24 January, 1911.
ALEXANDER SIEMENS, President,
in the Chair.

(*Paper No. 3910.*)

"The Bar Harbours of New South Wales."

By Gerald Harnett Halligan.

However much engineers may differ on matters of principle or on general details in the design of harbours, they are in agreement upon at least one point, namely, that each case must be treated entirely on its merits. Especially is this so when designing works for the improvement of river-entrances where moving sand is to be dealt with. Permanent or monsoonal ocean-currents, tides, the contour of the shore-line in the vicinity, the winds, the upland water, and the quantity and quality of the stone and timber available, must all be considered; and as these controlling factors cannot be the same for any two places, each harbour or river-entrance must be studied separately. General principles and known laws will, of course, form a guide; but the items to be considered are so varied and correlated that the problem at times becomes very complicated and almost insoluble.

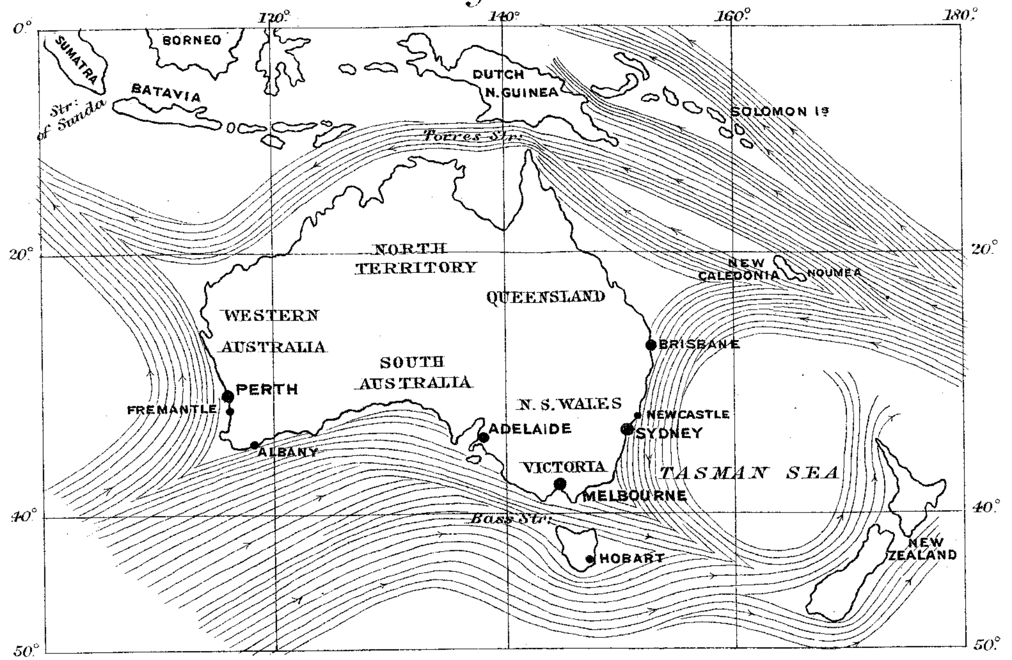
On the coast of New South Wales the problem is simpler than in many other places, but there are still numerous difficulties, and the object of this Paper is to point these out, in the hope that discussion of them may help to solve future problems both there and on works of a similar nature elsewhere.

The Author's 35 years' experience in the service of the New South Wales Government, under which he now holds the position of Hydrographic Officer, has given him an intimate personal knowledge of every harbour, headland, and island on the coast, and the statements in this Paper are based upon that knowledge.

It is proposed first to consider the controlling factors in harbour design in the order named in the first paragraph.

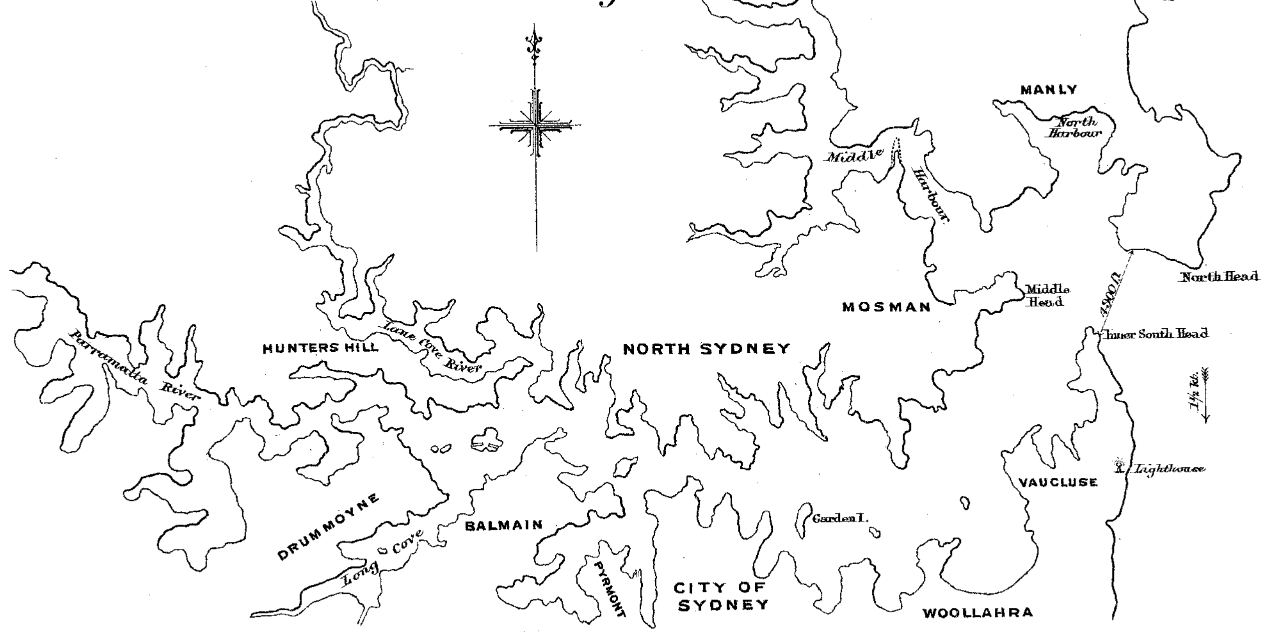
THE BAR HARBOURS OF NEW SOUTH WALES.

Fig: 1.



OCEAN CURRENTS OF AUSTRALIA.

Fig: 3.

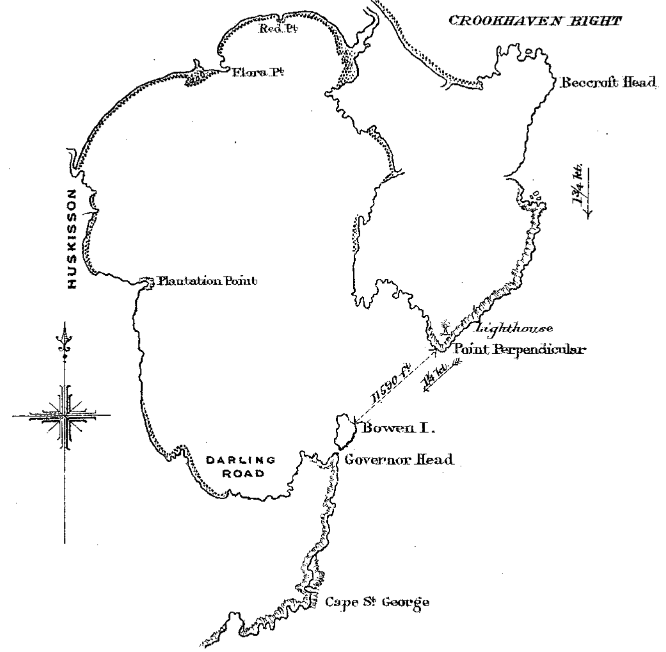


PORT JACKSON: SYDNEY.

Fig: 4.

BOTANY BAY.

Fig: 5.

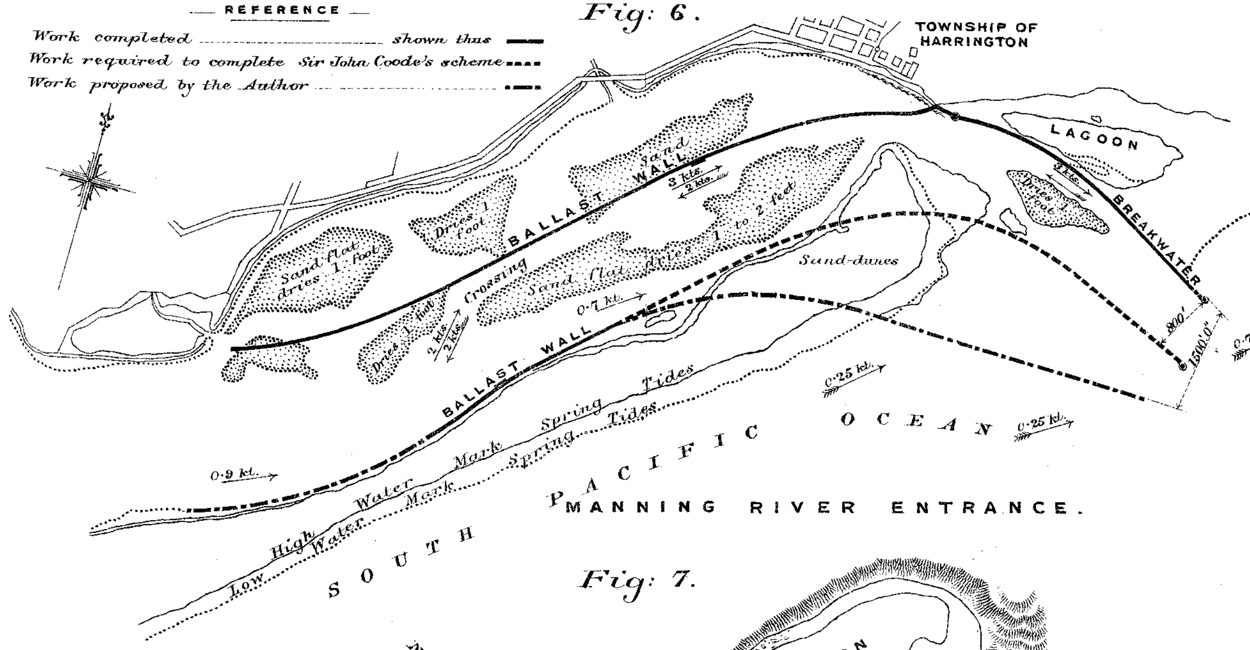


JERVIS BAY.

— REFERENCE —

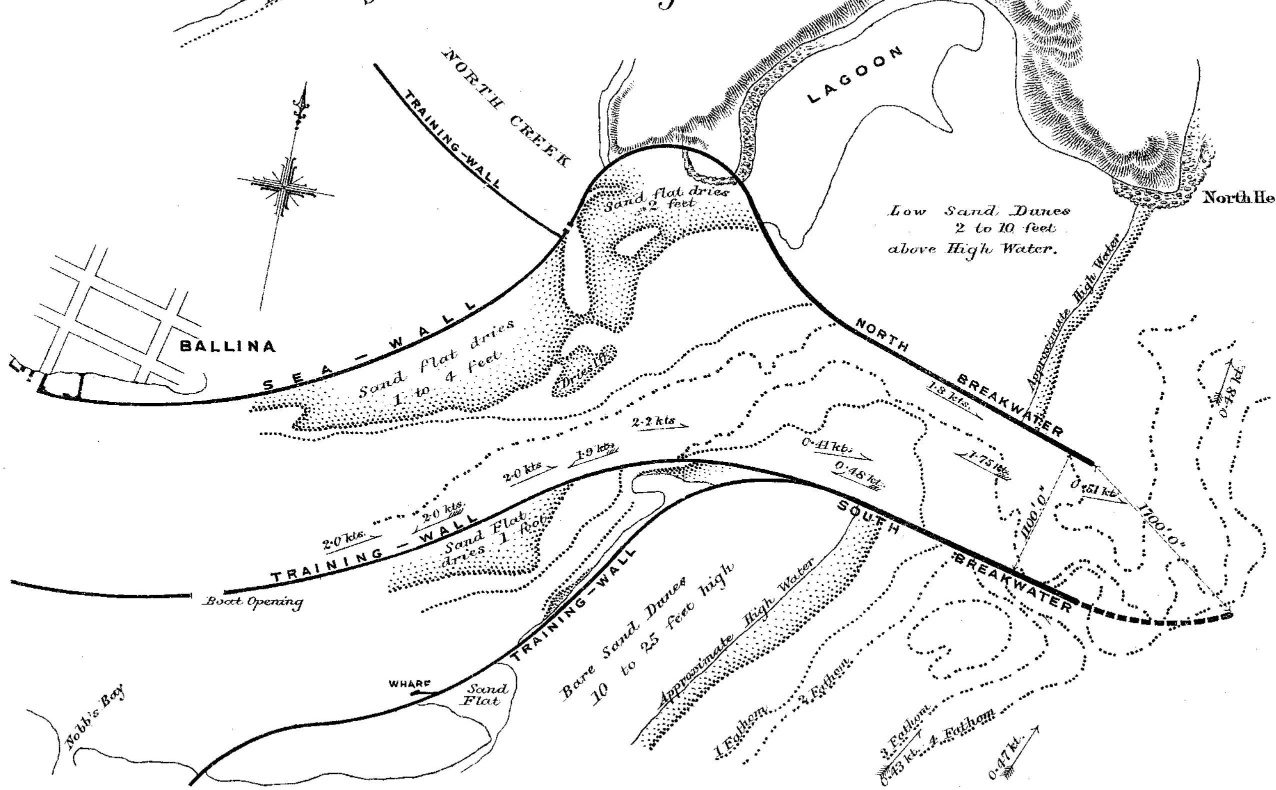
Work completed .... shown thus ▬
Work required to complete Sir John Coode's scheme ----
Work proposed by the Author .... -·-·-

Fig: 6.



MANNING RIVER ENTRANCE.

Fig: 7.



RICHMOND RIVER ENTRANCE.

— SCALES —

Fig: 3 ...... 1 Inch = 2 Miles.
Mile 1 ¾ ½ ¼ 0 1 2 Miles.

Fig: 4 ..... 1 Inch = 12,000 Feet.
Feet 10,000 5000 0 10,000 Feet.

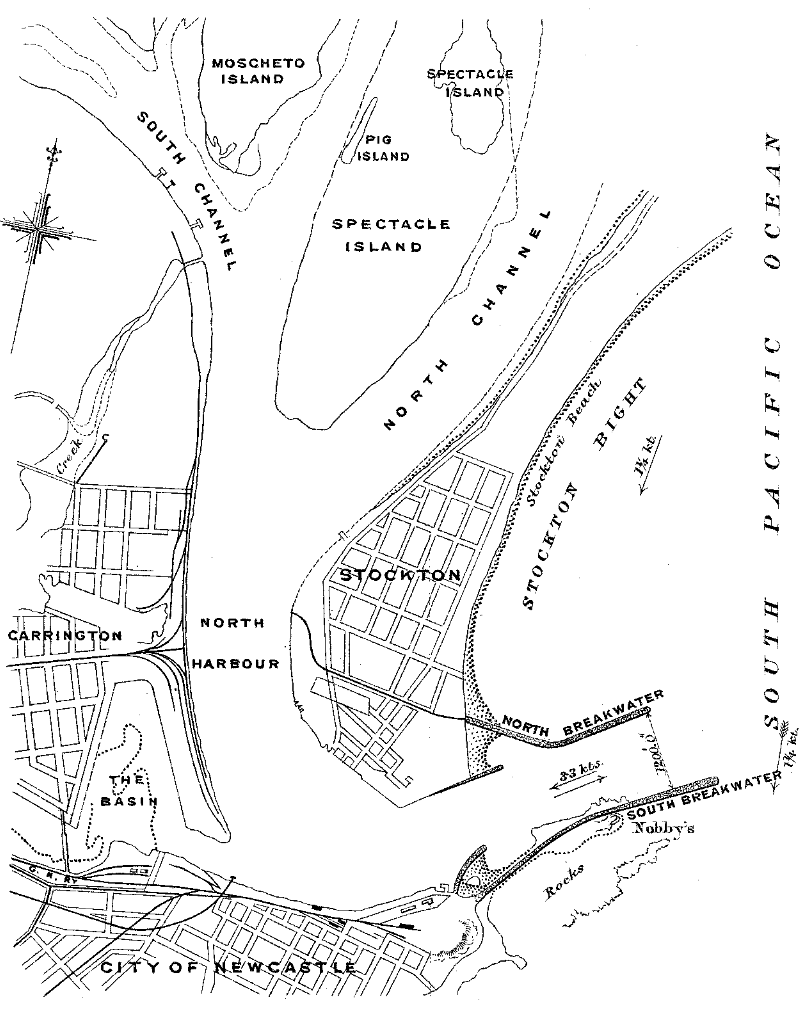
Fig: 5 .... 1 Inch = 20,000 Feet.
Feet 10,000 5000 0 10,000 20,000 Feet.

Fig: 6 ... 2 Inches = 1 Mile.
Mile 0 ¼ ½ ¾ 1 Mile.

Fig: 7 ...... 1 Inch = 1600 Feet.
Feet 1000 500 0 1000 2000 3000 4000 Feet.

Fig: 8 .... 1 Inch = 3000 Feet.
Feet 1000 500 0 1000 2000 3000 4000 5000 Feet.

Fig: 8.



PORT OF NEWCASTLE.

G. H. HALLIGAN.

THOS KELL & SON LITH 40 KING ST COVENT GARDEN

PERMANENT OCEAN-CURRENTS.

The ocean-currents of the Western Pacific in the southern hemisphere are shown in Fig. 1, Plate 5, which has been prepared from the Admiralty current-charts. It will be seen that the current flowing to the north-west, which is caused by the south-east trade-winds, bifurcates at or near New Caledonia: the northern part passes through Torres Strait into the Arafura Sea and thence to the Indian Ocean; the southern branch strikes the Australian coast about Hervey Bay, is deflected southward, and flows along the New South Wales coast as a southward current till it meets the eastward current of the roaring forties coming through Bass Strait. The superior strength and volume of the eastward stream then pushes the southward current to the east till it meets the western shore of New Zealand, along which it flows northward and merges again into the general Pacific current at the most northerly point of that island. On the New South Wales coast the surface current in the offing has a speed of 1½ to 2 knots per hour, and at all the salient points, from Point Danger to Jervis Bay, its speed and direction have been observed.

On the littoral the speed is, of course, diminished, and the direction often reversed, on account of the current meeting headlands of varying form. The effect of the contour of the shore-line is shown in *Figs. 2*, which indicate how a current may be deflected or reversed according to the concave or convex form of the headland on its northern or southern side,[1] and on the coast of New South Wales there are several examples of each of these conditions.

In *Fig. 2a* are represented the conditions which control the sand-movement at the Richmond, Nambucca, Macleay and Merimbula Rivers, and at Curl Curl, Manly, and Narrabeen Lagoons near Sydney. In each case the projecting headland or reef to the south causes a reversal of the southward current, which then flows north again along the beach, carrying the sand with it. These counter-currents are necessarily weak and therefore much influenced by the winds, so that it is often difficult to unravel the apparent tangle of results obtained by casual observations at various seasons of the year, unaccompanied by simultaneous records of wind-velocity and barometric readings. Without going into details of all the observations recorded, a study of the topography of the coast will prove that the sand at the places named does travel to the north, for

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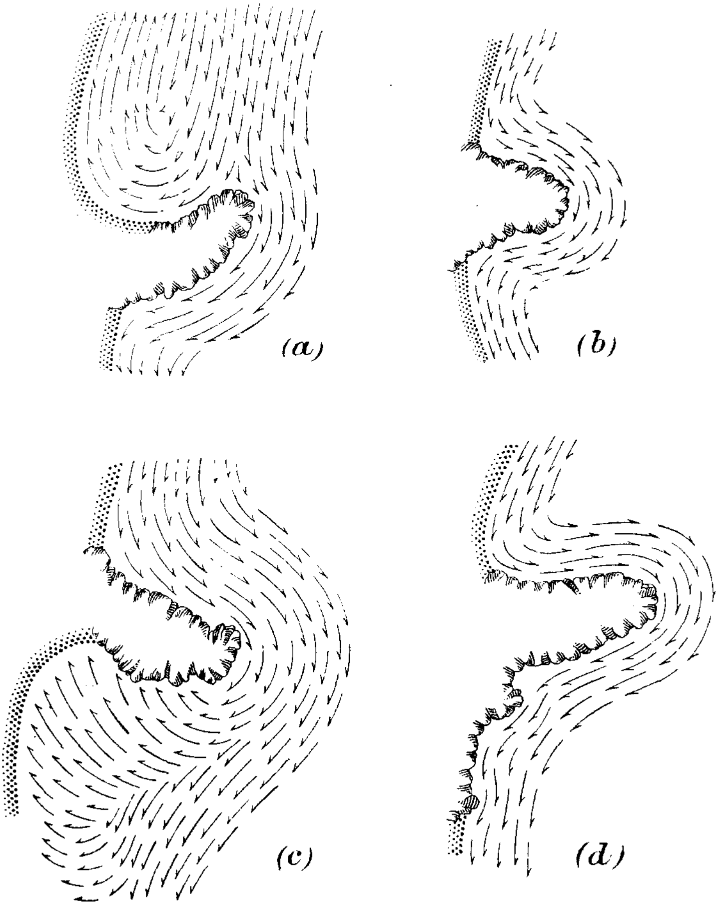
[1] G. H. Halligan, "Sand Movement on the New South Wales Coast," Proc. Linnean Society, N.S.W., vol. xxxi, p. 623.

the river-mouths are invariably forced against the headland at the northern end of the beach, often flowing parallel to it for a considerable distance; and this could not occur if the sand travelled from the north. The entrances to Curl Curl and Narrabeen Lagoons, which

Figs. 2.



are occasionally opened to the sea by flood-water, are always closed by sand advancing from the south.

The current-movements when the southern side of a headland is concave are indicated in *Fig. 2c*, such conditions being found at the Tweed and Manning Rivers, at St. George's Head and Disaster

Bay on a large scale, and at Deewhy Lagoon, near Sydney, on a smaller scale. The course of the current when the projecting headland is at right angles to the coast or trends southward is shown in *Figs. 2b* and *2d*. A little more convexity, or a slightly increased length of the headland in the case of the last figure, would result in a counter-current as shown in *Fig. 2a*.

The cause of the counter-currents at the Tweed and Manning Rivers and at Deewhy Lagoon, near Sydney, is that each has a projecting headland to the north with a concave curve to the south, as shown in *Fig. 2c*.

In these cases the return current cannot extend for many miles, as the main southerly stream is constantly endeavouring to maintain its supremacy, and the vortex behind the headland is soon filled in.

In the vicinity of the Manning River the return current extends for about 8 or 10 miles below Crowdy Head, and at this point the stream is very uncertain and sluggish. At Farquhar Inlet to the Manning the sand accumulates from the north or south as the wind prevails and influences the current which carries the sand.

MONSOONAL OCEAN-CURRENTS.

On the coast of New South Wales between Point Danger and Jervis Bay the prevailing wind is from the north-east quadrant, and is monsoonal. In the early summer months—October to December—it blows at 8 to 20 miles per hour; during January and February it is more persistent and frequently attains the force of a moderate gale; and it practically dies away at the end of March or early in April.

An analysis of the wind-records at the Sydney Observatory for the period 1894–1903 is given in the Table on p. 132, from which it will be seen that though the north-easterly winds prevail when all winds for the period are considered, they are in the minority when only gales or strong breezes over 20 miles per hour are recorded.

Practically the same results have been obtained from observations extending over a similar period at the Clarence River.[1] The amount of wind in miles from each point of the compass, i.e. the total travel of the atmosphere (obtained by multiplying the speed of the wind in miles per hour by the time of its duration) in any

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[1] G. H. Halligan, "Sand Movement on the New South Wales Coast," Proc. Linnean Society, N.S.W., vol. xxxi, pp. 619–639.

WIND-RECORDS AT SYDNEY IN HOURS: AVERAGE OF YEARS 1894–1903.

	All Winds.				Above 11 Miles per Hour. Gentle Breeze.			
	N.E.	S.E.	S.W.	N.W.	N.E.	S.E.	S.W.	N.W.
Yearly average .	2,588	1,967	2,315	1,860	116·1	108·5	89·6	29·6
Proportion	1·37	1·05	1·24	1·0	3·91	3·66	3·02	1·0
Ratio of easterly to westerly winds .	1·09		1		1·88		1	

	Above 20 Miles per Hour. Strong Breeze.				Above 30 Miles per Hour. Moderate Gale.			
	N.E.	S.E.	S.W.	N.W.	N.E.	S.E.	S.W.	N.W.
Yearly average .	47·4	57·9	59·6	18·4	1·2	13·7	23·5	6·8
Proportion	2·58	3·13	3·24	1·0	1·0	11·5	19·58	5·66
Ratio of easterly to westerly winds .	1·35		1		1		2·03	

direction for each month for the 24-year period 1883–1906, is averaged in the following Table[1]:—

TOTAL TRAVEL OF ATMOSPHERE IN MILES.

Month.	S.	S.W.	W.	N.W.	N.	N.E.	E.	S.E.
January .	1,655	433	344	172	296	2,358	1,355	995
February .	1,349	347	263	121	283	2,018	1,112	1,061
March . .	1,345	434	422	230	318	1,618	1,022	1,083
April . .	1,157	844	1,093	398	354	957	510	467
May . .	950	994	1,794	573	312	432	192	359
June . .	624	1,008	2,884	982	414	223	186	287
July . .	807	1,139	2,937	876	365	191	239	296
August . .	999	930	2,351	816	383	506	304	362
September .	873	812	1,815	683	452	974	533	456
October . .	1,274	674	1,210	673	463	1,501	900	704
November .	1,516	508	528	316	364	1,999	1,086	922
December .	1,590	354	392	272	333	2,121	1,423	959
Total . .	14,139	8,477	16,033	6,112	4,337	14,898	8,862	7,951

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[1] H. C. Dannevig, "Coastal Winds and their Influence upon Fish," Proc. Royal Society, N.S.W., vol. xli, 1907.

It will be seen that, with the exception of the westerly winds, which have no great influence on the coast of New South Wales, the north-easterly are the prevailing winds, as regards number, wind-mileage, and duration.

The hardest gales are from the south-east and south-west, and as the wind veers to the east when the anti-cyclone passes, and from that quarter is also directly onshore with unlimited "fetch," it is from there that the worst seas come. The southerly winds rarely last more than 3 days, but cases are on record where gales from that quarter have extended over 7 days, with rough seas all along the coast.

It will be interesting here to note the observed effects of the various winds on the ocean-currents and on the sand-movement on the coast.

The north-east wind, blowing in the same direction as the ocean-current, tends to accelerate it, and also to increase the velocity of the counter-currents. In consequence of this the greatest sand-movement occurs on the beaches between October and March, whether the movement is north or south; and the result is that during that period more sand is conveyed to the river-entrances to form bars and shoals.

The southerly winds are next in importance as regards number, duration, and wind-mileage; but as they blow in the opposite direction to the ocean-current, a large part of their energy has to be expended in retarding, stopping, and reversing the current before the effect becomes a factor in sand-transportation. These winds, however, have an important indirect effect, which will be referred to later, upon the formation of bars. They tend to accelerate the counter-currents where such exist; but this effect is largely overcome by the retardation of the main southward current, which, of course, lessens the speed of the counter-currents; so that the ultimate effect of the southerly winds upon sand-movement is much less than would appear at first sight.

During February, 1908, the Author successfully measured the current-velocity off the entrance to Newcastle harbour in a hard southerly gale which had been blowing almost continuously for 5 days. The wind-velocity at the time was 60 miles per hour, the height of the waves from trough to crest was 27 feet, and the observations were made at the low-water slack tide. The results may be regarded as the maximum disturbance due to southerly winds on this coast, such violent and persistent gales being of rare occurrence.

The surface velocity during calm weather was $1\frac{1}{4}$ knot per hour to the south, but during this gale the speed was 0·9 knot to the north, and at a depth of 18 feet the speed was 0·3 knot, still to the north. Two days after the gale had abated, the current resumed its normal speed and direction. Up to the present, no periodic observations during a southerly gale have been taken, but such data would be interesting and valuable, as showing the retarding effect of wind upon flowing streams. The difficulties in the way are not insurmountable, but the work is by no means pleasant.

From this it may be concluded that, even during the most violent gales from the south, the current is reversed only during the period of the blow; and as these storms are of rare and uncertain occurrence, their effect upon sand-movement *per se* cannot be large. On the other hand, the northerly winds increase the speed of the current and blow for the longest period, and so must have the largest effect upon the travel of sand on the beaches.

Dr. W. B. Dawson, M. Inst. C.E., Superintendent of the Canadian tidal surveys, makes the following statement:—[1]

> "It would be quite erroneous to suppose that the wind always causes a drift in its own direction. On the contrary, the set is primarily due to the nature of the current; and if it has any definite direction of its own, owing to the tide or other causes, it takes a strong wind a considerable time to overcome this, even with currents such as these, which do not exceed one knot. For example, on anchoring on June 18th, the wind had' been N.E. at 20 miles an hour for about 4 hours; yet the current set strongly N.N.W. or into the windward quarter."

Further examples of this are given by Dr. Dawson from the experience of fishermen while at anchor.

TIDES.

The range of spring-tides on the New South Wales coast is 5½ feet, and of neaps 3½ feet, and the crest of the tidal wave is approximately parallel to the coast. In consequence there is no appreciable tidal current up or down the coast, so that this may be left entirely out of the question as regards sand-movement on the littoral.

An examination of twenty-one of the more important river- and lake-entrances on the coast shows that in seven cases the outlet is forced to the northern end of the beach by sand-movement, and in

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[1] "The Currents on the South-Eastern Coasts of Newfoundland, and the Amount of Indraught into the larger bays on the South Coast," p. 11. Ottawa, 1904.

fourteen cases it is forced to the south. Travelling from north to south the following conditions occur:—

Tweed River	forced to the	North.
Richmond	,, ,,	,,
Clarence	,, ,,	South.
Bellinger	,, ,,	,,
Nambucca	,, ,,	North.
Macleay (old entrance)	forced to the	,,
,, (new ,,)	,, ,,	South.
Hastings	forced to the	,,
Camden Haven	,, ,,	,,
Manning	,, ,,	North.
Port of Foster	,, ,,	South.
Newcastle	,, ,,	,,
Lake Macquarie	,, ,,	,,
Tuggerah Lake	,, ,,	,,
Lake Illawarra	,, ,,	,,
Shoalhaven	,, ,,	,,
Moruya	,, ,,	,,
Tuross	,, ,,	North.
Wagonga	,, ,,	South.
Bermagui	,, ,,	,,
Merimbula	,, ,,	North.

A study of these facts leads unmistakably to the conclusion that sand-movement on this coast is, below high water, governed entirely by the direction of the littoral current. The heaviest seas are caused by southerly or easterly winds, and the prevailing wind is from the north-east; therefore, as the sand-movement is sometimes to the north and sometimes to the south, it is manifest that neither of these can be the dominant factor. The wind, in so far as it increases or diminishes the speed of the ocean-current, has a greater or less effect on sand-movement, but *per se* it can have no effect whatever. Sir John Coode, in his Paper on the Chesil Bank,[1] says: "... the ultimate movement of shingle is always found to be in the same direction as, and never against, the heaviest seas; ..." At the Chesil Bank, on the north-east side of Lyme Bay on the south coast of England, the ocean-current is purely tidal, and so changes in direction every 6 hours; the storm-wind that happens to be blowing in the same direction as the current raises the sea, which in turn stirs up the shingle, and the current, accelerated in speed by the wind, moves this along the beach.

The prevailing wind at Lyme Bay is also the wind which causes the highest tides and the largest onshore waves, and it blows from

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[1] Minutes of Proceedings Inst. C.E., vol. xii, p. 532.

the south-south-west; but the movement of shingle along the Chesil Bank and in the bay generally is not in the direction of the prevailing wind but varies in different places and follows more nearly the set of the flood-current.[1]

In New South Wales, as before stated, there is no flood-tide current, but an ocean-stream always in one direction and with but slightly diminished or increased velocity due to the winds; it is this current, in the Author's opinion, that must dominate the movement of sand on the littoral.

The function of the storm-wave is not to move the sand and shingle along the beach, but to tear the beach down and convey the sand seaward to a point where the agitation is less violent, or where the offshore current, created by the onshore wind, is not strong enough to move it farther out.

It is only on rare occasions, and then only for a short time, that the wind is sufficiently violent to cause waves to break obliquely on the beach, and these winds on this coast are as often from the north as from the south. There is therefore nothing in normal wave-action *per se* to cause sand to move laterally on the beach. As the large majority of waves break normally on the shore, their function is to move the sand from a short distance above high water to a short distance below low water, or vice versa; and it is during this movement, when the sand is more or less violently agitated, that the current is enabled to transport it in the direction of its flow.

Sir John Coode's statement as to the ultimate movement of shingle should be qualified by the addition of the words "on a shore where there is no continuous ocean-current in one direction."

The point which the Author wishes to make is that it is the current and the current only which causes lateral movement of the sand on the littoral. Where no continuous current exists, the present wind may cause a current sufficiently strong to move the sand, which has been stirred up by the waves, in the direction in which that wind is blowing. The sand may then be said to move in the same direction as the heaviest seas or in the direction indicated by the wind-vane; but it is not correct to say that it is the heavy sea or the wind-vane that causes it so to move. On this coast there are northerly and southerly gales, and onshore and offshore gales, and, as already pointed out, the southerly blows do at times retard, stop, or even reverse the prevailing southward current and thus stop temporarily the travel of sand; but at any one place on the coast the general direction of sand-movement is always

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[1] W. H. Wheeler, "Tidal Rivers." London, 1893.

the same. This has been shown so often by measurement and observation as to be beyond all question.

At every salient point the current is to the south, the speed ranging from $1\frac{1}{4}$ to 2 knots per hour between Point Danger and Jervis Bay, and slightly less between the latter place and Gabo Island. Standing on one of these headlands on a bright day, one may often see sand close to the rocks, held in suspension by the water; and by throwing in a piece of sea-weed a distinct southward movement of the water may be detected. The sand in the bays and inlets on the coast must thus work its way gradually around all projections, across river-entrances, and over reefs, until ultimately it meets the great eastward current from the Antarctic Ocean previously referred to. Whence this sand comes and whither it goes need not be discussed here: it is a subject sufficiently important to be treated in a separate Paper.

Mr. L. M. Haupt, in a Paper[1] read in 1890 before the American Society of Civil Engineers, said he believed it would be found that the unceasing action of the breakers upon a receding shore-line, as affected by the direction of the flood-tide and littoral currents, was far more effective than the prevailing winds.

He continued:

> "The coast of New Jersey from Sandy Hook to Cape May has been selected for investigation. Here, if the wind-wave theory be correct, and especially if the movement be due to the more violent gales from the north-east, as asserted, the resultant travel of the beaches should be uniformly to the southward; or from whatever quarter the maximum wind force may proceed, the sands should doubtless move to leeward, but always in the same direction for wind from the same quarter. It would seem anomalous, therefore, to find, as a matter of fact, that from a certain point on this coast-line the inlets and beaches are traveling northward, and at other points southward. But when it is noted that these directions correspond with those of the flood tide along this shore, it indicates more than an accidental coincidence."

On the coast-line referred to, there is no definite ocean-current, but, as in many, if not all, similar cases, the current of the flood-tide takes its place.

Many other confirmations of these observations could be quoted if more were needed, but it is sufficient for the present purpose to say that on the coast of New South Wales not one observation can be shown where sand or beach-gravel is moved, except temporarily, in any other direction than that of the littoral current.

It is a matter of common knowledge among pilots and others,

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[1] "Littoral Movements on the New Jersey Coast, with remarks on Beach Protection and Jetty Reaction," Trans. Am. Soc. C.E., vol. xxiii, p. 124.

confirmed by records in the Public Works Department, that during the summer months, when the north-east winds are strongest and accelerate the ocean-current, those bars at the entrances to all rivers at the southern ends of beaches carry less water than during the winter season; while the opposite effect is observed at bars at the northern ends of beaches.

SAND IN THE ESTUARIES.

The sand which accumulates in the estuaries on this coast and forms the bars at the entrances must come from one of two sources. It must have been carried down by the floods and freshets—helped, of course, by the ebb-tide—from the upper portions of the river, or it must have come from the sea-coast and have been carried in by the flood-tide.

The rivers on the coast of New South Wales, although in some cases possessing large catchment-areas, are for a considerable portion of their length only arms of the sea. In the rare and uncertain periods when heavy rain occurs, a small quantity of sand is brought down from the thickly wooded hills, and is, of course, deposited in the upper reaches of the salt-water stream. From here to the ocean there is no fall in the river-bed, and the banks are generally 2 to 5 feet above high water. It is clear that no sand, such as is found in the estuary, can be conveyed in a stream having so flat a gradient; even the fine mud which is held in suspension for a considerable time is almost all deposited before it reaches the ocean. Another sign that sand does not travel in any quantity down the river-bed, is that the bottom is invariably covered with a dense growth of sea-weed (mainly *Posidonia sp.*) for several miles from the mouth, and this could not occur if much sand were travelling over it. As a matter of fact, the end of the sea-weed is always regarded as the upper limit of the moving sand, and is a good guide when measuring its rate of advance.

Even a very casual examination of the sand will show that it comes from the beach in the immediate vicinity of the entrance. It is composed of comparatively coarse, clean, rounded grains of quartzite, entirely dissimilar to the alluvium which characterizes the river-bottom, and in the majority of cases it has its origin in rocks of a formation totally different from that of the catchment-area.

TIDAL CURRENTS.

At most of the river-entrances the tidal current has a velocity of 2 to 3 knots per hour, with a range of 5½ feet at spring-tides and of 3½ feet at neaps. As the rainfall is very uncertain, and the discharge takes place at the head of the salt water, which is always a considerable distance from the sea, it is only on rare occasions that the ebb-tide current is appreciably increased, and still more rarely is the flood-tide current entirely obliterated. Under normal circumstances, or, in other words, under those circumstances for which harbour-entrance works must be designed, the quantity of upland water which reaches the ocean, even in the largest coastal rivers, is insignificant, and may safely be neglected when calculating the effect of scour in keeping the entrance clear of sand. That this is so is abundantly clear from current-velocity measurements and from tidal observations at the river-mouths. The velocity of the ebb-stream, except immediately after heavy rain on the catchment-area, is never greater than that of the flood-tide, and the densities of the water at the various stages of the tide are rarely appreciably different. It is thus obvious that no assistance from upland water can be relied upon at ebb-tide, to scour away the sand brought in by the flood-tide.

When the sand, put into suspension by the waves, and slowly moving with the current along the beach, at length reaches an inlet, it is carried into the estuary by the flood-tide. At slack water this sand is deposited within the estuary, and as there are no waves to agitate the sand inside the estuary, the ebb-current, which, as before stated, is only just equal to the flood-stream, is unable to remove the whole of the sand which has been brought in. An accumulation thus takes place, and is the cause of all the trouble to the harbour-engineer.

It is quite clear that, the narrower the entrance, the stronger the flood-tide will be; and the stronger the flood-tide, the more sand will be carried into the estuary. The velocity of the flood-tide can be increased only by contracting the entrance, and decreased only by widening the entrance, and it therefore behoves the harbour-engineer to keep the entrance as wide as the circumstances will permit. If possible, the width should be so determined that the velocity of the ocean-current flowing past shall be greater than the velocity of the flood-tide between the ends of the breakwaters. The sand will then be carried past in the stronger stream and will be harmless. If these conditions can be obtained, all dredging within the estuary becomes a permanent improvement, and training-walls become necessary only where the channel is to be moved or directed for local reasons.

Where the sand-movement is to the south it will be necessary to build the northern wall out to such a distance as will ensure the current carrying the sand clear of the southern wall, where such is necessary.

Except in the case of the Macleay River new entrance and the Bellinger River, no second wall will be required, the rocky and broken nature of the southern shore being the best means of breaking up the sea that could be devised.

Where the sand moves northward, the converse obviously obtains.

It will, of course, be necessary to design the entrance so as to produce a sufficient degree of tranquillity within the estuary, and as this may involve contraction of the width, it is a matter for decision what amount of sand-dredging the tranquillity is worth. Each set of circumstances must be judged on its merits, the one fundamental principle being kept in mind that, the wider the entrance, the less sand will be taken in by the flood-tide. The scour of the ebb-tide —that will-o'-the-wisp of the harbour-engineer—may be wholly neglected, as under any circumstances it does not come into operation till the harm is done: but if the entrance is made wide enough, it is not wanted, and serves only to worry the mariner.

NATURAL HARBOURS WITH WIDE ENTRANCES.

As no artificial harbours on the New South Wales coast have been carried out on the principles here stated, it becomes necessary to refer to some of the natural harbours in order to demonstrate the truth of them. Fortunately, there are several of these available, and they are shown in Figs. 3, 4 and 5, Plate 5.

The entrance to Sydney Harbour (Fig. 3) is 4,900 feet wide at its narrowest part and has a depth of 90 feet. The velocity of the spring-tide current is about 1 knot per hour and of the ocean-current $1\frac{1}{4}$ to $1\frac{3}{4}$ knot, to the south. The north head projects farther to the east than the south head, so that the tendency of the ocean-current is to convey the sand, held partly or wholly in suspension, past the entrance, and as the velocity of the tide is so much less than that of the littoral current, no sand enters the harbour under normal circumstances, the depth thus remaining unaltered from year to year. During southerly and south-easterly gales, the ocean-current is temporarily retarded or reversed, and the sand then in suspension may be carried into the harbour and deposited where the current-velocity lessens. This occurs in the eastern channel between Sow and Pigs Reef and Camp Cove, and in middle harbour between Balmoral and Clontarf. The quantity so brought in is not large, for if dredged to a mean depth of 32 feet at low water, the eastern channel, which is about 800 feet wide, shoals to 29 feet in about 10 years, which represents about 12,000 tons of sand per annum. This sand consists of clean, well-rounded grains of quartzite, similar to the beach-sand to the north and south of the entrance; it is mixed with broken shell and undoubtedly comes from the ocean-beach and not from up the harbour.

The entrance to Botany Bay (Fig. 4) is 3,467 feet wide, with a depth of 60 feet, and the maximum velocity of the tidal current is 1¼ knot per hour. The velocity of the ocean-current at Cape Banks is 1¼ to 1½ knot, so that this entrance may be said to be as near to the ideal width as possible. There is, however, so little margin between the velocities of the tidal and littoral currents that a comparatively moderate gale will reverse the advantage which the littoral current possesses, and sand will be carried in more often, and in larger quantities, than if the entrance were wider. At the entrance to Cook's River, at the north-west corner of the Bay, the sand accumulates slowly, but soundings taken recently do not show any general shoaling of the Bay when compared with those taken by Captain Cook in 1770.

The entrance to Jervis Bay is shown in Fig. 5; it is 11,590 feet wide, with a depth of 120 feet. The tidal current at the entrance is about ½ knot per hour, while the ocean-current at Point Perpendicular is 1½ knot to 1¾ knot. As in Botany Bay and Sydney Harbour, the northern headland projects farther seaward than the south head, and all the sand held in suspension by the ocean-current is carried past. That such sand is carried past the entrance to Jervis Bay is clear from a consideration of the following facts. Current-observations by the Author show a movement of the beach sand southward at Crookhaven Head, and again a decided southward movement below Disaster Bay. The sand below Disaster Bay must come from somewhere, and as there is no recent accumulation between Crookhaven Head and Point Perpendicular, it is justifiable to assume that the sand is carried, wholly or partly in suspension, past the Jervis Bay entrance.

Soundings taken by Captain Sidney, R.N., in 1868, and again by the Admiralty in 1894, show no appreciable change of depth in Jervis Bay and no increase or decrease of depth at the entrance.

It must be quite obvious that the ebb-tide scour can have nothing to do with maintaining the great depth at the entrance to this bay. Neither can the sea have any effect in heaping up the sand to form a bar, nor can the upland water, or the absence of it, have any effect one way or the other. Though the bay is wide and the current is so sluggish as to be hardly appreciable, no training-walls are required to deepen channels or fix them, no dredging is necessary, and times of flood or times of drought make no difference whatever in the depth.

In the Author's opinion this can be due only to two causes: first, that headland upon which the ocean-current first impinges projects farther to the east than the other; and secondly, the entrance is wide enough to ensure the flood-tide current being less than the ocean-current, so that no sand can be carried in to cause trouble to the engineer.

There are several other places on the coast where similar conditions exist, but enough has been said to demonstrate the Author's contention that under the conditions which exist on the coast of New South Wales, wide entrances are required and not the narrow entrances which so many engineers have advocated in the past.

The following Table shows the minimum, maximum, and mean depth, the area of watershed, and the area of tidal compartment for each of sixteen of the principal bar harbours of New South Wales during the period June, 1907, to July, 1909. The depths are taken by the pilots every day, if the weather and sea permit, on most of the larger entrances, and twice or three times a week at the smaller or less important places. The returns are sent in to the Public Works Department, where the Table has been compiled.

The absence of any connection between the area of the watershed of the river and the depth of water on the bar at once strikes the observer. The largest catchment-area is that of the Clarence River with 8,505 square miles, and the smallest is that of Crookhaven River, with only 40 square miles; and yet they have the same mean depth of water on the bar, as indicated by 2 years' daily soundings—in spite of the expenditure of £462,000 on the Clarence River entrance and of £9,000 at Crookhaven.

The Richmond River with 2,683 square miles of catchment-area has the same depth on the bar as Wagonga River with but 52 square miles, though the Richmond entrance has had £422,000 expended on it in breakwaters, training-walls and dredging, and Wagonga not one penny. Similar discrepancies will be found on closer examination of the Table, all going to show that the quantity of upland water, even in the largest rivers, is not sufficient to cause any permanent

PARTICULARS OF THE PRINCIPAL BAR HARBOURS OF NEW SOUTH WALES.
June, 1907, to July, 1909.

Name.	Minimum Depth.				Maximum Depth.				Mean Depth.				Area of Water-shed.	Area of Tidal Compartment.
	Bar.		Crossing.		Bar.		Crossing.		Bar.		Crossing.			
	Ft.	Ins.	Ft.	Ins.	Ft.	Ins.	Ft.	Ins.	Ft.	Ins.	Ft.	Ins.	Square Miles.	Acres.
Tweed . . .	4	0	3	8	9	6	9	1	6	5	6	0	418	5,000
Richmond . .	8	0	9	6	11	6	14	3	10	3	11	6	2,683	6,800
Clarence . .	7	9	9	6	13	9	13	6	11	4	11	2	8,500	34,000
Bellinger . .	2	6	2	9	8	6	7	0	5	5	5	0	479	1,640
Nambucca . .	3	3	3	7	8	0	7	0	5	4	5	3	552	2,730
Macleay. . .	6	0	..		9	6	..		7	10	..		4,581	3,750
Hastings . .	6	0	3	0	7	6	8	0	6	6	5	11	1,389	6,400
Camden Haven.	1	7	1	6	4	10	6	0	3	4	4	7	238	7,240
Manning . .	4	0	5	0	9	0	10	0	7	4	6	10	3,164	6,800
Cape Hawke .	1	3	1	0	6	10	7	10	3	10	5	3	514	
Newcastle . .	21	3	19	6	22	6	25	0	22	0	22	8	8,269	10,280
Lake Macquarie	3	6	3	6	6	0	5	0	4	3	4	3	291	
Crookhaven .	9	0	3	4	13	0	7	3	11	3	5	2	40	
Bateman's Bay .	4	6	..		7	6	..		5	10	..		696	
Moruya . . .	6	2	5	2	8	8	8	0	7	2	6	10	609	
Wagonga . .	5	0	6	0	12	0	9	0	10	4	7	8	52	1,500

deepening of the entrance. It may, in fact, be wholly eliminated when designing the entrance-works, any possible good that may occur in times of flood being only at rare and uncertain intervals, and the effect only temporary; while, if the entrance is kept wide enough to ensure a low velocity for the flood- and ebb-tide, no congestion need be feared.

In order to ascertain if any definite connection could be traced between the area of the tidal compartment and the width of the entrance, the following Table was prepared:—

Harbour.	Width of Entrance.	Area of Tidal Compartment.	Ratio.
	Feet.	Acres.	
Sydney	4,900	13,775	1 : 2·81
Botany Bay	3,467	14,246	1 : 4·11
Jervis Bay	11,590	28,326	1 : 2·44

It will be seen that at Sydney there is 1 foot width of entrance to every 2·81 acres of water, at Botany Bay 1 foot to 4·11 acres, and at Jervis Bay 1 foot to 2·44 acres. With the exception of Jervis Bay, none of these entrances is so wide as to allow dangerous seas to run far from the entrance, so that, if the Author's contention is correct, when designing future harbours a ratio of 1 foot width of entrance to 3 acres of tidal compartment may safely be allowed; but unless it is intended to saddle posterity with heavy bills for dredging, it would appear that the ratio should not exceed 1 to 4.

NARROW ARTIFICIAL ENTRANCES.

The areas of the tidal compartments being given in the previous Table, the width required on this assumption for any river on the coast may be calculated.

Thus the Manning River entrance, in the Author's opinion, should be 1,700 feet wide, and Camden Haven 1,810 feet wide, to allow 4 acres of tidal compartment to 1 foot width of entrance. The width in each case is, of course, the distance between the outer ends of the breakwaters, and not necessarily the shortest distance across the entrance.

The plan of the Manning River entrance (Fig. 6, Plate 5) shows both the works proposed in 1885 by the late Sir John Coode, parts of which have been carried out, and the scheme now proposed by the Author. In his Report, Sir John Coode refers in several places to "a true and uniform channel which would be maintained by a scour without the aid of dredging." On p. 9, he says, "I am of opinion that the scour may be relied upon to produce this result without the aid of dredging." From these and other references in the Report, it is clear that it was assumed that the velocity of the ebb-tide would be greater than that of the flood, for otherwise no effective scour in the direction desired could be possible. From information now available it is known that the velocity of the ebb-tide is greater than that of the flood-tide only during the rare, uncertain, and short periods when heavy rain falls on the catchment, and could not have any such effect as was anticipated. The very narrow width of 800 feet proposed by Sir John Coode would cause the velocity of the flood-tide to be much greater than that of the ocean-current, and all the sand which should drift past the entrance would be carried in, and only part of it be taken out again on the ebb. That part which was not taken out would go to form an inner crossing, while the remainder would be deposited at the outer end of the breakwaters, causing the familiar sand-bar.

Further, the design proposed by Sir John Coode does not take cognizance of a continuous ocean-current in one direction that is now known to exist. As before stated, the width of the Manning River entrance, to ensure 1 foot width of entrance to 4 acres of tidal compartment, should be 1,760 feet, but 1,500 feet has been adopted by the Author in order to obtain greater tranquillity within.

The small amount of dredging thus rendered necessary in the future is the price posterity will pay for the additional convenience which smooth water affords.

Having thus far shown the effect of wide entrances of Nature's design in preventing the ingress of sand to estuaries on this coast, it is now necessary to show the effect of contracted entrances, for comparison.

In Fig. 7, Plate 5, is shown the Richmond River entrance, where the breakwaters and training-walls have been carried out on the lines recommended by the late Sir John Coode in 1885. The breakwaters are not yet quite completed, the northern being 539 feet short of the full length recommended, and the southern still wanting 170 feet; but it is not anticipated that any very marked improvement will result when the walls are finished. The net result of the £422,000 expended to date on this entrance has been to fix the position of the bar, which formerly wandered over 5,000 feet of coast; and in so far as this is an improvement, the works have been a success. Something more, however, might have been expected from the expenditure of so large a sum on so small a place.

The area of the tidal compartment is 6,800 acres, as shown in the Table on p. 143, so that the width of entrance, in order to ensure the ocean-current being stronger than the flood-tide, should be at least 1,700 feet. The width recommended by Sir John Coode was 1,000 feet, and as carried out is 1,100 feet; and the result is shown in Fig. 7.

A large bank of sand of marine origin has been formed between the two breakwaters, about 2,000 feet from the entrance, and this bank is continually increasing and encroaching upon the channel, which it has now narrowed to about 200 feet. Through this contracted area the flood-tide rushes at the rate of 2 knots per hour, carrying its load of sand to the inner crossing. The ebb-tide carries part of this sand out again, and deposits it at the entrance in the form of a bar, and as a bank at the end of the northern breakwater. That this sand is fast filling up the estuary may be gathered from the figures supplied by the departmental annual reports.

During the 3-year period, June, 1906, to July, 1909, 252,040 tons of sand were removed by dredging from the bar and inner crossing, at a cost of £4,180, but no improvement is reported in the depth at either place at the end of the period; in fact, rather the reverse.

In the report for the year ending the 30th June, 1909, it is stated that, "Of the two remaining bar-dredges, the 'Antleon' and 'Tethys,' the services of the latter have been almost exclusively required to maintain a sufficient depth of water at the important entrance to the Richmond River." As the annual results obtained by the "Tethys" may be stated at 350,000 tons lifted and conveyed to sea, it will be seen that the maintenance of even the present unsatisfactory, if not dangerous, entrance will be a serious charge against the port for all time.

The expenditure, however, may not be thought too heavy if the experience so gained is properly used. It can now be seen that in a river where there is practically no permanent upland water, there cannot be any effectual scour by the ebb-tide. Floods and freshets are so rare and uncertain, and so short in duration, that their effects must be of quite a temporary character, and in the case under notice they certainly have not been sufficient to prevent the steady influx of sand to the estuary, notwithstanding the large catchment-area of the river. Under any circumstances it is certainly not sound practice to allow sand to come in and then design works to scour it out again. It would seem to be more sensible to prevent the sand from coming in at all, and this can be done, in the Author's opinion, only by adopting wide entrances of proper design.

At the Richmond River the present distance between the ends of the breakwaters is 1,170 feet, though the width of the entrance is 1,100 feet. It is still quite possible, of course, to convert this into a wide-entrance port by continuing the southern breakwater, say, 1,300 feet, with a slight curve to the north to assist the northward current. The effective width of the entrance would then be 1,700 feet so far as sand-movement is concerned, but the entrance would present many undesirable features. The most that could be said of such a scheme would be that it was making the best of a bad job.

The works at Newcastle Harbour (Fig. 8, Plate 5) are another example of the erroneous idea that contraction of the entrance causes a scour of the ebb-tide in a river where there is no permanent upland water.

The catchment-area of the Hunter River is 8,269 square miles, and the annual rainfall is about 36 inches, but the distribution of the fall is so unequal that a permanent flow of water is impossible, and it is rare to find any difference between the flood-tide and the ebb-tide velocity a week after a heavy fall of rain.

The area of the tidal compartment is 10,280 acres, so that to ensure 1 foot width of entrance to 4 acres of tidal compartment the width of the entrance would require to be at least 2,570 feet; but the present width between the breakwaters is 1,200 feet, and, as a consequence, enormous quantities of sand are brought in by every flood-tide, which have to be dredged out again at heavy expense. During the year ending the 30th June, 1909, 546,250 tons of sand were dredged on the bar, but no additional depth was reported; the width of the navigable channel was, however, thereby enlarged from 350 feet to 450 feet. The Chief Engineer for Harbours, when giving evidence a few months ago before the Public Works Committee, said: "The bar dredge was away for 80 days last year on other work, and during that time the bar shoaled from 22½ feet to 18 feet, which represents an accretion of about 2,700 tons of sand." On another occasion, the dredge removed about 38,000 tons of sand from the bar in 6 weeks, and the depth was 1 foot more than when it started. It is now proposed to extend the northern breakwater 420 feet "in order to stop the travel of sand into the entrance," but the proposal does not explain what is to become of the sand which is continually travelling south along the Stockton beach. It is admitted that it does not accumulate north of the northern breakwater, and it can only cross the entrance by first entering on the flood-tide and then going out on the ebb; so that it is difficult to see how any extension of the wall can be of use.

In short, it must be admitted that, in the only two cases on this coast where contracted entrances have been tried, the expected results have not been achieved.

At the Richmond and Hunter rivers the entrances are kept navigable only by continuous and costly dredging, and there is no hope of alleviation while the cause remains. The entrance-works were designed on the assumption that the ebb-tide current would be stronger than the flood-tide, and thus cause a scour which would convey to sea the sand brought in by the flood-tide. When two streams of equal velocity, volume, and duration flow alternately and in opposite directions in the same channel, there cannot be any resultant movement in any one direction; but when one of the streams has any advantage over the other, the resultant movement must be in that stream's direction. In the case of bar harbours, the flood-stream has the sand stirred up for it by the waves, and thus carries more in suspension than the ebb-tide, which must depend wholly on its velocity for the sand it can move; and this advantage is so considerable that the velocity of the ebb must be very much greater than that of the flood before it is overcome.

The resultant movement of the sand is thus in the direction of the flood-tide, and it accumulates in the estuary where the speed of the current slackens.

That the current-velocity of the ebb-tide and the flood-tide is equal on the coast of New South Wales has been proved by many hundred observations by the Author on almost every river on the coast.

CONCLUSION.

There yet remains much to be done in the way of observation of the coastal current of New South Wales before one may speak with certainty of its many peculiarities, but sufficient work has already been carried out to indicate its general direction and its influence on shore-formation. As the direction of the sand-movement is practically constant for any one locality, it becomes, in the Author's opinion, the dominant factor in the designing of harbour-entrances. The area of the watershed and the supposed scour of the ebb-tide, due to the upland water, may be eliminated, as may also the existence of a tidal current in the ocean. The number of controlling influences may thus be reduced to three:—

The speed and direction of the coastal current,
The area of the tidal compartment, and
The rise of spring-tides at the proposed entrance.

The problem thus becomes much simpler than on some other coasts where such favourable conditions do not exist.

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The Paper is accompanied by eight drawings, from which Plate 5 and the Figures in the text have been prepared.