to its mouth, 20 miles away, and if the height of the bed at the river mouth were to be so determined by a sill that the slope from narrows to sill would serve for the transportation of a maximum load of débris, the height of the sill would be more than 100 feet above the highest flood level of Feather River. It would be feasible, therefore, as a project in hydraulic engineering and without reference to cost, to carry Yuba River by an aqueduct across Feather River, taking with it the largest load of débris ever imposed on it by mining and delivering the load in Sutter Basin.

If it is true, as I believe, that the community can not afford to permit more mining débris to be sent to the bays and that the chief parts of the unworked auriferous gravels are not rich enough to meet the expense of permanent storage of tailings, whether in the mountains, in the foothills, or in the valley, the outlook for any important enlargement of the hydraulic mining operations is certainly not assuring. There remains, however, a possibility that something may be accomplished through cooperation with other industries. Cooperation between the great users of the Sierra water, the irrigator and the distributor of power, has probably already begun; if not, then it impends, for it is the logical relation; and there may be places where to the interests of these two the interests of the miner can be joined, so that a single plant for water control may serve three purposes.

In a tentative way I have developed such a project for the control of Yuba River at the edge of the Great Valley, and the scheme will be presented in brief outline, notwithstanding the fact that I have been informed by a competent engineer that the cost of the projected works would be prohibitive. The project will serve to illustrate my idea as to the general character of possible cooperative undertakings, and it may contain suggestions toward a better-considered scheme.

South of the Yuba near Hammonton is an outlying foothill of which the north base is called Hallett Point. It is connected with the main line of foothills by a ridge, which is notched at several points by cols. The project includes a dam running straight northward from this hill and of such height as to divert the river across one of these cols. The diverted river would follow the line of Reed Creek to Feather River, being guided by training walls. The reservoir created by the dam would have an initial capacity of 560,000,000 cubic yards, or 350,000 acre-feet. It would catch and store all débris delivered by the river, except the very finest. If the old mining débris and the soil waste for 50 years are estimated at 100,000,000 cubic yards the reservoir could still receive 250,000,000 cubic yards of new mining débris before its serviceability for irrigation and power development would begin to be impaired. In computing power development I assumed that the head would vary from 175 to 95 feet, the daily requirement in discharge being inversely as the head, and I computed only the theoretic power, without allowance for the coefficient of efficiency. I assumed that the development of power would be uniform through the year, so that during the height of the irrigation season a certain portion of the discharged water would not be utilized for power but only for irrigation. In computing the acreage for irrigation, I allowed a duty of one-third acre per acre-foot and estimated the quotas of water for different months on the basis of the experience at Orland. The run-off of the Yuba River basin was taken month by month from gaging records at the narrows, and the monthly requirements for power and irrigation were treated in combination with the monthly run-off, so as to take continuous account of the water level in the reservoir. An allowance of 10 per cent was made for evaporation and seepage. Independent computations were made (1) for the average annual run-off and (2) for the smallest recorded run-off, that of the year 1910. The resulting figures are as follows:

TABLE 29.—*Irrigation and power from Yuba River project.*

	With average run-off.	With run-off of 1910.
Area furnished with water for irrigation....................acres..	159,000	133,000
Continuous (theoretic) power developed............horsepower..	27,600	20,400

The intake of the irrigation canals, being below the outfall of the projected power house, was placed at the 100-foot contour above sea level, and the lands to be served all lie east of Feather and Sacramento rivers and north of American River. The tracts under the lines of canal, after deducting lands already irrigated in 1912 and after deducting 10 per cent for roads, etc., contain 191,000 acres.

If such a reservoir were to be used only for the storage of débris, its capacity would be about 750,000,000 cubic yards, and the provision for new hydraulic tailings would be 650,000,000 yards, instead of the 250,000,000 admitted in the cooperative scheme. If it were to be used for power development alone the output estimated, for a year like 1910, is 26,700 horsepower, instead of 20,400. If it were to be used for irrigation alone, high-level as well as low-level canals could be employed, increasing the available area east of Feather and Sacramento rivers to about 350,000 acres; and the water supply in a year like 1910 would suffice for about 300,000 acres.

In addition to its service in power development and its service to agriculture and mining, the project would benefit commerce by increasing or conserving the depth of water at points of critical importance to navigation. Not only would it arrest a large body of soil waste and old mining débris at its point of issue from the mountains, but it would fix beyond possibility of future erosion all that remains of the Yuba piedmont deposit. The Yuba, which now brings more débris to clog the navigable channels below Marysville than all other streams combined, would be loaded only with fine mud in suspension, and its water would help to scour channels deeper; while the regulation of its flow would increase the low-water discharge and the low-water depth on river bars. The trouble at Pinole Shoal would be slightly reduced, and the contraction of the bays which is slackening the tidal current at the Golden Gate would be retarded. The project would thus serve the interests of the community as a whole, and because of this service the State might assume, without injustice to its taxpayers, a share of the cost.

APPENDIX A.—OBSERVATIONS OF CURRENTS IN THE GOLDEN GATE.

PURPOSE AND PLAN OF THE WORK.

In discussing the effects of encroachments on the tidal prism of the San Francisco Bay system it was found important to estimate the contributions made by the different parts of the prism to the currents flowing through the Golden Gate. The computations required, in addition to data furnished by the Coast Survey Tide Tables, a knowledge of the time intervals from high water to the following slack water and from low water to the following slack water. It was because existing information as to these intervals was not satisfactory that the observations here to be described were undertaken.

The time of slack water in any part of a tidal channel is the time at which the direction of the current changes from outward to inward or from inward to outward. It is not the same for all parts of a cross section of channel, and there is often a long period during which the currents in different parts of the section have opposite directions. For the purpose of the present study the point of time desired is that in which the inward elements of current at the Golden Gate are balanced by the outward elements, so that the net movement of water in either direction is zero. Direct observation of this time is impracticable, because of the difficulty of making simultaneous observations at many points on and below the surface of the water. The indirect method of determination that was employed was suggested by Dr. R. A. Harris, of the United States Coast and Geodetic Survey, to whose expert advice I am indebted in many ways. It consists in observing directly the velocity of the main current during its ebb and flood phases, so as to determine the general sequence of changes and especially the times of greatest strength, and then inferring the times of net slack water by interpolation. Incidentally this procedure has given information as to the total volume of water passing the strait during a tidal period.

The general plan for the field work included two series of current measurements, each covering a period of 24 hours, made on such dates that one should compass an epoch of lunar high declination and the other an epoch of zero declination. The locality selected was the middle of the strait at its narrowest constriction, between Fort Point and Lime Point. Because the currents there are strong and the depth is great, the mooring of a vessel is not easy, but this difficulty was overcome through the cooperation of the Lighthouse Service. Capt. Harry W. Rhodes, inspector of lighthouses, anchored a steel buoy at the desired point, and to this buoy was moored the patrol boat *Suisun*, placed at our service by the courtesy of Lieut. Col. Thomas H. Rees, United States Army, engineer officer in charge of rivers and harbors. The undertaking was largely indebted for its measure of success to the assistance rendered by these gentlemen and by Capt. L. H. Westdahl, assistant in charge of the Pacific coast division of the United States Coast and Geodetic Survey.

THE OBSERVATIONS.

As shown by the map (fig. 21), the strait is narrowest opposite Fort Point. Between Fort Point and Lime Point the ebb current moves in a single body, but just beyond the constriction there are shore eddies; and the same statement is true of the flood current. To avoid complication by eddies it was desirable, with reference to the computation of discharge, to make the observations on the line between the two points, but because of a telegraphic cable on that line anchorage there is forbidden, and the mooring was accordingly placed somewhat farther west. A depth of 54 fathoms was found at the position of the anchor, and this necessitated a somewhat greater length of connecting cable, with the result that the positions given to the mooring buoy by the ebb and flood currents were several hundred yards apart. As the boat trailed downstream from the mooring, and as the observations were made near the stern of the boat, the observation stations were farther separated than the positions of the buoy. As determined from time to time by sextant observations, and as shown on the map, the stations were about one-fourth mile apart. The more easterly station was not far from the direct line between Fort Point and Lime Point.

The chief observer was Roger C. Rice, assistant engineer, United States Geological Survey.

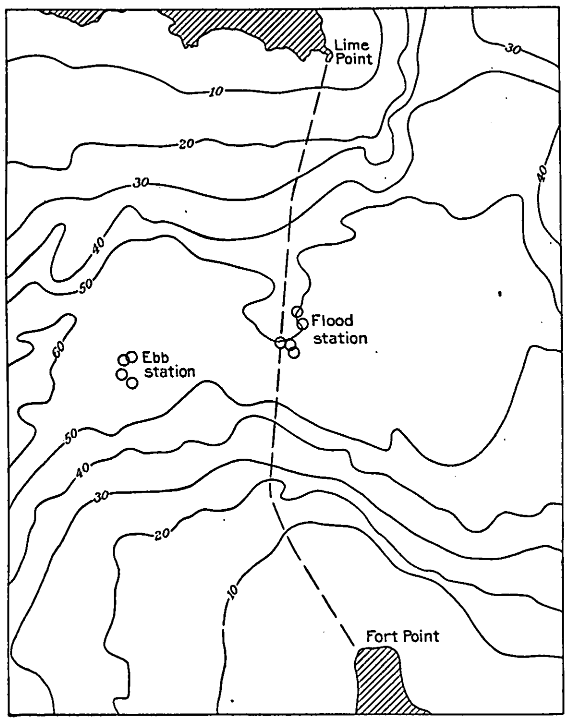


FIGURE 21.—The narrows of the Golden Gate, showing the configuration of the bottom (contour interval, 10 fathoms) and the position of the line of smallest section. Groups of circles indicate positions of the observation boat during current observations in September, 1914. Details of the contours are from manuscript charts in the archives of the United States Coast and Geodetic Survey. Scale, 3 inches = 1 mile.

He was assisted in the first series of observations by Arthur Taylor, instructor in engineering, Stanford University, in the second by Charles Leidl, junior engineer, United States Geological Survey.

The periods of observation were from 11.10 a. m. September 12 to 10.50 a. m. September 13, 1914; and from 10.17 a. m. to 11.31 p. m. September 19, 1914. The occupation of the station for the full period of 24 hours on the second occasion was prevented by the occurrence of fog, which made it unsafe for a boat to lie at anchor in the fairway of the harbor entrance.

During the first of the two periods of observation the tides were tropic and neap; during the second, equatorial and spring. The astronomic dates, given below, are stated in standard time of the 120th meridian, the hours being numbered in a single series from midnight to midnight.

TABLE 30.—*Lunar epochs associated with periods of observation of tidal currents at the Golden Gate.*

	Date.	Time.	
		H.	*m.*
Moon at last quarter	Sept. 12	9	48
Moon farthest north	...do	23	11
Moon on equator	Sept. 19	13	10
New moon	...do	13	33

Current observations were made with a Price meter, lowered to a depth of 35 feet. As a check on its work a few simultaneous observations were made with an Eckman meter, and a longer series with a meter of the Haskell type, but only the Price meter records were used in the final discussion, and only those are here reported.

Table 31 contains the observations on velocity or, more strictly, the velocities measured by the observations. In the use of the instrument the revolutions of the meter vanes are heard, by telephone, as clicks; the clicks are counted during a period measured by a stop watch; and the velocity is then obtained from a rating table. The instruments used had previously been rated in the usual manner.

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12–13 and Sept. 19, 1914.*

[The observations of the first series (Sept. 12–13) were made with Price meter No. 891, with single-point head (rated Nov. 6, 1913); those of the second series (Sept. 19) with Price meter No. 903, with penta head (rated July 20, 1914). Depth of observation, 35 feet.]

First series.

Date.	Time. H. m.	Velocity. Ft. per sec.	Direction.	Observer.	Remarks.
Sept. 12	11 10	1.39	Ebb	R. C. Rice	
	11 13	1.41	do	do	
	11 17	1.23	do	A. Taylor	
	11 19	1.83	do	do	Erratic.
	11 20	1.91	do	do	
	11 21	1.79	do	do	
	11 23	1.63	do	do	Good.
	11 25	1.69	do	do	Do.
	11 40	1.45	do	R. C. Rice	
	11 42	1.54	do	do	Boat rolled.
	11 45	1.43	do	do	Do.
	11 55	1.30	do	do	
	11 58	1.20	(?)	do	The time of change from ebb to flood was indefinite. At 12.15 the boat was swung halfway, effects of wind and tide balancing.
	12 10	1.35	(?)	do	
	12 12	1.04	(?)	do	
	12 14	1.14	(?)	do	
	12 15	1.22	(?)	do	
	12 18	1.14	(?)	A. Taylor	
	12 26	.80	Flood	do	
	12 28	.98	do	do	
	12 30	.99	do	do	
	12 33	.99	do	do	
	12 35	.95	do	do	
	12 40	1.03	do	do	
	12 41	1.27	do	do	Boat rolled.
	12 43	.95	do	do	
	13 04	1.84	do	R. C. Rice	
	13 06	1.65	do	do	
	13 07	1.81	do	do	
	13 09	1.75	do	do	
	13 26	1.96	do	A. Taylor	
	13 27	1.78	do	do	
	13 29	1.93	do	do	
	13 30	1.87	do	do	
	13 32	2.06	do	do	
	13 33	1.87	do	do	
	13 55	2.22	do	do	
	13 57	2.32	do	do	
	13 58	2.37	do	do	
	13 59	2.42	do	do	
	14 15	2.52	do	do	
	14 16	2.37	do	do	
	14 17	2.47	do	do	
	14 18	2.52	do	do	
	14 37	2.64	do	do	
	14 40	2.58	do	do	
	14 41	2.58	do	do	
	14 45	2.64	do	do	
	14 57	2.71	do	do	
	15 00	2.78	do	do	
	15 04	2.85	do	do	
	15 06	2.85	do	do	
	15 20	2.97	do	do	Rolled slightly.
	15 21	2.97	do	do	Do.
	15 23	2.67	do	do	Do.
	15 24	3.04	do	do	Do.
	15 40	2.91	do	do	Do.
	15 42	2.97	do	do	Do.
	16 00	2.23	do	R. C. Rice	Do.
	16 02	2.39	do	do	
	16 04	2.39	do	do	
	16 06	2.27	do	do	
	16 08	2.39	do	do	
	16 25	1.93	do	A. Taylor	
	16 27	1.99	do	do	
	16 28	1.87	do	do	
	16 48	1.57	do	do	

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12-13 and Sept. 19, 1914*—Continued.

First series—Continued.

Date.	Time.		Velocity.	Direction.	Observer.	Remarks.
	H.	*m.*	*Ft. per sec.*			
Sept. 12	16	50	1.72	Flood ...	A. Taylor......	
	16	53	1.66	...do.....	.....do.........	Sea rolled higher.
	16	55	1.66	...do.....	.....do.........	Do.
	16	56	1.69	...do.....	.....do.........	Do.
	17	00	1.72	...do.....	.....do.........	
	17	23	.75	...do.....	R. C. Rice.....	Boat rolled sideways pretty strongly.
	17	25	1.01	...do.....	.....do.........	Do.
	17	27	1.35	...do.....	.....do.........	Do.
	17	28	1.08	...do.....	.....do.........	
	17	30	.74	Ebb.....	.....do.........	
	17	31	1.07	...do.....	.....do.........	
	17	33	1.01	...do.....	.....do.........	
	17	37	1.18	...do.....	A. Taylor.......	
	17	39	1.35	...do.....	.....do.........	
	17	40	1.20	...do.....	.....do.........	
	17	42	1.38	...do.....	.....do.........	
	17	44	1.16	...do.....	.....do.........	
	17	45	1.32	...do.....	.....do.........	
	17	47	1.32	...do.....	.....do.........	
	17	52	1.20	...do.....	.....do.........	
	17	54	1.32	...do.....	.....do.........	
	17	55	1.20	...do.....	.....do.........	
	17	56	1.26	...do.....	.....do.........	
	17	58	1.28	...do.....	.....do.........	
	20	30	5.69	...do.....	R. C. Rice.....	
	20	34	5.25	...do.....	.....do.........	
	20	36	5.01	...do.....	.....do.........	
	20	46	5.17	...do.....	.....do.........	
	20	48	5.33	...do.....	.....do.........	
	20	50	5.69	...do.....	.....do.........	
	20	52	5.47	...do.....	.....do.........	
	20	59	5.59	...do.....	.....do.........	
	21	09	5.50	...do.....	.....do.........	
	21	25	5.59	...do.....	.....do.........	
	21	27	5.50	...do.....	.....do.........	
	21	30	5.59	...do.....	.....do.........	
	21	46	5.50	...do.....	.....do.........	
	21	49	5.41	...do.....	.....do.........	
	22	00	5.59	...do.....	.....do.........	
	22	03	5.17	...do.....	.....do.........	
	22	05	5.69	...do.....	.....do.........	
	22	16	5.25	...do.....	.....do.........	
	22	18	5.41	...do.....	.....do.........	
	22	22	5.25	...do.....	.....do.........	
	22	34	5.99	...do.....	.....do.........	
	22	35	5.69	...do.....	.....do.........	
	22	37	5.59	...do.....	.....do.........	
	22	49	5.59	...do.....	.....do.........	
	23	20	4.54	...do.....	.....do.........	
	23	22	4.36	...do.....	.....do.........	
	23	23	4.54	...do.....	.....do.........	
	23	47	3.31	...do.....	.....do.........	
	23	48	3.78	...do.....	.....do.........	
	23	52	3.19	...do.....	.....do.........	
	23	53	3.43	...do.....	.....do.........	
	23	57	3.03	...do.....	.....do.........	Good.
	23	58	3.31	...do.....	.....do.........	
Sept. 13	0	00	3.13	...do.....	.....do.........	
	0	03	3.13	...do.....	.....do.........	
	0	15	2.52	...do.....	.....do.........	
	0	17	2.43	...do.....	.....do.........	
	0	20	3.49	...do.....	.....do.........	Boat rolled.
	0	22	2.73	...do.....	.....do.........	
	0	25	2.91	...do.....	.....do.........	
	0	26	2.97	...do.....	.....do.........	
	0	33	2.98	...do.....	.....do.........	
	0	50	2.47	...do.....	.....do.........	O. K.
	0	52	2.47	...do.....	.....do.........	
	0	54	2.35	...do.....	.....do.........	

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12–13 and Sept. 19, 1914*—Continued.

First series—Continued.

Date.	Time.	Velocity.	Direction.	Observer.	Remarks.
	H. m.	*Ft. per sec.*			
Sept. 13	0 58	2.35	Ebb	R. C. Rice	
	1 15	1.63	do	do	
	1 17	1.87	do	do	
	1 19	1.75	do	do	Rolled.
	1 20	1.75	do	do	Do.
	1 35	1.35	do	do	O. K.
	1 43	1.26	do	do	Pretty steady.
	1 54	1.53	do	do	
	2 00			do	Bumping buoy; boat swinging around.
	2 41	2.22	Flood	do	Steady; no wind
	2 45	2.39	do	do	Do.
	2 47	2.19	do	do	Do.
	2 48	2.35	do	do	Do.
	2 52	2.35	do	do	Do.
	3 00	2.52	do	do	Wind up again.
	3 07	2.13	do	do	
	3 10	2.35	do	do	
	3 12	2.43	do	do	
	3 17	2.39	do	do	
	3 31	2.18	do	do	Rolled.
	3 32	3.08	do	do	
	3 34	2.70	do	do	
	3 35	2.90	do	do	
	3 46	2.97	do	do	
	3 48	2.85	do	do	
	4 03	3.63	do	do	
	4 04	3.43	do	do	
	4 06	3.63	do	do	
	4 17	3.49	do	do	
	4 31	3.31	do	do	
	4 32	3.25	do	do	
	4 34	3.31	do	do	
	4 51	4.13	do	do	
	4 52	3.72	do	do	
	4 54	4.13	do	do	
	4 55	3.85	do	do	
	4 57	4.20	do	do	
	4 58	4.28	do	do	
	5 00	3.78	do	do	
	5 01	3.72	do	do	
	5 05	3.85	do	do	Excellent; no rolling; no wind.
	5 15	3.26	do	do	Do.
	5 17	3.47	do	do	Do.
	5 18	3.41	do	do	Do.
	5 27	3.59	do	A. Taylor	Do.
	5 29	3.53	do	do	Do.
	5 30	3.47	do	do	
	5 41	3.59	do	do	
	5 43	3.31	do	do	
	5 45	3.72	do	do	Erratic.
	5 47	3.36	do	do	Excellent.
	5 49	3.47	do	do	Do.
	5 58	3.65	do	do	Sea rolled slightly.
	6 00	3.59	do	do	Do.
	6 02	3.53	do	do	Do.
	6 15	3.53	do	do	Do.
	6 17	3.41	do	do	Excellent; sea rolled slightly.
	6 19	3.37	do	do	Do.
	6 20	3.13	do	do	Do.
	6 22	3.43	do	do	Erratic; sea rolled slightly.
	6 28	3.13	do	do	Do.
	6 31	2.80	do	do	Good.
	6 33	2.80	do	do	Do.
	6 35	3.07	do	do	Sea rolled slightly.
	6 37	2.90	do	do	Good; sea rolled slightly.
	6 43	2.75	do	do	
	6 44	2.47	do	do	
	6 46	2.73	do	do	
	6 48	2.73	do	do	

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12–13 and Sept. 19, 1914*—Continued.

First series—Continued.

Date.	Time.	Velocity.	Direction.	Observer.	Remarks.
	H. m.	*Ft. per sec.*			
Sept. 13	6 57	2.79	Flood	A. Taylor	Excellent; very calm.
	6 59	2.79	...do	...do	Do.
	7 02	2.79	...do	...do	Do.
	7 04	2.57	...do	...do	Do.
	7 05	2.52	...do	...do	Do.
	7 07	2.43	...do	...do	Do.
	7 13	2.47	...do	...do	Do.
	7 15	2.47	...do	...do	Do.
	7 22	2.43	...do	...do	Do.
	7 31	1.99	...do	R. C. Rice	Very calm.
	7 32	1.93	...do	...do	Do.
	7 40	1.93	...do	A. Taylor	Do.
	7 56	1.37	...do	...do	Do.
	7 58	1.35	...do	...do	Do.
	8 00	1.32	...do	...do	Do.
	8 10	1.10	...do	...do	Do.
	8 12	1.06	...do	...do	Do.
	8 14	1.03	...do	...do	Do.
	8 15	.85	...do	...do	Do.
	8 21	.93	...do	...do	Do.
	8 24	.75	...do	...do	Do.
	8 42	1.00	...do	...do	Good.
	8 45	1.01	...do	...do	Do.
	8 46	.85	...do	...do	
	8 55	.69		...do	
	8 56	.78		...do	
	8 58	.72		...do	
	9 00	.70		...do	
	9 52	1.04	Ebb	...do	Poor; sea rolled; breeze.
	9 54	1.08	...do	...do	Do.
	9 57	1.83	...do	...do	Poor; sea rolled.
	9 58	1.32	...do	...do	Do.
	9 59	1.80	...do	...do	Poor.
	10 00	1.56	...do	...do	Do.
	10 02	1.83	...do	...do	Do.
	10 04	1.95	...do	...do	Do.
	10 05	1.72	...do	...do	Fair.
	10 06	1.56	...do	...do	Do.
	10 07	1.77	...do	...do	
	10 22	1.79	...do	R. C. Rice	Rolled.
	10 23	1.99	...do	...do	Brisk breeze.
	10 25	1.51	...do	...do	
	10 34	1.99	...do	A. Taylor	Rolled.
	10 36	2.12	...do	...do	Do.
	10 38	1.99	...do	...do	
	10 40	1.72	...do	...do	
	10 45	1.99	...do	...do	Rolled; wind.
	10 47	2.17	...do	...do	Do.
	10 48	2.03	...do	...do	Do.
	10 50	2.03	...do	...do	Do.

Second series.

Date.	Time.	Velocity.	Direction.	Observer.	Remarks.
Sept. 19	10 17	5.62	Flood	R. C. Rice	
	10 19	5.26	...do	...do	Steady.
	10 22	5.62	...do	...do	Do.
	10 25	5.62	...do	...do	Do.
	10 28	5.26	...do	...do	Rolled gently.
	10 30	5.26	...do	...do	Do.
	10 37	5.02	...do	...do	Do.
	10 51	4.81	...do	...do	Do.
	10 53	5.18	...do	...do	Do.
	10 55	4.95	...do	...do	Do.
	11 00	4.88	...do	...do	
	11 02	4.81	...do	...do	Do.
	11 04	5.35	...do	...do	Do.

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12–13 and Sept. 19, 1914*—Continued.

Second series—Continued.

Date.	Time.	Velocity.	Direction.	Observer.	Remarks.
	H. m.	*Ft. per sec.*			
Sept. 19	11 06	4.57	Flood	R.C.Rice	Rolled gently.
	11 10	4.57	...do	.....do	Do.
	11 25	2.95	...do	.....do	Breeze southwest.
	11 27	3.51	...do	.....do	
	11 29	3.58	...do	.....do	
	11 35	3.26	...do	.....do	Rolled gently.
	11 41	2.30	...do	.....do	
	11 43	2.42	...do	.....do	
	11 48	2.42	...do	.....do	
	11 51	2.06	...do	.....do	
	11 53	1.98	...do	.....do	
	11 56	2.22	...do	.....do	
	12 00	1.74	...do	.....do	Cross currents.
	12 21	1.33	...do	.....do	Do.
	12 23	1.56	...do	.....do	
	13 02	2.62	Ebb	C. Leidl	Rolled.
	13 04	3.33	...do	.....do	
	13 10	3.58	...do	.....do	
	13 15	3.51	...do	.....do	
	13 20	4.00	...do	.....do	Do.
	13 25	4.16	...do	.....do	Do.
	13 30	4.16	...do	.....do	Do.
	13 35	4.57	...do	.....do	Do.
	13 40	3.88	...do	.....do	Do.
	13 45	4.77	...do	.....do	Do.
	13 55	4.44	...do	.....do	Rolled; choppy.
	14 00	5.82	...do	.....do	
	14 02	5.82	...do	.....do	Rolled.
	14 05	5.92	...do	R. C. Rice	Heavy swell.
	14 15	6.74	...do	.....do	Do.
	14 20	7.68	...do	.....do	Do.
	14 26	5.62	...do	.....do	Do.
	14 31	6.74	...do	.....do	Do.
	14 32	6.13	...do	.....do	Do.
	14 34	6.24	...do	.....do	Do.
	14 36	6.61	...do	.....do	Do.
	14 38	6.74	...do	.....do	Do.
	14 40	6.61	...do	.....do	Do.
	14 42	7.03	...do	.....do	Do.
	14 45	6.88	...do	.....do	Do.
	14 50	6.88	...do	.....do	
	14 55	7.18	...do	.....do	
	15 00	6.74	...do	.....do	
	15 05	6.88	...do	.....do	
	15 07	6.61	...do	.....do	
	15 10	7.18	...do	.....do	Wind not as strong.
	15 34	7.68	...do	C. Leidl	Do.
	15 38	7.18	...do	R. C. Rice	Do.
	15 40	7.03	...do	.....do	Do.
	15 45	7.10	...do	.....do	Do.
	16 00	6.42	...do	.....do	
	16 05	6.48	...do	.....do	Rolled heavily.
	16 10	6.24	...do	.....do	Do.
	16 25	5.72	...do	.....do	Do.
	16 30	5.82	...do	.....do	Do.
	16 35	5.22	...do	.....do	Do.
	16 38	5.35	...do	.....do	Do.
	16 40	4.99	...do	.....do	Do.
	16 45	5.10	...do	.....do	Do.
	16 50	4.67	...do	.....do	Do.
	16 55	4.52	...do	.....do	Do.
	17 00	4.39	...do	.....do	Do.
	17 05	4.39	...do	.....do	Do.
	17 10	3.88	...do	.....do	Do.
	17 15	4.07	...do	.....do	Rolled heavily; wind blowing hard.
	17 17	4.31	...do	.....do	Do.
	17 21	3.80	...do	.....do	Do.
	17 25	3.59	...do	.....do	Do.

TABLE 31.—*Observations of tidal currents in Golden Gate, Sept. 12–13 and Sept. 19, 1914*—Continued.

Second series—Continued.

Date.	Time.		Velocity.	Direction.	Observer.	Remarks.
	H.	*m.*	*Ft. per sec.*			
Sept. 19	17	30	3.88	Ebb	R. C. Rice	Rolled heavily and pitched; wind blowing.
	17	35	3.53	do	do	Do.
	17	40	3.01	do	do	Do.
	17	45	3.19	do	do	Rolled heavily and pitched; wind less.
	17	50	3.01	do	do	Rolled heavily and pitched. Bucking buoy.
	19	05	1.71	Flood	do	
	19	10	2.18	do	do	
	19	15	2.32	do	do	
	19	20	2.73	do	do	
	19	25	3.07	do	do	
	19	35	3.73	do	do	Gentle swell; light wind.
	19	40	4.04	do	do	Do.
	19	45	4.35	do	do	Do.
	20	05	4.88	do	do	Do.
	20	10	4.88	do	do	Do.
	20	15	4.88	do	do	Do.
	20	20	5.10	do	do	Do.
	20	25	5.26	do	do	Do.
	20	30	5.52	do	do	
	20	35	5.38	do	do	
	20	40	6.36	do	do	Tide rip caused increase.
	20	45	6.74	do	do	
	20	50	6.74	do	do	Rolled gently.
	20	55	6.48	do	do	Do.
	21	00	6.36	do	do	Do.
	21	05	6.48	do	do	
	21	10	6.88	do	do	
	21	15	5.52	do	do	(?).
	21	20	6.88	do	do	
	21	25	6.61	do	do	
	21	30	6.88	do	do	
	21	35	5.92	do	do	
	21	40	5.82	do	do	
	21	45	5.92	do	do	
	21	55	5.92	do	do	
	22	00	6.02	do	do	
	22	05	5.82	do	do	
	22	10	5.62	do	do	
	22	15	5.72	do	do	
	22	20	5.92	do	do	
	22	25	5.92	do	do	
	22	30	5.18	do	do	
	22	31	5.62	do	do	
	22	35	5.52	do	do	
	22	40	4.98	do	do	
	22	45	5.48	do	do	
	22	46	5.48	do	do	
	22	50	5.22	do	do	
	22	51	4.99	do	do	
	22	55	4.39	do	do	
	22	56	4.52	do	do	Wind rising.
	23	00	4.67	do	do	
	23	05	4.48	do	do	
	23	06	4.57	do	do	
	23	10	4.99	do	do	
	23	11	4.62	do	do	
	23	15	4.31	do	do	
	23	16	3.79	do	do	
	23	20	3.86	do	do	
	23	21	3.35	do	do	
	23	25	3.26	do	do	
	23	27	3.96	do	do	
	23	28	3.44	do	do	
	23	30	3.81	do	do	
	23	31	3.65	do	do	

The conditions of observation did not permit a close determination of the time of slack water, even for the division of current on which the boat rested. At about that time the boat drifted from one of its positions to the other and the relative motions of boat and water were affected in part by the wind and by the heavy anchor chain. After a few trials the attempt to make direct observation of the time of slack water was abandoned. The indications of the meters never approached zero and the lowest velocity recorded is 0.69 foot per second.

The failure of the meter to record zero velocity when the water appeared not to move past the boat may have been due in part to subsurface current but is ascribed chiefly to the fact that the vanes of the meter are acted on not only by horizontal movement of the water but by vertical movement of water or meter. At all times the boat rose and fell on a swell coming in from the ocean and, the vertical element of the swell being greater at the surface than at a depth of 35 feet, there was a differential vertical motion between meter and water. The meter was suspended from the side of the boat near the stern and was thus subject to vertical movement whenever the boat rolled or pitched, and as there was much wind, and often a choppy sea, these movements affected many of the observations. They were likely to be strong near the change of tide, when the boat would swing broadside to the westerly wind.

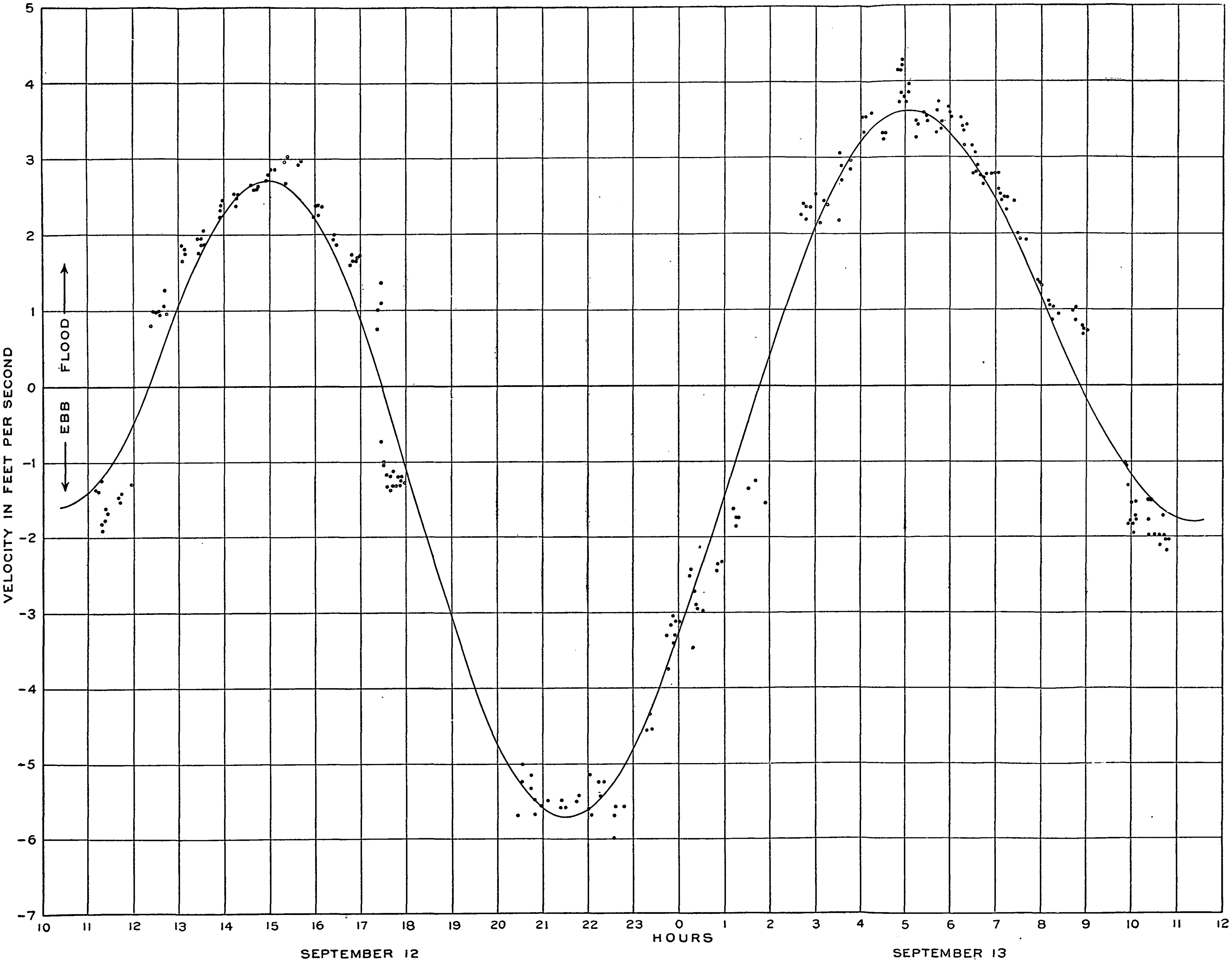
The influence of vertical movements of the meter on the measurement of the velocity of a current was afterward investigated by Mr. Rice in the following manner: In a tidal current unaffected by wind or waves ordinary readings with the meter in a fixed position were alternated with readings when the meter was moved upward and downward in a manner to simulate the movements affecting observations in the Golden Gate. It was found that the vertical movements increased the meter indications by an important ratio when the velocities under observation were small, but that they did not appreciably affect the measurement of velocities equaling or exceeding 3 feet per second. It is believed therefore that the higher determinations of velocity in the Golden Gate may be accepted as accurate.

One of the noteworthy features of the observed velocities is their variability. So far as the lower velocities are concerned, we can not be sure that this was not occasioned by the motions of the boat, but it affected also the higher velocities. Among velocities greater than 3 feet per second there were many abrupt changes of 0.2 foot or more, and on 22 occasions the change occurring between observations from 2 to 5 minutes apart was as great as 0.5 foot per second. Such fluctuations indicate a turbulent current, full of rapidly revolving vortices, the internal velocities of which were combined with the general advance downstream, and this indication finds support in the character of the channel bed, which is beset with rock ledges.

LAG OF SLACK WATER.

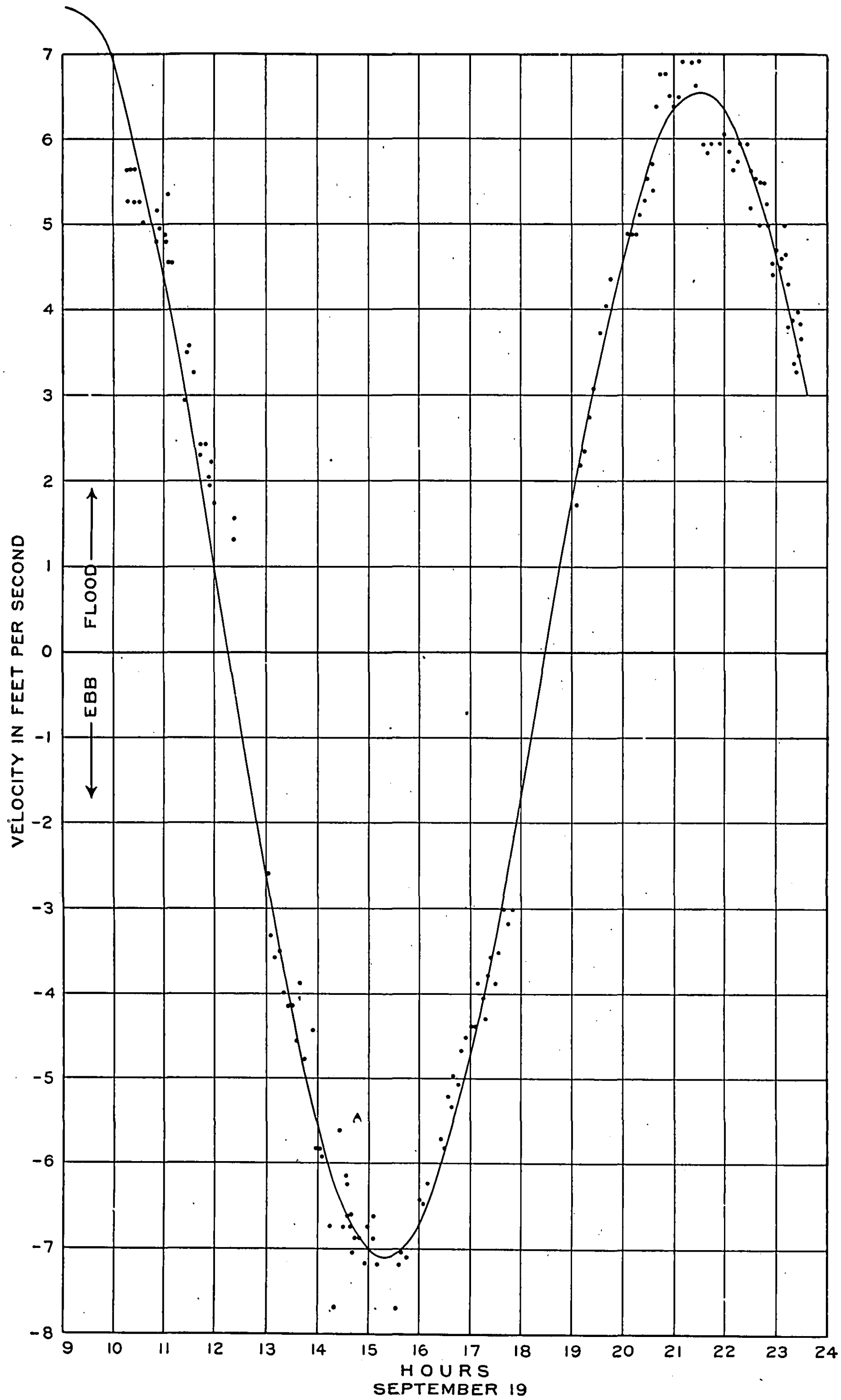
Each slack water is associated with and follows a high water or low water, and I find it convenient to speak of the interval of time between the high or low water and the following slack water as the lag of slack water. The determination of the lag in the present case involves the determination of the times of slack water and of the times of high water and low water.

For the determination of times of slack water the observed velocities of current were plotted in relation to time, as shown in Plates XXX and XXXI. The ordinates for flood velocities were laid off above the horizontal axis, and the ordinates for ebb velocities below, the ebb velocities being treated as negative. It was assumed that the accelerations follow some simple law irrespective of the direction of motion, and therefore that the velocity-time curves above the axis should be continuous with those below the axis. For the data of September 19, a day on which the diurnal inequality, alike of tides and currents, was small, it was assumed that the true curve, from maximum ebb or flood velocity to the following maximum of flood or ebb velocity, is a cosine curve; and the curves were so drawn. For the data of September 12–13, when the diurnal inequality of tides was coordinate with the mean range of tide, the same assumption did not seem admissible, but the cosine curve was nevertheless used for purposes of trial. The adjustments afterward made were such that



OBSERVATIONS OF MIDSTREAM VELOCITY OF CURRENT IN THE GOLDEN GATE, SEPTEMBER 12-13, 1914.

The time scale is horizontal; the velocity scale vertical. Ebb velocities are represented as negative. The measurements were made with a Price meter at a station midway between Lime Point and Fort Point, as shown in figure 21.



OBSERVATIONS OF MIDSTREAM VELOCITY OF CURRENT IN THE GOLDEN GATE, SEPTEMBER 19, 1914.

The time scale is horizontal; the velocity scale vertical. Ebb velocities are represented as negative. The measurements were made with a Price meter at a station midway between Lime Point and Fort Point, as shown in figure 21.

the line adopted is a compromise between a system of cosine curves, each from maximum velocity to maximum velocity, and a system of sine curves, each from zero velocity to zero velocity. Otherwise the curves were adjusted by eye to the plotted observations, the control being assigned mainly to the velocities greater than 3 feet per second. Because of the systematic errors of low-velocity measurements, due to motions of the boat, it was assumed that the records of low velocities were too high.

The intersections of the curves with the horizontal axis constitute determinations of the times of slack water. They are listed in Table 32.

TABLE 32.—*Estimates of the lag of slack water in the Golden Gate.*

Date.	Type of water culmination.	Time of high water or low water at Fort Point.	Time of slack water in Golden Gate.	Lag of slack water.	Relative precision.
1914.		*H. m.*	*H. m.*	*Minutes.*	
Sept. 12	Low water	9 56	12 10	144	Poor.
Do	High water	16 31	17 28	57	Good.
Sept. 12–13	Low water	23 50	1 47	117	Do.
Sept. 13	High water	7 59	8 53	54	Fair.
Sept. 19	do	11 09	12 17	68	Good.
Do	Low water	16 46	18 29	103	Do.

The correlative data for the determination of the lag of slack water are the times of high water and low water. The series of observations from which the tidal constants of the locality were computed and on which the predictions of the Tide Tables are based were made at Fort Point, a promontory of the south coast opposite the stations for current observations. Afterward the primary tidal station was transferred from Fort Point to Presidio wharf, about 1.3 miles farther east. An automatic gage is there established, producing a marigram, or continuous curve of water stage, and from that record were read the times of high water and low water on the dates of the current observations. The reading is a matter of interpretation and judgment, somewhat analogous to the interpretation of the velocity observations but on the whole less subject to error. The results are more accurate when the range of tide is great than when it is small. Because the tides are on the average 4 minutes later at Presidio wharf than at Fort Point, a correction of −4 minutes was applied to the readings.

Table 32 shows the estimated lags of slack water, together with the times on which they are based. A column has been added to indicate my judgment as to their relative trustworthiness.

For the purpose of estimating the tidal prism it is desired to know (1) the general averages of the lag of slack water after high water and low water, severally, and (2) the average lags of slack water after the several tides of the tropic sequence, especially the higher high water and the lower low water. It is conceivable that if a perfect theory of tidal currents could be combined with a complete understanding of the local conditions, these quantities might be directly computed. In default of that equipment, the best available data are those assembled in Table 32, with such concomitant facts as are contained in the Presidio gage record and the tabulated tidal constants. Having little acquaintance with the subject on the theoretic side, I have scanned the figures gropingly in their relation to a variety of concomitant facts, as illustrated in Table 33.

TABLE 33.—*Comparison of the lag of slack water in the Golden Gate with associated data.*

1	2	3	4	5	6	7	8	9	10	11
Value of lag of slack water.	Characterization as to relative precision.	High water or low water.	Water stage at Presidio wharf above lower low water.	Preceding rise or fall of tide.	Following rise or fall of tide.	Ratio of preceding change to following change.	Duration of following rise or fall of tide.	Phase of moon.	Declination of moon.	Relation to tropic tides.
Minutes.			*Feet.*	*Feet.*	*Feet.*		*Minutes.*			
144	Poor..	Low..	3.75	0.31	1.70	0.18	395	Quadrature..	Maximum..	Higher low water.
117	Good.	...do..	.78	4.67	3.64	1.28	489	.....do.......	...do.......	Lower low water.
103	...do..	...do..	1.06	4.59	4.69	.98	393	New.........	Minimum..	
68	...do..	High.	5.65	5.60	4.59	1.22	337	.....do.......	...do.......	
57	...do..	...do..	5.45	1.70	4.67	.34	439	Quadrature...	Maximum..	Higher high water.
54	Fair..	...do..	4.42	3.64	.42	8.56	244	.....do.......	...do.......	Lower high water.

It will be observed that column 1 of the table contains the estimates of lag previously shown in Table 32 but here arranged in the order of magnitude. This makes it possible to see by simple inspection that none of the numerical data assembled in columns 4 to 8 exhibit either the same order of magnitudes or the inverse order. Certain elements of correlation appear, however, in other columns. First, the lags after low water are all greater than the lags after high water. The least of the low-water lags differs from the greatest of the high-water lags by a large amount, 35 minutes. Second, the contrast between low-water lags and high-water lags is greater at the time of quadrature (neap tides) than at new moon (spring tides). Third, the contrast is greater at the time of maximum declination (tropic tides) than at the time of minimum declination (equatorial tides). The second and third correlations are coincident, because the neap tides observed were also tropic tides, and the spring tides were also equatorial. It is evident that one or the other of the two correlations may be accidental, and I judge that this is true of the correlation with neap and spring tides. The position of the sun affects chiefly the magnitude of tidal ranges, and the data in columns 4, 5, and 6 indicate that the lag is independent of tidal range. The essential correlation appears to be that with the moon's position in relation to the plane of the Equator; the difference between low-water lag and high-water lag is greater when the moon is far from the Equator.

It would be possible to draw inferences as to the magnitudes of lag in relation to individual tides of the tropic sequence, but they would depend too largely on the weakest of all the estimates of lag.

The direction of the moon's position when it is far from the plane of the Equator is the chief cause of the diurnal tide. The diurnal tide is manifested in many ways, but most conspicuously in the diurnal inequality of the semidiurnal tide. I find it convenient to discuss the lag of slack water in the Golden Gate with reference to the diurnal inequality of tides. That inequality is usually not greatest on the day of maximum lunar declination, but a few days later. It is usually not least at the time of zero declination, but a few days later. Therefore our observations, made as nearly as possible at the times of greatest and least declination, do not correspond to either the maximum or the minimum of diurnal inequality. They do correspond, however, to diurnal inequalities observed at the Presidio wharf on the same days, and by means of that correspondence they can be compared with other inequalities. The inequalities with which we are specially concerned—because we wish to know the corresponding slack-water lags—are (1) the mean high-water inequality, (2) the mean low-water inequality, (3) the mean high-water tropic inequality, and (4) the mean low-water tropic inequality. The mean tropic inequalities at the Presidio wharf are given in the Tide Tables. The mean inequality, high-water or low-water, is related to the corresponding mean tropic inequality approximately as 2 to π; and the Presidio values have been computed.

TABLE 34.—*Lag of slack water in the Golden Gate and diurnal inequality of tides at Presidio wharf; observations and inferences.*

	High water.		Low water.	
	Inequality.	Lag.	Inequality.	Lag.
	Feet.	*Min.*	*Feet.*	*Min.*
Equatorial	0	69.2	0	96.3
Observed Sept. 19, 1914	0.10	68	1.01	103
General mean	0.89	58.7	2.48	112.8
Observed Sept. 12–13, 1914	1.03	57	3.12	117
Mean tropic	1.4	52.6	3.9	122.1

In Table 34 the second column contains five values of the diurnal inequality of high waters, namely, the equatorial value (zero), the general mean, the mean tropic, and two observed values. These are arranged in the order of their magnitude. In the third column are corresponding values of the lag of high-water slack, the second and fourth being observed values and the others computed. The basis of the computation is the assumption that the variation of the lag is (inversely) proportional to the variation of the inequality. This assumption is not founded on theory. Having no knowledge of the actual law of relation, I have postulated the simplest law.

The fourth and fifth columns of the table contain similar series of values of low-water diurnal inequality and of lag of low-water slack. The order of magnitude is in this case the same for both columns, and the assumption controlling the computation of the first, third, and fifth values of lag is that the variation of the lag is directly proportioned to the variation of the inequality.

The computed values of lag of low-water slack are subject to an additional qualification, in that the data from which they were computed are not wholly homogeneous. The lag of slack water observed September 12–13 was associated with a lower low water, but that observed September 19 was associated with a higher low water. As the purpose for which the lag estimates were sought pertains to lower low waters, the inharmonious datum is that of September 19. As the low-water inequality on that day was not large, it is possible that the lags following the two low waters did not differ greatly.

It remains to apply a correction for river discharge. Whatever water the bays receive from other sources than tide passes out through the strait. It has the effect of increasing the ebb currents and ebb volumes and reducing the flood currents and flood volumes. At change of tide it gives advantage to ebb currents, thereby making the epoch of high-water slack earlier and that of low-water slack later.

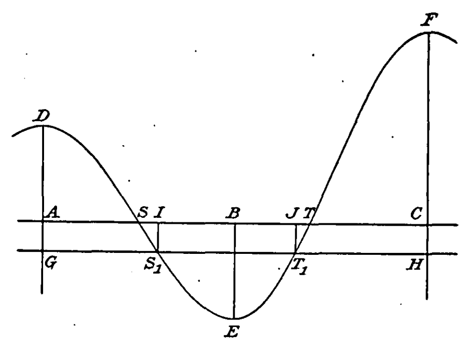


FIGURE 22.—Diagram to illustrate the influence of discharge from rivers on tidal currents in the Golden Gate.

In figure 22 horizontal distances represent time and vertical distances measured from the line AC represent velocity—the mean of simultaneous velocities in the cross section of the Golden Gate. The positions A and C represent times of greatest strength of flood current and B represents time of greatest strength of ebb, ebb velocities being treated as negative. The curve DEF indicates the progressive change of the velocity of tidal current, and the points S and T in which the curve intersects AC show, respectively, times of high-water slack and low-water slack. The effect of adding a constant river discharge is to increase all ebb velocities by a certain amount and decrease all flood velocities by the same amount, and this effect may be expressed in the diagram by moving the zero of velocities from the position AC to the position GH, the distance AG or CH representing the uniform change in velocities. New points, S_1 and T_1, now correspond to slack water, S_1 being earlier than S and T_1 later than T. It is evident that SI and TJ, the changes in the times of slack water, can be computed if the type of curve and the constants which afford its dimensions are known. Assuming that each of the two parts *DE* and *EF* is a cosine curve, I have computed the time changes for several sets of conditions.

At the time of the current observations in September, 1914, the river discharge measured at United States Geological Survey gaging stations on streams tributary to the bays was 8,300 cubic feet per second. The average discharge at the same points is greater than this, and account should be taken of the difference in correcting the estimates of lag of slack water. In a later paragraph (p. 121) the mean discharge at the same points is estimated at 43,000 cubic feet per second. Its excess above the discharge in September, 1914, is 38,000 cubic feet per second. To this are to be added an estimated discharge for unmetered land areas, 20,000 square miles, with an average run-off of 3 inches per annum, giving 4,400 cubic feet per second; and 1,900 cubic feet per second for rainfall on the bays and tidal marshes. The average rainfall in the bay and marsh region is 20 inches per annum, and as the tide marshes are permanently saturated, their run-off equals the precipitation. An allowance might also be made for evaporation from the water surfaces, but the rate of evaporation for September does not differ greatly from the mean rate for the year.

The total nontidal discharge for which correction is to be made is thus $38,000+4,400+1,900=44,300$ cubic feet per second, a quantity competent to produce a mean velocity in the Golden Gate of $\frac{44,300}{920,000}=0.048$ foot per second. The corresponding corrections to the estimates of epochs of slack water are, for mean tide 1.40 minutes, for the slack water preceding the great tropic ebb 1.37 minutes, and for that following the great tropic ebb 1.23 minutes.

The adopted estimates of lag are:

Average lag of slack water in the Golden Gate.

	Minutes.
After all high waters	57
After all low waters	114
After tropic higher high waters	51
After tropic lower low waters	123

The discussion leading to these estimates is far from satisfactory. It was actuated by a pressing need for the estimates, and this need prompted me to follow paths of uncertain analogy where the routes of competent theory were not apparent.

It is to be observed that the generalizations here associated with the estimates of lag pertain only to the particular locality. They are not extended to other bays nor to other parts of the San Francisco Bay system. Dr. Harris has pointed out to me that the tides of San Francisco entrance have a special character which is probably related to some of the lag phenomena. In general at such entrances the fall of tide occupies more time than the rise, but in the Golden Gate the mean duration of rise is 47 minutes longer than the duration of fall. In other words, high water is there exceptionally late and low water exceptionally early. This peculiarity would of itself shorten the interval from high water to slack water and lengthen the interval from low water to slack water. Perhaps the asymmetry of the mean tide curve should not be called a cause of the difference between the lags of high-water slack and low-water slack, but the two phenomena should be regarded as concomitant results of the local conditions affecting the regimen of the tides.

RIVER-DISCHARGE DATA.

In the preceding column an estimate of river discharge is used, but the basis of the estimate is not there given because its statement would interrupt the discussion of slack-water lag. The matter will now be recorded, however, for the reason that an independent interest attaches to the estimate and its basis. It is impracticable to gage the flow of Sacramento and San Joaquin rivers at their mouths, because there the rivers are tidal. The best available data on their discharge are derived from the gagings on numerous branches, made for the most part where they issue from the uplands. The records used were those of Sacramento River near Red Bluff, the Feather at Oroville, the Yuba near Smartsville, the Bear near Van Trent, the American at Fairoaks, the Cosumnes at Michigan Bar, the Mokelumne at Clements, the Calaveras at Jenny Lind, the Stanislaus at Knights Ferry, the Tuolumne near La Grange, the Merced near Merced Falls, the San Joaquin near Friant, Cache Creek at Yolo, and Putah Creek at Winters. From these records were compiled the total discharge for seven seasonal years, each year beginning on October 1.

As a seven-year record is too short to give a trustworthy estimate of average discharge, I compared the discharge data with the precipitation records of stations at which observations have been made for periods of 15 to 50 years, selecting a group of stations in the Sierra Nevada, another group in the drainage basin of the upper Sacramento, and a third group to represent the Coast Range catchment areas of Cache and Putah creeks. For each station the Weather Bureau reports give precipitation by seasonal years and also the general mean or normal. For each of the selected stations and for each seasonal year represented in the discharge data I computed the ratio of the year's precipitation to the normal; and then for each year I derived a composite ratio in the making of which the data of the Sierra, Sacramento, and Coast Range groups were weighted as 23:10:1, that being the approximate proportion in which those regions contribute to the total discharge.

The data thus assembled are as follows:

TABLE 35.—*Discharge measured at gaging stations and ratio of precipitation in the same regions.*

Seasonal year.	Metered discharge (cubic feet per second).	Composite ratio of precipitation.
1905–6	58,400	1.21
1906–7	72,000	1.34
1907–8	26,600	.67
1908–9	61,500	1.19
1909–10	39,700	.94
1910–11	58,100	1.27
1911–12	20,000	.56

These data were first plotted on ordinary section paper, and it was seen that the line to best represent their law must be a curve. They were then plotted on logarithmic paper, when it appeared that their law could be fairly well represented by a straight line. The data are not, however, sufficiently harmonious to demonstrate their law. The best representative straight line on logarithmic paper gives the equation $Q=45{,}400P^{1.41}$, where Q is the metered discharge or run-off and P the ratio of annual precipitation to mean precipitation. The constant, 45,400 cubic feet per second, is the run-off corresponding to mean precipitation. This is not identical with mean run-off, which, from the nature of the function, is somewhat greater. A computation using the precipitation record of a single Sierra station, Colfax, indicated the difference as about 2 per cent; and this allowance yields 46,300 cubic feet per second as an estimate of mean discharge at the 14 gaging stations.

TIDAL VOLUME.

The discharge (in cubic feet per second) through the Golden Gate at any time is measured by the observed velocity (in feet per second), multiplied by the sectional area of the current (in square feet), multiplied by a constant.

The constant is the ratio between the mean velocity of the current in the direction normal to the plane of section and the observed velocity. The observations having been made in the strongest part of the current the value of the constant is necessarily less than unity, but its assignment is a matter of judgment. The controlling condition is the resistance afforded by the bed and sides of the channel. Large values are appropriate to straight, smooth channels and relatively small values to rough channels. The soundings in the Golden Gate have been elaborate, and their record shows that the bed is very rough, being largely composed of rock ledges. For this reason I make use of a small value, 0.75.

The area, at half tide, of the cross section on the line from Fort Point to Lime Point is 1,035,000 square feet. There is, however, a section of smaller area which seems preferable for present use, especially as it lies nearer to the velocity stations. Its course is marked on figure 21 (p. 109) by a broken line, and its area is 920,000 square feet.[1] The length of the shorter section is 5,270 feet; of the longer, 5,660 feet.

The volume of water passing through the strait during a flood or ebb tide is measured by $\frac{2}{\pi}$ times the product of the discharge at "strength of tide" by the number of seconds during which the tide runs, or the period from slack water to slack water. If V is the maxi-

[1] In computing these areas I made use of details of configuration shown by the record of soundings but not brought out by the contours.

mum velocity during a flood or ebb period (taken from the curve in Pl. XXX or Pl. XXXI) and T the duration of the period in seconds, then the volume of the flood or ebb current, in cubic feet, equals

$$VT \times 0.75 \times \frac{2}{\pi} (920{,}000 + c),$$

the quantity c being a small correction to the sectional area dependent on the temporary level of the water surface.

The data for velocity and time are sufficiently good to warrant the computation of volumes for four ebbs and floods, given in Table 36.

The ranges of the corresponding rises and falls at the Presidio wharf were, severally, 4.67, 3.64, 4.59, and 4.69 feet. As the mean range of tide is 4 feet, it is evident that these velocities and volumes represent ordinary tides. The greatest tides have a range about twice as great as the mean.

TABLE 36.—*Velocity, time, and volume of ebb and flood tides in the Golden Gate.*

	Velocity.	Time.	Volume.
	Feet per second.	*Seconds.*	*Cubic feet.*
Ebb Sept. 12–13..	5. 7	29, 940	74, 390, 000, 000
Flood Sept. 13.....	3. 6	25, 920	41, 030, 000, 000
Ebb Sept. 19.....	7. 1	22, 320	68, 950, 000, 000
Flood Sept. 19.....	6. 5	[22, 380]	64, 570, 000, 000

APPENDIX B.—THE TIDAL PRISM OF TIDAL MARSHES.

OBSERVATIONS IN RAVENSWOOD SLOUGH.

Ravenswood Slough drains a tract of tide marsh bordering the southwest shore of San Francisco Bay near its south end. The locality was selected for special study because marsh and slough are still in their natural state, because a tract of marsh is there served by a single slough instead of by a member of a communicating system, and because the tidal range is there large. Near the mouth of the slough is a branch which communicates through West Point Slough with Redwood Slough, and to avoid this complication the gaging station was located at a point above the branch.

There was, however, a minor complication which was not escaped. The Coast Survey chart from which figure 23 is copied shows free communication between slough and bay at all stages of tide, but in 1914 the channel at the mouth had been so modified as no longer to remain open at the lowest stages. The slough then communicated with the bay by way of West Point Slough, and the route of communication was 5 miles longer than at high tide. Low-water conditions in Ravenswood Slough were necessarily affected—in what manner was not learned—by tidal movements in West Point and Redwood sloughs.

The marsh tract served by the portion of the slough above the station has an area of 2.822 square miles or 78,660,000 square feet. It is bounded on the south by an alluvial plain, on the west by tide lands tributary to West Point Slough, and on the north and east by a belt of marsh land which the tides invade directly from the bay.

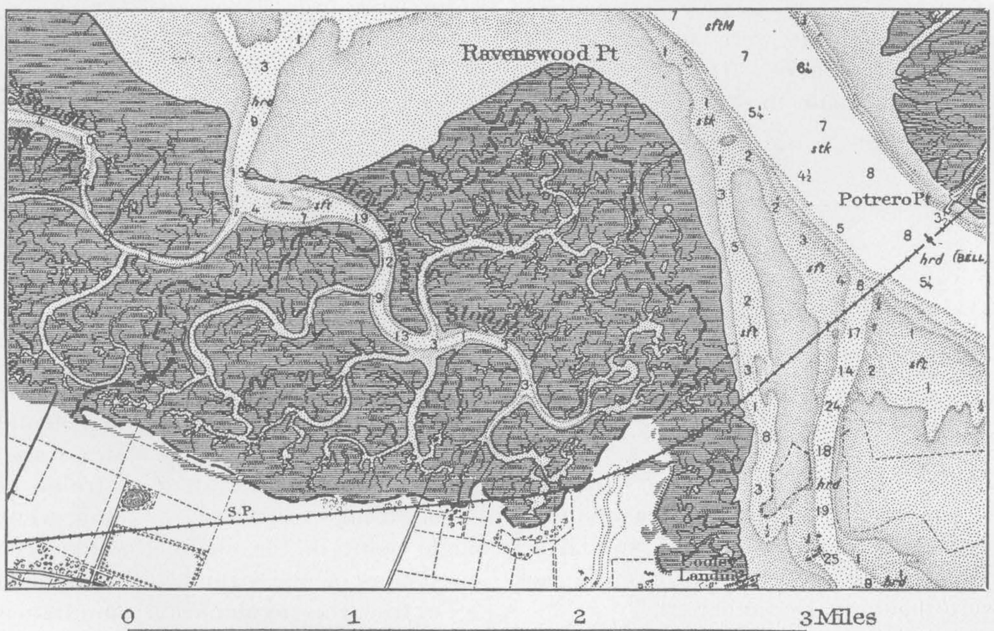


FIGURE 23.—Map of Ravenswood Slough and marsh. From United States Coast and Geodetic Survey chart 5531. The marsh was surveyed in 1898. A (broken) line has been added to show the area drained by that part of the channel above the United States Geological Survey observation station, the station being where the line crosses the slough.

At the station the channel is curved, the main current being thrown toward the right bank and the greatest depth being found to the right of the middle, as shown in figure 24. The bottom is of mud and is bare of vegetation, except at the banks. The width from bank to bank is about 355 feet. At the highest water stage observed the maximum depth was 25.6 feet, and both banks were submerged. At the lowest stage the width and depth were 287 and 15.4 feet, respectively. The sectional area ranged from 5,800 to 2,560 square feet.

Water stages were observed on a gage erected for the purpose. Velocities were observed with a Price current meter (No. 891). The chief observer was Roger C. Rice, assistant engineer, United States Geological Survey. He was assisted by Arthur Taylor and for a part of the time by A. M. Gilbert and by me. Observations were made on September 25, 1914, from 2.30 p. m. to 9.30 p. m., and a continuous series from November 16, at 11.30 a. m., to November 17, at 3.40 p. m. The observations of water stage were made at irregular intervals but were sufficiently frequent to define the curve. The measurements of velocity were made mostly at intervals of

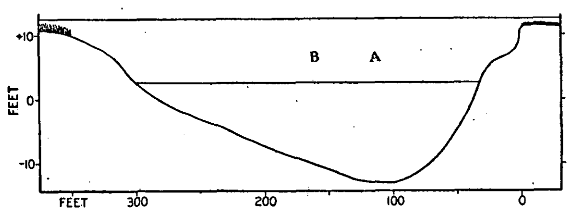


FIGURE 24.—Cross profile of Ravenswood Slough at station for observations, looking bayward. Vertical scale five times the horizontal. The zero of the vertical scale corresponds to the zero of the tide gage. Horizontal lines show highest and lowest observed water levels. A, Principal meter station; B, special meter station.

five minutes, but the interval was sometimes varied. The whole number of measurements in the regular series was 345. A special set of observations to determine times of slack water were made on December 22.

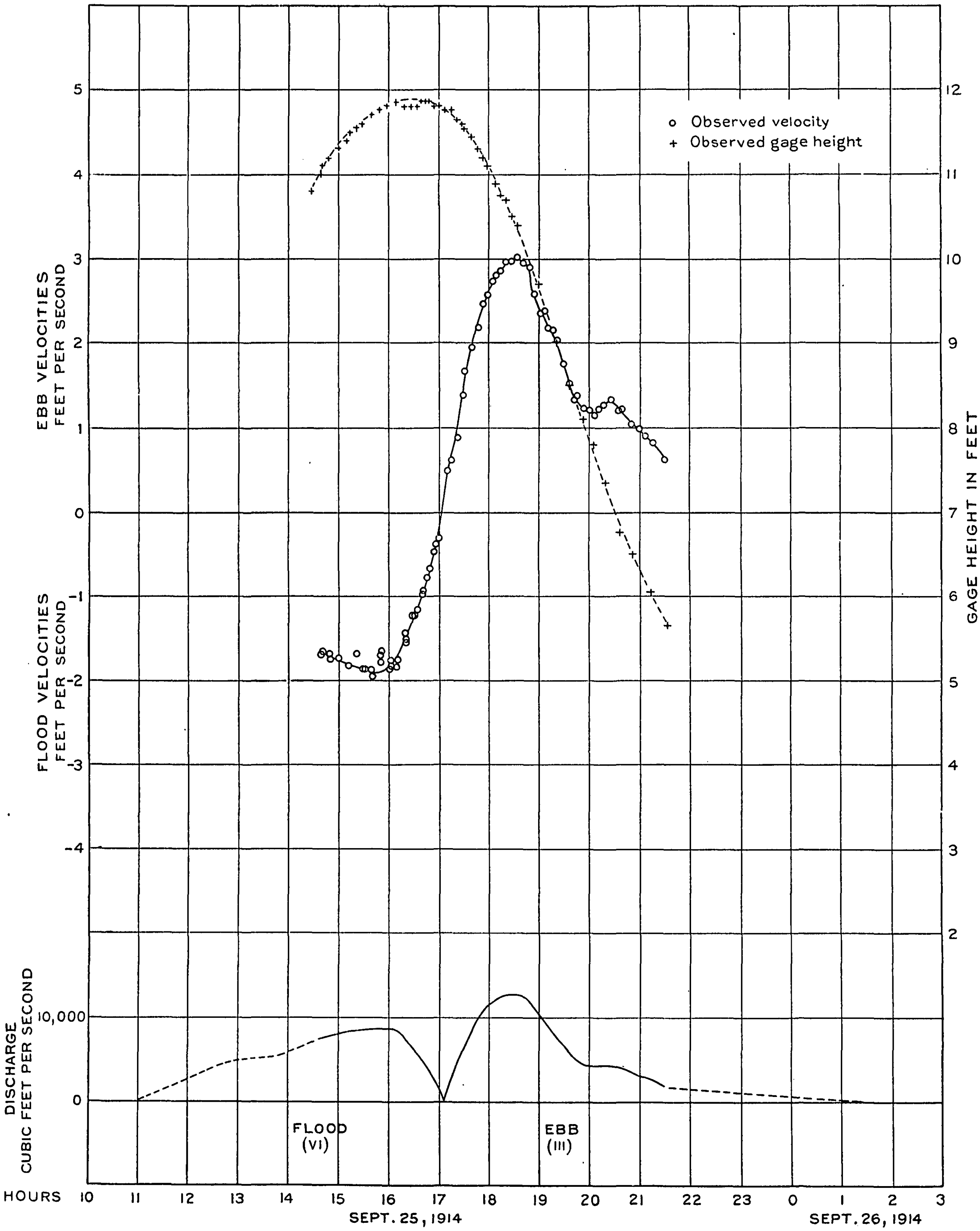
From previous experience the determinations of the meter were not regarded as trustworthy for velocities below 0.5 foot per second, but in this work a few measurements made of lower velocities appeared to be good.

The observations are here reported only in graphic form. In Plates XXXII and XXXIII the horizontal scale represents time. One vertical scale represents water stage, in feet, as read on the local gage. Another represents velocity of current in feet per second and is read both upward and downward from a zero line. The ebb velocities are plotted above the line and the flood below. The two scales pertain to the same spaces, so that the curves of varying water stage and of varying velocity can readily be compared. A third vertical scale, limited to the lower parts of the diagrams, shows discharge in cubic feet per second.

The records of velocity are eminently harmonious for all but the highest velocities—so harmonious as to leave no question as to details of the curve. There is some irregularity in the records of velocities above 3 feet per second, and this is ascribed with confidence to actual irregularity of velocity—not that the current as a whole was affected by pulsations, but that when the flow was strongest it was also most varied by whirls or vortices. As a vortex passed the meter it might yield a velocity greater or less than the normal.

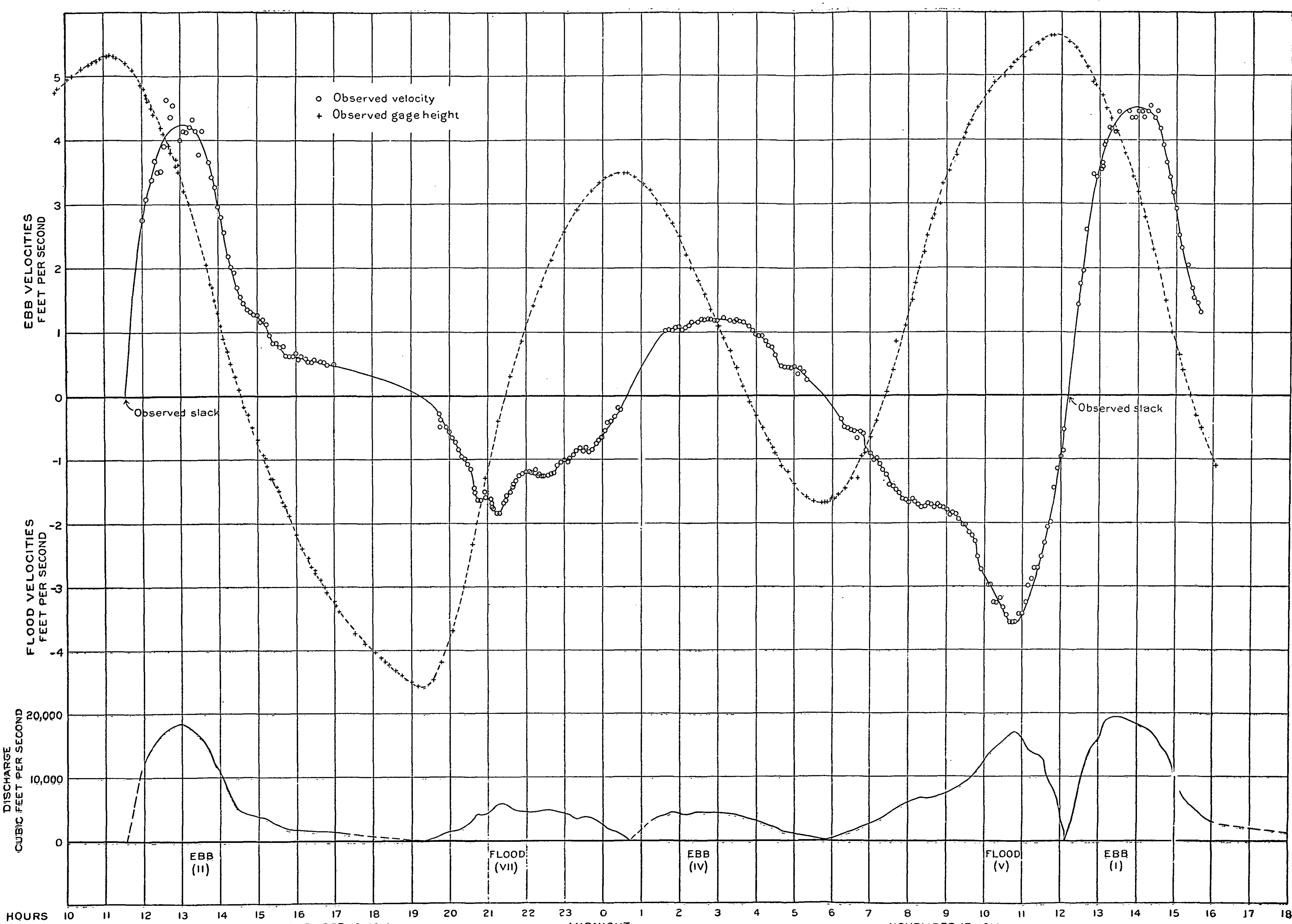
In the records of lower velocities the plotted points give clear definition to a curve, but the curve is irregular. This irregularity I ascribe to changes in the distribution of velocities within the channel. In a curved channel the velocities are not arranged symmetrically, as they may be in a straight channel, but divisions or strands of the current move in somewhat different directions, as well as with different velocities. In the determination of these details, momentum and frictional resistance are factors; each water stage, in combination with a particular general velocity, has its own system of oblique strands; and with progressive change of water stage and of general velocity the system of strands changes. Observations restricted, as ours were, to a single point in the channel would record the speed now of one strand and now of another.

To test this explanation simultaneous observations of velocity were made at two points in the same cross section. If the irregularities of the curve are due to variations of the general velocity, the two series of measurements should yield parallel curves. If they are due to the shifting of strands, the results of the two series would probably not be parallel. While the regular series of measurements was in progress at a point (A, fig. 24) about 115 feet from the right (east) bank, a second meter was installed at a point (B) about 160 feet from the same bank, and the readings were made for 2.5 hours. The results are shown in figure 25. It happened that the period chosen was not one of great irregularity of the main velocity curve, but the



WATER STAGES, VELOCITIES, AND DISCHARGES IN RAVENSWOOD SLOUGH, SEPTEMBER 25, 1914.

Observations of water stage (gage height) are shown by crosses; observations of velocity of current by circles. The time scale is horizontal. There are three vertical scales representing, severally, gage height in feet, velocity in feet per second, and discharge in cubic feet per second. Ebb velocities are plotted above the line of zero velocity; flood velocities below. The roman numerals connect individual ebbs and floods with data in Plate XXXIV and Tables 37, 38, and 40.



WATER STAGES, VELOCITIES, AND DISCHARGES IN RAVENSWOOD SLOUGH, NOVEMBER 16–17, 1914.

Observations of water stage (gage height) are shown by crosses; observations of velocity of current by circles. The time scale is horizontal. There are three vertical scales representing, severally, gage height in feet, velocity in feet per second, and discharge in cubic feet per second. Ebb velocities are plotted above the line of zero velocity; flood velocities below. The roman numerals connect individual ebbs and floods with data in Plate XXXIV and Tables 37, 38, and 40.

comparison shows that fluctuations at the two stations were not strictly parallel. During the 35 minutes from 14 h. 40 m. to 15 h. 15 m. the velocity at station B was notably lower than at station A by an average difference amounting to 11 per cent; and for 15 minutes from 16 h. 05 m. to 16 h. 20 m., the average velocity at station B was the higher, with an average difference of 18 per cent.

The results first sought in the discussion of the observations were discharges and their distribution through the tidal periods. Representing discharge by Q, the area of the cross section, in square feet, by a, and mean velocity

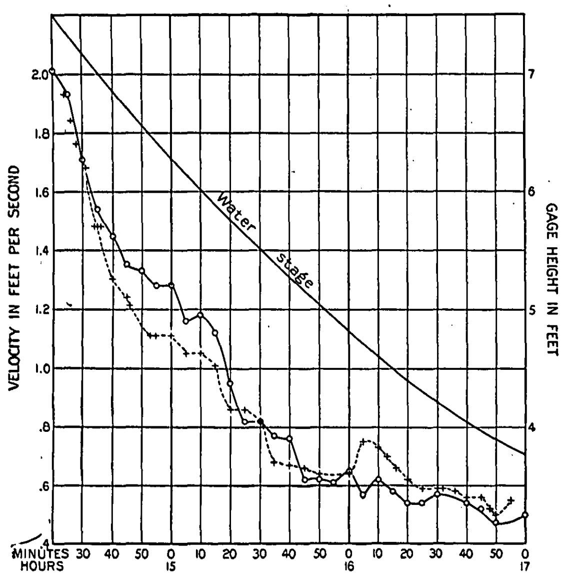


FIGURE 25.—Velocities at two points in the same section of Ravenswood Slough Nov. 16, 1914. Observed velocities at A (fig. 24) are shown by circles, at B by crosses.

for the entire section, in feet per second, by V_m, we have

$$Q = a V_m$$

V_m is in strictness the mean, with reference to space, of the components of velocity normal to the plane of section.

Velocities were observed at a single point in the section, and their directions, which it was not practicable to observe, doubtless deviated somewhat from the normal. A certain amount of obliquity would be given by the vertical motion to which some of the irregularities of the record have been ascribed, and also by the weaving of current strands to which other irregularities are ascribed.

In the selection of a position for the meter, the aim was to measure the strongest surface velocity, and it is probable that if the meter had been kept continuously in the strongest current the velocity curve would be comparatively simple and smooth. The meter was not strictly at the surface but was submerged about 2 feet, being suspended at the side of a small boat at anchor.

A single series of velocity measurements in the vertical beneath the observation boat showed only slight changes in velocity from the surface downward until the bottom was approached.

Consideration was given to these several factors in selecting a coefficient for the reduction of observed velocity, V_o, to mean velocity, and also to the fact that the smooth channel bed afforded little frictional resistance. The coefficient used was 0.85, giving

$$Q = 0.85\ a V_o.$$

The area of the stream's section varied with the stage of tide and was computed for each stage by aid of a diagram based on a large cross profile similar to figure 24. The values of a were thus determined at 10-minute intervals, the stage values necessary for the computations being read from the water-stage curves in Plates XXXII and XXXIV.

The simultaneous values of V_o were read, in similar manner from the velocity curve in the diagram, and the data were thus completed for the computation of discharges. The discharges at 10-minute intervals are plotted in Plates XXXII and XXXIII, and the lines joining them are curves of discharge in relation to time.

VOLUME.

In the space inclosed between one of these curves and the line of zero discharge horizontal distances represent time, and vertical distances represent volume divided by time. An area therefore represents time × volume ÷ time, which is volume. If the horizontal elements are reckoned in seconds, to correspond with the time unit of the vertical elements, then the total area inclosed by one of the curves (and its zero line) represents the total volume of water traversing the section during the corresponding flood or ebb movement.

The computations of volume, however, were based primarily on the numerical data from which the curves had been plotted, and the curves were used chiefly in the extrapolation of discharges for times not covered by the observations. Except in the case of the flood tide of September 25, extrapolation applied only to discharges so small that the associated velocities could not be measured with the Price meter. Table 37 not only contains the computed volumes but records other data pertaining to the several tides observed. The extrapolated times have no claim to precision; the interpolated, with one exception, are thought to be as trustworthy as those obtained by direct observation.

To obtain the figures in the right-hand column of the lower division of the table ("mean depth of storage"[1]) each tidal volume, in cubic feet, was divided by the area of the marsh tract (including channels) in square feet. The quotient is the depth of a layer of water having the area of the marsh tract and the volume of the particular tide.[2]

TABLE 37.—*Tidal data at station on Ravenswood Slough and comparative data at the Presidio wharf.*

Date.	High water at station.		High-water slack at station.		Low water at station.		Low-water slack at station.		High water at Presidio.		Low water at Presidio.	
	Time.	Gage reading.	Time.	Gage reading.	Time.	Gage reading.	Time.	Gage reading.	Time.	Above reference plane.	Time.	Above reference plane.
1914.	*H. m.*	*Feet.*	*H. m.*	*Feet.*	*H. m.*	*Feet.*	*H. m.*	*Feet.*	*H. m.*		*H. m.*	
Sept. 25							[a]11 00				9 18	3.25
	16 40	11.85	[b]17 05	11.80					15 24	6.25		
							[a]1 00				22 54	0.05
Nov. 16	11 09	12.30	11 33	12.28					9 43	6.65		
					19 15	2.45	[b]19 20	2.50			16 28	−1.24
16–17	0 30	10.48	[b]0 35	10.46					23 26	4.61		
17					5 43	5.32	[b]5 48	5.34			4 00	2.39
	11 49	12.62	12 10	12.56					10 25	7.03		
							[a]20 30				17 22	−1.44
Dec. 22					11 04	6.21	11 06	6.21			9 48	3.14
	16 34	10.87	16 36	10.87					15 13	5.33		

Date.	Type.	Designation in Pls. XXXII and XXXIII.	Time of beginning.	Time of ending.	Duration.	Volume (cubic feet× 10⁻⁶).	Mean depth of storage.
1914.			*H. m.*	*H. m.*	*H. m.*		*Feet.*
Sept. 25	Flood	VI	[a] 11 00	[b] 17 05	6 05	109.7	1.40
25–26	Ebb	III	[b] 17 05	[a] 1 00	7 55	119.0	1.51
Nov. 16	do	II	11 33	19 20	7 47	184.2	2.34
16–17	Flood	VII	[b] 19 20	[b] 0 35	5 15	62.4	.79
17	Ebb	IV	[b] 0 35	[b] 5 48	5 13	52.8	.67
	Flood	V	[b] 5 48	12 10	6 22	178.8	2.27
	Ebb	I	12 10	[a] 20 30	8 20	195.2	2.48

[a] Extrapolated with aid of record at Presidio. [b] Interpolated by velocity curve. See Pl. XXXII or XXXIII.

In the upper division of the table the four columns at the right contain data from the self-registering tide gage of the United States Coast and Geodetic Survey at the Presidio, San Francisco.

As noted in the table, most of the times of slack water were either interpolated or extrapolated. Only two were observed directly, by watching the surface of the water. The extrapolated times have no claim to precision; the interpolated, with one exception, are thought to be as trustworthy as those obtained by direct observation.

The low-water stage of the afternoon of November 16 differed but little from the low-water

[1] For definition of "depth of storage" see pp. 75, 130.

[2] In the technical terminology of tidal phenomena the rise and fall of the water surface are tides and the horizontal movements (flood and ebb) of the water are currents. In colloquial usage the word tide is not restricted to rise and fall but is often applied to currents. Having frequent occasion to speak of the entire flood or ebb movement, from one slack to the next, as a unit, and discovering no appropriate technical term, I have found it convenient to call it a tide. The context usually distinguishes this use of the word and prevents ambiguity.

stage of the following afternoon. At the Presidio it was 0.2 foot higher. It is therefore presumable that in the intervening 25 hours the same quantities of water entered and flowed from the slough. The measurements of the two flood tides of that period give a total volume of 241,000,000 cubic feet; the measurements of the two ebb tides give 248,100,000 cubic feet. The ebb volumes exceed the flood volumes by 3 per cent.

In my judgment this discrepancy is greater than should be ascribed to instrumental and personal errors of observation, and I prefer to ascribe it chiefly to certain assumptions involved in the mode of reducing the observations.

Certain irregularities in the velocity curves have been explained as due to the shifting of current strands, so that the meter was not always in the same part of the main current. For that reason it is believed that the ratio of the observed velocity to the mean velocity was not constant. Nevertheless, as no way was discovered for applying corrections, the assumption of constancy seemed the best practicable assumption.

Another insecure assumption pertains to deep flooding of the marsh. The marsh tract dependent for its flooding on Ravenswood Slough has a hard and fast boundary only on the dry-land side. (See fig. 23.) On other sides it adjoins other marsh tracts which receive tidewater either through other sloughs or else directly from the bay. During the prevalence of an overmarsh water stage the tracts are not distinguishable; the sheet of water is continuous. It is only as the stage is lowered that water partings are revealed, and even then the evidence is not in visible crests but in the fading out of small channels. While the stage is high it is not only possible for water to flow gently from one slough district to another, but such transfers are known actually to occur. They probably occur on all intermarsh boundaries that are reached by high water earlier from one side than from the other. In many places the transfers are of such volume that cross channels are established in which the direction of flow normally alternates. The boundaries of the Ravenswood Slough tract are exceptionally free from such evidence of cross-boundary currents, and this fact helped to determine its selection for special duty, but we must nevertheless suppose that there are interchanges between this and other tracts. Evidently the assumption, till now tacitly made, that the entire water movement for the flooding and draining of the tract on November 16–17 was through the slough will bear qualification.

RELATION OF DISCHARGE VARIATION TO THE TIDAL PERIOD.

The tidal period here considered is not that from a time of high or low water to the following time of low or high water but is the interval between two consecutive times of slack water. It is the duration of a flood or ebb tide. In figures 26 and 27 the curves of discharge already shown in Plates XXXII and XXXIII are assembled, with certain modifications. The horizontal scale represents time, but its unit, instead of being an hour, is the tidal period. In changing from the scale of hours each curve was compressed or stretched, but the area inclosed by it was not changed. To conserve the areas, the vertical scale was given a compensatory change. The ordinate of the new curve is not discharge but is the product of discharge by the ratio between the particular tidal period and the average tidal period.[1] The purpose of this arrangement is to enable the eye to appreciate at the same time the relative volumes of the several tides and the distribution of each volume within the tidal period. The tides represented are numbered from I to VII.

The ebb curves (fig. 26) are evidently of two types. Curves I, II, and III ascend rapidly to a high maximum, from which there is also a steep descent, and this feature is absent from curve IV. The explanation of the high maximum is connected with the system of reliefs in the tide marsh. The marsh is a plain, nearly horizontal and traversed by a system of branching channels. In the main, the channels have clearly defined banks, so as to be sharply differentiated from the plain. The high-water stage preceding the ebb, which corresponds to curve IV, was below the marsh-plain level. The high waters associated with curves I, II, and III were above the plain, and they were so far above that the volume to be drained from the plain was larger than the volume to be drained from channels. The

[1] This statement might be qualified by saying that a constant factor was included in the computations for the sake of giving the curves convenient proportions.

acute maximum in each of the three curves represents the draining of water from the marsh plain. The gentler slope following the maximum and the entire form of curve IV

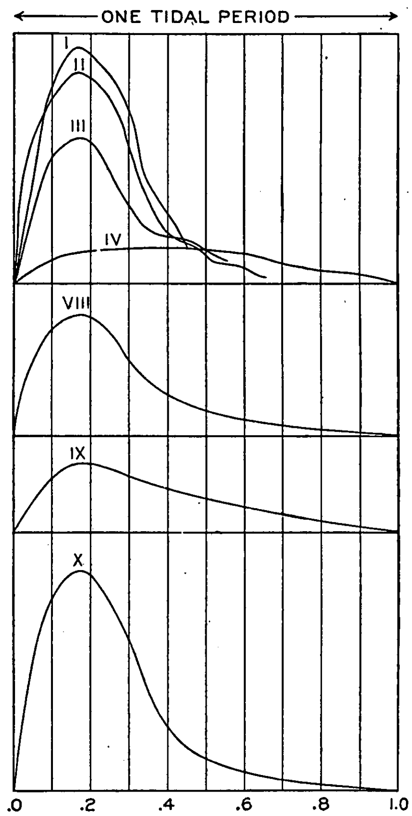


FIGURE 26.—Curves showing variation of ebb discharge at entrance of a tide marsh during a tidal period. The ordinates are proportional to the product of discharge by the length of the tidal period.

represent the draining of channels. It is convenient to call the tides which carry water to and from the marsh plain overmarsh tides, and to speak of those draining only channels as channel tides.

The three curves of overmarsh tides differ among themselves not only in the height of the maximum but in the position of the point at which the steeply descending slope is exchanged for a gently descending slope. The greater the volume of water spread on the marsh plain the longer the time consumed in its draining away.

The overmarsh-tide curves intersect the channel-tide curve and for the second half of the tidal period lie below it. This is connected with the fact that each overmarsh ebb tide not only began with a very high water stage but ended with a very low stage, whereas the channel ebb tide began and ended with stages of intermediate height, and with the further fact that the area of water surface in the channels is less at low stages than at high. The last units of fall of the overmarsh tides as the tide goes out yield less water than the same units of the channel tides.

Of the flood tides represented, those producing curves V and VI (fig. 27) were overmarsh tides and that of curve VII was a channel tide. Curve V carries a high maximum, analogous to that of its companion ebb (I, fig. 26), but the maximum occurs near the end of the period instead of the beginning. The rising water invaded the channels first and the marsh plain afterward. The imperfect curve VI, representing a tide which covered the plain to a smaller depth, has a lower and less acute maximum in the same position.

Curve VII, representing a channel tide, lacks the distinctive maximum of the overmarsh tides but shows a low maximum somewhat before the middle of the period. I have not satisfied myself as to the cause of this

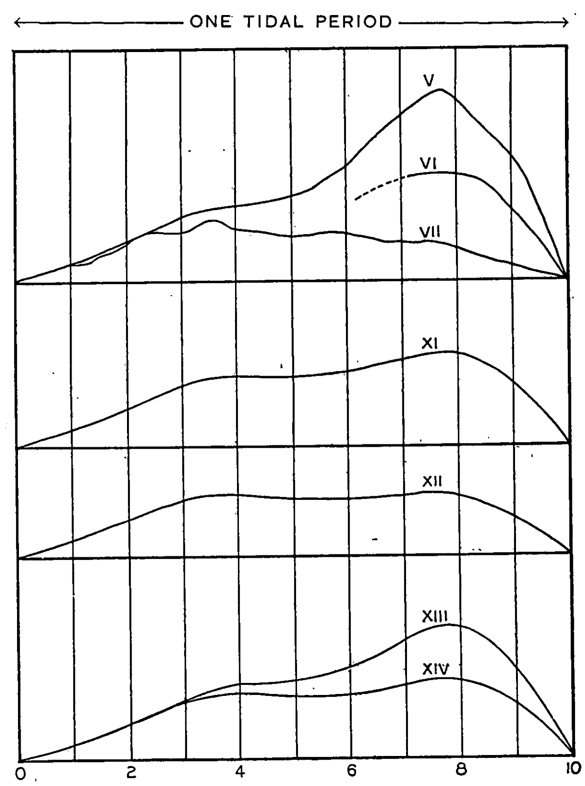


FIGURE 27.—Curves showing variation of flood discharge at entrance of a tide marsh during a tidal period. The ordinates are proportional to the product of discharge by the length of the tidal period.

maximum but accept it as an observed feature. Whatever condition is responsible for it appears to have affected also the tide represented by curve V.

It is now proposed to deduce from these observational data some generalized curves to exhibit for ebb and for flood tides, the sequence of discharge, or volume transfer, at the mouth of a tidal slough (1) for the average of all overmarsh tides, (2) for the average of all tides, (3) for the average tropic tides, and (4) for the average of the 30 largest tides of the year. In deducing these curves, it is convenient to make use of certain results belonging to a later division of the appendix, and they will be cited in the present connection without explanation. The discussion leading to them may be found on pages 135–136. They are: (1) The overmarsh tides are numerically about one-seventh of all the tides, the overmarsh ebbs being one-seventh of the ebbs, and the overmarsh floods one-seventh of the floods. (2) The channel ebb tides have on the average about one-third the volume of the overmarsh ebb tides. (3) The channel flood tides have on the average about one-half the volume of the overmarsh flood tides. (4) The estimates of average volume on which the preceding statements rest make possible a quantitative comparison of each of the measured tides with the mean for its class.

The average volume of overmarsh ebb tides is less than the volume of either of the observed overmarsh ebbs, being about one-tenth smaller than the volume corresponding to curve III. In the region of the maxima, therefore, the position of its curve is a little below that of curve III. Its form, as interpreted from a study of the four curves, appears in figure 26 as curve VIII.

Curve IV corresponds to a tidal volume greater than the average volume of channel ebb tides in the ratio of 10 to 7. Its form is assumed to be representative of the class and has been combined with that of curve VIII to obtain a curve for the average of all ebb tides. The ratio of combination, account being taken of the facts that the channel tides are six times as numerous as the overmarsh tides and have an average volume only one-third as great, is $(7:10) \times (6:1) \times (1:3) = 7:5$. The resulting curve, for the average of all ebbs, is curve IX of figure 26.

Tropic ebb tides are dominantly of the overmarsh type, and their average volume (p. 136) is little less than that of the overmarsh ebb tides. The distribution curve for the latter (VIII) may serve also for the tropic ebb tides.

The tides corresponding to curves I and II were among the largest ebb tides of the year 1914. The average volume of the thirty largest ebb tides of the year falls between the volumes of these two. The type curve for the thirty ebb tides, curve X (fig. 26) was accordingly based on curves I and II, with omission of details supposed to be accidental.

The data for the discussion of flood-tide distribution curves are comparatively meager. Because curve V (fig. 27), representing the one fully measured overmarsh flood tide, coincides for the first third of the tidal period with curve VII, representing the one observed channel flood tide, the assumption was made that all types of overmarsh flood-tide curves agree as to the first part of the period and differ only in respect to the maximum characteristic of the remainder of the period.

The average volume for overmarsh flood tides is less than the volumes corresponding to curves V and VI, being three-fourths of the volume corresponding to curve VI. The distribution curve for overmarsh flood tides is assumed to have a maximum (curve XI) notably lower than that of curve VI. The average volume for channel flood tides is less than the volume corresponding to curve VII in the ratio of 3 to 5, but curve VII was nevertheless used as its representative. The distribution curve for the average of all flood tides (curve XII) was obtained by combining curves VII and XI. The combination ratio, involving the relative frequencies and relative volumes of channel and overmarsh flood tides, was $(3:5) \times (6:1) \times (1:2) = 9:5$.

The average volume of tropic flood tides is one-sixth less than the average for overmarsh flood tides, and the distribution curve assigned to tropic floods (curve XIV, fig. 27) differs little from curve XI. The average volume of the thirty largest flood tides predicted for 1914 is one-fourth less than the volume corresponding to curve V, and the distribution curve for the thirty tides (curve XIII) was based on curve V.

The purpose of the six generalized curves representing the volume-time relation for all flood tides (XII) and all ebb tides (IX), for tropic flood tides (XIV) and tropic ebb tides

(VIII), and for a group of thirty great ebb tides (X) and the associated flood tides (XIII) is to aid in the computation of the tidal volume at the Golden Gate by showing what fraction of the volume of tide water that enters and leaves a tide marsh is so related to the tidal period at the Golden Gate as to augment that volume. For example, if, when the average volume of all tides is being considered, it is found that the ebb tidal period at the Golden Gate includes the first one-third only of the ebb period of a particular marsh, then the area covered by the left-hand third of curve IX is proportional to the fractional part of the tidal storage of the marsh which is effective at the Golden Gate, whereas the area covered by the remaining two-thirds of the curve is proportional to that part of the marsh's storage which is not effective at the Golden Gate.

RELATION OF TIDAL STORAGE TO THE RISE AND FALL OF TIDE AT THE MOUTH OF RAVENSWOOD SLOUGH.

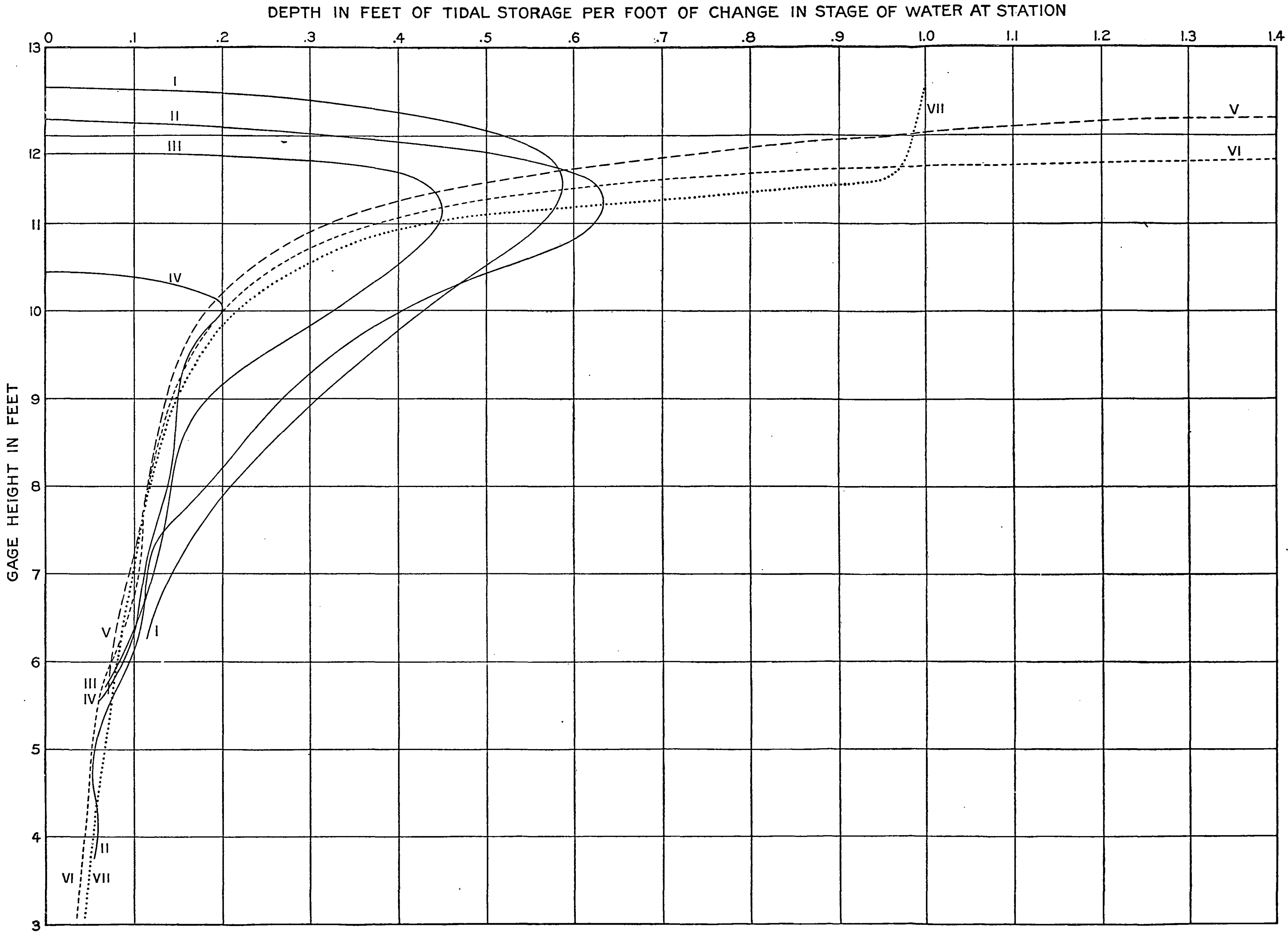
I have thus far treated the storage of tidal waters by the Ravenswood Marsh tract as a matter of volume, but it is convenient at this point to introduce a different measure of tidal storage.[1] To apply the Ravenswood results to other marsh tracts it is necessary to take account of relative areas, and arrangement for this is most readily made by translating the Ravenswood data into volume per unit area. The translation has been accomplished by dividing each volume of storage by the area of the tract, including both marsh plain and channels. The volumes being given in cubic feet, the area was expressed in square feet (78,660,000), and the quotients are therefore in linear feet. As the divisor is a horizontal area, the linear quotients are vertical. Each one is an expression for average depth of storage on the entire tract and may be called for brevity depth of storage.

What has been seen of the relative volumes of overmarsh and channel tides serves to illustrate the general fact that the storage of tides on marshes is not proportional to range of tide—the vertical interval between the high-water and low-water stages—but depends largely on the relation of the high-water plane to the level of the marsh plain. In order to deduce from the observational data the average depth of storage for all tides, or the average depth of storage for a particular group of tides, it is important to know how storage is affected by increment to stage at different stages. The observations contain information on this point, but it does not lie on the surface.

Each determination of discharge is a determination of the volume by which tidal storage is increased (or diminished) per second at a particular time. Each derived determination of depth of storage is the increment per second to depth of storage at a particular time. For the same particular time there is a record of water stage, and this record is a member of a series. The series of stage records, taken in connection with their time intervals, serves to show how rapidly the water surface was rising or falling at the particular time. The sequence of changing water stage has been expressed in Plates XXXII and XXXIII by a curve, and the direction of the curve at the point corresponding to the particular time indicates the rate at which the water stage was then changing. By drawing a line tangent to the curve at the point it is possible to read off, in terms of the scales of the diagram, the rate of change of the water stage at the particular time—that is, it is possible to read directly the number of tide-gage or water-stage units traversed by the water surface in a unit of time, or the number of time units corresponding to a unit change of water stage. Such readings were actually made, the thing read being the number of seconds corresponding to a change in water stage of 1 foot. This number was then multiplied by the increment to depth of storage per second and thus was obtained the increment to depth of storage per foot of change in water stage. In other words, the computation gave, for a particular time and for a particular water stage, the relation between increment to depth of storage and increment to water stage.

A series of such determinations were made for each observed flood tide and ebb tide, and the results were plotted in relation to gage height or water stage. They appear in Plate XXXIV as a set of curves, each of which pertains to a tide. The ebb-tide curves are distinguished by full lines, the flood-tide curves by broken lines. Each curve shows the rela-

[1] The use of the term "tidal storage" is explained on pp. 75, 85.



RELATION OF STORAGE OF TIDAL WATER BY RAVENSWOOD MARSH TO RISE AND FALL OF TIDE AT OBSERVATION STATION NEAR MOUTH OF RAVENSWOOD SLOUGH.

The vertical scale represents water stage or gage height. The horizontal scale represents the ratio which increment to depth of storage bears to increment to water stage. The full-line curves correspond to ebb tides; the broken-line curves to flood tides. The roman numerals connect individual ebbs and floods with data in Plates XXXII and XXXIII and in Tables 37, 38, and 40.

tion to water stage of the ratio between increment to depth of storage and increment to water stage.

Before attempting a generalization of the curves it is necessary to consider the causes of certain of their characteristics and diversities.

The water surface within the marsh tract is never level. During the main part of each flood period it slopes landward, during the main part of each ebb period it slopes bayward, and near the times of slack water it undulates in a more or less complicated manner. Moreover, its slopes are continually changing. The record of changing water stage as it was observed near the mouth of the slough does not, therefore, show accurately the changes of stage in other parts of the tract, and the rate of change at the point of observation is not identical with the average rate of change for the entire tract of water. If the surface were always level the sequence of changes in storage during a rising tide would be identical with the sequence of changes during a falling tide, except that it would follow the reverse order; and (so far as this factor is concerned) the flood-tide curves of Plate XXXIV would not differ from the ebb-tide curves.

It is true in a general way that the ebb curves and flood curves are influenced in opposite ways by the water-slope factor, so that they tend to fall into two groups; and it is assumed that the position of what may be called the normal curve—the ideal curve uninfluenced by water slope—lies between these groups.

The curves corresponding to flood tides do not diverge widely one from another. The ebb-tide curves lie close together in the region of the lower water stages, but between the 6-foot and 10-foot levels they stand apart. Curve I, which lies farthest to the right, corresponds to the ebb tide following the highest of the high waters, and the order of the four curves from right to left—I, II, III, IV—is also the order of the high waters with which they are associated. It will be noted also that as the curves ascend from the 6-foot level the first to swing to the right is curve I, and then successively curves II and III, while curve IV does not leave the vicinity of the flood-tide curves. These peculiarities are connected with the fact that curve IV alone corresponds to a channel tide, while curves III, II, and I correspond to overmarsh tides of successively increasing magnitude. The divergence of the curves is thus correlated with the draining away of the overmarsh water. The flow of that water was retarded by vegetation, so that the arrival of the water at the mouth of the slough was delayed; and the effect of this delay was greater and more prolonged as the body of overmarsh water was greater. As the time sequence of the ebb-tide curves is from high stage to low stage, the relative prolongation of the effect carries the aberration of the curve to a relatively low level. (Compare the corresponding and similarly numbered curves in fig. 27.)

As the curves ascend toward their upper limits, special features of striking character appear. All the ebb curves are reflexed to the left, returning quickly to the axis or zero line and in fact crossing it, and the flood curves are flattened so as to extend indefinitely to the right. These features are connected with the fact that the time of slack water is not coincident with the time of high water but follows it.

To understand the connection, let us return to the definition of the ratio represented by the abscissas. It is the ratio, R, between D, the increment to the depth of storage, and S, the simultaneous increment to water stage:

$$R = \frac{D}{S}$$

Let us call the increment to depth of storage positive during the flood current and negative during the ebb. Let us call the increment to water stage positive while the stage is rising and negative while the stage is falling. If water stage as recorded in our observations were the mean stage for the entire tract, the increment to stage would always have the same sign as the increment to depth of storage, but because the record gives the change of stage at a single point of the tract only, the signs are not always the same. In general, during flood tide both D and S are positive and R is therefore positive, and, in general, during ebb tide both D and S are negative and R is therefore positive; but other relations exist during the changes from flood to ebb and from rising to falling. High water is reached before slack water. At high water S is zero, while D is still positive and finite, and R is therefore infinite. Just after high water S is negative, but D is still positive, and so R is negative. R has changed from positive to negative through infinity. Soon slack water is reached, when the value of D is zero and R also is zero. With the beginning of the ebb D becomes negative and R becomes again positive. R has changed from negative to positive through zero.

To return to the diagram, the flood curve V flattens toward the right and is destined to become horizontal at plus infinity. It returns to the diagram from minus infinity and, crossing the zero line, becomes the ebb curve I.

A similar series of changes belong to the end of the ebb tide and beginning of the flood, but their importance is less because the interval between low water and low-water slack is relatively small. Their influence is not shown by the curves because our observations do not include the very low velocities of the current near the low-water epochs.

These curious pranks of the curves serve to illustrate the fact that the analysis on which our computations were based failed to include all factors involved in the phenomena, but they need not be held to discredit the results of the curve study so far as they pertain to the lower and middle water stages. The discordances referable to the noncoincidence of high water and slack water are not of importance below the 10-foot level. For the higher levels it is manifestly impossible to infer the character of the generalized or normal curve from the distorted flood and ebb curves, and aid must be sought from other considerations.

Above the level of the marsh plain the rising water is bounded on three sides by the waters of other marsh tracts which are also rising. If they rise at the same rate they constitute a barrier to retain the water of the particular tract, and their effect is that of a vertical wall. If they rise at a different rate, the particular tract may receive water from other tracts or may part with water to other tracts. Such transfers affect simultaneous discharges at the mouth of the slough but do not affect to an appreciable extent the actual storage of tide water by the particular tract. It appears proper, therefore, to ignore them in the construction of the normal curve. So far as the water boundaries of the marsh prism are concerned, the increment to depth of storage exactly equals the increment to stage.

On the fourth side the rising water is bounded by the shore of the marsh. This has the slope of the adjoining dry land, which is much steeper than the slope of the marsh plain.

On the basis of these facts and inferences, the portion of the generalized curve corresponding to stages above the marsh plain has been made to slope steeply, and at its extremity the ratio it represents has been given the value of unity.

The great increase of the ratio takes place within the narrow range of stage traversed while the water surface is expanding across the gentle slopes of the marsh plain, and the corresponding portion of the curve should be much more nearly horizontal than any other portion. Marsh conditions observed near the station while the tide was rising indicate that the most rapid expansion occurs between stages 10.6 and 11.6 feet.

Under control of these considerations the portion of the generalized (dotted) curve in Plate XXXIV above the 10-foot level was drawn. It represents, progressively, the relation between change in depth of storage and rise or fall of tide, except as the factors are modified by slope of water surface.

An abscissa of the curve, a horizontal line from one of its points to the axis of ordinates, representing the quotient of the increment to depth of storage by the coincident increment to water stage, is the graphic expression of the differential of depth of storage with respect to stage. Moved upward or downward, with coordinate change of length, it produces a surface, and the area of that surface is the graphic expression of the corresponding integral. That is, the area covered by the curve between any two stages measures the depth of storage corresponding to the rise or fall of the water surface from one of the stages to the other. This property of the diagram affords a check on its general accuracy. In Table 38 depths of storage computed by the diagram are compared with the corresponding depths obtained more directly from the observations.

For several reasons this check is of a rough character. For three of the seven tides the low-water level was not observed at the slough stations but was inferred by means of comparative data from the marigram at the Presidio.

The other low-water levels and all the high-water levels, being observed at a single point in the Ravenswood marsh tract, did not necessarily represent the mean height of the water surface in the tract, but in the computations they were assumed to represent the mean height. Perhaps it would be proper to speak of the comparison as a check on the consistency of two series of results obtained in different ways from the same body of data.

TABLE 38.—*Comparison of graphic generalization on depth of tidal storage with individual determinations.*

Designation of tide.	Type.	Depth of storage.		A−B	A/B
		A. Computed by generalized curves in Plate XXXIV.	B. Computed directly from observations.		
		Feet.	*Feet.*	*Feet.*	
I	Ebb	2.41	2.48	−0.07	0.97
II	...do	2.12	2.34	− .22	.91
III	...do	1.61	1.51	+ .10	1.07
IV	...do	.67	.67	0	1.00
V	Flood	2.24	2.27	− .03	.99
VI	...do	1.41	1.40	+ .01	1.01
VII	...do	.83	.79	+ .04	1.05
All ebbs		6.81	7.00	− .19	.97
All floods		4.48	4.46	+ .02	1.00
All tides		11.29	11.46	− .17	.98
Average disparity				± .07	[a] 3.4

[a] Per cent.

RELATION OF TIDAL STORAGE IN RAVENSWOOD MARSH TO RISE AND FALL OF TIDE AT THE PRESIDIO.

In order to apply the data obtained in the Ravenswood marsh to the tides of other marshes of the bay system, it is necessary to deduce annual averages. Probably this could be accomplished by an expert in tidal theory in a relatively direct manner, but for the layman it is easier to first correlate the Ravenswood observations with observations made at the Golden Gate. From a long series of observations at Fort Point the United States Coast and Geodetic Survey has derived the constants which are used in the prediction of tides for the locality, and the tidal elements of all stations in the bay region are referred to Fort Point as the primary station. A continuous record is now made at the Presidio wharf, only a short distance from Fort Point, and the data from that record have been used for correlation with the Ravenswood data.

The tides have greater range in Ravenswood Slough than at the Presidio, and correlation involves a comparison of scales. The zero of the gage used in Ravenswood Slough is independent of that at the Presidio wharf, and correlation involves a comparison of zeros.

In the Tide Tables the mean range of tides at the entrance to Redwood Slough is given as 1.56 times the range at Fort Point. At Cooley Landing the ratio is 1.54. For the entrance to Ravenswood Slough, which is midway between those points, a ratio of 1.55 may be interpolated. These ratios represent means. For individual tides the ratio is usually different from the mean.

The ranges of five tides were accurately observed at Ravenswood Slough. Comparisons of these ranges with ranges recorded at the Presidio illustrate the inconstancy of the ratio. It will be observed that the smaller ratios are associated with the larger ranges.

TABLE 39.—*Comparison of ranges of tides at Ravenswood Slough and at the Presidio wharf.*

Range at Ravenswood Slough.	Range at Presidio.	Ratio.
Feet.	*Feet.*	
9.85	7.89	1.25
8.03	5.85	1.37
7.30	4.64	1.57
5.16	2.22	2.32
4.66	2.19	2.13
Sum 35.00	Sum 22.79	1.54

Some experiments in the correlation of scales served to show that with the use of a small ratio the results for the higher water stages were made relatively consistent at the expense of the results for medium stages, while the reverse effect followed the use of a large ratio. A relatively small ratio, 1.40, was therefore chosen, because the great magnitude of storage by overmarsh tides gave special importance to the results connected with high stages.

In the correlation of zeros, also, prime consideration was given to data connected with overmarsh tides, the adjustment being that which retained the most consistent relation between high-water planes and the level of the marsh plain. Stage 11.5 feet on the Ravenswood gage was correlated with stage 6.1 feet at Fort Point and the Presidio.

On this basis the generalized curve of Plate XXXIV was redrawn on the scale of the Presidio gage, giving curve IX in figure 28. The new curve represents the relation of depth of storage on Ravenswood marsh to rise and fall of tide at the Presidio. As 1.0 foot on the Presidio gage corresponds to 1.4 feet on the Ravenswood gage, the change in depth of storage due to a rise of 1 foot at the Presidio is 1.4 times the change due to a rise of 1 foot at the Ravenswood station. The abscissas of the new curve were therefore made greater than those of the original in the ratio of 1.4 to 1.0. The abscissas having been increased in the ratio by which the ordinates were diminished, the areas were preserved; therefore the areas between the new curve and the axis of ordinates are measures of depth of storage. As a check on the adjustments, the depths of storage for the seven observed tides were computed by the new diagram. The

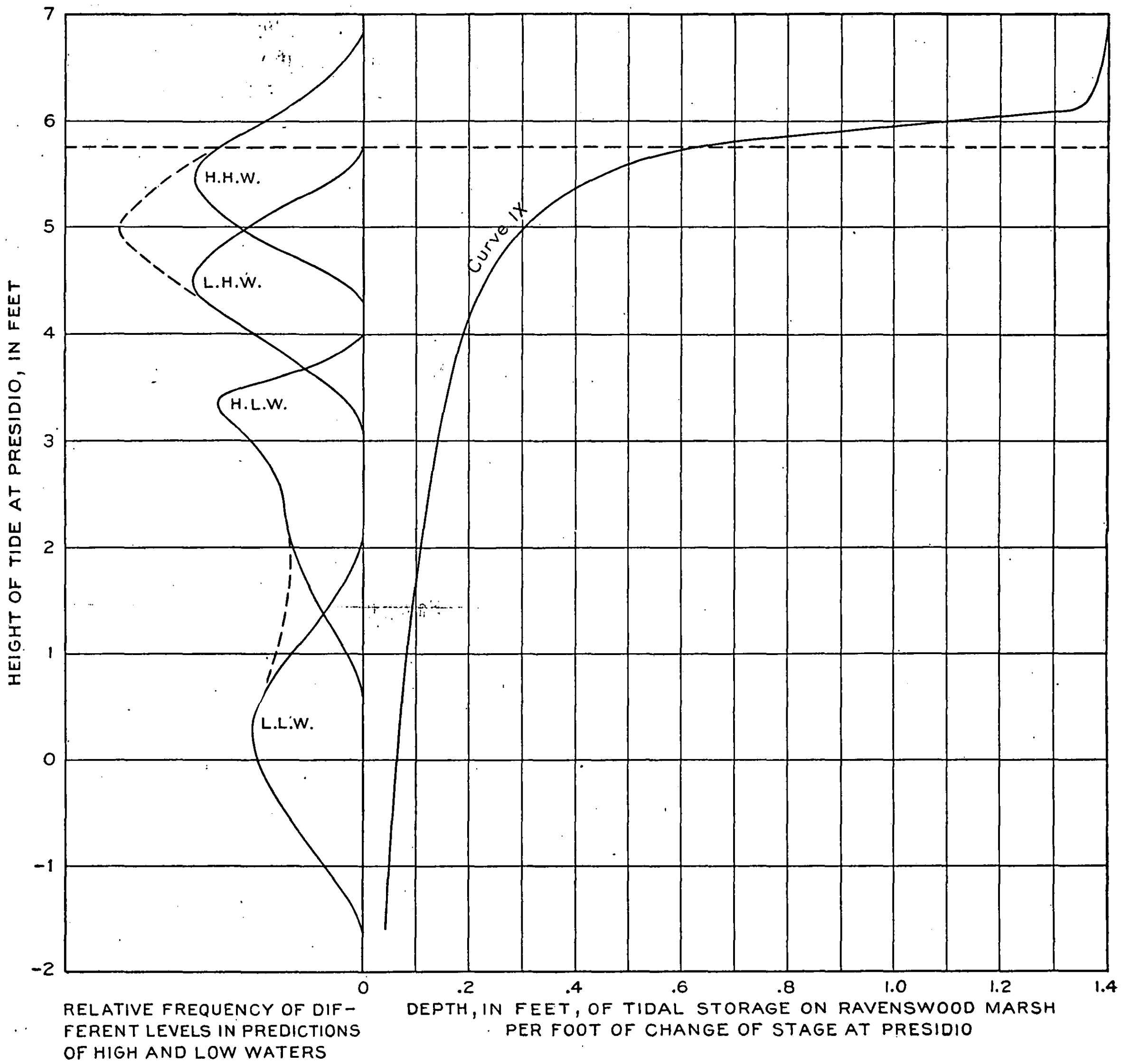


FIGURE 28.—Relation of tidal storage in Ravenswood marsh to water stage at the Presidio wharf. The vertical scale is of water stages at the Presidio. The vertical line marked 0 is the zero for horizontal scales. Distances to the right represent the ratio of increment of depth of storage (Ravenswood) to increment of water stage (Presidio). Distances to the left represent the relative frequency with which tidal culminations (high water or low water) occur at different levels. H. H. W., Higher high water; L. H. W., lower high water; H. L. W., higher low water; L. L. W., lower low water.

resulting values are shown, with comparative data, in Table 40.

TABLE 40.—*Second comparison of graphic generalization of tidal storage with individual determinations.*

Designation of tide.	Type.	Depth of storage. A. Computed by generalized curve for Presidio gage (fig. 28).	Depth of storage. B. Computed directly from observations.	A−B	A/B
		Feet.	*Feet.*	*Feet.*	
I	Ebb	2.71	2.48	+0.23	1.09
II	do	2.17	2.34	− .17	.93
III	do	1.55	1.51	+ .04	1.03
IV	do	.35	.67	− .29	.57
V	Flood	2.42	2.27	+ .15	1.06
VI	do	1.21	1.40	− .19	.86
VII	do	.66	.79	− .13	.83
All ebbs		6.81	7.00	− .19	.97
All floods		4.29	4.46	− .17	.96
All tides		11.10	11.46	− .36	.97
Average disparity				+ .17	[a] 14

[a] Per cent.

The values in this table are different from those obtained with the aid of the original diagram (Table 38) because the arguments were not the same. The first diagram was entered with water stages observed in Ravenswood Slough at high-water slack and low-water slack, the second with Presidio records of high water and low water. The values are also less accordant, the present comparison showing an average disparity of 14 per cent, while the previous comparison showed less than 4 per cent. The lack of accord is not a matter of surprise, because the procession of tide waves has opportunity for important modification in passing from the Golden Gate to Ravenswood Slough, but it serves nevertheless to qualify such numerical results as may rest on the correlation of phenomena at the two localities.

COMPUTATIONS OF AVERAGE DEPTH OF STORAGE.

TABLE OF STORAGE DEPTH.

Computations of the average depth of storage on Ravenswood marsh for certain classes of tides were made with the aid of the diagram reproduced in figure 28. For this purpose a table was formed showing for each tenth of a foot of tidal stage at the Presidio the depth of storage corresponding to a fall from the particular level down to that of the stage designated, 1.6 feet. Then to obtain the storage corresponding to a rise or fall from any specified stage to another, the depths for the two stages were taken from the table and the less was subtracted from the greater.

CURVES OF FREQUENCY.

If the function of depth of storage in relation to stage were a straight line, the depth of storage corresponding to the average tide would not differ sensibly from the average depth for all tides. Because of the strong curvative of the function it is necessary to take account of the relative frequency with which high tide and low tide, severally, occur at different levels. No attempt was made to determine the laws of frequency by analytic methods, but the frequencies for different levels of high water and low water were taken, by counting, from the tables of predictions for Fort Point. Curves were derived separately from the tables for 1908, 1912, 1913, and 1914 and were found to be so similar that their composites were accepted as adequate for the purpose.

The curves of frequency are reproduced in figure 28, where they are associated with the curve for depth of storage. The vertical scale represents water level, or stage of tide, in feet, and has for its zero the "plane of reference" for tidal predictions. Toward the right from the vertical line marked 0 distances represent depth of storage, in feet, per foot of change of stage. Toward the left they represent relative frequency.

The uppermost of the frequency curves, H. H. W., indicates that higher high water may reach any level between 4.3 and 6.8 feet but occurs most frequently at levels midway between these. Lower high water, L. H. W., has an overlapping range, with maximum frequency about 1 foot lower. The frequency curve for all high waters, obtained by adding the ordinates of the H. H. W. and L. H. W. curves, is distinguished by a broken line. In similar measures the frequency curve for all low waters was produced by adding the ordinates of the curve for higher low waters (H. L. W.) to those of the curve for lower low waters (L. L. W.).

GENERAL AVERAGE.

The method of computing the average depth of storage for all tides was as follows: Within the range of the high waters the tabulated depth for each stage was multiplied by the corresponding factor of relative frequency. The sum of the products was then divided by the sum of the frequency factors, giving an average depth of storage (H) for tidal ranges from the high-water stages to stage 1.6 feet. By the same process was next derived an average depth of storage (L) for tidal ranges from the low-water stages to stage 1.6 feet. (L) was then subtracted from (H), the remainder being the required average depth of storage for all tides. The depth obtained is 0.602 foot. This is greater by one-fifth than the depth of storage, 0.484 foot, corresponding to the range from mean high water to mean low water.

OVERMARSH-TIDE AND CHANNEL-TIDE AVERAGES.

The stage at the Presidio wharf that corresponds to the separation of overmarsh and channel tides in the Ravenswood marsh is not accurately defined by the data but is about 5.75 feet. A line at that level (fig. 28) divides the area inclosed by the frequency curve for high water into parts that bear the ratio of 1:6; the smaller part corresponds to the overmarsh tides. As shown by the diagram, all high waters of that division belong to the group of higher high waters. The sequence of tides in the Golden Gate is such (see fig. 18, p. 80) that each of the higher high waters is preceded by one of the higher low waters and followed by one of the lower low waters. These facts make it possible to compute with fair approximation the average depths of storage for the overmarsh flood tides and the overmarsh ebb tides. As the average depths of storage for all flood tides and for all ebb tides are known (being the same as for all tides), the average depths of the channel floods and channel ebbs are readily found.

Average depth of storage.

	Feet.
Overmarsh flood tides	1.05
Overmarsh ebb tides	1.37
Channel flood tides	.53
Channel ebb tides	.47

Channel floods bring in about one-half as much water as overmarsh floods. Channel ebbs deliver about one-third as much water as overmarsh ebbs.

TROPIC TIDES.

In their relation to the marshes some great tropic tides—that is, tides associated with the tropic higher high water—belong to the channel group, but the majority are overmarsh tides. Their average depth of storage is somewhat less than that of the overmarsh tides. As it varies from year to year, computations were made, with data from the Tide Tables, for four years (1908, 1912, 1914, and 1915), and the four-year means were adopted. They are, for the great tropic ebb tide, 1.27 feet; for the flood tide immediately preceding the great ebb, 0.87 foot.

SUMMARY OF COMPUTED RESULTS.

TABLE 41.—*Depth of tidal storage, in feet, in Ravenswood marsh.*

	Flood.	Ebb.
Average for overmarsh tides	1.05	1.37
Average for channel tides	.53	.47
Average for tropic tides	.87	1.27
Average for all tides	.602	.602
For tide of average range	.484	.484

The relative frequency of overmarsh and channel high waters is as 1 to 6.

LAG OF SLACK WATER.

Each observation of the time of slack water at the Ravenswood Slough station was accompanied by an observation of the time of the associated high water or low water. The slack came later than the high or low. Most of the observations of high and low water were fairly accurate, but all determinations of the time of slack water were unsatisfactory. On four occasions the slack was observed by watching the surface of the water, and the moment was selected when there appeared to be as much movement landward as bayward, but doubt remained as to the conditions below the surface. Five determinations were made by means of the plotted curves of velocity, and they involved interpolation through a considerable space. In every case the uncertainty as to the determination of lag amounts to several minutes. The values of the lag, or the time elapsing from a high water or low water to the following slack water, are given in Table 42, with associated data.

TABLE 42.—*Lag of slack water after high water and low water at Ravenswood Slough station.*

Date.	Type of water stage.	Height of water stage.	Lag of slack water.	Ratio between area of water surface in marsh tract and sectional area of slough at station.
1914.		*Feet.*	*Minutes.*	
Nov. 17	Overmarsh high water	12.56	19	13,600
Nov. 16	.....do	12.28	24	13,900
Sept. 25	.....do	11.80	25	14,300
Dec. 23	Channel high water	10.87	2	5,800
Nov. 17	.....do	10.46	8	4,400
Dec. 22	Low water	6.21	2	1,900
Nov. 17	.....do	5.34	5	1,700
Nov. 16	.....do	2.50	Small.	1,200

The conspicuous fact brought out by the tabulated data is that a group of lags decidedly greater than the others are associated with overmarsh high waters, and for this association a plausible explanation is at hand. When a broad bay communicates with the ocean or other tided body of water by a very narrow strait the phenomena are those of the filling and emptying of a reservoir. Because time is required to pass water through the strait the surface in the reservoir does not rise and fall in complete unison with the surface outside. When high tide is reached outside the filling of the reservoir is still incomplete, and the current continues to set inward until the surface outside has fallen below the level of the surface inside; and, similarly, the outward current through the strait continues for some time after the level outside has begun to rise. So the reservoir factor occasions a delay in each reversal of current, or, in other words, causes a lag of slack water. This is not the only cause of slack-water lag, but it is a concurrent cause wherever the reservoir effect modifies the normal movements of the tide wave. When the tide water advancing through the sloughs of a marsh tract begins to flood the marsh land itself the area served becomes very large in relation to the sectional area of the serving channel, and the reservoir factor is then important. To illustrate this point I have computed the ratio between the water surface and sectional area for the several stages associated with the determinations of lag and recorded the values in Table 42. It will be seen that not only are the ratios exceptionally high for the overmarsh high waters, but those three ratios have the same sequence in magnitude as the corresponding lags.

The inequalities among the smaller lags do not admit of profitable discussion, because the values of the lags are not greater than the uncertainties of their determination.

The lag of slack water at slough entrances enters as a datum into the computations of tidal volume for the sake of which the Ravenswood study was made, and in order to serve the purpose values of the lag must be known or assumed for each of many marsh-serving sloughs and for each of several classes of high waters and low waters. In developing a general scheme for the estimation of lags, those of overmarsh high waters were regarded as a class by themselves, but no distinctions were recognized between the lags of low waters and those of channel high waters. Large values were assigned to the lags of tropic higher high waters, because those belong to the overmarsh class; relatively small values were assigned to the lags of low waters; and the values for mean high water were made intermediate but nearer to the values for low water. (See fig. 29.)

The scheme adopted takes account of several other factors, and especially of the length of the slough, or rather of the mean distance along water routes from the slough entrance to all parts of the associated marsh tract. It was observed at the Ravenswood station that in a short tributary slough slack water was sensibly coincident with high water and occurred before slack water in the main slough. This phenomenon is believed to illustrate a general fact with reference to tidal marshes, that the lag of slack water at slough entrances is greater for long sloughs than for short; and it is connected with the general law that high water (or low water) and slack water are simultaneous at the head of an estuary but are elsewhere separated by an interval. Near the head the interval, or lag, increases with distance from the head, and in estuaries of moderate length—the class to which the marsh sloughs under consideration belong—the law of increase is probably continuous, so that the greatest lag occurs at the entrance. In an estuary of great length and uniform section—

a river channel—the theoretic limit or maximum value of the lag occurs, its measure being one-half of the period from one slack water to the next, or, on the average, three lunar hours.[1]

Under guidance of these general considerations the scheme has been so developed that

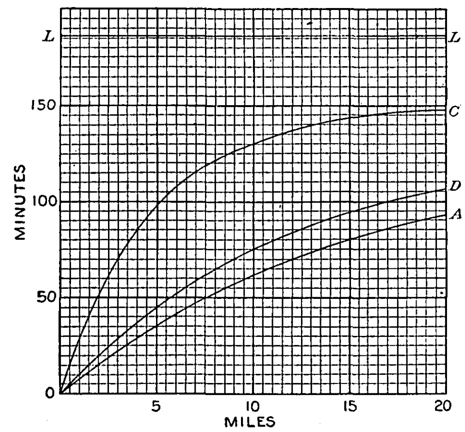


FIGURE 29.—Diagram used in estimating the lag of slack water after high water and low water at entrances to the sloughs that serve tide marshes. Vertical scale gives lag in minutes. Horizontal scale gives average distances in miles of a tide-marsh tract from the mouth of the slough serving it. Each curve corresponds to a group of high or low waters: *A*, Low waters; *D*, mean for all high waters; *C*, mean for tropic higher high waters. The line *LL* corresponds to the limiting value of lags, 186 minutes.

the assigned values of lag increase systematically with an element related to slough length but increase at a diminishing rate so as never to exceed three lunar hours (186 minutes). This scheme is embodied in a graphic table, which is reproduced in figure 29. The three curves of the diagram correspond severally to tropic higher high tides, mean high tides, and low tides. The ordinates represent values of the lag of slack water. The abscissas represent mean distance of the marsh tract from the slough entrance, or the mean radius of the tract from the entrance as a center. In order to conform strictly to the considerations stated in preceding paragraphs, the mean distance represented by the abscissas should be measured along lines of current, but such measurement was found impracticable, and the simpler measurement of right-line distance was substituted.

It is evident that the control afforded by the observational data, as well as by theoretic relations, is not rigid but admits great latitude in the drawing of the curves. Their form was somewhat influenced by some imperfect observations of the times of slack water in San Joaquin River at Antioch, and it was also influenced by the consideration that relatively large values of slack-water lag have been found to give relatively consistent results when used in the computation of tidal volume at the Golden Gate and other straits.

It is easy to see that the time of slack may be greatly modified by the discharge of land streams that are tributary to a slough. Stream discharge, by strengthening the ebb current, increases the lag of the low-water slack; by weakening the flood current it reduces the lag of the high-water slack and may even give it a negative sign. At the times of our observations the Ravenswood Slough received no discharge from the land.

[1] See Harris, R. A., U. S. Coast and Geodetic Survey Rept. for 1897, pp. 334, 343.

Appendix C.—COMPARISON OF SURVEYS OF THE BAR AT THE ENTRANCE TO SAN FRANCISCO HARBOR.

GENERAL STATEMENT.

There have been three comprehensive surveys of the bar outside the Golden Gate, all executed by the United States Coast and Geodetic Survey. The first, in 1855, was less detailed than the others. The second, in 1873, and the third, in 1900, were elaborate, each covering the area with a close network of lines of sounding. There was a less complete survey in 1884, and a small area, including the crest of the bar at the crossing of the main channel, was resurveyed in 1909. The various comparative studies mentioned below made use of the original plots and other manuscript data preserved in the archives of the Coast Survey.

The charts of 1855 and 1873 were compared by Lieut. Col. G. H. Mendell, United States Army, whose examination was part of an investigation of causes tending "to lessen the tidal scour on the bar of San Francisco and thereby decrease the depth of water on said bar." In his report, which was addressed (in 1881) to the Chief of Engineers, United States Army,[1] he says:

> We have two surveys of the bar—one made in 1855, the other in 1873. The latter is as full as could be desired. The former, while sufficient for the purposes for which it was made, is meager in its soundings. These two surveys have been placed on the same sheet, and corresponding sections have been plotted and compared. This study justifies the statement that the bar has not retreated, and that the depth on the crest has not been diminished. There are some indications of deposit on the inside, below the depth of 10 fathoms. Indeed, the indications are that the bar was smaller and the depth somewhat greater in 1873 than in 1855.
>
> The want of fullness in the first chart may fairly be held to throw some doubt on these latter indications, which on their face are not probable. It is thought, however, that the conclusion may be safely stated, that the bar was as good in 1873 as in 1855.

In 1884 Prof. George Davidson communicated to the Geographical Society of the Pacific the result of an elaborate comparison of the charts of 1855 and 1873 and expressed the general conclusion that "no perceptible change had taken place, or if there were it was in favor of better water."

An unpublished diagram (Boat sheet 2504) in the files of the Coast and Geodetic Survey shows a compilation of crest-line profiles by Nautical Expert J. T. Watkins, based on data from the surveys of 1855, 1873, and 1900. The profiles are longitudinal, each following the crest of the bar around its entire arc, and where the crest lines are not identical in position they are coordinated by means of radii from a point within the arc. Their combination in the diagram illustrates the fact that deposition and scour may take place on different parts of the bar at the same time, so that general tendencies are best shown by averages; and it also indicates that the character of the general change was not the same during the whole period from 1855 to 1900. From 1855 to 1873 the apparent general change was through deposition, the crest of the bar receiving an average addition of 0.48 foot, and from 1873 to 1900 the apparent general change was through scour, the crest suffering an average loss of 1.07 feet.

As both Mendell and Davidson, although quoted above with reference to the bar as a whole, gave special attention to the crest, there is a real discrepancy between their results and the result obtained by Watkins for the same interval of time, 1855 to 1873. This discrepancy is connected with the fact that Watkins applied corrections for changes in the plane of reference. All the soundings have for their zero "the plane of reference," which is the mean for the year of the lower of the two daily low tides. With progressive refinement in tidal observations and in the method of their reduction the accepted plane of reference has been changed from time to time; the plane used in 1855 was 1.0 foot lower than the plane now adopted, but the planes used in 1873 and 1900 differed less from the present plane.[2]

[1] Chief Eng. U. S. Army Ann. Rept. for 1881, pp. 2515-2524.

[2] Letter from the tidal division, U. S. Coast and Geodetic Survey, Jan., 15, 1909.

The survey of 1873 was regarded by both Mendell and Davidson as a trustworthy record of the condition of the bar at that time, and each of them recommended resurvey after an interval for the purpose of discovering changes. It is therefore probable that the surveys of 1884 and 1900 were followed by comparative studies, but if such were made I am not acquainted with them. The following paragraphs describe a comparison by myself of the charts of 1873 and 1900.

The two charts have the same scale, 1:20,000. They agree also in the fact that the records of soundings are in feet. Most of the soundings were made in linear series, and the lines were so arranged as to intersect one another at many points. Wherever the depth at the same point is given by soundings of two lines the two measurements were independent, having been made at different times. Thus the comparison of records at intersections affords a measure of precision so far as accidental errors are concerned. Such measures were derived from each chart for a tract where the depth is less than 5 fathoms and for another tract where the depth ranges from 10 fathoms to 16 fathoms. Table 43 gives averages of difference between two measurements of the same depth and also the corresponding probable error of a single measurement. It will be seen that the precision obtained in 1900 was somewhat higher than that obtained in 1873 and that the soundings in shallow water are notably more accurate than those in deep water.

TABLE 43.—*Precision of soundings in surveys of the Golden Gate bar.*

Year of survey.	Depth of water.	Number of intersections.	Average difference between two measurements.	Deduced probable error of a single measurement of depth.
	Fathoms.		*Feet.*	*Feet.*
1873	4–5	105	0. 84	±0. 5
1873	10–16	48	2. 08	±1. 3
1900	4–5	114	. 62	± . 4
1900	10–16	47	1. 56	±1. 0

For the purpose of comparison the area covered by the charts was considered in three divisions—northern, middle, and southern. (See fig. 30.) The northern division includes the 4-fathom bank and its surrounding slopes but not the Bonita Channel. The middle includes one-third of the crest of the bar, with the somewhat troughlike channel lying between this and the strait; it is limited outside by the 10-fathom contour and inside by the 16-fathom contour. The southern includes the remainder of the bar crest, with its expansion into a broad bank at a depth of about 6 fathoms, but does not include the South Channel. Their several areas are about 10, 16, and 18 square miles.

In comparing one chart with the other two methods were employed—a method of contours, adapted to definite slopes, and a method

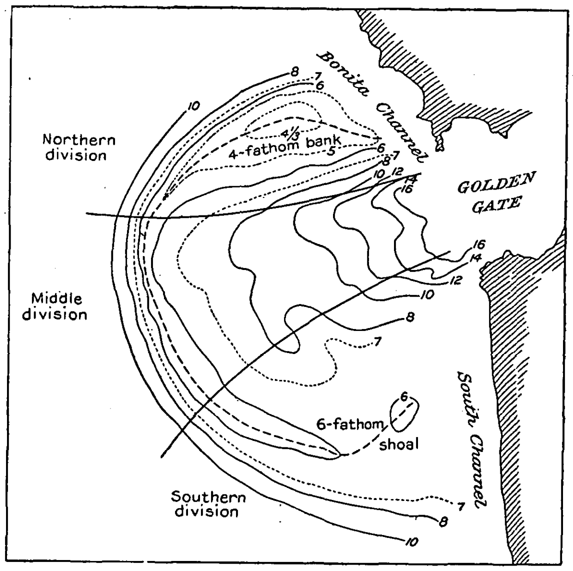


FIGURE 30.—Plan of the Golden Gate bar, showing the divisions referred to in the text. The full-line contours have an interval of 2 fathoms; intermediate contours are dotted. All contours are based on the survey by the United States Coast and Geodetic Survey in 1900.

of small tracts, adapted to surfaces of small or indeterminate slope. As a matter of record it seems desirable to describe these methods.

Each of the "hydrographic sheets" bears contour lines that were drawn by hydrographers of the Coast Survey and used in the preparation of the generalized charts of smaller scale for the information of navigators. For the security of navigators it is important that the indication of depth be not too great, and this consideration determined the rule that each contour for a particular depth should pass either through or below all points where that depth was measured and below all points where a less depth was measured. Because of the accidental errors of the measurements the application of the rule makes the contours represent the minimum possible depth instead of the most probable depth, and they misrepresent the depth by an amount which is greater as the discordance of measurements is greater. Because that discordance was greater in 1873 than in 1900 such contours tend to show somewhat smaller depths in 1873 than in 1900. It is evident that for the estimation of changes in the configuration of the bar it is better to use contour lines that represent for each date of survey the most probable positions of the actual lines of equal depth. These were attempted in the following manner: A sheet of tracing paper was laid over one of the hydrographic sheets and its position was established by elements of the projection. A depth was selected for contouring—for example, 8 fathoms, or 48 feet. Each line of soundings which included depths both greater and less than 48 feet was then examined. If one of its soundings showed exactly 48 a mark was made at that point. If a consecutive series of soundings bore the number 48 a line was drawn through those points. If the number 48 did not appear, but adjacent numbers were the one greater and the other less, a mark was made at the interpolated position of 48 feet depth. When this work had been completed there appeared on the tracing paper a series of marks, each of which contained the information afforded by a line of soundings as to the position of the 8-fathom contour. Usually these marks were found not to fall absolutely in line but to occupy a belt, the belt being narrow in a region of steep slopes and wider in a region of low slopes. Within this belt the contour was then drawn as a line of simple flexure, the several marks of the belt being regarded as observations of equal weight. By the same process contours for other depths were then drawn, and a series of contours for corresponding depths were prepared on a second sheet of tracing paper from the soundings of the other hydrographic sheet. The contours thus drawn were, for the outer slope of the bar, the 6, 8, and 10 fathom; for the inner slope, the 6, 7, 8, 10, 12, 14, and 16 fathom; and about the 4-fathom bank, the 5-fathom.

One transparent contour sheet was then placed over the other and adjusted by means of the projection lines, when changes in contours between 1873 and 1900 became apparent. Measurements were then made of the spaces through which contours had moved, slopes were computed from the vertical and horizontal relations of contours on the same sheet, and from these results the vertical changes in the configuration of the bar were computed.[1]

For regions of very gentle slope, mainly summit regions, where the contour method breaks down, corresponding small tracts were marked out on the transparent contour sheets, the sheets were placed in position over the hydrographic sheets, and a mean depth for each of the tracts was computed from the sounding records appearing within its boundaries. A separate mean was obtained for each line of soundings, and the mean of these means was taken to represent the tract. Thus each line of soundings was given the same weight, without reference to the number of individual soundings it contained within the tract. Each tract on the average included data from 7 lines of sounding, the number ranging from 4 to 10. On the 6-fathom shoal of the southern division of the bar there were 42 equal tracts, each representing a square 1,667 feet on a side, with an area of about one-tenth square mile. After their mean depths of sounding had been plotted the 6-fathom contour line was drawn through their district. On the higher part of the 4-fathom bank there were 18 such tracts, and when their mean depths had been plotted a contour line was drawn for the depth of 26 feet.

Another system of tracts was arranged to include the crest line of the bar so far as the approximate position of the crest could be seen. These tracts were trapezoidal, with approximately equal lengths (about 3,300 feet) in the direction of the crest line but with unequal widths, being narrowest where the crest is best defined by the soundings. As the crest did not have the same position at the time of the two surveys the lines of the tracts on the two oversheets were not identical. They were coordinated by means of radial lines, a method of coordination employed by Watkins in his study of crest lines.

To all sounding data of the earlier chart I applied a general correction. In the original reduction of the observed depths allowance was made for the difference in level between

[1] The computations were in fact less simple than as here described. It was necessary to take account of a general correction to the soundings of 1873, described in a later paragraph.

the water surface at the time and place of sounding and an ideal plane, the plane of reference. The level of the plane to which soundings were referred in 1873 was not the same as the level afterward adopted. It appeared also from a critical examination of the records, made at my request by the section of tides and currents of the Coast Survey, that the treatment of fractions of feet was not the same in 1873 as in 1900. Because of these two differences in the treatment of the observations the soundings plotted on the chart of 1873 were not directly comparable with those on the chart of 1900 but needed a correction of −0.6 foot, and that correction was accordingly applied.

The results of the comparison are given below.

NORTHERN DIVISION.

The crest of the 4-fathom bank had substantially the same position in 1900 as in 1873 but was lower. Of the 18 square tracts separately compared in that region the five showing shallowest water gave the following mean depths:

TABLE 44.—*Comparison of mean depths (in feet) of water on 4-fathom bank, 1873 and 1900.*

	1	2	3	4	5	Mean of five.
Depth in 1873	24. 0	24. 9	24. 5	24. 5	25. 2	24. 6
Depth in 1900	25. 3	24. 5	25. 1	25. 4	25. 3	25. 1
Change in depth	+1. 3	− . 4	+ . 6	+ . 9	+ . 1	+ . 5

The mean for the 18 tracts is a gain in depth of 0.9 foot. On the marginal slopes of the bank, both inward and outward, there was a net gain in depth, so that on the whole that part of the bar became narrower. The estimated mean gain in depth for the whole division is 1.2 feet.

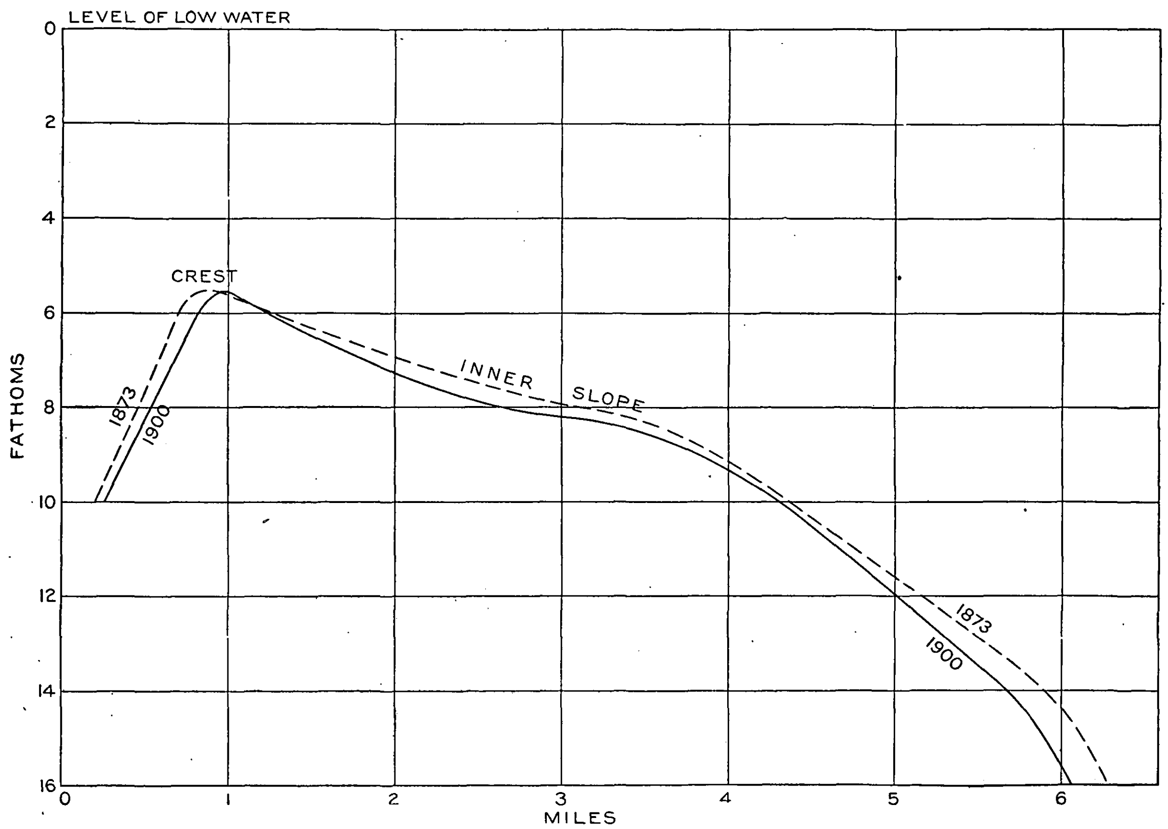


FIGURE 31.—Generalized cross profiles of the Golden Gate bar in its middle division.

MIDDLE DIVISION.

In the discussion of data of the middle division use was made of generalized cross profiles, the first to be drawn being that for 1873. (See fig. 31.) The chief data for this profile are (1) the mean distances between contours as measured on the oversheet (see Table 45) and

(2) the mean depth of water on the crest, 32.5 feet. The position of the 8-fathom contour of the inner slope is less definite than the positions of other contours because of a sigmoid inflection. In the northern part of its course the line runs parallel to other contours, but at the south it is turned back on itself to outline a subaqueous spit. The shoulder appearing at this level in the profile represents a compromise between the continuous slope at the north and the interrupted slope at the south. The mean distances through which contours migrated between 1873 and 1900 (see Table 45) were then used to plot points of the profile for 1900, and the profile was drawn. The vertical spaces between the profiles show gain or loss in depth. On the inner slope close to the crest (of 1873) there was a small loss in depth but everywhere else a gain. Amounts of gain are shown in the table. In computing the mean change for the whole division, 2.1 feet, account was taken of the form of the tract, which is relatively broad toward the ocean and narrow toward the Golden Gate.

As each contour line drawn represents a compromise between the indications of position given by different lines of sounding, the distances of the indicated positions from the line afford a rough measure of precision, and they were used to compute the probable errors in position of the contours. No refinement is possible because the bendings ascribed to the contours are necessarily a matter of judgment. The measures of precision have most meaning for the contours of the outer slope, the courses of which are relatively simple. From the probable errors of the contours were derived the probable errors of the estimates of horizontal change, and also, with allowance for other factors that need not be specified, the probable errors of the estimates of vertical change.

The general features of the indicated changes are (1) erosion of the outer slope, the loss amounting to several feet; (2) a slight lowering of the crest; (3) the migration of the crest line toward the land, the distance traversed being several hundred feet; and (4) the erosion of the inner slope, the loss being greatest on the lower part of the slope.

TABLE 45.—*Changes in the middle division of the Golden Gate bar, 1873 to 1900.*

Contour.	Distance from next contour at west.	Direction of horizontal change.	Amount of horizontal change.	Gain in depth of water.
	Feet.		*Feet.*	*Feet.*
10 fathoms, outside		Landward	330±40	3.0±0.4
8 fathoms, outside	1,380	do	430±30	4.0± .5
6 fathoms, outside	1,290	do	650±30	6.2± .4
6 fathoms, inside	2,820	Oceanward	20±60	.2± .2
7 fathoms, inside	4,230	do	1,250±100	1.7± .2
8 fathoms, inside	5,400	do	2,100	1.6
10 fathoms, inside	6,950	do	360±100	1.0± .4
12 fathoms, inside	4,230	do	850±100	2.8± .6
14 fathoms, inside	3,860	do	1,200±120	5.0± .7
16 fathoms, inside	2,080	do	1,200±100	8.6±1.5
Mean for whole division				2.1± .2

SOUTHERN DIVISION.

Over the broad 6-fathom shoal, which is a prominent feature of the southern division, there was a general gain in depth. For the 42 square tracts separately compared, the average gain was 1.7 feet, and for the squares showing least water the average gain was 2.0 feet. There was also a narrowing of the shoal, the outside contours moving toward the Golden Gate and the inside contours moving from the Golden Gate. The estimated gain in depth for the whole division is 1.6 feet.

THE TOP OF THE BAR.

The assumption usually made in the interest of safe navigation, that the crest-line depth is the least of the reported soundings, must in general give results in depth which are too small; errors of defect are included, and they are not offset by errors of excess. The method of the present comparison involves the untenable assumption that the mean depth for an area including the crest line is also the mean depth on the crest line and evidently must in general give results in depth which are too great. The second assumption is here preferred because its errors presumably affect the estimates from the two charts equally and therefore do not affect the differences, which are the quantities sought; whereas the first-mentioned assumption presumably affects estimates from the two charts unequally.

The chain of trapezoidal tracts described on page 141 started at the landward end of the 4-fathom bank, followed the crest through the northern and middle divisions of the bar area, and threw three of its links into the southern division. It could not well be carried farther because of the great difficulty of tracing the course of the highest line across the 6-fathom shoal, and estimates for the remaining five links were based on data of the square tracts.

A generalized longitudinal profile of the crest is shown in figure 32, with indication of the more important changes between the dates of survey; and the depths for the several tracts, with the changes in depth, appear in Table 46. The tracts are also grouped with reference to the three general divisions of the bar area. The indicated changes are least in the middle division and greatest in the southern division.

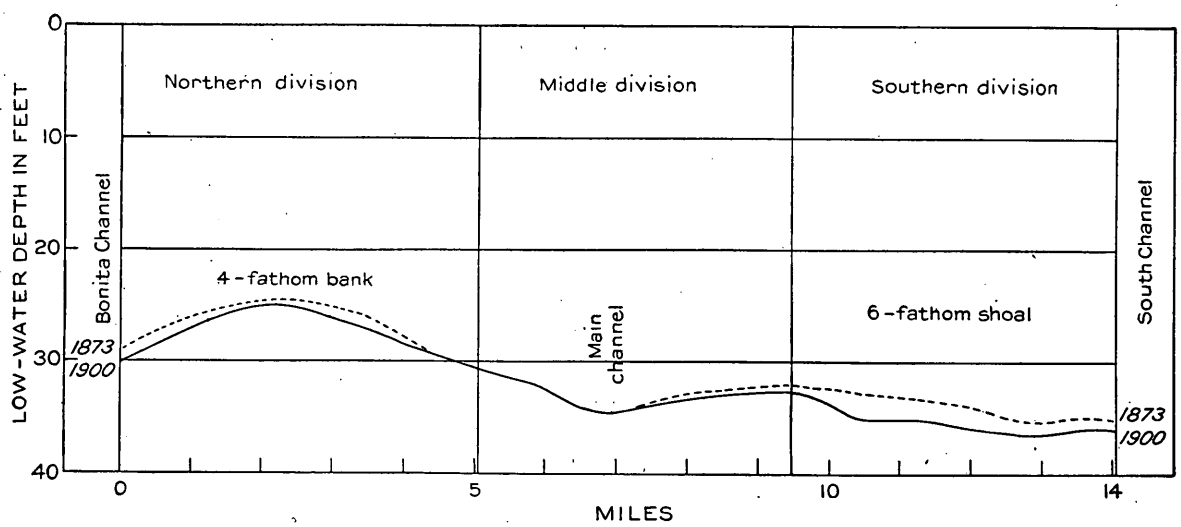


FIGURE 32.—Longitudinal profiles of the Golden Gate bar in 1873 and 1900.

TABLE 46.—*Estimates of mean depth of water on crest-line tracts of the Golden Gate bar in 1873 and 1900.*

	No. of tract.	Mean depth, 1873.	Mean depth, 1900.	Change in depth.	Mean gain for division.
		Feet.	*Feet.*	*Feet.*	*Feet.*
Northern division (4-fathom bank)	1	27.9	29.1	+1.2	+0.8
	2	25.7	27.2	+1.5	
	3	25.3	25.6	+ .3	
	4	24.4	25.0	+ .6	
	5	24.4	25.7	+1.3	
	6	25.8	27.3	+1.5	
	7	28.1	28.0	− .1	
	8	29.8	30.0	+ .2	
Middle division	9	31.3	30.9	− .4	+0.3
	10	31.4	32.1	+ .7	
	11	34.5	34.5	0	
	12	33.7	33.9	+ .2	
	13	32.4	33.2	+ .8	
	14	32.0	32.7	+ .7	
	15	32.7	32.7	0	
Southern division	16	32.0	32.8	+ .8	+1.7
	17	32.6	35.2	+2.6	
	18	32.4	35.0	+2.6	
	19	33.9	35.5	+1.6	
	20	34.0	36.5	+2.5	
	21	35.5	36.4	+ .9	
	22	34.8	35.8	+1.0	
General mean	....	....	....	....	+ .9

MIGRATION OF THE CREST LINE.

The revelation, by the generalized profiles of the middle division of the bar, that the crest line lay farther east in 1900 than in 1873 led to a special study of changes in the position of the crest line, a study including the interval of 45 years, from 1855 to 1900.

The process of running a line of soundings is such that certain classes of errors, and especially the errors connected with reduction to mean low water, do not affect in an important way the differences between the individual soundings. The differences are, as a rule, less in error than the soundings themselves. For this reason a single line of soundings which crosses the bar crest, although of low precision as a measurement of the height of the bar, may show the position of the crest line somewhat definitely. In the study of the crest line with reference to horizontal position, a profile was constructed from each available line of soundings, the position of the summit was inferred from the profile, and the crest-line points thus determined were then plotted in proper horizontal relation.

The method could be used to advantage only where the crest line has the most definite expression, and it was actually applied to about 3 miles of the bar, running south from the 4-fathom bank. In that region the crest line of 1900 was mapped by the data from 13 lines of soundings, and the line of 1873 by data from 15 lines. Six points on the crest line of 1855 were determined, but they did not suffice for the drawing of the line. By reference to figure 33, where the lines and points are mapped, it will be seen that the line for 1873 is everywhere west of the line for 1900, and that all determined points of the crest in 1855 lie west of the lines for later years. The lines determined for 1873 and 1900 overlap for a distance of 2.3 miles, and in that space the average movement of the crest toward the Golden Gate was 465 feet. Four of the crest points of 1855 can be compared with the crest line of 1873, and their average distance, measured on lines toward the Golden Gate, is 425 feet. Three of these points and one other can be compared with the crest line of 1900, and their average distance from that line is 1,125 feet. If the sum of 465 and 425 feet is taken to represent the whole shifting in 45 years, the average annual movement is 20 feet. With 1,125 feet as the dividend, the estimate of average annual rate is 25 feet.

SUMMARY OF CHANGES.

Between 1873 and 1900 there was a general gain in depth of water over the whole area of the San Francisco bar, including not only the region of the crest but the inner and outer slopes. Of 22 tracts into which the crest belt was divided for the purpose of comparison, only two showed loss of depth—0.1 foot and 0.4 foot,

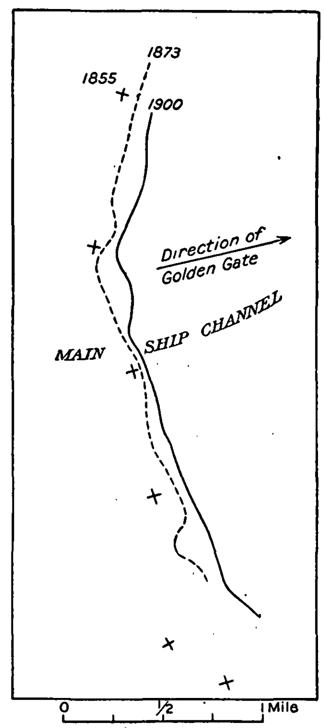


FIGURE 33.—Plan showing positions of the crest of the Golden Gate bar in 1855, 1873, and 1900. The full line gives the profile in 1900; the broken line in 1873; the crosses in 1855.

respectively—while the greatest gains were of 2.6 feet, and the average gain was 0.9 foot. The change in depth was small in the vicinity of the main ship route, a locality where the crest belt is exceptionally narrow, and the region of greatest change was the broad shoal into which the crest expands in approaching the South Channel.

Above the outer slope of the bar there was a general gain in depth of several feet; the gain was greatest in the middle division and diminished thence in both directions. Above the inner slope the gain in depth was probably general, although a few points bordering the 4-fathom bank appeared to show loss. The region of greatest gain was that of deepest water, the amount increasing from 2.8 feet at the 12-fathom line to 5.0 feet at the 14-fathom line and 8.6 feet at the 16-fathom line.

The average gain in depth for the northern division was 1.2 feet, for the middle 2.1 feet, for the southern 1.6 feet, and for the whole area compared 1.7 feet. That area is a tract of about 44 square miles, but does not include the entire bar, being limited in two directions by the limits adopted for one of the surveys. It does, however, include nearly the whole of the bar, so that the product of 1.7 feet by 44 square miles gives approximately the volumetric change in the bar. That product is 2,100,000,000 cubic feet, or 77,000,000 cubic yards.

The outer slope of the bar was moved landward through a space of several hundred feet. The inner slope was moved seaward through a space which, on the average, was about the same, but was much greater at low levels than at high. The crest line was moved landward, the change amounting to nearly 500 feet in the middle division and being less on the 4-fathom bank.

The crest line was also moved landward in the interval from 1855 to 1873, and in this earlier interval of 18 years the space transgressed was about the same as in the later interval of 27 years.

ACCIDENTAL ERRORS.

The accidental errors of the hydrographic surveys, the errors which tend to cancel out in the taking of averages, are probably fully represented in the discrepancies that appear where lines of sounding intersect. Each of those discrepancies is a difference between the indications given by two lines of sounding at their common point. As lines of sounding, instead of individual soundings, were used in all the comparisons of one chart with another, the checks at intersections may properly be used to measure the general accuracy of the results of comparison so far as that accuracy is affected by accidental errors. Probable errors corresponding to certain groups of intersection differences are given in Table 43 (p. 140). The probable error of a line of soundings in 1873 was for shallowest water 0.5 foot, for deepest water 1.3 feet. The half-sum of these, 0.9 foot, may be taken to represent the average probable error of a line of sounding made in 1873. Similarly 0.7 foot, the half-sum of 0.4 foot and 1.0 foot, may be taken as the average probable error of a line of soundings in 1900. When a change in depth at any point is inferred from a comparison of a sounding in 1900 with a sounding in 1873, the probable error of the inferred change is (on the average) $\sqrt{0.9^2+0.7^2}$ feet $=\pm 1.2$ feet. For a result which is a mean of n such inferred differences the probable error is $\pm\frac{1.2}{\sqrt{n}}$ feet. The use of this formula gives ± 0.4 foot as the average probable error of the computed change in depth in one of the small tracts by means of which the shoaler parts of the bar were compared. For the probable errors of the results for several of these tracts estimates were made also by an independent method, and similar values were obtained.

The formula is not strictly applicable to the results of comparisons made by the method of contours, because the mode in which vertical changes were inferred from horizontal changes involved errors of independent character. The formula gives for the probable error of the mean gain in depth for the middle division a value less than ± 0.1 foot, and though this value is surely too small, it serves in a measure as a check on the value ± 0.2 foot given in Table 45, which was deduced in a different manner.

The estimate of average gain in depth in the southern division, depending largely on the estimates for 44 small tracts, has a probable error of about ± 0.1 foot. The estimate of average gain in depth in the northern division is less trustworthy, and a probable error of ± 0.3 foot is assigned without any attempt at actual computation. For the most general result, that the gain in depth over the entire bar had an average value of 1.7 feet, the probable error is thought to be not greater than ± 0.2 foot.

SYSTEMATIC ERRORS.

Systematic errors, or such as are always or dominantly affected by the same sign, do not tend to cancel out in the taking of averages and are not covered by the computed "probable error." There is no royal road for the discovery of the existence of such errors; they become known only through the method of hypothesis and test. Having undertaken the comparison of charts because of the supposed flow of hydraulic mining débris to the bar, I was not prepared to find the later chart showing a gain in depth of water, and when that result developed I was led to suspect the existence of a systematic error. My search for such an error was handicapped by lack of personal familiarity with methods of hydrographic surveying, but I was able to avail myself of the expert knowledge of the officers of the Coast Survey.

The method by which the horizontal relations of points of sounding were determined was the same in both surveys and seems adequate. It is true, moreover, that systematic errors in position could not account for the more important of the unexpected results of the comparison of charts.

So far as appears by the record the method of sounding was the same on both occasions. It is a method so long established as to have been taken as a matter of course and therefore not specifically described in the printed code of instructions to hydrographers which was in force at the time of the two surveys. The sounding line should be vertical at the moment when the depth is read, and the tension should be such as to hold the oblong leaden weight vertical. If the line is oblique or curved, or if the lead lies on its side upon the bottom, the observation gives a depth too great. In case leadsmen were more faithful and efficient in one survey than the other the differences with which we are concerned might be affected in a "systematic" way.

An attempt to investigate this point was based on the fact that it is specially difficult to bring the line to the vertical position when the course of the moving boat is crossed by the direction of a strong current, and upon the further fact that errors from obliquity of the line are proportional to the depth. There is a tract of deep water inside the arc of the bar where the direction of the stronger currents is known; they are either toward or from the strait. On each chart one set of lines of sounding runs nearly parallel to the direction of the current, while another set crosses nearly at right angles. If full precautions for verticality were not taken the chief errors would presumably occur on the crossing lines, and those lines would show the greater depths at the intersections. On the chart of 1873 I found within this tract 11 intersections where the greater depth was recorded in crossing the current and 14 where the greater depth was recorded in following the direction of current. The sum of differences was 41 feet for the first-mentioned group and 40 feet for the second. On the chart of 1900 I found 26 intersections with greater recorded depths on the cross-current lines and 15 with greater depths on the along-current lines. The corresponding sums of differences were 57 feet and 23 feet. The average excess of depth obtained on the cross-current lines was in 1873, 0.0 foot; in 1900, 0.7 foot. While the data thus assembled are not so full as to yield a positive conclusion, their indication is that precautions for verticality were less successful in 1900 than in 1873, and in that event the exaggeration of depth was greater in 1900 than in 1873. I am disposed to question the value of this indication, because the same data show the average discrepancy at intersections, without regard to sign, to have been 3.0 feet in 1873 and only 1.5 feet in 1900. The fact that the leadsmen of 1900 checked their work better at intersections does not sustain the inference that they were less successful in securing verticality.

The water surface above the bar is subject to regular oscillations of at least three kinds—tides, ground swell, and the waves created by the existing wind. In the work of sounding the ground swell is usually ignored, but the resulting error is of the accidental type and does not affect averages. Wind waves are not ignored; the leadsman endeavors to eliminate their effect by referring each sounding to an ideal plane—the level of the water if not disturbed by wind. This is a matter of judgment, and it is to be supposed that each leadsman has in regard to it a personal equation. It is possible also that the personal equation of the chief of party influences the practice of the leadsmen whose work he directs. There is thus a distinct possibility of systematic error in the treatment of wind waves, although the magnitude of the possible error can hardly be more than a small fraction of a foot.

The effects of the tidal oscillation received elaborate attention at the time of the surveys, a correction being applied to each record of sounding for the vertical difference between the plane of reference and the height of the water surface at the time and place of sounding. The local and temporary height of water surface was inferred from observations at tidal stations at the shore, due allowance being made for the fact that like phases of the tide occurred earlier at the sounding stations than at the tidal stations. Unfortunately the methods of accomplishing this were not identical for the two surveys. The tide stations were differently placed, the planes of reference were different, and there were differences of detail in the mode of applying the tidal data to the reduction of the observations. As mentioned in an earlier paragraph, this subject received critical attention from a tidal expert of the Coast Survey, with the result that −0.6 foot was applied as a correction to the charted soundings of 1873. Of this correction −0.4 foot pertains to the plane of reference and −0.2 foot to the method of reducing the observations.[1] These corrections, though evidently proper, do not necessarily cover all sources of error. The tidal correction is so large, ranging from zero to 6 or 7 feet, that minor differences in the mode of its derivation may have noteworthy influence.

This review of the principal factors recognized as possible sources of systematic error does not encourage the belief that the apparent gain in depth from 1873 to 1900, a gain having an estimated average value for the whole tract of 1.7 feet, is illusory. It is true that the failure to discover adequate sources of systematic error has the character of negative evidence, but there is also evidence of more positive character tending to show the verity of the apparent gain.

Mention has already been made (p. 143) of a submerged spit running northward from the flank of the 6-fathom shoal and causing an S-shaped inflection of the 8-fathom contour. The spit is shown by that contour on both charts but not in the same position. In 1900 it was farther west than in 1873, its change of position harmonizing with the general change of position of the 8-fathom line. On the assumption that the spit is a permanent detail of the inner slope of the bar and is associated in a causal way with a particular depth, its movement is confirmatory of the general inference that the inner slope was moved outward between 1873 and 1900.

If the apparent general gain in depth were apparent only, the appearance being caused by a systematic error affecting all soundings of one survey by 1.7 feet, the application of the proper correction would still leave great changes in the bar to be accounted for. It would then appear that the bar crest, all through its acute portion, had grown toward the water surface, that several feet of sand had been eroded from the outer slope, and that there had been great erosion from the lower part of the inner slope, the depth of scour averaging 7 feet at the 16-foot contour. To my understanding it is no easier to explain a loss of substance by the lower slopes of the bar accompanied by a gain on the higher parts than to explain a general loss of substance which is greater on the slopes than on the crest. The question of explanation, however, is outside the scope of this appendix; it is considered in Chapter IX of the main text.

Only a small part of the preceding discussion of errors applies to the estimates of horizontal migration of the bar crest. The method by which those estimates were reached is one that furnishes no data for the computation of probable error. A possible source of systematic error lies in the triangulation that gave horizontal control to the hydrographic mapping, but the same triangulation controlled also the mapping of the shore, and the agreement of shore features seems to afford a satisfactory check. A recognized source of error lies in the selection of the position of the summit on a profile line drawn among plotted points not altogether harmonious. That is a matter of judgment, and judgment may be subject to personal equation and bias. As all the profiles were drawn in the same half-day they were presumably affected by the same personal equation. To guard against unconscious bias I plotted the three crest lines independently on separate sheets, and computed that part of the work before bringing them together in the drawing from which figure 33 is copied.

[1] The basis of these corrections is given in a memorandum by R. A. Harris, attached to a letter dated Feb. 7, 1916, from the Superintendent of the United States Coast and Geodetic Survey to G. K. Gilbert, and a copy of the letter and memorandum are on file in the office of the Coast Survey.

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