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(*Translated from the French and abridged.*)

"Estuaries."

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Estuaries are inlets on or near the sea-coast, containing banks which the tides successively cover and lay bare. They may be divided into two classes, namely: (1) Estuaries devoid of rivers; and (2), Estuaries into which rivers flow. Each of these classes, moreover, may be sub-divided into estuaries expanding to a wide outlet into the sea, and estuaries with a narrow outlet, formed either naturally by banks or the land, or artificially by protecting breakwaters.

1. Estuaries devoid of Rivers.

Funnel-shaped Estuaries.

These estuaries are generally found in the indentations of the coast, and vary considerably in form and extent. The materials which encumber them are brought in by currents and waves, or are formed on the spot by the erosion of the coast, and the gradual disintegration of this detritus. The rate of travel of these materials along the coast depends on the frequency and direction of the winds in the locality.

Formation of an Estuary.—Where an inlet exists on the coast, the waves tend to fill it with the shingle and sand they bring in; and a little estuary is thus formed in this creek. If the obliqueness of the prevailing winds is great enough, and the duration of winds normal to the coast small, the advance of the sandy beach closes the estuary before it is filled up. Being thus completely shut off from the sea, it is converted into a marsh, of which the marshes at Cayeux, near the mouth of the Somme, are instances. If the line of beach does not quite close the entrance, but leaves a passage for the tides, it protects the estuary, and forms a narrow outlet.

Dunes.—Besides the materials eroded from the coast, the waves carry along alluvium brought down to the shore by rivers; and often also the sea casts up sand from its bed, of which the coast of Gascony exhibits a striking instance. There the sandy bed of the ocean rises with a gentle slope towards the shore; and the waves raised by the prevailing westerly winds cast the sand upon the shore, and the winds in their turn drive it inland. This is the origin of the long line of dunes which extend from the Gironde to Biarritz; and the shore, which was formerly intersected by numerous creeks, has now a straight line of sandy beach, 138 miles in length, which, under the influence of north and north-westerly winds, has closed the bays before they were silted up. These bays, into which only small streams flow, have consequently become pools and marshes, Fig. 1, Plate 4. The bay of Arcachon, however, into which the little river Leyre discharges, has become an estuary whose outlet is nearly closed by the shore-line. The sands had begun to fill up this vast bay, and the winds had formed some dunes near Andernos; and the travel of the sands along the shore, after pushing the outlet $3\frac{3}{4}$ miles to the south of Arcachon, has left this bay, which has a width of $6\frac{1}{4}$ miles, an opening into the sea only 1,100 yards wide. The dunes formerly progressed slowly inland like waves, invading the land and burying whole villages. Their progress was arrested at the beginning of the century, by fir plantations; but more recently Mr. Chambrelent succeeded in stopping the sand in front of the first dune, by forming a palisade of upright planks, with intervals of an inch between them, at the toe of the dune, about 400 feet from high-water mark, which are raised by a lever as the dune rises against them, till, when the height of the dune attains 26 to 32 feet, this height and the steepness of the slope cause the sand to fall back towards the shore, where the winds drive it back into the sea.[1] Thus an artificial dune is formed, with its steepest slope facing the sea, the reverse form to natural dunes. Sands mixed with silt or clay, being less affected by wind, do not form dunes.

Filling up of Funnel-shaped Estuaries.—Funnel-shaped bays, devoid of rivers, and exposed to the inroad of sand, gradually fill up, the rate of accretion depending on the amount of sand provided by the coast or the bed of the sea. The deposit results from the slackening of the flood-tide in the bay on encountering any bank or the shore; and the bank or shore gradually extends seawards, this accretion taking place at the expense of banks nearer the sea, or actually in the sea. The silting up of the inner part of the bay entails eventually a shoaling of the lower part, and a reduction of the tidal water entering the bay, by which the depth of its channels and outlet have been maintained. Reclamations in the estuary produce the same results; and, therefore, artificial accretions at the mouth and in the tidal portion of rivers should be rarely

[1] "Les Landes de Gascogne," M. Chambrelent, Paris, 1887, pp. 92–94.

undertaken, and only with the utmost caution. The estuary of the Wash, and Vays Bay and Mont St. Michel Bay on the coast of Normandy, furnish examples of silting up.

Estuaries with Narrow Outlets.

The narrow opening, or neck, through which the tide enters some estuaries, may be very short, as at the mouth of the Gironde and of the Foyle, or may have a certain length, as in the Tagus and the Mersey. These estuaries would be exposed to the same external influences as the open estuaries just considered, if they were not protected by the narrowness of their outlet, which protection is attended by very important benefits to navigation.

Effect of a Neck.—All the water flowing in and out of these estuaries is obliged to traverse the neck; and instead of spreading out over a wide outlet, where the water which does not flow through the channel is lost to navigation, it is concentrated into a single passage, and, consequently, acts more powerfully on the bar and deepens the channel. These estuaries, moreover, are more sheltered from storms, for the waves are almost wholly stopped outside; whereas funnel-shaped estuaries are favourable to their propagation, and increase their height. The waters, also, at the farthest end of the estuary, reaching the neck near the end of the ebb, have a great effect in maintaining the depth of the channel. These advantages give a decided superiority to restricted outlets; whilst observation further demonstrates that deep channels exist both above and below the neck for a considerable distance. Thus the Jade estuary, in North Germany, with a length of about 10 miles and a width of $9\frac{1}{3}$ miles, has an outlet of only $3\frac{1}{10}$ miles, having a depth of 65 feet, the rise of tide at the mouth being $12\frac{3}{4}$ feet at springs, Fig. 2, Plate 4. Three channels stretch into the estuary inland of the neck, one having a depth of 33 feet for $4\frac{1}{3}$ miles, and the other two being $16\frac{1}{2}$ feet deep for about $1\frac{1}{8}$ and $2\frac{1}{3}$ miles respectively; whilst below the neck, a channel $17\frac{1}{2}$ miles long, with depths of from 33 to 82 feet, extends out to the sea. Poole harbour, on the south coast of England, has a length and width of $9\frac{1}{9}$ miles, and an entrance about 1,000 feet wide, with a rise of tide of only $6\frac{1}{2}$ feet at springs outside, Fig. 3. There are three inner channels, having depths of 10 feet for $3\frac{3}{4}$, $3\frac{1}{9}$, and $1\frac{2}{3}$ miles respectively, and an outer channel, $1\frac{1}{3}$ mile long, with depths of $16\frac{1}{2}$ to 39 feet, obstructed by a bar at its extremity having a depth of barely 8 feet over it at low tide. The bay of Arcachon on the French coast, and of San Martino on the coast of

Portugal, as well as the estuary of Mikindani on the east coast of Africa, furnish similar examples. The formation of these channels, above and below the neck, may be traced to the following causes:—The increased speed of the current through a narrow neck, at the outlet of an estuary with a sandy bed, creates a deep hollow, leading into which the ebb, having drawn the sands from above which are unable to remain in the hollow, has gradually formed a channel in the estuary; and the flood-tide has similarly formed a channel below the neck. The sands thus carried along create banks inside and outside the estuary, which in estuaries devoid of rivers, tend to attain a state of equilibrium, undergoing very little change. The lengths of the deep channels, above and below the neck, are greater in proportion as the water flowing from each channel is larger in volume, and the neck deeper. Consequently, a vast estuary, especially if reinforced by the large tidal capacity of a river up which the tide flows for a long distance, augments the discharge above the neck during the ebb, and aids the deepening of the inner channels and the maintenance of the estuary. Below the neck, tides with a large range are especially favourable for forming the outer channel, and for maintaining a pass over the bar. The correctness of the foregoing explanation is rendered more probable by the consideration that the ebb and flood waters, on issuing from the neck, must rapidly lose their velocity in spreading over great widths, and therefore can then have only a feeble scouring action on the channels, which is confirmed by observation. Thus Mr. Guérard has stated that the depth of water over the bar at the mouth of the Rhone is to some extent independent of the discharge of the river.[1] Similarly, during the progress of the Seine training-works, it was found that the current issuing from the trained channel had little effect on the banks in front of the outlet. The velocity, also, of the flow over the bar of the Mersey is very small, and does not scour the sand of which the bar is formed; whereas the currents in the neck in front of Liverpool have an average velocity of 5 to 6 knots an hour during springs, so that the scour must be increased as the neck is approached. The inner and outer slopes of the bar, moreover, are steeper than those which a similar embankment would assume elsewhere; for, owing to the small quantity of alluvium brought down by the Mersey, the slopes of the bar and of the channel are those of cuttings excavated by the currents. The

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[1] "Amélioration de l'Embouchure du Rhône," A. Guérard, Congrès de Navigation intérieure. Paris, 1892, p. 34.

Author has also pointed out elsewhere [1] that, in the tidal Garonne, the hollows which are formed alongside a projection in the bank, causing a reduction in the width of the channel, are due to the ebb above the point, and to the flood below, otherwise the hollow which follows closely the curve of the projecting bank both above and below the point, would diverge from the bank on each side of the point if the scour was owing to the impulse given to the currents beyond the point by the narrowing of the river. It is therefore certain that contractions in tidal rivers produce their effects above, in relation to the direction of the current, rather than below, and that these effects depend on the rise of tide. It also follows that the effects of necks, as described above, should be visible along the whole course of tidal rivers, and in tideless rivers should be propagated above similarly to below, which observation appears to demonstrate. Beyond certain limits the influence of the neck upon banks in the sea necessarily ceases.

The coarser and heavier portions of the sand brought into the neck by the flood-tide stop in this channel, and are carried seawards again by the ebb; whilst the finer particles are carried on to the banks; and there the small waves put them again in suspension, so that they are drawn into the channel by the ebb currents, and return to the sea with the coarser sands during the ebb-tide. This explains how Arcachon bay, Poole harbour, and other estuaries are maintained, in spite of the abundance of sand which surrounds their entrances. The height of their banks depends upon the depth at which the little waves inside lift the sand, and on the currents which pass over the banks. The sands transported as above described settle outside the neck, on the sides of the outer channel. The channels branch out in estuaries devoid of rivers, generally extending close to their shores. In estuaries into which a river flows, an inner bar is sometimes found above the channels, as for instance in the Gironde and the Foyle, Figs. 13 and 15, Plate 4; but this bar does not appear to be due to any influence of the neck, which on the Gironde is $11\frac{3}{4}$ miles distant, and on the Foyle $11\frac{1}{5}$ miles. The inner bar is due to an enlargement in the channel; and it shows that the river should be trained down to a point where the channel due to the neck is sufficiently deep.

The banks seaward of the neck depend mainly on the conditions of the coast. The sand discharged from the estuary settles at the sides and end of the channel; and the portion

[1] "Étude sur les Rivières à marée et les Estuaires," H. L. Partiot. Paris, 1892.

deposited on the side from which the materials travelling along the coast come, arrest these materials, and give rise to a bank. If the sand transported to the extremity of the channel reaches a descending sea-slope, it forms a mound, unless removed by a littoral current or waves. This mound, which diverts under water the sand travelling along the coast, forms a bar, whose height depends on the action of the neck and the abundance of the sands, and through which the flood and ebb waters form a passage. If the materials from the estuary do not meet with a descending slope, and deposit at the limit of action of the neck, the channel soon elongates, and the bar progresses seawards. Though a narrow outlet, accordingly, does not always remove the bar at the mouth of estuaries, nevertheless, if the state of estuaries with a neck are compared with funnel-shaped estuaries in which the ebbing waters spread over a great width, leaving a shallow channel intersected by shoals which are real bars, the Author considers that estuaries with necks will be unhesitatingly preferred. These necks bring all the water in the estuary into the channel for deepening it; on the sea side they concentrate the flood-tide waters so as to open a channel of access towards the estuary; and the ebb-tide creates for its discharge a channel which extends sometimes beyond the limit of action of the neck, removes the bar further away, and lowers it. Some examples are given in the following Table of the position and depths over the bar in this class of estuary:—

Name of River or Estuary.	Distance of Neck from Bar.	Depth of Water over the Bar.	Remarks.
	Miles.	Feet.	
Jade	$8\frac{3}{4}$	42	Plate 4, Fig. 2.
Gironde	15	29	Plate 4, Fig. 13.
Tagus	$5\frac{1}{2}$	36	Plate 4, Fig. 14.
Scheldt	10 $14\frac{1}{4}$	25 25	The Scheldt flows through two channels into the North Sea.
Foyle	$3\frac{1}{2}$	48	Plate 4, Fig. 15.
Mersey	$9\frac{1}{3}$	9	Small estuary above neck; extensive sandbanks below; strong tides.
Rio Grande do Sul .	$2\frac{3}{4}$	12	Rise of tide, 2 feet.
Tay	$8\frac{3}{4}$	21	Plate 4, Fig. 11.
Scorff and Blavet .	$1\frac{1}{2}$	18	Small estuary.
Liffey	$1\frac{1}{8}$	15	Artificial estuary.

As the Foyle has a minimum depth of 48 feet in the main channel, and of 42 feet in the central channel between the neck and deep water in the sea, it may be said to have no bar. The shortest lengths and smallest depths are naturally found in the smaller estuaries. Since the estuaries protected by a neck have existed for centuries, it is evident that the sands brought in by the flood-tide are carried out again by the ebb.

Advantages of Estuaries with a Narrow Outlet.—As necks cause a channel to be formed seawards, any works narrowing the outlet of an estuary would produce a displacement seawards, or the lowering of any bar within the limits of action of the contraction. Consequently works of this kind would produce an effect at a considerable distance beyond the outlet, and might, therefore, be created on the foreshore more economically than those which would be required for training a channel into deep water, or for maintaining the depth over the bar by dredging, sometimes to an indefinite extent.

Reclamations in Estuaries.—Riparian proprietors, and persons who have carried out works for improving estuaries, have often caused accretions on the shores of estuaries, and reclaimed very valuable land. It has been stated that the deposits formed behind the training-walls were eroded from the estuary, and thus compensated by an increase in depth elsewhere for the reduction in tidal area; but the motion of the sands above the necks of estuaries is at variance with this view. It is true that the alluvium accumulating behind the training-walls comes from the estuary; but the sands brought in by the flood-tide, which partially deposit outside the channels, will fill up the hollows thus formed at least to the level of the original deposits, owing to the causes which regulated their height, so that the reclaimed area will not be compensated for, and there will be a diminution in the volume of tidal water entering the estuary. Before attempting, therefore, such reclamations, the possibility of excluding a corresponding volume of water from the estuary, without injuriously affecting the maintenance of the channels both above and below the neck, or the action of the tides on the bar, should be investigated with the greatest care. It may occasionally be possible; but the Author considers that these reclamations are almost always injurious to navigation.

2. Estuaries into which Rivers Flow.

Those estuaries alone are included in this class into which large enough rivers flow to affect their condition, especially at their outer end. They will also be divided into funnel-shaped estuaries, and estuaries having a narrow outlet.

Funnel-Shaped Estuaries.

In order to explain the formation of funnel-shaped estuaries and the actions which take place in them, the Author will refer to the estuary of the Seine, which he has had occasion to study in a very special manner.

Investigation of the Seine Estuary.—Previously to the improvement works commenced in 1844, the Seine estuary extended up to La Mailleraye, 40 miles above Havre, Fig. 4, Plate 4. As the river above this point possessed depths of 23 to 50 feet at low water for long distances, it constituted a great inner basin separated from the sea by the sands of its estuary. On the Meules bank, about 2 miles below La Mailleraye, the depth was only $7\frac{1}{3}$ feet at low water, below which a series of sills existed, over one of which, at Villequier, there was a depth of only $1\frac{1}{3}$ foot at low water; whilst below Quillebeuf there were shoals over which the depth was only $6\frac{1}{2}$ to 4 feet. The width of the river, which was 1,000 feet between Rouen and La Mailleraye, increased to 4,100 feet at Villequier, and 9,840 feet at Quillebeuf; and it reached 5 miles in front of Honfleur, and $6\frac{2}{3}$ miles opposite Havre. The estuary altogether formed a long weir, which kept up the summer water-level of La Mailleraye $16\frac{1}{2}$ feet above low water of spring-tides at Havre.

Various circumstances indicate that the Seine in old times flowed through a deep bay into the sea. The tide indeed must formerly have extended much further up the river than at present, for the slope of the Seine at a low stage between Rouen and Bougival, near Paris, a distance of 102 miles, still averages only 0·105 per 1,000, in spite of the raising which all this part of the valley must have undergone; and the quays of Rouen are at the same level as those of Havre. The stratum of rock, moreover, which extends over the bottom of the bay near Tancarville, is about 30 feet below low water at Havre. Lastly, the sands near Havre extend to more than 46 feet below the same level, outside the solid strata at the entrance to the bay, which in old times formed part of the adjacent coast. The old formation at the mouth of the Seine, underlying the alluvium, consists of the middle and upper chalk on the east side, and of the lower and middle jurassic beds to the west, similar to the adjoining coasts.[1] The estuary faces

[1] "L'Estuaire de la Seine," M. Lennier. Havre, 1881, vol. i. pp. 18, 19.

the prevailing westerly winds; and the tidal wave, coming in from the north-west, creates currents which bring into the bay the débris eroded from the coast between the cliffs of Calvados to the west, and Cape Antifer to the north of Havre. The chalk cliffs between this cape and Havre, being only 15 miles in length, supply merely a small quantity of shingle, sand, and silt; but the shingle has formed a beach up to the mouth of the River Lézarde near Harfleur, whose extremity forms Hoc Point. The jurassic coasts of Calvados, however, furnish an abundant supply of sand, which constitutes the main portion of the marine deposits which have been brought into the bay through the large entrance, $6\frac{1}{5}$ miles in width.

Filling up of the Bay of the Seine.—The waters of the Seine, flowing in a channel 1,000 feet wide at La Mailleraye, were evidently incapable of counterbalancing the sea-water, and consequently the once deep bay filled up with sand. If the entrance had been only about $1\frac{1}{4}$ to 2 miles wide, the Seine might perhaps have remained deep, on account of its discharge and the efflux of tidal water on the ebb, instances of which are found elsewhere. Notwithstanding, however, the larger quantity of tidal water entering the bay, it has been filled up; and the Seine flows over the large weir of sand which the sea has formed. Observations in the bay of the Seine have proved that when a portion of the estuary has been withdrawn from the action of the river, by a change in the direction of the channel, it has soon been raised, the sand first deposited being brought from the part directly below. Similarly, when the construction of a training-wall formed a closed angle between the wall and the shore, the sand which filled up this angle came from just below, producing a hollow, which in its turn was filled up by the sand from below; and this action progressed seawards. When the hollow, temporarily formed, reached the end of the training-wall, the river water flowing into it caused the Seine to make a sharp turn at this point, which was gradually rectified by the filling up of the hollow with sand. The periodical changes, however, of the channel, which promoted the formation of banks in one part, made the river undermine accretions in another part during the ebb and carry the materials seawards, which served to keep down the average level of the bed of the estuary; and therefore the English were very wise in refusing to allow the Mersey to be trained through its upper estuary, which the changes in its channel have helped to preserve up to the present time.

A portion of the deposits which still take place is due to the meeting of the currents which flow into the Seine estuary, for all causes which reduce the velocity of waters charged with alluvium give rise to accretions.

Flood-tide Pockets.—In some parts of the estuary of the Seine, blind channels closed at their upper end are formed by the flood-tide, termed flood pockets. The current of the early flood-tide is fairly rapid, and soon attains its maximum; and if at that time two currents converge to the same point, or if the flood-tide impinges upon a concave bend of a training-wall, or of the shore, a powerful erosion occurs; but as the velocity of the flood soon diminishes rapidly, it does not generally form a long channel. Nevertheless, the flood-tide may deviate the main channel formed by the ebb, if in forming a pocket it meets the ebb-tide channel, and thereby provides a new exit for the ebb waters.

Nature of the Sands forming the Seine Estuary.—The deposits of sand found near the bed of the Seine between Paris and Rouen prove that the river has carried some sand down; and its estuary must, therefore, contain a certain amount of sand from inland. Nevertheless, the volume must be small, since the basin of the Seine consists mainly of permeable strata; and having in old times been covered with forests, the river was noted for its purity; whilst in borings made at Aizier, marine sand alone was found. At the present day, Paris absorbs all the sand the river produces, so that the river now brings hardly anything into its estuary, beyond silt during floods.

Propagation of the Flood-Tide.—The introduction of sand by the flood-tide at the mouths of rivers has been attributed to the sea-water, owing to its density, flowing along the bottom like a wedge, and lifting the fresh water. Observations indicate that the sea-water ascends only a short distance above the mouth, and that the propagation of the tide is everywhere effected by driving back the river water. The flood-tide, at some distance from the mouth, has been proved by experience to drive back the descending waters more easily along the banks and bed of the channel where the current is less rapid; and nearer the sea, the action is analogous; and the flood-tide, entering along the bed and sides of the channels, carries along some of the sand, which partially justifies the wedge theory. The fine sand and silt, however, are carried in the mass of the current, and the fresh water mingles with the salt water, although the saltness of the water remains greater at the bottom in the centre of the channel than at the surface; but, owing to the mingling, the fresh water becomes more salt as it approaches the mouth, and it cannot be said that the sea-water penetrates under the fresh water and lifts it. There is, in every section, a successive driving back of the layers of water, according to their velocity, even when the river only contains fresh water. In flood-time, this action is not powerful enough to reverse the more rapid portions of the downward current. Thus, in the roadstead of St. Nazaire, the current on the surface does not change its direction during the great floods of the Loire; but the flood-tide runs up underneath, and makes vessels of large draught swing round. Sometimes the whole river preserves its ebbing flow, its speed merely being reduced during the flood-tide. When the tides are very feeble, the fresh water spreads out on the surface for some distance over the sea, as happens at the mouth of the Rhone in flood-time.

Action of the Wind.—The wind had two principal effects in the estuary of the Seine up to the commencement of the training-works. During high tides, the westerly winds and the funnel shape of the bay facilitated the entry of the tidal waters, so that at Tancarville and Quillebeuf the level of high water was raised about 20 inches, which was subsequently lost in the trained channel. Another effect of the wind in the estuary was noted by Mr. Godot, who observed that so long as the channel was at a distance from the southern shore, being exposed to the prevalent winds, and especially those from the south and south-west, it was constantly driven against the northern shore. These kinds of effects should be investigated in each special case, but could not occur in a trained channel.

The tidal wave travelling from Cherbourg to Havre produces two secondary waves, one going from Cape Antifer to Havre, and the other from Port-en-Bessin to Honfleur. These two waves meet at the mouth of the Seine in somewhat contrary directions, and do not produce the raising of high-water level which is found in the Bristol Channel and the Severn.

Conditions necessary for the Preservation of an Estuary.—The description of the Seine estuary, and the explanations furnished seem to the Author to demonstrate that, in order to preserve an estuary, an equilibrium must exist between the action of the sea and of the flood-tide, and that of the fresh-water discharge and tidal water which flow away during the ebb. When an estuary has too large an entrance, or too expanded a form, it is inevitably filled by degrees with sand. This result also depends upon the contributions of the river and the sea; for a bay which opens upon a deep shore may be filled up by alluvium from a river, and a bay which receives no sediment from a river may be filled by sand from the sea. Lastly, the width at the entrance of an estuary may be such as to produce an equilibrium between the effects of the flood and ebb, which preserves the estuary, whether or not it receives the alluvium of a river. The way, therefore, to improve a river flowing into a funnel-shaped estuary is to reduce the width of the river by training-walls, prolonged out to deep water in the sea. The estuary would be protected by narrowing the width of its entrance; and it would then be possible to reduce the length of the training-walls of the river, by connecting them with one of the channels which would be formed above the neck.

Improvement of the Mouth of a Tidal River.—As the volume of water discharged by a tidal river increases in proportion to its proximity to the sea, the width between training-walls must be enlarged towards the outlet. A method of calculating the increasing sections of the channel seawards[1] was employed for an investigation on the Loire in 1869, and was recently applied to the Weser by Mr. Franzius; and the Author has lately developed it.[2] The formula for determining the future discharge of a river about to be improved depends upon the new form which the tidal wave ascending the river will assume after the execution of the works; and the formulas hitherto obtained can only be used, with the data available beforehand, by neglecting certain terms. On the other hand, the average velocity of the current, which requires to be known at the outset for these calculations, can only be determined approximately by experimental formulas, or by a comparison of the future state of the river with observed facts under analogous conditions. Nevertheless, the results obtained by these formulas accord sufficiently with observations to be accepted. As the discharge during the flood-tide is greater than during the ebb, it is expedient to employ it for calculating the sections of the channel, as these should be able to discharge the maximum quantity of water which they receive.

Dredging.—If the bed of a river is capable of being eroded, the currents scour the bottom during the construction of the training-walls, and after their completion; and the flood-tide carries back the eroded materials behind the training-walls. Thus, on the completion of the training-walls down to the River Rille in 1866, the Seine had scoured its bed to an average depth of $14\frac{3}{4}$ feet between La Mailleraye and Tancarville; and the flood-tide had brought in behind the training-walls 22,368,000 cubic yards of silty sand. Silt, sand, or gravel pass down with the water in a river with a movable bed. If the velocity of the current in-

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[1] "Étude sur le mouvement des Marées dans la partie maritime des Fleuves," H. L. Partiot. Paris, 1861, p. 23.

[2] "Étude sur les Rivières à marée et les Estuaires," H. L. Partiot. Paris, 1892, p. 4.

creases, more material is carried along, and the bed is eroded; and, if the velocity diminishes, the bed is raised by the deposit of material. Consequently, if the channel of a river with a movable bed is deepened by dredging, without a corresponding reduction in width by training-walls or other means, the sands, if sufficiently abundant, will soon fill up the excavations, and destroy the effects of the dredging. These considerations explain the effect of training-walls which narrow the bed of a river, and the inconveniences of dredging under unfavourable conditions. If the amount of sand brought down by a river is small enough, it is possible to maintain the desired depth by constant dredging; but if the materials brought down are very abundant, they fill up these excavations again, rendering the dredging and expenses useless. This refilling renders sometimes the results attained by dredging uncertain, and may prove a danger to vessels. This method of obtaining the requisite depth has been widely adopted in recent times, owing to the reduction in cost of dredging operations; but it is an economical question, whether it is preferable to burden the future with works which must be continually renewed, or to undertake more costly works which avoid indefinite expenses. The choice depends on circumstances; but the Author considers that the second alternative should generally be adopted if the cost is not excessive, and that works requiring almost constant renewals, such as dredging in a movable bed, should be resorted to as little as possible.

Dredging enables depths to be obtained which scour could not effect; and a deeper access has been provided by this means to the port of Newcastle than could have been created by the discharge and tides of the Tyne. The formation, deepening, and maintenance of most ports and their entrances necessitate dredging; which may also be employed for facilitating the action of the currents on the bed of rivers and estuaries. Nevertheless, wherever natural causes tend to fill up the channel again, large dredging operations should not be undertaken, unless the interests involved amply justify the expenditure.

Successive Lowering of Movable Sills.—When a sill has been lowered by certain works, leading to a lowering of the low-water level at the same place, the slope of the ebb is increased above, and the sand formerly retained by the sill is carried down towards the sea. The next shoal above is lowered in its turn by the increased slope and velocity of the ebb, which produce a corresponding scour higher up; so that the removal of one shoal may lead to the lowering of shoals for a long distance above. The improvement of the Seine below Villequier, and the dredging of the Meules bank below La Mailleraye have produced a lowering of the bed of the Seine for about 19 miles above this latter point. On the Gironde, the dredging of the natural sill, Beyschevelle, near Pauillac, over which there was a depth of 9½ feet at low water, has brought down the sands from above, has made other sills disappear, and has improved the Garonne as far up as Bordeaux. This connection between different parts of a river shows how important is an investigation of the shoals of a river, for a simple work on one may lead to a spontaneous partial, or total, improvement of a more troublesome shoal higher up.

When the size of the channel has been suitably determined, and a sufficient velocity obtained to ensure the scour of the bed of a river, an equilibrium will be established between the discharges and the depths. If a hard shoal is able to withstand the scour of the current, it is certain that on the removal of the shoal to the desired depth by dredging or other means, the channel will be maintained for the future by the current.

Form to be chosen for the calculated Section of a Tidal River.—The proper sectional area of the channel having been calculated, its form has to be determined, the simplest being a trapezium. The calculated depth, being the mean depth in the section, is necessarily less than the maximum depth which will be obtained in the curves, and wherever the river has a well-defined, deepest channel. Where the main current crosses over to the opposite bank, the bottom is uniform; and as the current is oblique to the general direction of the river, the depth at this part is rather less than that given by the formulas, which has rightly led Mr. Fargue and other engineers to point to the necessity of reducing the width a little at these places. The Author would propose to adopt a width equal to the average width multiplied by the cosine of the angle which the central line of the river makes with the approximate line of the main channel. The crossing over of the current, and the depth of the channel along the concave banks have also led to the proposal to construct the training-walls alternately along each bank, so as only to maintain the direction of the channel along the concave portions. The variations, however, of the line of deepest channel, produced by variations in the discharge resulting from floods and the tides, are such as to prevent the securing of a fixed channel, except by two nearly parallel longitudinal training-walls.

It has also been proposed to form the cross-section of tidal rivers with a low-water and a high-water channel, the former corresponding to the discharge of a river at low tide and at a low stage, bounded by nearly low-water training-walls, and the latter a much wider channel, affording a free passage for floods and the tidal waters. This system has the advantage of concentrating the ebb in a small trained channel, of providing the space required for floods, and of admitting a much larger quantity of tidal water, which partially returns down the low-water channel and deepens it. There is, however, reason to fear that the spaces left behind the low training-walls, and which bound the high-water channel, might be silted up by the tides higher than low-water level, and might end by being covered with vegetation and forming part of the banks. This system has been adopted on the Weser; and in reply to this objection of the Author's, Mr. Franzius, the engineer of the Weser, stated that the spaces left behind the low training-walls, and which still comprise a void of about 25,000,000 cubic yards below low water, would be filled by alluvium scoured from the low-water channel, and would thus contribute to its improvement. It would only be after the filling up of these large spaces that the accretions could reduce the sections proposed for the high-water channel; and in this interval a state of equilibrium will be established in the river, which will by degrees render the assistance of the large masses of water spread over these lateral spaces less and less necessary; whereas for a very long period the action of these masses of water will have been very useful in regulating the river; and as the arrangement involves no serious expenditure, Mr. Franzius considers that it would have been a mistake not to have profited by it. These views appear to the Author to be sound; but, nevertheless, it must be noted that the eventual widths will be those between the low-water training-walls, and, therefore, should be calculated according to the suitable cross-sections, omitting the side spaces of the high-water channels, for these will only serve for a time as a means of construction, and to bring the river into the desired condition.

Closure of Secondary Channels.—If the channel divides into several branches, their total sectional area must be rather larger than that calculated for a single channel, owing to the increased friction. The quantity of tidal water coming in is consequently rather greater—an advantage which must be considered. Secondary channels, however, have almost always the inconvenience of creating shoals, which can only be removed by uniting all the waters of the river in a single bed. To solve this difficulty on the Weser, Mr. Franzius has closed some secondary channels by a low dam midway, and by the longitudinal training-walls of the principal channel at their extremities, kept down to low-water level so that the flood-tide can still ascend them. The action of the tide has been increased in the main channel, which has deepened rapidly; and the materials scoured out have been carried by the currents over the dams at the entrance and outlet of the secondary channels, in which they have been partially deposited. The damming of these branches produced a temporary raising of the low-water line, since the river below the point where the secondary channel branches off no longer afforded an adequate section for the discharge of the ebb. This raising, however, has nearly disappeared in consequence of the deepening of the main channel; and it is certain, that owing to the general improvement of the river, the level of low water will soon fall lower than it was previously to the works. The accretions resulting from the damming of the branches by the low training-walls will before long rise above low water, and become covered with vegetation, unless some stream can be led into them; the tides will eventually cease to flow through them; and the water which they received will be lost for the maintenance of the river. As, however, the depth of the main channel is the object in view, and the branches disturb the bed of the river, and produce a loss of energy in the tidal wave, the Author is of opinion that secondary channels should be suppressed as far as possible, and that the main channel should be widened so as not to possess a greater depth than necessary for the navigation.

Form of the Trained Channel in Plan.—The quantity of tidal water entering a river is proportionate to the size of the surface of the river, and it is therefore advantageous to increase it. As the sectional area of a river should continually increase towards its mouth, whereas there is no advantage in increasing the depth beyond the requirements of navigation, it has been concluded that a tidal river should have a regularly enlarging channel down to the sea. This form is certainly the most favourable for the admission of the flood-tide, and for raising the high-water line inland; but it is not so as regards the effect of the ebb for maintaining the channels, and especially for freeing the entrance from the sands which tend to block it up, because the water is dispersed over an excessive width. The trained channel must, therefore, be extended beyond these sands to the deep sea. The form of the channel, moreover, should offer the least possible obstacles to the propagation of the tidal wave; and since curves are unfavourable to this propagation, the channel between the two training-walls should be straight, which form is also suitable for the variations which the serpentine form of the deepest channel may undergo between the training-walls, from the effects of the tides and floods. If the prevalent winds and the direction of the tidal wave come towards the shore, and if travelling sands and banks are found at the mouth of the river, the most economical solution would appear to be to train the channel at right angles to the coast. The prolongation of the jetties in a straight line to deep water would produce an advance of the foreshore, which would soon obstruct the entrance, and necessitate a further prolongation seawards; but Mr. Bouquet de la Grye has indicated a method of avoiding the difficulty in the case of the River Senegal.[1]

Arrangements to be adopted at Outlet.—Near low-water mark, a curved jetty on the side of the channel opposite to the quarter from whence the sands come, would stretch into the bed of the river, so as to receive the ebb on its concave face, Fig. 5, Plate 4. A passage would be left facing the jetty for a portion of the sand travelling along the coast; and this sand would push the ebbing tide against the jetty. This jetty would direct the current against the concave face of another curved jetty on the opposite side of the outlet, which would convey it to deep water, with the alluvium brought down by the river. The portion of the travelling sands coming against the convex side of the second jetty would pass round its outer end, and would be carried by the current of the river approximately in its previous direction; and the winds and waves would soon throw it back on the coast. It is assumed in this arrangement that the waves can act on the sands at the end of the jetty, and over the whole width of the outlet. The vertical limit of the effective wave-action being somewhat restricted, the depth at the outlet is also limited, unless it is influenced by a littoral current as well. The travel of the sands along the coast, however, is not arrested, so that they are unable to cause an indefinite advance of the foreshore.

As the double inflexion of the current in front of the entrance to the trained channel might check the influx of the flood-tide, and as a deep channel is better maintained along a curve than in a straight bed, it might be well to train the channel in one or several circular arcs of very large radius, with the extremities of the training-walls projecting into deep water at an angle to the coast, so as to facilitate the passage of the sands scoured from the outlets by the ebb- and flood-tide currents, Fig. 6.

In neither case are the parts of the estuary outside the training-

[1] "Revue Maritime et Coloniale," June, 1886, p. 543.

walls protected against the action of the flood-tide; and being deprived of the changes of the channel, and offering a wide entrance to the sea, they are exposed to rapid silting up. As a very great portion of the water, moreover, which covers them returns to the sea over the banks without assisting in the deepening of the channel, the partial reclamation of these littoral spaces would be effected without detriment to the navigation.

Since the formation of sand, and its travel along the coast are the result of permanent causes, the sand must either be allowed to travel along so as to cause as little inconvenience as practicable to navigation, or it must be stopped and utilized. The first system has been just described; but it might not always secure an adequate depth. The sand might be arrested by constructing, at right angles to the shore-line *a b*, a groyne *c d*, which might have to be prolonged to *d'*, at an angle to its first direction, to prevent the sand travelling round the end of the groyne, Fig. 7, Plate 4. The sand will accumulate in the angle *a c d* formed by the groyne, and rising up the gentle slope of the groyne, will form dunes which can be stopped from travelling inland by the processes previously described; whilst the accumulation can be prolonged along the shore by successive groynes d_1 d_2 d_3, and thus wooded lands could be formed along the coast. The new outlet would be trained to the desired depth in the sea, sheltered from the accumulation of sand thus formed, and directed so as to scour away any sand coming either from the sea or from inland. If an estuary, A B C, had to be crossed, the prolongation of the shore-line *a' b* might be hastened by a supporting groyne suitably directed. Nature exhibits examples of outlets formed in an analogous manner, the river being impeded by a bank of sand projecting from the side from which the sand travels; but as this bank is mostly under water, and nothing is done to raise it, the sand eventually travels round it. It would only be necessary to complete the work already begun naturally, by aiding the raising of the bank; and the improvement of the channel could easily be effected behind the reclaimed lands. At the mouth of the Foyle, the foreshore has progressed across the bay, forming a narrow outlet for the river, and a long sandy beach bordering the sea; dunes have also been formed; and the sandbank of Tuns, on the right side of the channel, is continually growing by the accumulation of sand brought along the coast.

Small-Scale Models, and Wattling.—In recent investigations of estuaries, small-scale models have been sometimes employed of the estuary to be improved, in which the vertical scale is necessarily much larger than the horizontal. The movable banks are represented by very fine sand, as they exist previously to the works; the training-works and jetties proposed to be constructed are formed of little strips of metal; and the tidal waves are produced by an immersed float, or by a movable reservoir set in motion by clockwork; whilst a reservoir with a sluice supplies the discharge from inland. The currents produced in these models displace the sand, which is deposited according to the conditions of the site and the works introduced. The banks at the mouths of certain tidal rivers have been fairly reproduced, as, for instance, those of the Mersey. In these models, however, the shore and the banks are distorted, owing to the difference in the scales; and account is not taken of floods, waves, or the action of wind, so that their results must be accepted merely as indications without much claim to exactness.

On the tidal Garonne and the upper Gironde, a surer method was adopted, too costly to be used for the extensive and numerous experiments that can be made with small models, but affording much better results, which may often lead to important economies in the execution of the actual works. The system consists in placing wattlings along the line of the proposed works, fastened to a double row of piles driven at intervals apart by aid of a water-jet, which also enables the piles to be readily shifted if necessary. When, however, the line adopted proves satisfactory, these wattlings serve for a long time in place of training-walls, and accretions take place behind them; and when more solid works become necessary, they often provide a support, and enable the amount of rubble for the training-walls to be considerably reduced, affording a saving much in excess of their cost. The wattlings on the Gironde, raised only $3\frac{1}{4}$ feet above low water, cost 14*s.* 6*d.* per lineal yard; and each square yard extra cost 3*s.* $1\frac{1}{2}$*d.* This system would be applicable to a number of cases.

Estuaries with Narrow Outlets.

Utilization of all the Water of an Estuary.—Though the spaces at the back of the training-walls in a funnel-shaped estuary might be reclaimed in most cases without injury to the river, the Author considers that it would be better to utilize all the tidal water flowing over the estuary for the improvement of the channel and lowering the bar, which may be accomplished by constructing high jetties between the channel and the shore on each side, Figs. 8 and 9, Plate 4, making all the water in the estuary pass through the outlet-channel. This conversion of a funnel-shaped estuary into an estuary with a narrow outlet, will produce the ordinary effects, of a great depth in the neck, one or more channels in the estuary, one of which will form a continuation of the river-bed, and an outer channel extending across the bar, if the bar is situated within the zone of influence of the neck. It would even be possible to reduce the length of the training-walls in the estuary, because one of the channels formed would be in continuation of the trained channel. According to circumstances, either a straight channel might be formed, as in the case of the Liffey and the Tyne, or a channel with curves of large radius as on the Tees; and if a curved channel was selected, it would be advantageous to continue a low training-wall along the concave bank as far as the neck, Fig. 9, Plate 4.

Training-Walls with varying Curvature.—In cases where the scour of the ebb predominates for deepening the channel, it must be remembered that the current following along a concave training-wall loses a portion of its energy by friction against the wall, in proportion to the length of the wall. As, however, the centrifugal force is in inverse ratio to the radius of curvature, the friction might be partly compensated for by diminishing the radius, in proportion as the training-wall extends seawards. The training-walls at the mouth of the Dwina in the Baltic appear to have been designed with this view.

Reservoirs.—The discharge of an estuary during the ebb depends upon the volume of tidal water which enters, the amount which is forced back by the flood-tide, and the relative discharge of fresh water in flood-time and during the low stage. Reservoirs within the neck, and even a certain distance up a river, may very usefully increase the volume of the ebb, when in good condition; and a tidal river, besides discharging its fresh water, affords a passage at the same time to a large volume of water which it has stored up like a reservoir. Thus, for instance, though the quantity of water backed up by the flood-tide in the Garonne, the Dordogne, and the Isle, has only a small influence on the discharge of the ebb at the outlet of the Gironde, 47 miles below the confluence of its two main tributaries, the action of the reservoirs formed by the Garonne and Dordogne increases rapidly on approaching their confluence into the Gironde,[1] Fig. 13, Plate 4. Moreover, as the discharge at each point regulates the section, and consequently the

[1] "Étude sur les Rivières à Marée et les Estuaires," H. L. Partiot. Paris 1892, p. 58.

volume of water which flows up and down at this place, the section, even of the outlet of the Gironde, depends upon the volume of water stored in the upper reservoirs formed by the two large rivers.

A similar effect is produced when a river traverses large areas covered and uncovered by each tide, for the outflow from these reservoirs increases the section of the channel below them, and usually increases its depth. The little river Odet, discharging only 140 to 280 cubic feet per second at its low stage, flows through a large mere 2 miles below Quimper, called Lédanou, which is in communication with several lateral branches maintained by small streams, together forming regular inner estuaries.[1] The rise of equinoctial spring-tides is $14\frac{3}{4}$ feet, and the capacity of these reservoirs amounts to about 18,000,000 cubic yards. The bed of the Odet below the mere constitutes a neck 8 miles long, 820 feet wide in its upper portion, and 720 feet wide at its outlet. The river, which is barely 12 miles long, and brings down very little alluvium, has a very small depth above the mere, and its high- and low-water lines have sharp slopes; but below the mere, the depth in the main channel varies from 17 to 40 feet, and even 50 feet, and the lines of high and low water are nearly horizontal. If a portion of this reservoir was cut off, the tidal water entering and leaving the river would be diminished; and though the tidal range might be slightly increased in the upper part of the river, the depth in the neck would be reduced; whereas an enlargement of the reservoir would produce a deepening in the channel below.

The Yare furnishes a similar instance, for near Yarmouth it flows through a vast expanse, called Breydon Water, which is uncovered at low tide; but as the range of springs on that part of the coast is only 6 feet, the river, along the 2 miles between the port of Yarmouth and the North Sea, only attains a depth of 10 to 14 feet.

The tidal water which enters a tidal river is generally much larger in volume than the fresh water; and it especially assists the ebb current in deepening the approach to the river, if, spreading over an estuary, it is concentrated into the outlet channel by a narrow mouth. Thus if the channel of the tidal Seine was prolonged to Havre between two training-walls, Fig. 4, Plate 4, so as to attain a depth of about 45 feet at low water, the channel would receive, during the flood of a spring-tide, about 3,000,000

[1] "Procès-Verbaux des Séances des Sections," Congrès de Navigation intérieure, Paris, 1892, p. 645.

cubic yards of fresh water from inland, and 504,000,000 cubic yards of water from the sea. Including, however, the contents of the estuary outside the channel, between its shores and the proposed Villerville breakwater, the tidal water would be increased by 783,000,000 cubic yards; so that during the ebb, adding the fresh-water discharge during a whole tide, the total discharge of the Seine would amount to 1,293,000,000 cubic yards, as compared with 3,000,000 cubic yards of fresh water discharged during the ebb.

The reclamation of natural tidal reservoirs injured the port of Ostend, and sluicing-basins have had to be formed to supply their place. Estuaries with a narrow outlet are likewise reservoirs; and it is almost always very important to avoid reducing them by reclamations. This was fully appreciated by the Dublin authorities, who prohibited any reclamation of land within the artificial estuary of the Liffey, formed by breakwaters at its mouth. In order that reservoirs may be really useful, the waters which flow into them must not fill them up with sediment; their entrance must not be so situated as to produce dangerous eddies in the main channel; and the channel of the river below must be sufficiently wide or deep to afford a free outflow for the water from the reservoir and from the river. If the outlet is not large enough, the level of low water is raised; the river above is deprived of a portion of the tidal water; and the level of high water is depressed.

Changeable Narrow Outlets.—Some narrow outlets, like the outlet of Arcachon Bay, Fig. 1, Plate 4, are formed by the travel of sand or shingle along the coast; and their width is altered by the prolongation of the shore-line of drift, or by the erosion of the coast. If the shore-line is cut in various places, as at the mouth of the River Senegal, Fig. 10, Plate 4, the outlet is too changeable to produce the effect of a neck seawards; but this is not so above, although the changes in the outlet are not without influence if the neck is prolonged inland by a narrow stable channel. Thus the estuary channel has a depth of 59 feet opposite Arcachon; and the Senegal has a depth of 26 to 36 feet between its outlet and St. Louis. As the outlet-channel of the Senegal, diverted by the drift along the coast, is stopped at the Mousseguiob dunes, where the tenacity of the soil prevents erosion from prolonging the channel southwards, Mr. Bouquet de la Grye has proposed to create similarly a fixed outlet to the north, by guiding it between jetties arranged as shown on Fig. 5, Plate 4, so as not to stop the travel of sand along the coast. The Author has proposed the adoption of a similar plan for creating a fixed deep entrance to Arcachon Bay, near the lighthouse of Cape Féret; and the changes of the outlet of the Yare were stopped by a similar expedient.

Investigation of various Mouths of Rivers.—The Author proposes now to examine some estuaries belonging to the second class, and to point out the theoretical consequences which appear to result from these investigations. In order, however, to understand better the phenomena taking place in these estuaries, it will be useful to note the facts observed at the mouth of the Rhone, where the range of tides is extremely small. As described by Mr. Guérard,[1] there is, at the mouth of the Rhone, a mound of deposit over which the river flows between two submarine banks; and the materials carried down by the river are deposited on the sides and end of the basin formed by the river, and raise them gradually, till at length, when the outlet becomes insufficient for the waters of the Rhone, a passage is forced through the bar at the end, which consequently varies in height.

The east coast of Great Britain is sheltered from the direct action of the prevalent westerly and north-westerly winds; and it is, moreover, intersected by great recesses, such as the Moray Firth, the Firth of Forth, and the Thames, reducing the quantity of sand and shingle travelling along the coast. The amount of drift, therefore, which reaches the mouths of the rivers, is sometimes very small, whilst it is greater in the indentations of the coast.

The Tay.—The River Tay, unlike the Seine, brings down large quantities of sand and detritus; whilst little material arrives from along the coast, Fig. 11, Plate 4; and Mr. D. Cunningham, M. Inst. C.E., has stated that the sands in the lower part of this river are continually descending to the sea,[2] their rate of travel increasing as they approach the contraction in the estuary at Tayport, a little below Dundee, where the width, which is about $2\frac{1}{2}$ miles above, is reduced to 270 yards, with a depth of 59 feet. The rise of the tide at springs at the mouth of the Tay is $15\frac{3}{4}$ feet. Two channels extend above the neck with depths of 18 feet, one to the north for 6,200 yards, nearly up to Dundee, and the other to the south for about 5,700 yards. Below Tayport, the sands and shingle have formed two converging banks, between which the river flows, with a bar at their outer ends, $8\frac{2}{3}$ miles beyond the neck, over

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[1] "Amélioration de l'Embouchure du Rhône," A. Guérard, Congrès de Navigation intérieure, Paris, 1892, p. 22.

[2] Minutes of Proceedings Inst. C.E., vol. c. p. 182.

which there is a depth of 21 feet at low water. In this enclosure the current increases in velocity out to the bar; and the sand is carried rapidly to the sea, partly in suspension, but mostly rolled along near the bottom. The left bank has formed a groyne, which retains the small amount of sand coming from the north, creating a little bank near Buddon Ness.

The travel of the sands is in exactly opposite directions in the estuaries of the Seine and the Tay, owing to their different origin; for the Seine estuary has been blocked up by sand coming from the sea; whereas in the Tay estuary, where the low-water level of spring-tides at Dundee differs by only 6 inches from low-water level in the sea, the tidal currents have brought down large quantities of sand into the lower estuary, which have increased the banks near the mouth without encumbering the channel.

Estuaries will next be considered which receive sand both from above and below, such as the Maas, the Gironde, and some others.

The Maas.—After receiving the waters of the Waal and the Leck, the Maas flows into the North Sea through several branches, the principal one of which passes Rotterdam; and the rise of average spring-tides is only 5 feet 7 inches. Receiving both the alluvium of the Maas and the sands of the Dutch coast from the north, the funnel-shaped estuary, Fig. 12, Plate 4, tended to fill up; and the action of the sea has been aided by reclamations alongside the river, its water area having been reduced from 42 square miles in 1739 to 27 square miles in 1860. The Rotterdam channel discharged through two branches into the midst of the banks which bordered the coast, it became shallower, and the bar was raised $4\frac{1}{4}$ feet.

To remedy this condition, the Hook of Holland was cut through, and the Maas was regulated from Krimpen and Rotterdam down to the sea. The width between the jetties at the outlet, which was at first made 2,953 feet, has been reduced to 2,300 feet; and small groynes have been placed along the coast to the north, to check the progress of the sands. The lines of soundings of 33 feet, about $1\frac{1}{3}$ mile off the coast, have not advanced seawards; but the smaller depths have notably decreased near the new outlet;[1] thus the head of the north jetty, built in a depth of $26\frac{1}{4}$ feet at low water, is now in a depth of only $16\frac{1}{2}$ feet; and the line of soundings of $16\frac{1}{2}$ feet, which was formerly 1,100 yards from the shore, has gone 820 yards further out. Since 1880,

[1] "Le nouveau Chenal d'accès de la Mer à Rotterdam," Baron Quinette de Rochemont, Congrès des Travaux Maritimes, Paris, 1889.

however, this progression has ceased;[1] the deepening near the shore is proceeding slowly under the action of the concentrated current in front of the ends of the jetties; and, unlike all the other outlets to the sea in Holland, there is no sign of a bar or shoal opposite the new outlet. In spite of the present relatively stable condition at the outlet, it is to be apprehended that the sands from the north, which created the Hook of Holland, will eventually form a bank on the north side of the channel, and even overlap it; but an adequate depth might remain over the bar.

Hitherto the results of the work have been most satisfactory, for the minimum depth in a channel 110 yards wide, between the jetties and beyond, has reached $23\frac{2}{3}$ feet; and deep water has penetrated further into the channel. Except at Zuiden, about $3\frac{3}{4}$ miles below Maassluis, there was in 1891, over all the shoals between Rotterdam and the sea, a minimum depth of $21\frac{1}{3}$ feet at low water for a width of at least 110 yards.

The Gironde.—This estuary has been described at length elsewhere by the Author.[2] The rise of tide at the mouth of the Gironde is $16\frac{3}{4}$ feet at springs. A considerable amount of alluvium is brought down by the Garonne and the Dordogne; and sand is brought into the Gironde from the sea by the flood-tide round the Pointe de Grave, Fig. 13, Plate 4. Nevertheless, this long estuary maintains itself by discharging into the sea the materials brought into it. The contraction at the Pointe de Grave, which reduces its width from $6\frac{2}{3}$ to 3 miles, gives rise above to three channels, with depths of at least 33 feet for $9\frac{1}{3}$ to 10 miles from the Pointe de Grave. At their upper end in front of By, nearly 12 miles above Grave, there is a wide flat shoal or inner bar, over which there is a depth of 10 to $14\frac{3}{4}$ feet at low tide, which the Author considers to be beyond the influence of the neck, and attributes to the undue width of the estuary in relation to its discharge at this part. In the neck itself, the depth attains 100 feet; and a channel below, 15 miles long, extends to the bar, over which there is a depth of $29\frac{1}{2}$ feet. Beyond the neck, sand comes in abundantly from the west and south-west; and the channel leaves on this side a series of banks, through which it occasionally opens a passage. The materials brought down by the Garonne and the Dordogne are readily distinguished, and are found partly on these banks, and partly beyond the bar, $17\frac{1}{2}$ miles

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[1] "Amélioration de la Voie fluviale de Rotterdam à la Mer," J. W. Welcker Congrès de Navigation intérieure, Paris, 1892.

[2] "Étude sur les Rivières à Marée et les Estuaires," H. L. Partiot. Paris, 1892, p. 51.

from the Pointe de Grave. Although the width varies in the Gironde, the sectional area below mean tide increases regularly from the Bec d'Ambès to the Pointe de Grave, and even in the neck. The effect of the neck is most distinct; and the desired equilibrium for maintaining an estuary appears to be realized on the Gironde.

The Tagus.—A similar equilibrium is not attained in the Tagus, where a neck, about $6\frac{1}{3}$ miles long, separates its estuary from the sea, Fig. 14, Plate 4. The tide rises 12 feet at springs outside this neck, whose width is about $1\frac{1}{8}$ mile opposite Belem Castle, and is fairly uniform, and whose depth attains 118 to 160 feet. The estuary, known as the Bay of Lisbon, has a width of $5\frac{1}{2}$ miles; and there is a channel in it which has a depth of 33 feet as far as $4\frac{1}{3}$ miles from the neck; whilst the channel below the neck extends for $7\frac{1}{2}$ miles out to the southern bar, over which there is still a depth of 36 feet. The lower part of this outer channel resembles in form the Rhone bar previously described; it arrests the sands travelling northwards along this coast, and has formed the bank of Alpeidao, which resembles the banks outside Poole harbour and the estuaries of the Tay and the Foyle, due to similar causes. The Tagus is torrential throughout its course, passing abruptly from an insignificant flow to a very large discharge; it has a rapid fall down to its outlet into its estuary, and it carries along a quantity of sand and gravel. Consequently, this estuary tends to silt up, though it has existed for many centuries.

The Foyle.—This river flows into an estuary on the north coast of Ireland, $15\frac{1}{2}$ miles long and $13\frac{2}{3}$ miles wide, which is protected from westerly and north-westerly winds by the mountains of Donegal, Fig. 15, Plate 4. The sands are driven along the coast by easterly winds, as proved by the neighbouring outlet of the little river Bann; and these sands have formed a shore-line like that at Arcachon, which would skirt the east coast of the bay if a gap in the range of mountains near Londonderry did not give vent to the south-west winds. These winds turn the sands from the coast towards the north; and their action, combined with that of the east-north-east winds and of the littoral current, has gradually formed a triangular point, which has now a base of 6 miles and a projection of 4 miles, and has formed a neck between its extremity at Macgilligan Point and the opposite shore. Dunes have been formed by north-north-east winds on the northern shore of this triangle, and by south-west winds on the shore inside the bay. The neck, which is maintained by the outflowing waters, is about

1,470 yards wide, and has a depth of 72 feet. Above the neck, a channel, having a depth of 33 feet for 6 miles, has a bar 11 miles from the neck, over which there is a depth of $10\frac{1}{3}$ feet at low tide; and below the neck, a channel of similar width possesses a depth of 39 feet out to deep water. The sands arrested on the eastern side of the channel below Macgilligan Point have formed Tuns bank, which is very similar in shape to the bank outside Poole harbour, Fig. 3, Plate 4.

The Slaney.—Wexford harbour, on the east coast of Ireland, into which the little river Slaney flows, has a length and width of $3\frac{3}{4}$ miles, and is enclosed on the sea side by a long narrow spit ending at Rosslare Point, leaving on its north side an outlet 980 yards wide, with depths of 33 to 49 feet, Fig. 16, Plate 4. The rise of spring-tides at that part of the coast is only 5 feet. Two channels branch off above the neck, one of which, the Coal Channel, has depths of 10 to 26 feet for nearly 3 miles; and the other, leading to the port of Wexford, has depths of $6\frac{1}{2}$ to 10 feet, and at $2\frac{2}{3}$ miles from the neck has an inner bar over which the depth is only $5\frac{1}{2}$ feet at low tide. Seawards of Rosslare Point, a channel extends for $1\frac{1}{4}$ mile out to the outer bar, with a depth of 10 feet over it. The Dogger bank has been formed on the south side of the channel by the sand coming from the south, in the same manner as the banks at the mouth of the Tagus, Poole harbour, and other places previously mentioned. The small depth of the channels is due to the feeble rise of tide, the small discharge of the river, and reclamations in the estuary.

The Tees.—A fairly large quantity of alluvium is brought down by the Tees in flood-time; and its estuary also receives the sands which travel from north to south along the east coast of England. The Tees estuary is $3\frac{3}{4}$ miles long and $4\frac{1}{3}$ miles wide; and the sandbank which enclosed it to the east in advance of Tod Point, left it an outlet to the sea $1\frac{3}{4}$ mile wide, which has been partially closed by a long breakwater.[1] The rise of spring-tides at its mouth is 15 feet. Two channels have been formed above the outlet, one extending to the inner part of the estuary, into which the Tees flows at Cargo Fleet, and the other running westwards towards Greatham Creek. The improvement works carried out on the Tees, and their results, have been already described in detail by the late Mr. John Fowler, M. Inst. C.E.[2] It has been possible to reclaim 2,600 acres from the estuary without injury

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[1] Minutes of Proceedings Inst. C.E., vol. xc. Plate 8.
[2] *Ibid*, vol. lxxv. p. 239; also vol. xc. p. 344.

to the navigation. Latterly the accretions in the estuary behind the outer part of the half-tide training-wall on the left bank have led to the removal of its outer end; and the prolongation of the north breakwater has been provisionally stopped. The width left at the outlet has been reduced by a bank which has formed on the right bank near the end of the south breakwater. The channel at this part has hitherto maintained the same depth; but time only will show whether the opening left to the sands of the coast is not wide enough to promote the silting up of the estuary. In this case the north breakwater would be extended towards the end of the south breakwater, which would divert into the channel the water which escapes along the coast during the ebb, and by forming a fixed neck would ensure the maintenance of the desired depths in the neighbouring parts of the channels. A project for a funnel-shaped mouth was rejected in 1842.

The Tyne.—In addition to training-works and dredging in the river up to Newcastle, the channel across the sandy bar, formed by the sea at the mouth of the Tyne, has been protected by two converging breakwaters, which enclose a little estuary $1\frac{1}{2}$ mile long and $\frac{2}{3}$ mile wide.[1] These breakwaters extend into a depth of 33 feet, and leave an outlet of about 1,000 feet between their extremities, the rise of tide at springs being $14\frac{1}{2}$ feet. The channel of the Tyne at the port of Shields has the same width as the outlet, and depths of 26 to 36 feet at low tide.

The Liffey.—Two converging breakwaters have also been constructed at the mouth of the Liffey, at the approach to the port of Dublin, enclosing an estuary about 3 miles long and $1\frac{1}{5}$ mile wide, and leaving an outlet 1,000 feet wide, with a depth of 26 feet at low tide, the rise of tide at springs being 13 feet.[2] There is a channel up to Dublin, improved by dredging, with a minimum depth of 12 feet; and an outer channel extends nearly a mile beyond the outlet, with a depth of 18 feet; whilst the depth over the bar, which formerly was only $6\frac{1}{2}$ feet, is now 15 feet. A project for a funnel-shaped mouth was urged for a long time for the Liffey, and was finally rejected.

The Author would observe that there is hardly a case in England of the mouth of a river trained in a funnel shape to deep water; whereas closed estuaries with a narrow outlet have been created in front of the Liffey, the Tyne, and the Tees. This latter system

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[1] Minutes of Proceedings Inst. C.E., vol. lxx. Plate 3, Fig. 9; also vol. lxxxvii. p. 148, and Plate 8.

[2] *Ibid*, vol. lviii. Plate 1.

appears to have been preferred by engineers, and the choice appears to the Author to have been amply justified by its success.

Final Considerations.

The divergence of opinion manifested by engineers as to the from to be given to the mouths of rivers is partly due, the Author considers, to its not having been sufficiently observed that the free propagation of the tides up a river, and their ready outflow, require the progressive increase of the sectional area of the channel far more than that of the width. A deep, narrow channel affords a greater discharge, and renders easier the propagation of the tidal wave than a shallow channel of the same sectional area. It is no doubt advantageous to augment to the utmost the volume of tidal water entering a river; but local contractions offer no serious obstacle to this, unless the sectional area does not comply with the law of the regular increase of the discharge, and of the propagation of the tidal wave up the centre of the river. The increase in the quantity of tidal water introduced may result from the creation of a channel increasing regularly in width seawards, with only the depth absolutely necessary for navigation. It may also result, as on the Odet and the Yare, from the existence or formation of reservoirs in places on the tidal river, or near its mouth. The concentration of the whole of the waters of an estuary in the channel during the ebb, by the creation of a neck near the sea, transforms the estuary into a vast reservoir at a favourable point, and assists very effectually in securing the same object.

The form of the channel through the estuary, and wherever it has to be regulated, should be arranged so as to preserve to the utmost the energy of the flood-tide in ascending the river, and also to facilitate the efflux of the ebb. It is expedient to adopt curves of very large radius, and to approximate, especially in the estuary, to a straight course.

The necks which certain estuaries form possess some precious qualities. Not only do they collect the waters for maintaining the channel during the ebb, but they also produce channels above and below, whose depth and length depend on the fresh-water discharge of the river and the tidal range. The upper channel formed by the neck enables the length of the training-walls through the estuary to be reduced, or only low training-walls to be adopted below a certain point. In all cases the training-walls must extend beyond the point where the river might form an inner bar, which is above the end of the channels due to the contracted outlet, and almost always a long distance from the outlet. The channel below the neck nearly always extends far enough out to lower the bar. The influence of the neck extends a long way seawards of its jetties, and thus enables them to be constructed near the shore, and consequently more easily. The enclosure of the estuary, moreover, calms the water in the estuary, which is thus sheltered. Dredging or other works can also be carried out in shelter from the sea and the inroad of sand; and a roadstead or outer harbour is provided of the greatest value to navigation. Lastly, if the neck is made adequately narrow, as is assumed, it secures the estuary from the incursion of sea sand, or facilitates, as on the Gironde and the Tay, the discharge of the materials brought down by the river; and it produces a state of equilibrium which ensures the maintenance of the estuary.

The passage of the channel across the foreshore between the coast and deep water causes the formation of a bank on the side from which the travelling sands come; and these sands and the alluvium of the river form a sort of basin, as Mr. Guérard has pointed out in the case of the Rhone, which generally projects from the coast, and in which the channel prolongs itself. The sand driven by the waves continues its travel along the coast, in rounding the extremity of the basin which constitutes the bar. The arrangement of jetties at the mouth of a river, proposed by Mr. Bouquet de la Grye, Fig. 5, Plate 4, allows of this travel of sand not being stopped; but it cannot always ensure an adequate depth at the entrance for vessels of large draught.

By prolonging the training-walls by jetties out to a distance where the waves no longer affect the bottom, the depth of which varies with the exposure of the site and the height of the waves, the travel of the sand is stopped; but it accumulates against one of the jetties, and, causing a progression of the shore seawards, eventually comes round the end of the jetty. A method, however, of obviating this defect by groynes and the formation of land and dunes along the coast has been described, Fig. 7, Plate 4.

The sand from the coast which arrives in front of the outlet of a trained river comes in with the flood-tide; but the ebb carries it out to sea with the alluvium from the river, and it soon continues its travel along the shore. This assumes that the ebb current is as strong as the flood-tide, which explains the silting-up of estuaries too much expanded, or with too wide an outlet. It is, therefore, expedient to make the outlet of the trained channel adequately narrow, to prolong the jetties out to deep water, and to give them such an inclination to the general line of the coast that the prevailing winds shall throw on to the shore the sands carried down the channel. If, in spite of the depth into which the windward jetty extends, the bar should be raised, it is advisable to prolong the channel seawards. It may even be expedient to make the end of the longest jetty project beyond the general line of the sands along the coast, since the sea maintains the depths round capes and projecting points of the shore. The Author, however, considers it preferable to arrest the sand, as previously described, before it reaches the trained channel; and the travel of the sand, which will continue below the channel, will gradually clear the mouth.

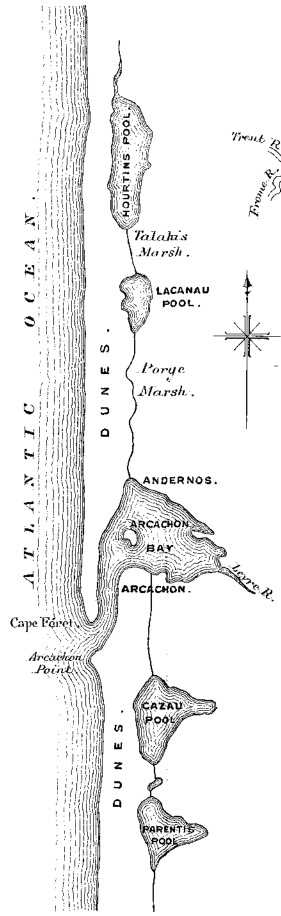
It is advantageous to place the outlet of a trained channel, in a funnel-shaped estuary, on the side of the entrance away from the quarter whence the sands arrive. But the best plan is to enclose such an estuary by breakwaters, leaving only a narrow outlet just sufficient to enable the flood-tide to fill the estuary. This system will be the more advantageous in proportion as the estuary is large, the tidal range higher, and the sea-slope steeper; and for the reasons already given, it appears preferable to training a river out to deep water, even in some cases lowering the bar outside to such an extent as to present no impediment to navigation, as at the outlet of the Tagus and the Foyle.

If a river flows only into a small estuary, or if there is no estuary at its mouth, an estuary can often be created by converging jetties projecting from the coast. This method has been adopted with success for the Liffey and the Tyne. As the outlet for the latter river projects beyond the general line of the shore, the maintenance of a suitable depth at the entrance of this new estuary will be more fully assured.

The Paper is illustrated by four sheets of drawings, from which Plate 4 has been prepared.

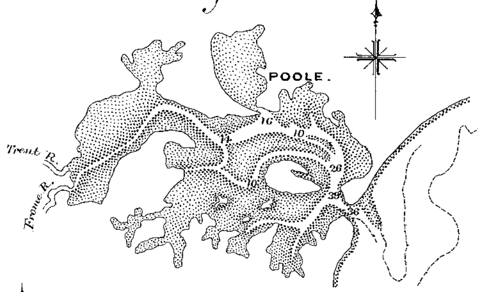
ESTUARIES.

Fig: 1.



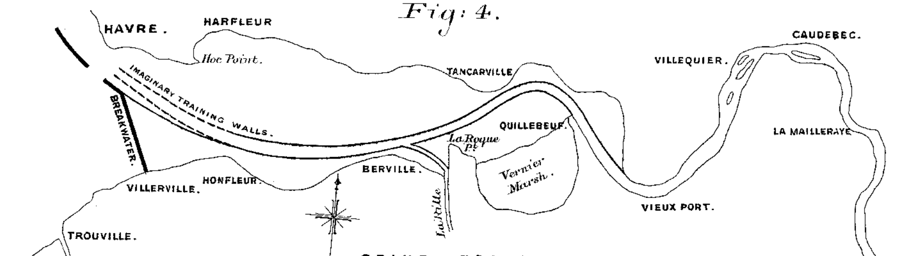
COAST OF GASCONY.

Fig: 3.



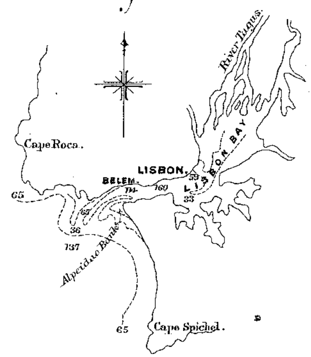
POOLE HARBOUR.

Fig: 4.



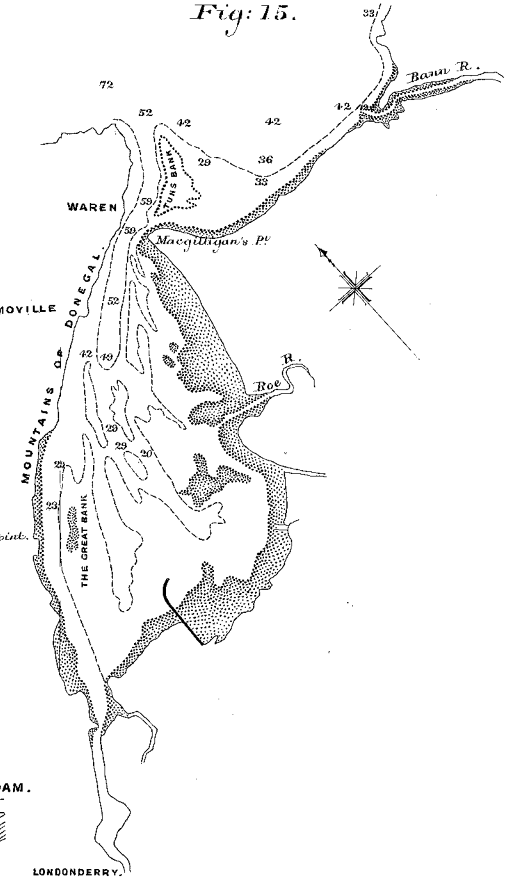
SEINE ESTUARY,
WITH EXTENSION OF TRAINING WORKS PROPOSED BY Mr PARTIOT.

Fig: 14.



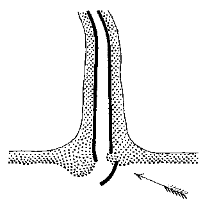
RIVER TAGUS.

Fig: 15.



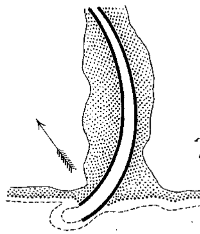
RIVER FOYLE.

Fig: 5.



STRAIGHT CHANNEL.

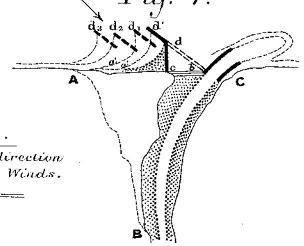
Fig: 6.



CURVED CHANNEL.

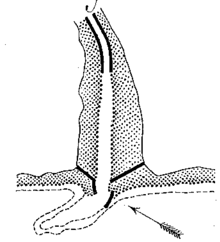
NOTE.
Arrows show direction of Prevailing Winds.

Fig: 7.



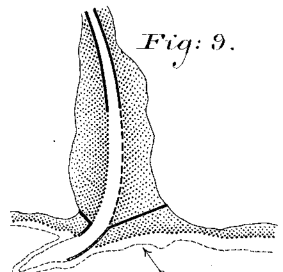
ARREST OF SAND ON THE SHORE.

Fig: 8.



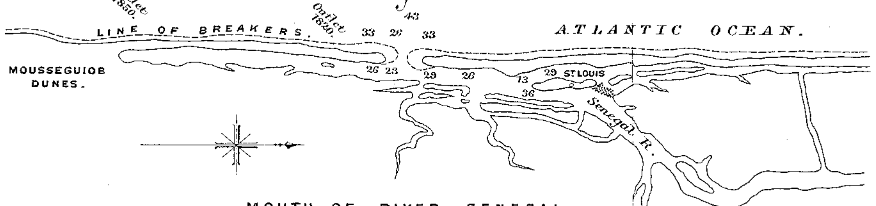
STRAIGHT CHANNEL WITH NECK.

Fig: 9.



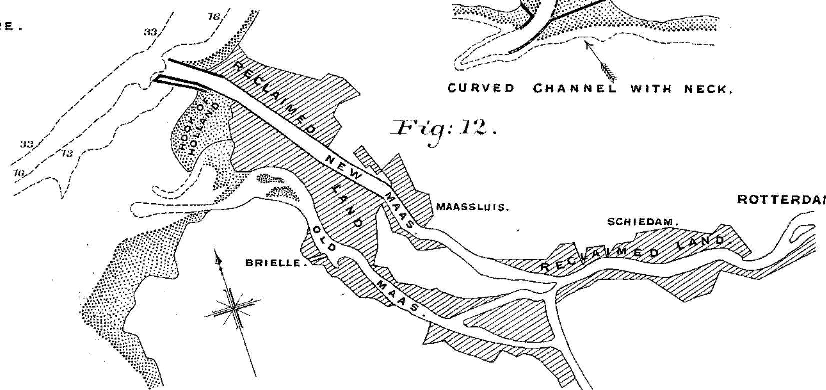
CURVED CHANNEL WITH NECK.

Fig: 10.



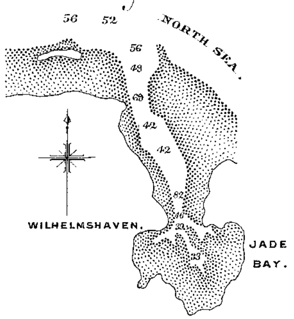
MOUTH OF RIVER SENEGAL.
1867.

Fig: 12.



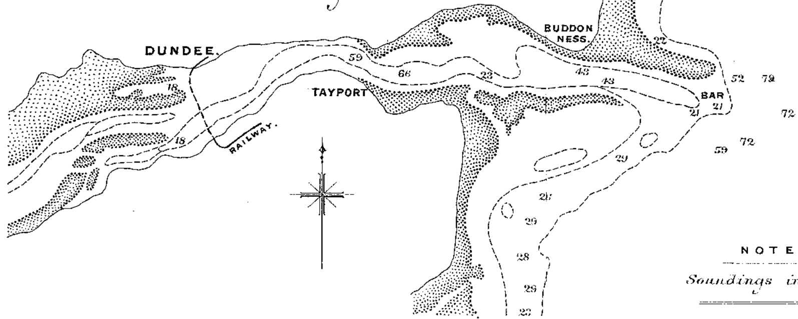
RIVER MAAS.

Fig: 2.



JADE HARBOUR.

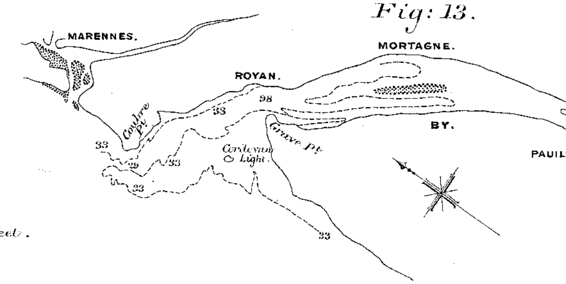
Fig: 11.



NOTE.
Soundings in Feet.

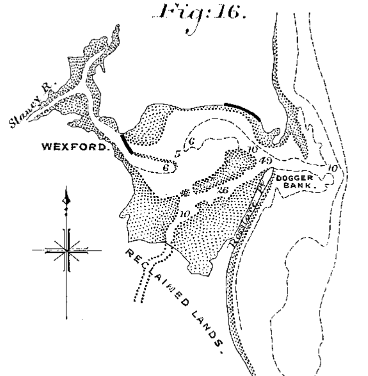
RIVER TAY.

Fig: 13.



RIVER GIRONDE.

Fig: 16.



RIVER SLANEY & WEXFORD HARBOUR.