CHAPTER 186

NUMERICAL MODELLING - AN AID TO ASSESSING FIELD DATA

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ABSTRACT

After the completion of 5 years of field measurements, complemented by extensive numerical modelling in 1974, the hydraulics of Cockburn Sound, Western Australia, are now understood in enough detail to allow the rate of exchange of water between the Sound and the ocean to be determined. Flow patterns in Cockburn Sound tend to be complicated by the superimposition of many driving influences, the most important being wind, but by using the output of a numerical model most of these patterns are predictable.

Current magnitudes within Cockburn Sound have not reduced so that the rate of dispersion of effluents released by the industrial complex on the eastern side of the Sound has not changed. However, flow rates through the southern entrance to Cockburn Sound have been reduced to between 30 to 45% of the rates which occurred prior to the causeway construction. This means that the mean discharge rate is now 570 m^3/sec through the causeway bridges compared to a rate of about 1500 m^3/sec before the causeway construction.

1. INTRODUCTION

The hydraulic and environmental conditions in Cockburn Sound, Western Australia (see locality map, Fig. 1), an area with a very small tidal range, have been the subject of intensive investigation since 1969 in order to assess the effect on Cockburn Sound currents of constructing a causeway, with two bridge openings, between Garden Island and the mainland. The causeway was constructed in the period 1971-1973 so that field data has been collected before, during and after completion of the project. However, because of the complexity of the driving forces which control currents in Cockburn Sound, much of the data collected before the start of 1974 appeared contradictory and there was still a large degree of uncertainty in the interpretation of the field data.

In 1972 some exploratory numerical modelling was conducted using 'System 21 - Jupiter', a general purpose system for studying two dimensional nearly horizontal flows which has been adequately described in the literature by Abbott et al (1). From these early numerical modelling runs, it appeared that the incomplete picture provided by the field data could be improved by detailed numerical modelling. Consequently, extensive numerical modelling of currents due to ocean currents, wind and tide were carried out both for currents caused by individual driving forces and for selected combinations of driving forces during July-August 1974.

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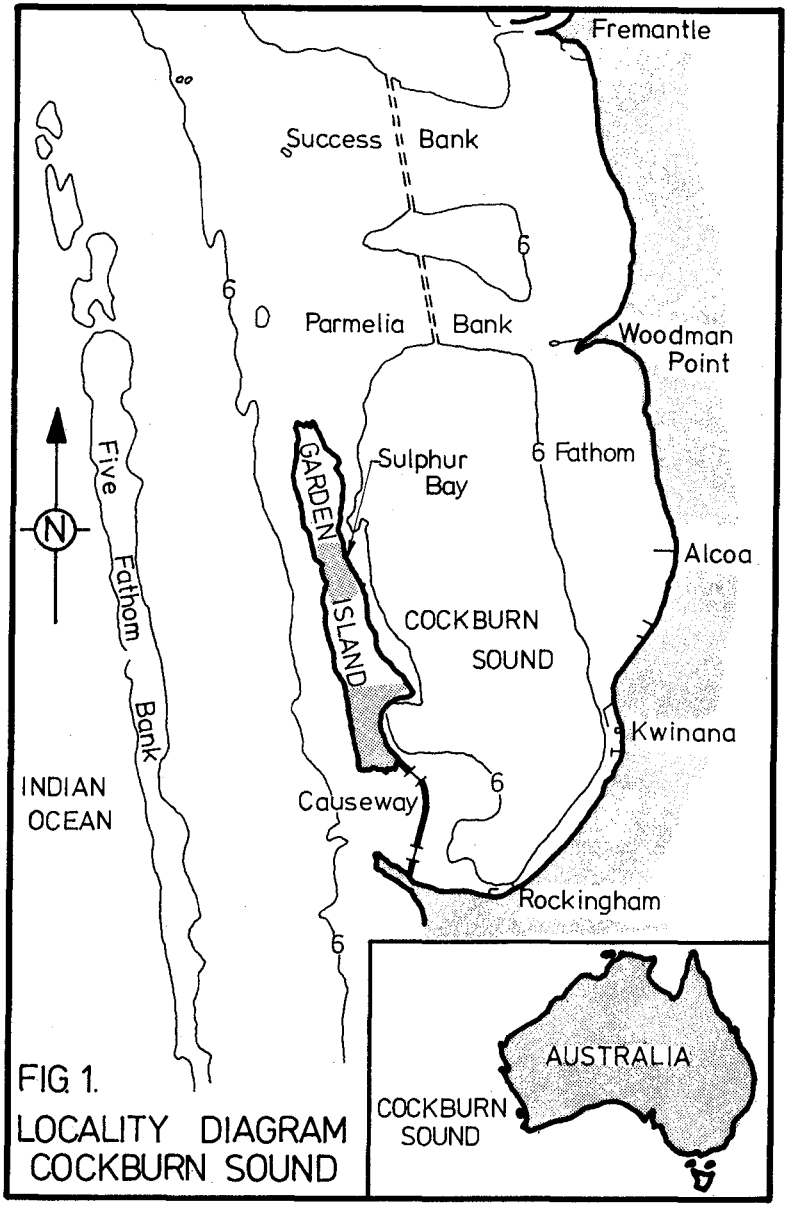


FIG. 1.
LOCALITY DIAGRAM
COCKBURN SOUND

In all, 26 modelling runs were executed in order to compare water movements in Cockburn Sound before and after the causeway construction, in particular in areas where field measurements had given rise to ambiguities.

2. FACTORS CAUSING CURRENTS IN COCKBURN SOUND

Currents in Cockburn Sound are caused by the combination of several driving forces which may be sub-divided into primary and secondary groups. The available information shows that water exchange between Cockburn Sound and the ocean is predominantly governed by wind induced currents within Cockburn Sound and by oceanic currents moving north or south along the West Australian coast. Secondary influences are tides, surges during storms, long waves and short period waves. The current patterns and magnitudes are also largely influenced by bottom topography.

The magnitude of wind induced currents in an open body of water are typically up to 3% of the wind velocity. When considering wind effects on an enclosed or semi-enclosed body of water with a complex bottom topography, the cause and effect relationship between the wind and the water becomes quite complex. Consequently, the water current cannot be inferred directly from the wind velocity and must either be directly measured or theoretically determined by the use of modelling.

The oceanic current is derived from the West Australian current which is a large scale current present in deep water off the West Australian coast. See Neumann (2) for a more complete description. It is partially driven by other currents circulating in the Indian Ocean and is part of a larger oceanic system which is the result of a balance between geostrophic, inertial and prevailing wind driven currents. The oceanic current is then modified locally by :

(i) the effect of wind systems along the West Australian coast;

(ii) the intensity and rate of movement of atmospheric pressure systems;

(iii) nearshore bottom topography

to yield currents at the boundaries of Cockburn Sound.

Either of the primary currents may dominate the flow field and mask the effect of any other current. Generally, ocean currents tend to be persistent, their time scale being of the order of days and many explanations of observed water movements must make reference to this parameter for a satisfactory interpretation of the data. Wind induced currents are relatively easy to detect and can easily be correlated with wind data. Many of the observed flow rates and patterns can easily be explained in terms of wind induced currents, especially when the velocity field is predicted from a numerical model. However, for short duration strong winds there have been instances where current directions are observed opposite to the wind direction due to the predominence of the ocean current, or the presence of a seiche of 2-3 hours period. The natural frequency of seiching for Cockburn Sound in the north-south direction is $2\frac{1}{2}$ hours.

Tidal currents are of small magnitude because of the small diurnal tidal range, however, the exchange of water between Cockburn Sound and the ocean caused by the tide is basically steady from day to day resulting in about 3% of the volume of Cockburn Sound being exchanged daily.

Currents induced by long and short period waves affect small scale water circulation rather than gross exchange. These currents are most noticeable in the shallow Southern Flats area, particularly at the bridge openings while in the bulk of the Sound they are often not detected.

With the construction of the causeway, current patterns and magnitudes have changed, significant changes being confined mainly to areas within 1500 metres of the causeway.

3. FIELD MEASUREMENTS

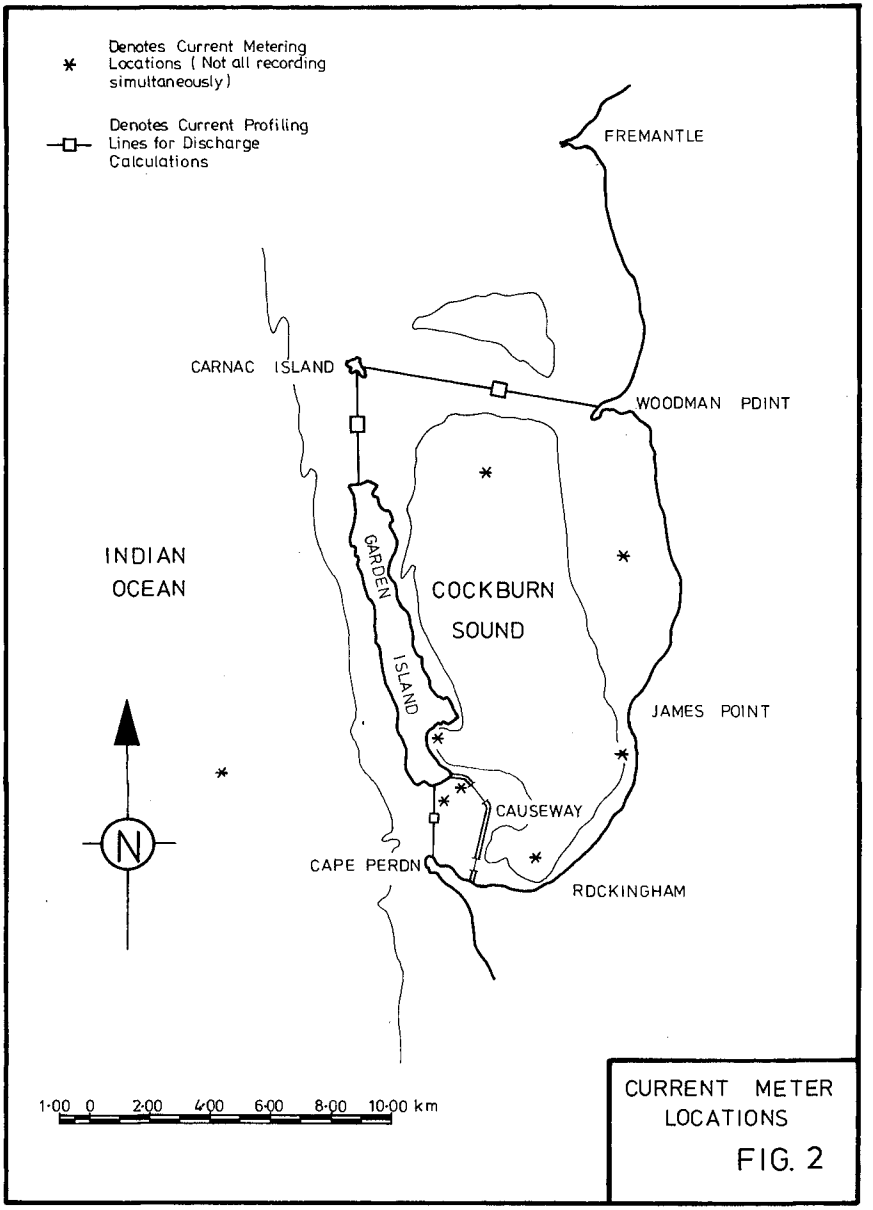
These measurements consist of

(a) Current Metering, which has been in progress for the full duration of the field measurements with current meters placed at the locations shown in Fig. 2 at various stages of the study. Unfortunately, conventional off the shelf meters, as used in this study, generally have two restrictions on their use. They have a threshold velocity of about 4 cm/sec so that they usually do not respond to the low velocities present in the deep waters of the Sound, and they tend to oscillate and give unreliable results if waves are present with periods greater than about 5 seconds. Consequently, most of the useable data has been confined to current measurements made across the Garden Island to Cape Peron gap.

These measurements were made in 1969-70 before the causeway and in 1974-75 after the causeway construction and form the basis for the quantitative assessment of discharges through the southern entrance to Cockburn Sound.

(b) Salinity-Temperature Metering, which was used at one metre depth intervals for about 30 points throughout Cockburn Sound. Measurements were conducted twice daily for periods up to 10 days in an attempt to track the motion of discrete bodies of water labelled by their salinity/temperature characteristics. Flushing rates estimated using this method were sometimes 5 times the rate estimated by other methods and indicated practically unchanged flushing rates before and after the causeway construction. The unchanged apparent flushing rates between 1971 and 1973 may be explained by current magnitudes after the causeway construction remaining constant through the intensification of a large scale circulation in the centre of Cockburn Sound. This occurred even though the nett discharge through the entrances to Cockburn Sound had changed significantly. Data using salinity metering has been ignored for any quantitative analysis, and no further data was collected after 1973.

(c) Float Drogue Tracking, which was used extensively up until 1974 with most of the tracking concentrated along the causeway route and within 1500 metres of the causeway. The main problem with the float drogues was wind drag on that portion of the float above the water surface. Also there is a partial integrating effect because of drag on the float as well as on the drogue vanes. Considering these factors the float drogues can only be expected to yield qualitative data in Cockburn Sound which is an extremely windy area.



CURRENT METER LOCATIONS

FIG. 2

(d) Dye Tracking, which consisted of instantaneously releasing a quantity (about 10 kg) of Fluoroscein or Rhodamine B and then tracking the dye patch from aerial photos and/or by a fluorometer mounted in a runabout. It was attempted to obtain quantitative data but the information was only used for descriptive purposes because of problems with instrument operation.

(e) Tidal data. Tide records are available continuously for the port of Fremantle and, as would be expected, short term tide recordings taken within Cockburn Sound correlate well with the Fremantle data. The predominating feature of the West Australian coast in the vicinity of Fremantle is the very small, diurnal tidal range. The tidal range rarely exceeds 0.6 metres and tidal velocities tend to be negligible in water depths greater than 5 metres. The average tidal range is 0.4 metres which results in about 3% of the volume of water in Cockburn Sound being exchanged daily by this mode.

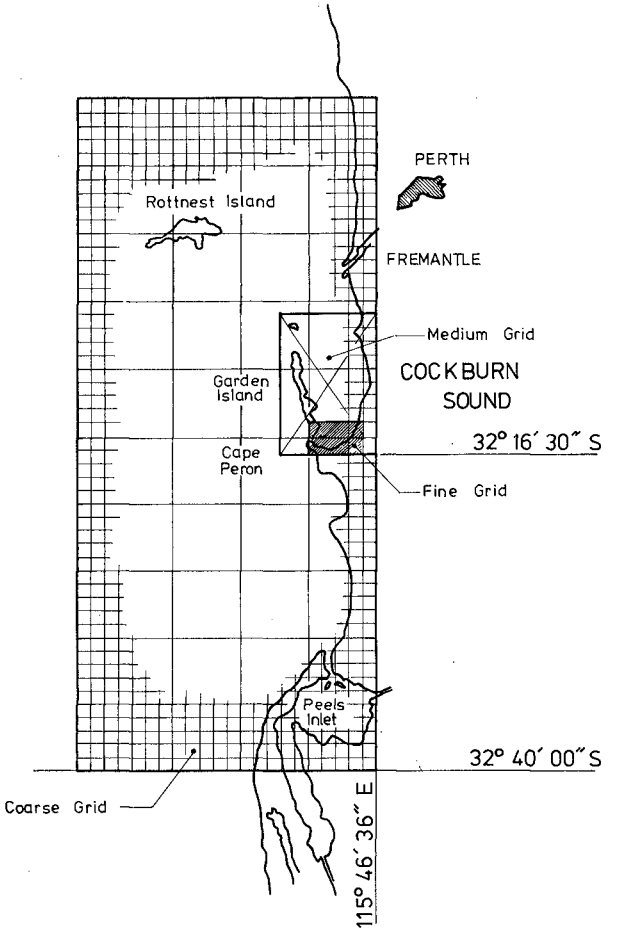
(f) Meteorological data. Wind and barometric pressure records were available from the Fremantle Port Authority and again the difference between observations of these parameters at Fremantle and within Cockburn Sound was negligible, except for a time lag in the wind, in particular in the arrival of the sea breeze. The wind data was necessary in estimating the component of water currents caused by wind shear and the barometric data usually explained any discrepancy between the predicted and observed tidal heights. It is also thought that the passage of intense pressure systems will induce seiching and water currents because of the 'inverted barometer' effect but it is difficult to isolate this phenomena when there are so many other driving influences present.

The overall picture presented by the collection of the above field data up to December 1973 was one of uncertainty and clarification was required, and it was thought that numerical modelling would be the method most likely to succeed.

4. THE NUMERICAL MODEL

Numerical modelling studies were made using System 21 'Jupiter', a computional system consisting of a set of computer routines with back up documentation which is used to construct a numerical model of any region of two dimensional nearly horizontal flow when presented with the hydrography of the region and operates the model from given initial and boundary conditions, wind velocities, atmospheric pressure differences, tidal-tractive forces, latitude and other external conditions as required. It provides output in the form of velocity and water surface level plots for selected regions on the complete computation field. A detailed description of the model may be found in Ref. (1)

In all, 26 computer runs were made using 3 different grid sizes with boundary conditions chosen to represent the most commonly occurring current generators. A very coarse grid (C) of 1 nautical mile spacing was used (Fig. 3) to include a sufficient ocean area so that the penetration of the oceanic current into Cockburn Sound could be reliably reproduced. Runs 1-4 were run on the coarse grid and were used as boundary conditions for medium grid runs involving the oceanic current. For these runs an oceanic current of 20 cm/sec was modelled for a real time duration of 13 hrs which was the time required to reach a steady condition.



MODEL GRIDS

Coarse Grid Spacing = 1 Nautical Mile

FIG. 3

A grid with a spacing of 1/3 nautical mile, termed a medium grid (M), was used for most of the study to predict flow patterns and water throughput for Cockburn Sound. Run numbers 5-22 were based on the medium grid and covered all the commonly occurring wind, oceanic and tidal conditions affecting Cockburn Sound. The wind applied in runs 5-14 was increased linearly from 0 to 20 knots over a period of 3 hours and then held constant for the next 3 hours by which time a steady state had been reached.

In order to obtain a clear pattern of velocity vectors for tidal flows, runs Nos. 15 and 16, an extreme tide range of 0.8 m was modelled rather than the mean range of 0.4 m. A full diurnal tidal cycle was modelled and the only affect of the causeway was to push the null point of the tide within Cockburn Sound further south. As expected the tidal range did not change.

Runs 17 to 20 used a hot start from runs 1 to 4 respectively, ie. the boundary conditions at the edge of the medium grid were obtained from the steady condition of the coarse grid and held constant for 3 hours in order to let the medium grid runs reach a steady state. Then a SW or NW wind is applied in the same way as for runs 5 to 8.

Runs 21 and 22 on the medium grid were used to simulate a sea breeze pattern which is a common occurrence at Cockburn Sound during summer. The sea breeze cycle consists of an overnight land breeze from the NE followed by a change of the wind to the SW during the day.

Runs 25 and 26 were made on a fine grid (F) with a spacing of 1/9 nautical mile and only covered the area in the vicinity of the causeway. This grid was not used to predict discharges but was used to look closely at seiching and other oscillations which may have been induced by varying boundary conditions arising from the influence of the sea-breeze.

Table 1 lists the modelling runs. By combinations or superposition of the results from the 26 runs it is possible to estimate the currents for any physically occurring situation. The only significant limitation in using the model is that it is depth integrated and so only gives velocities averaged over the depth at any point. This means that where wind shear is the driving force which moves the surface water roughly in the direction of the wind to a depth of, say, 10 metres, there may be a return current below this depth in order to satisfy continuity, but the numerical model effectively gives the average of these two components which may not resemble either of them. It is in this type of situation where discrepancies between field observed currents and numerically computed currents is most likely to occur. However, in shallow water areas the model will give a representative indication of the currents. The model is however, directly useful for estimating gross rates of water exchange as the depth averaged velocities relate directly to water transport or "flux".

TABLE 1 - MODEL RUNS

Run No.	Grid	Boundary Condition	Time step (sec)	Real time duration (Hrs)
1	C	N-S current w/o causeway	300	13
1A	C	N-S current w/o causeway (modified)	"	13
2	C	N-S current with causeway	"	13
3	C	S-N current w/o causeway	"	13
4	C	S-N current with causeway	"	13
5	M	SW wind w/o causeway	"	6
6	M	SW wind with causeway	"	6
6B	M	SW wind with causeway (modified)	"	6
7	M	NW wind w/o causeway	"	6
8	M	NW wind with causeway	"	6
9	M	E wind w/o causeway	"	6
10	M	E wind with causeway	"	6
11	M	S wind w/o causeway	"	6
12	M	S wind with causeway	"	6
13	M	N wind w/o causeway	"	6
14	M	N wind with causeway	"	6
15	M	Tide w/o causeway	"	25
16	M	Tide with causeway	"	25
17	M	N-S current, SW wind w/o causeway	"	14
18	M	N-S current, SW wind with causeway	"	14
19	M	S-N current, NW wind w/o causeway	"	14
20	M	S-N current, NW wind with causeway	"	14
21	M	Sea breeze w/o causeway	"	15
22	M	Sea breeze with causeway	"	15
25	F	Sea breeze w/o causeway	"	15
26	F	Sea breeze with causeway	"	15
25A	F	Sea breeze w/o causeway	15	2
26A	F	Sea breeze with causeway	15	2

5. COMPARISON OF FIELD DATA WITH NUMERICAL MODELLING SOLUTIONS

Comparison of field data with the numerical modelling solutions was divided into two categories - comparison of flow patterns on a qualitative basis as is possible with float drogue data, and comparison of measured discharges through the southern opening to Cockburn Sound. Both types of comparison can only be attempted in situation where wind controls the flow and wind fields are similar in the model and in the field. Direct comparison of oceanic current model runs with field information is not possible because this current was not measured successfully in the field. All the field data gathered at times for which there are model solutions with comparable wind fields are presented in the comparisons and any poor correlations can usually be explained by seiching, the oceanic current or tidal currents.

5.1 Flow Patterns

Float drogue measurements were made over a period of four years during which float tracks were obtained for all wind directions. However, in order to compare these current measurements with the model output it was considered that the wind should average at least 5 m/sec and not change in direction by more than 45° for a 6 hour duration. Six hours was chosen because in this time a wind induced current would approach a steady state condition.

The general type of results obtained are shown for the case of a SW wind, the most common weather condition, in Figs 4 and 5, which show flow patterns before and after the causeway construction respectively. Comparisons for other wind conditions give similar agreement but because of space limitations the results for only two other weather conditions will be shown.

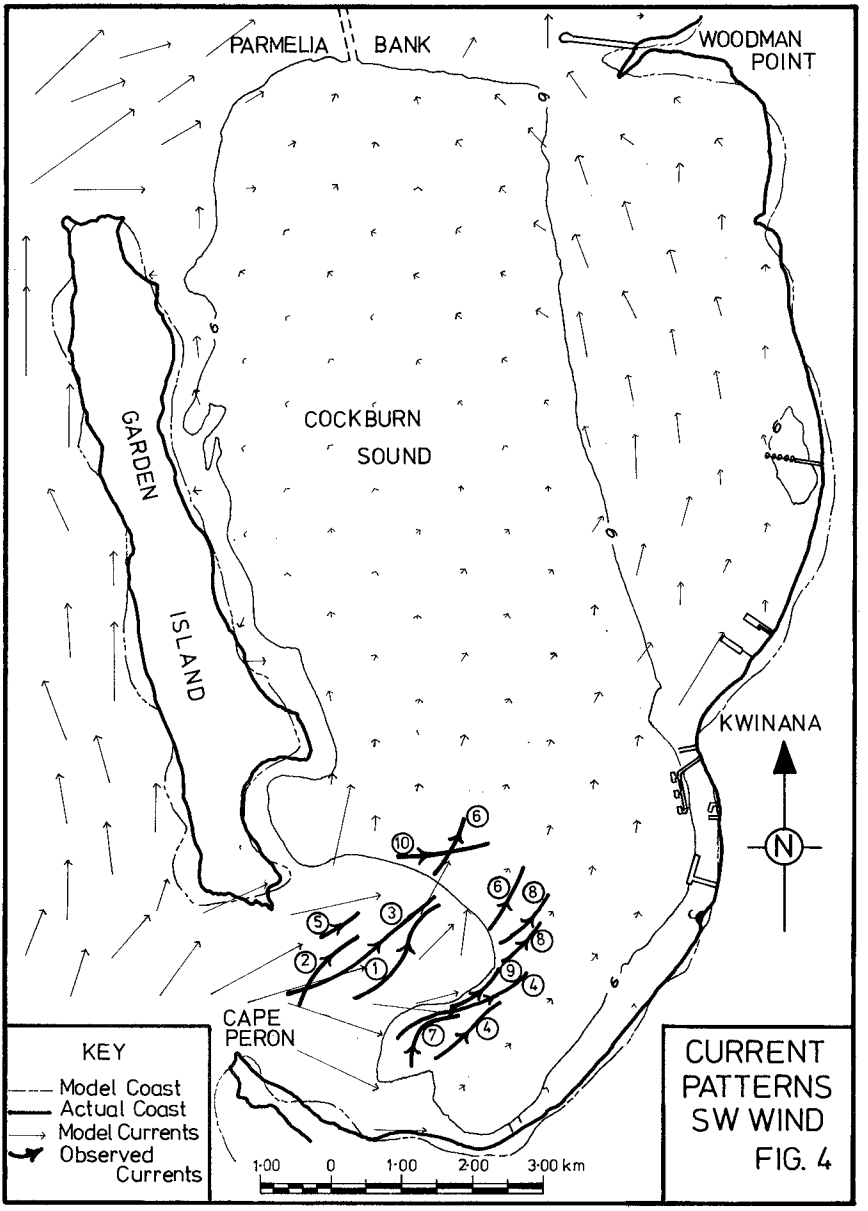
It is emphasised that the current pattern comparison is qualitative only and the current depicted by the float drogue paths show direction only and are not scaled. A quantitative comparison is not valid because the float drogue usually measures a surface current whereas the model calculates a current averaged over the whole depth and additionally there is a wind drag on the float which usually results in the velocity of the float drogue being higher than that of the water current. From a combination of these two effects the current magnitudes of the float drogues are on an average approximately 50% greater than the currents estimated by the comparable numerical model. However, the current directions taken by the float drogues were reproduced remarkably well by the models.

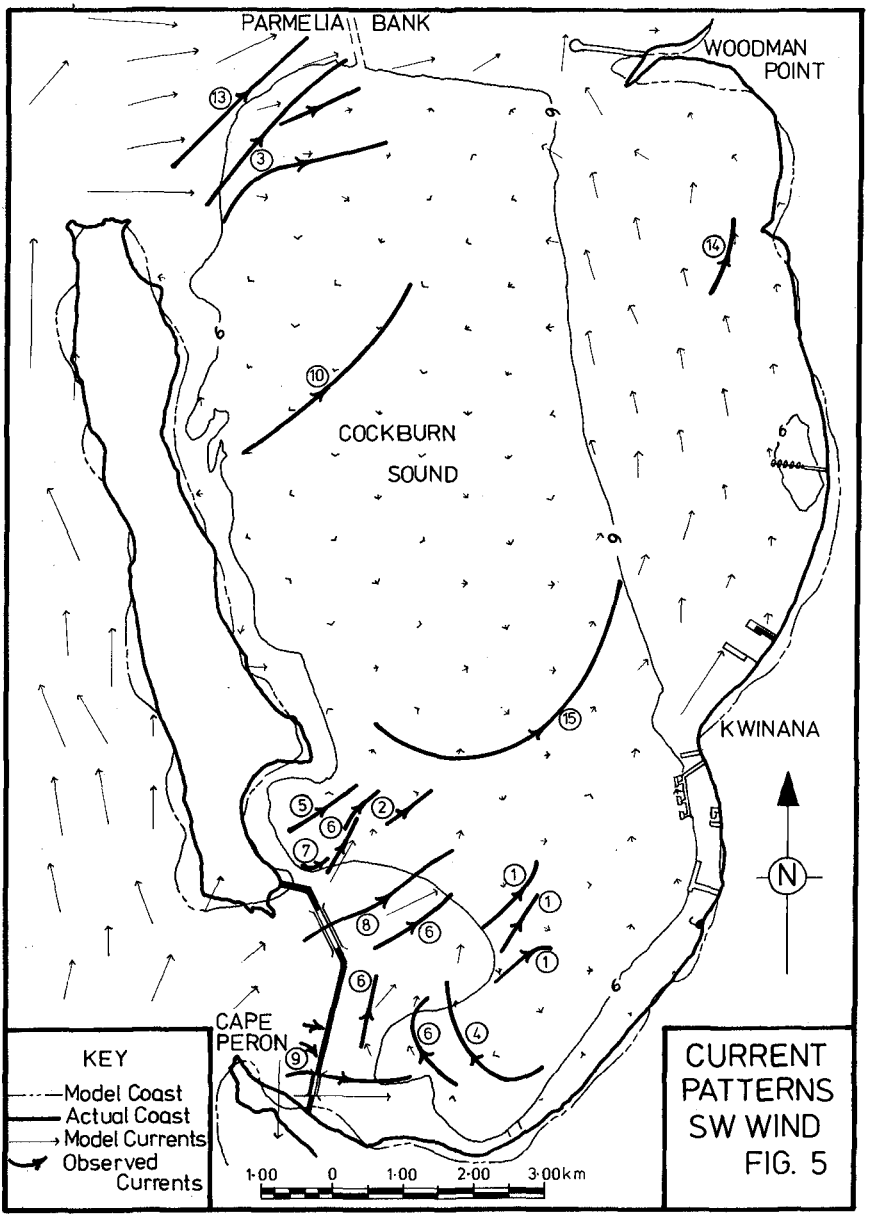
Fig. 4 shows the comparison between observed float drogue tracks and model predictions prior to the causeway construction. Each arrow shows the average path of 10 to 20 float drogues released at one time over a length of about 200 metres at the start of the arrow and excellent agreement occurs between the measurements and predictions except for days 2, 7 and 10.

The appearance of a possible eddy in track No. 7 is probably caused by the causeway construction having proceeded to the trestle bridge and flows in the Rockingham area could follow the post-causeway predictions which do show eddies in this area. The movement of float drogues on days 2 and 10 are not in agreement with the model prediction, possibly because on day 2 the wind was SSW to SW and on day 10 it was WSW to SW.

Since the causeway construction there were 15 occasions on which winds exceeded 5 m/sec from the SW during which float drogue measurements were made and these observations are shown in Fig. 5. Of these tracks only those of days 1 and 10 do not agree with the model predictions. Both these tracks exhibit obvious wind drag effects on the float and could illustrate a surface flow in the direction of the wind whereas the net flow as depicted by the model is slightly against the wind.

Fig. 6 shows the comparison between observed float drogue tracks and model predictions after the causeway construction for a NW wind and Fig. 7 shows a similar comparison for a N wind. Both these examples are presented because they show float drogue tracks which were difficult to understand without the model output. Figs. 6 & 7 show how each float drogue group follows the vector plot as depicted by the model. Yet using the float drogues alone it would not be possible to deduce the current patterns.


PARMELIA BANK
WOODMAN POINT
COCKBURN SOUND
GARDEN ISLAND
KWINANA
N
CAPE PERON
KEY
Model Coast
Actual Coast
Model Currents
Observed Currents
1·00 0 1·00 2·00 3·00 km
CURRENT PATTERNS SW WIND FIG. 4


PARMELIA BANK
WOODMAN POINT
COCKBURN SOUND
KWINANA
CAPE PERON
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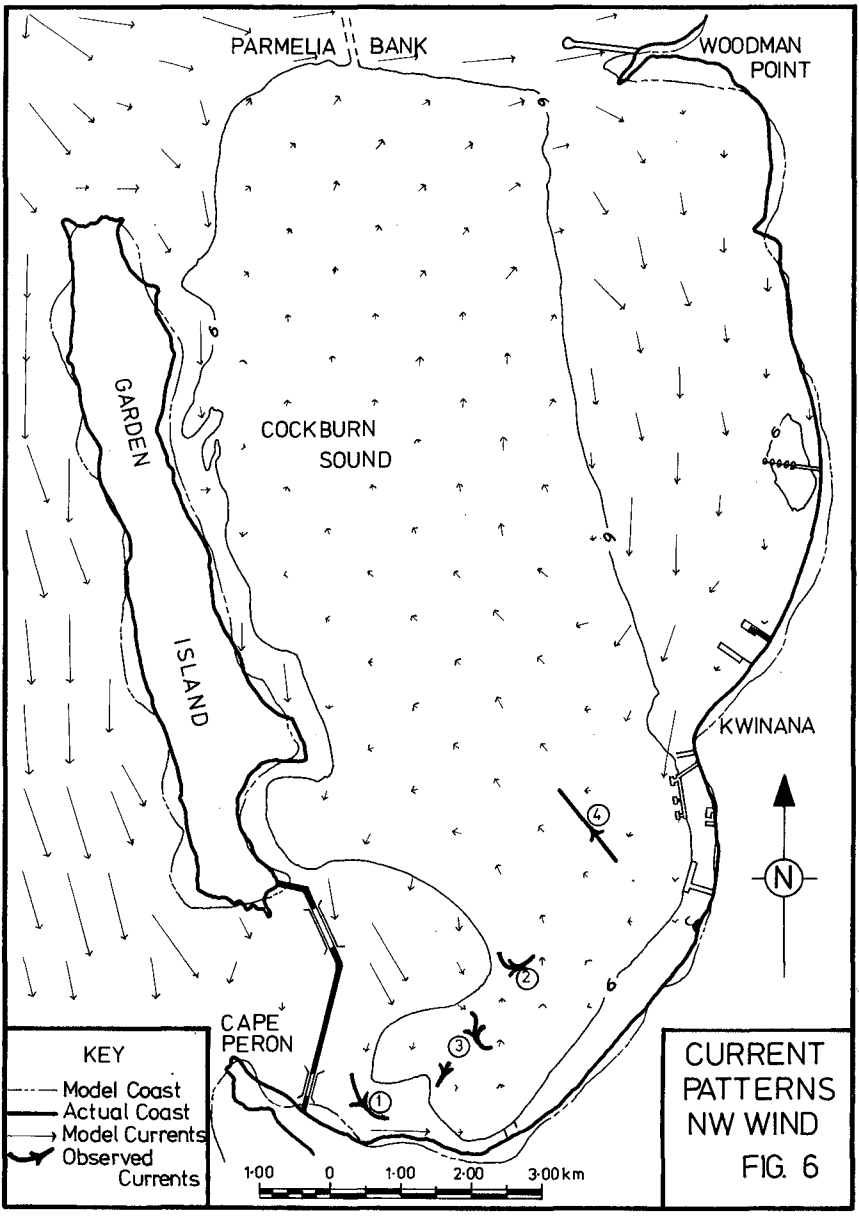
KEY
Model Coast
Actual Coast
Model Currents
Observed Currents
1·00 0 1·00 2·00 3·00km
CURRENT PATTERNS SW WIND FIG. 5


PARMELIA BANK
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GARDEN ISLAND
COCKBURN SOUND
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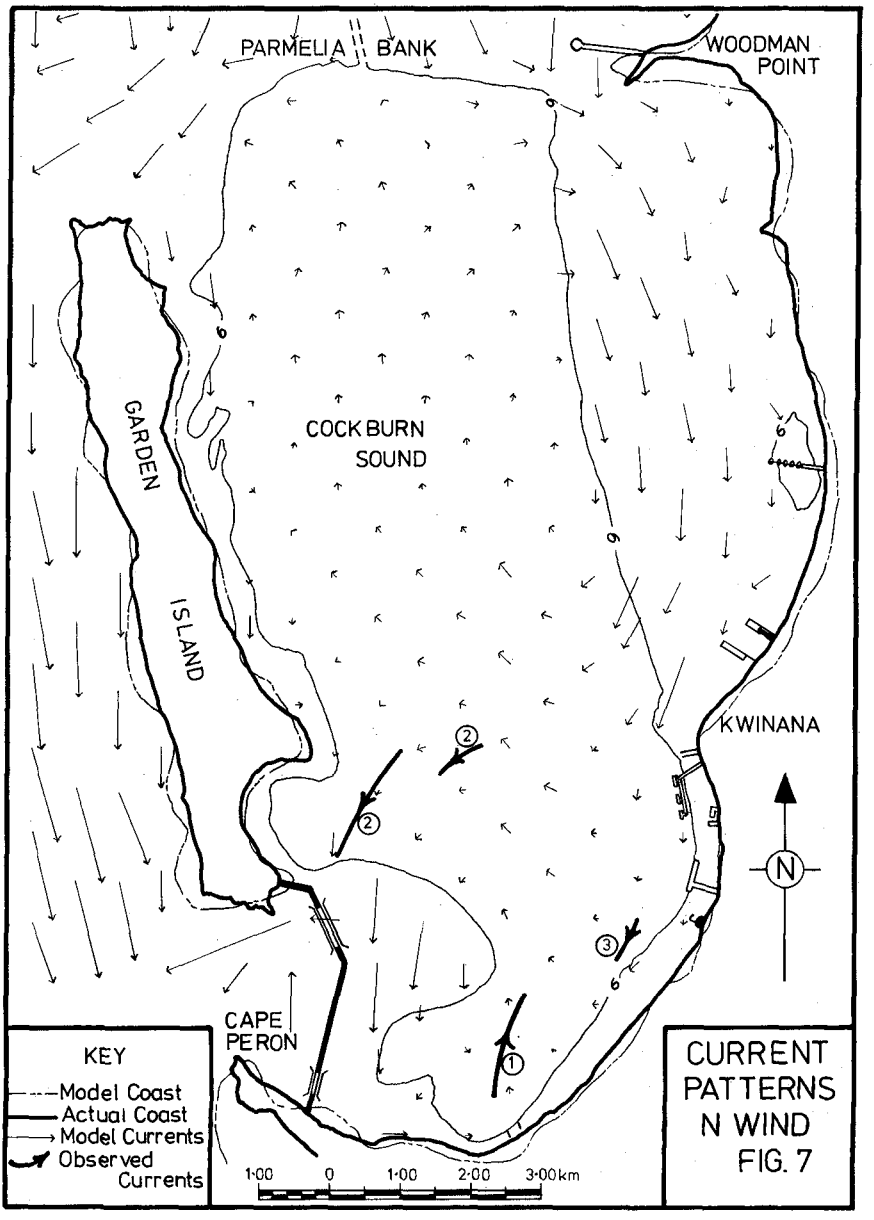
CURRENT PATTERNS NW WIND
FIG. 6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COCK BURN SOUND
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Model Coast
Actual Coast
Model Currents
Observed Currents
1·00 0 1·00 2·00 3·00 km
CURRENT PATTERNS N WIND FIG. 7

5.2 Discharge Rates

Current magnitudes within Cockburn Sound and net discharges through Cockburn Sound are the most important factors controlling the ability of the Sound to adequately dissipate pollutants. A knowledge of these factors would also allow the determination of the most suitable discharge points for effluents into Cockburn Sound.

Discharges through Cockburn Sound have been measured both before and since the causeway construction. This information has been augmented by discharge calculations under similar conditions using numerical modelling. In general terms the following sections will show that current magnitudes in the bulk of the Sound are not reduced significantly but the net discharge of water through Cockburn Sound has been reduced on the average to 30-45% of the discharge which occurred before construction of the causeway.

5.2.1 Measured discharge rates before and after the causeway construction

Field measurements in the form of twice daily current profiles were made at approximately two week intervals across the gap between Cape Peron and Collie Head for a period of 14 months during 1969-70. Measured discharge rates averaged over the two profiles taken on each day varied from 3300 m^3/sec out of the Sound to 2400 m^3/sec into the Sound via the southern entrance. The average magnitude of the flow rate over the 28 sets of readings taken during the 14 months was 1500 m^3/sec.

Since July 1974 there have been regular current profile measurements under both of the causeway bridges and the range of discharge rates, averaged over a day's observations, up to January 1976 was 2700 m^3/sec out of the Sound to 780 m^3/sec into the Sound. It needs to be noted that the observation of 2700 m^3/sec is double the rate of the next highest observation which in turn is 50% greater than the 3rd highest flow rate observed. In comparison, there were 6 observations of flow rates above 2,300 m^3/sec prior to the causeway construction. Consequently a true comparison of flow rates can only be obtained by comparing means rather than extremes. The average magnitude of the flow rate over 33 sets of readings was 570 m^3/sec, which is 38% of that occurring before the causeway was constructed.

The range of field measurements is shown in Figs. 8 and 9.

5.2.2 Discharge rates computed by the model before and after the causeway construction

The basic numerical model output which was used in the assessment of currents and discharges was the steady state solution reached after the application of a 20 knot wind from the direction of interest. A steady state condition was reached approximately 6 hours (prototype time) after the start of the wind. For the model runs where the forcing function was not steady such as for tidal runs, runs where a wind is superimposed on an oceanic current or sea breeze runs, the output was analysed at about one hourly intervals because a steady state condition did not exist. Table 2 compares the discharge through the southern opening with the causeway and without the causeway for each of the model runs.

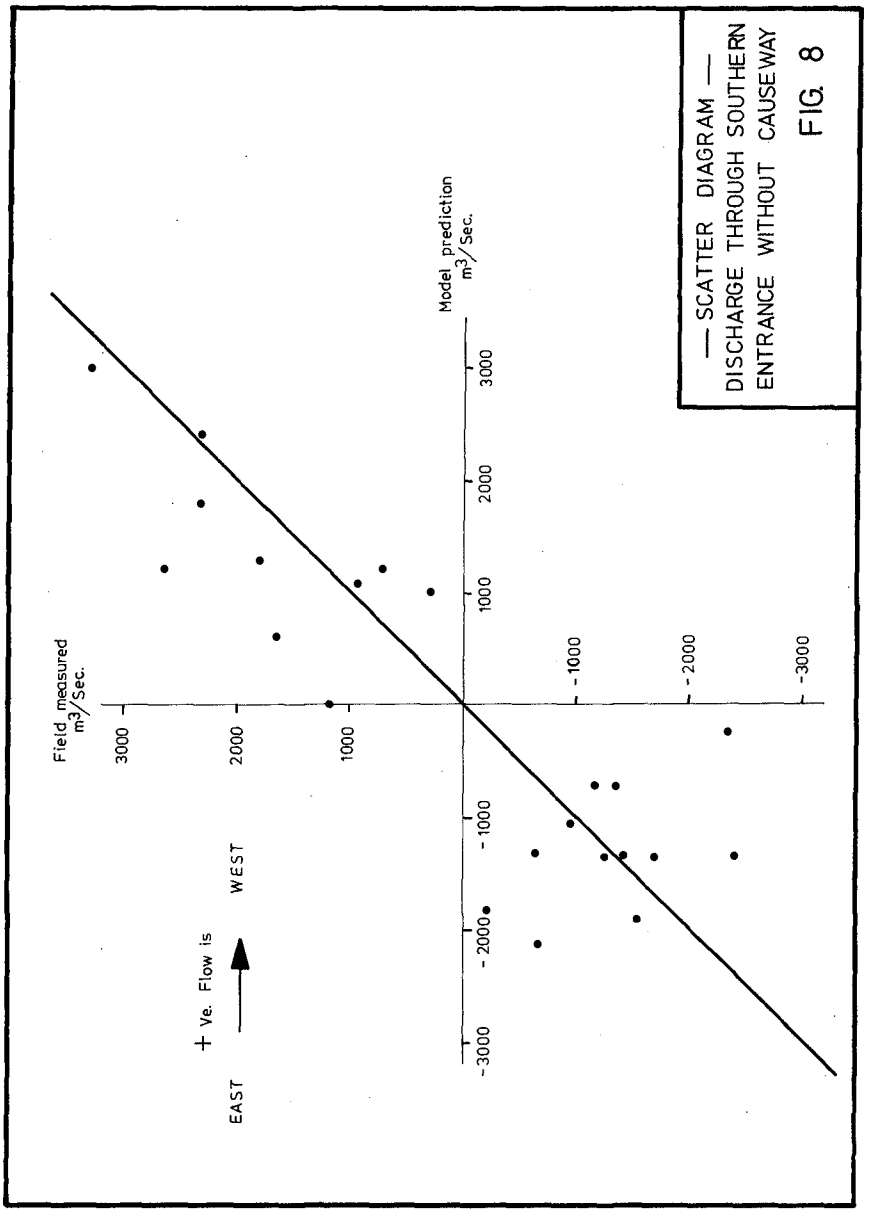
Field measured m³/Sec.
Model prediction m³/Sec.
3000
2000
1000
-1000
-2000
-3000
+ Ve. Flow is
EAST
WEST
— SCATTER DIAGRAM —
DISCHARGE THROUGH SOUTHERN ENTRANCE WITHOUT CAUSEWAY

FIG. 8

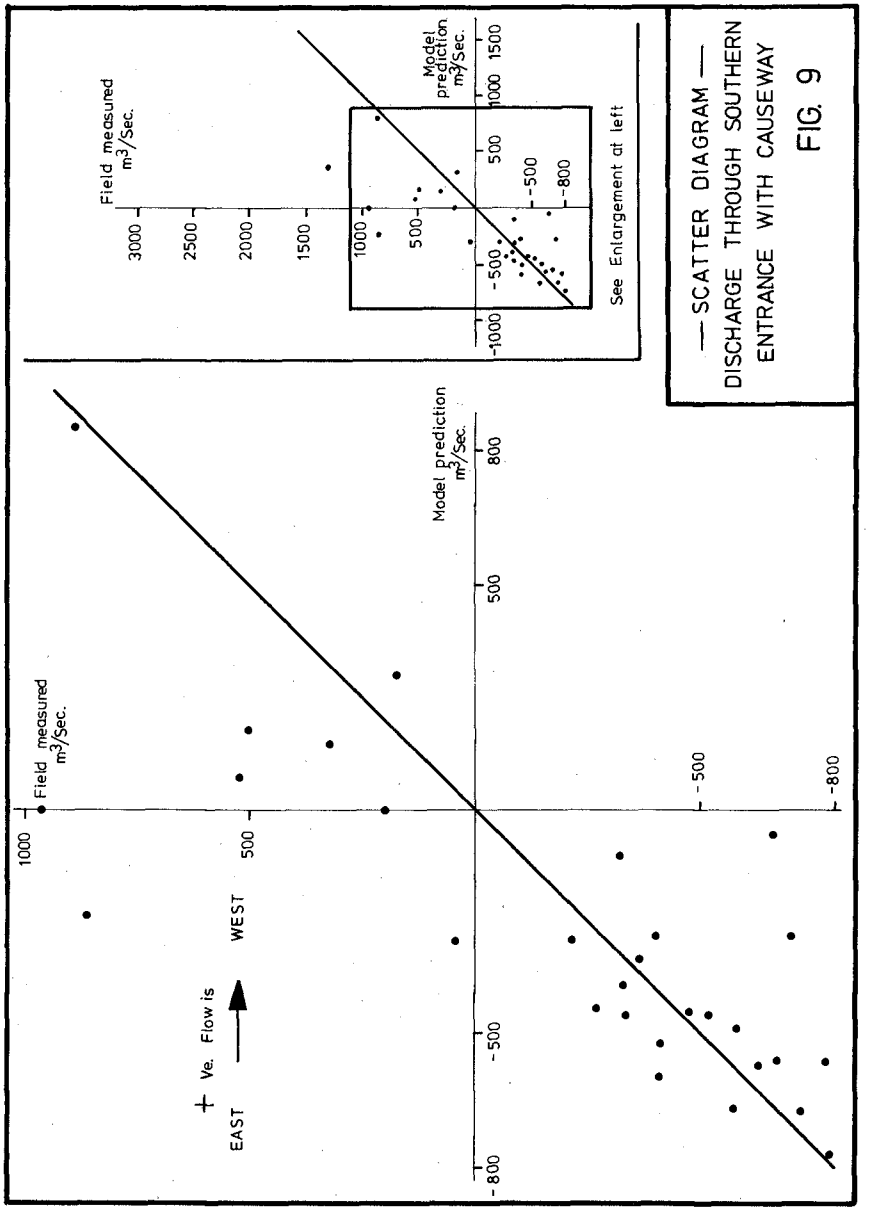
Field measured m³/Sec.
Model prediction m³/Sec.
+ Ve. Flow is
EAST
WEST
1000
500
-500
-800
800
See Enlargement at left
3000
2500
2000
1500
-1000
— SCATTER DIAGRAM —
DISCHARGE THROUGH SOUTHERN ENTRANCE WITH CAUSEWAY

FIG. 9

TABLE 2

Boundary Condition	Discharge (m^3/sec) w/o causeway	Discharge (m^3/sec) with causeway	Discharge with causeway / Discharge w/o causeway %
20 knot N wind	+ 2410	+ 946	39
20 knot E wind	+ 1835	+ 780	42
20 knot S wind	- 2590	- 1020	39
20 knot SW wind	- 2780	- 1125	40
20 knot NW wind	+ 754	+ 240	32
NE wind	+ 2657	+ 725	26
N to S oceanic current	+ 3070	+ 1057	34
N to S oceanic current & sea breeze	+ 1062	+ 389	37
S to N oceanic current	- 2583	- 896	35
S to N oceanic current & NW wind	- 2126	- 779	37
Sinusoidal tide	varying		Range 29% - 40%

Table 2 shows that the numerical model predicts that on an average, weighted for frequency of occurrence of conditions, the discharge through the southern opening to Cockburn Sound has been reduced to 38% of the flow occurring before the causeway construction. This ties in closely with the discharge measurements reported in 5.2.1.

5.2.3 Comparison of measured and computed discharges.

In the comparison of measured and computed discharges as shown in the scatter diagrams of Figs. 8 and 9 it has been assumed that the relationship between wind speed and current is linear and that each of the measured currents is purely attributable to the wind blowing during the previous 6 hours. Consequently, there is quite a wide scatter on both diagrams, with the scatter reflecting the effects of the oceanic current, seiching and tidal flows. The redeeming feature in the scatter is that current magnitudes predicted by the model and those measured in the field correspond both before and after the causeway construction. It may be concluded that the model gives a good representation of net discharge through the southern entrance to Cockburn Sound and that if the magnitudes of the currents resulting from seiching and from the oceanic influence could be measured, and corrected for, the data points would exhibit less scatter.

5.2.4 Currents in the Bulk of Cockburn Sound

Inspection of the vector plots from the numerical model results shows that current magnitudes have not changed noticeably within Cockburn Sound for all runs except those involving the oceanic current. In some cases the extra constriction at the southern entrance has resulted in an intensified eddy in the centre of the Sound resulting in current magnitudes greater than those occurring prior to the causeway construction. See Cases 1, 3 and 5 of Table 3. An exception is the oceanic current which does not cause eddy formations because it is controlled by a simple head difference between the two ends of the Sound. In this case currents are reduced to 1/3 of the magnitude occurring prior to the cause, (cases 6 and 8). Usually the oceanic current does not occur on its own but is accompanied by a wind induced current so that generally currents have not changed in magnitude appreciably after the causeway construction, cases 7 and 9.

TABLE 3

Case	Boundary Condition	Gross Discharge across Section Between Sulphur Bay and Alcoa (m^3/sec) w/o causeway	with causeway
1	20 knot N wind	2840	3960
2	20 knot E wind	1890	1010
3	20 knot S wind	2730	3850
4	20 knot SW wind	2740	2310
5	20 knot NW wind	3230	3600
6	N to S oceanic current	3070	1060
7	N to S oceanic current and SW sea breeze	4550	4030
8	S to N oceanic current	2400	930
9	S to N oceanic current and NW wind	5770	4790

The only field data verification for currents in the bulk of Cockburn Sound comes from the salinity/temperature measurements which indicated that the rate of movement of bodies of water described by their salinity had not changed as a result of the causeway construction.

6. CONCLUSIONS

(i) For large bodies of water where wind generated currents greatly influence the flow, only sufficient field data should be obtained to determine the driving forces and then numerical modelling can be used as an effective tool in explaining and determining details of the flow field. More field data may then be desirable to confirm features of the flow highlighted by the model.

(ii) The exchange of water between Cockburn Sound and the Indian Ocean has been reduced to 30-45% of the exchange which occurred prior to the causeway construction. This figure is validated both by field data and numerical modelling.

(iii) Current magnitudes in the bulk of Cockburn Sound have remained nearly constant compared to those occurring before the causeway construction. Thus the rate of mixing or dispersion of effluents within the Sound has not changed significantly.

ACKNOWLEDGEMENTS

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