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AIR–SEA–RIVER INTERACTIONS

R. RADOK

Horace Lamb Institute of Oceanography, Adelaide, South Australia

SUMMARY

Extensive recording of currents, collection of water samples and routine meteorological and tide records provide a base for this study of the dynamics of Australia's largest river, the Murray, during one of its rare floods in 1974. The results suggest that the Coorong, a narrow lagoon extending from the river mouth to the Southeast, at right angles to prevailing winds, was formed as a flood escape mechanism. Geological evidence displays the existence of similar geometries formed in the past in an area which at one time was a deep gulf of the Southern Ocean extending into Australia. The same mechanism may have been at work elsewhere in the world.

BACKGROUND

Australia's River Murray (Figure 1) offers unique opportunities for studies of interactions between atmosphere, ocean and land-run-off, and the roles these processes play in the building of continents. At the end of its 3,000 km long path from the Australian Alps to the Eastern Great Australian Bight, the Murray moves sluggishly through predominantly arid regions where in the historical past droughts have reduced it to strings of water holes. On the other hand, when heavy rainfall over its upper catchment area swells it to its maximum width and this water mass propagates slowly along its length, its discharge into the Southern Ocean reaches the orders of magnitude of the discharges of the world's large rivers.

Not far from its mouth, the Murray enters shallow Lake Alexandrina and progresses through it to five channels leading into a 2–3 km wide lagoon, the Coorong, which extends from the river mouth on Encounter Bay over 100 km to the Southeast. The high dunes of narrow Younghusband Peninsula separate this lagoon from the Southern Ocean with its predominantly southwesterly winds. During this region's geological history, this geometry has been repeated several times, as is evidenced by relic barriers and chains of fossil dunes and swamps running parallel to the present day shoreline.

In June 1974, the Murray experienced a major flood. Barrages which had been constructed before 1940 across the five channels leading from Lake Alexandrina for purposes of control of salt water intrusion (Johnston (1913)) offered convenient platforms for measurements. Before recording the currents in these channels, temperatures, salinities, currents, etc. were studied for one week in the Coorong in order to investigate its role in the discharge mechanism of the river and to resolve questions of the origin of possible environmental deterioration.

OBJECTIVES. METHODS OF THEIR ACHIEVEMENT

The measurements described below provide partial answers to the following questions and instigate an intense study of the conditions in the Coorong, including its stratification, interaction with diurnal heating, agitation by winds, etc. by the discipline of Oceanography at the Flinders University of South Australia (Krause, per. comm.).

1. How are the water level changes in the Coorong generated?

2. Is the Coorong an integral part of the Murray estuary or is its existence conditioned by swamps south of it which were drained during this century, in other words, is it deteriorating as a consequence of this drainage scheme?

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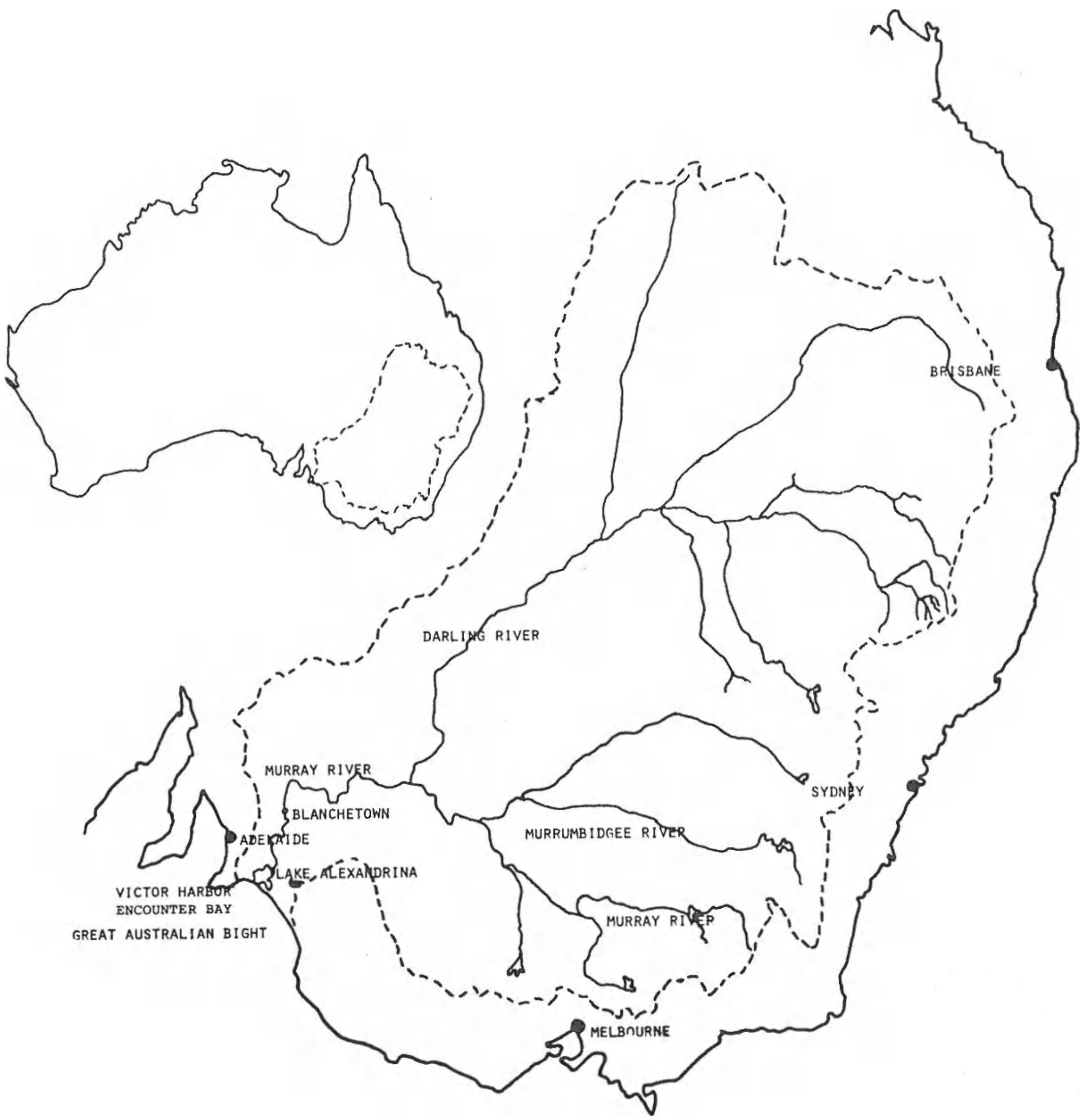

Figure 1. Murray River system and its catchment area

3. How does the Murray discharge through the channels from Lake Alexandrina?
4. What are the interactions between air, sea and river in the vicinity of the river mouth?

Eight Alekseev recording current meters of the type BPV-2r, a salinity-temperature bridge, a reversing thermometer and chemical analysis of water samples collected provided the input into this study. For one week [25.5.–1.6.1974], three current meters were deployed at Tauwicherie Barrage, Pelican Point and Hells Gate (Figure 2) where the Coorong is subdivided by a constriction into North and South Lagoons, temperatures and salinities were measured several times at a number of cross-sections of North Lagoon, and coastal samples collected along the Coorong's entire length for chemical analysis.

During the second stage [15.6.–13.7.1974], attention was focussed on the flows through the channels from Lake Alexandrina. All current meters were suspended from the barrage structures, and wind and

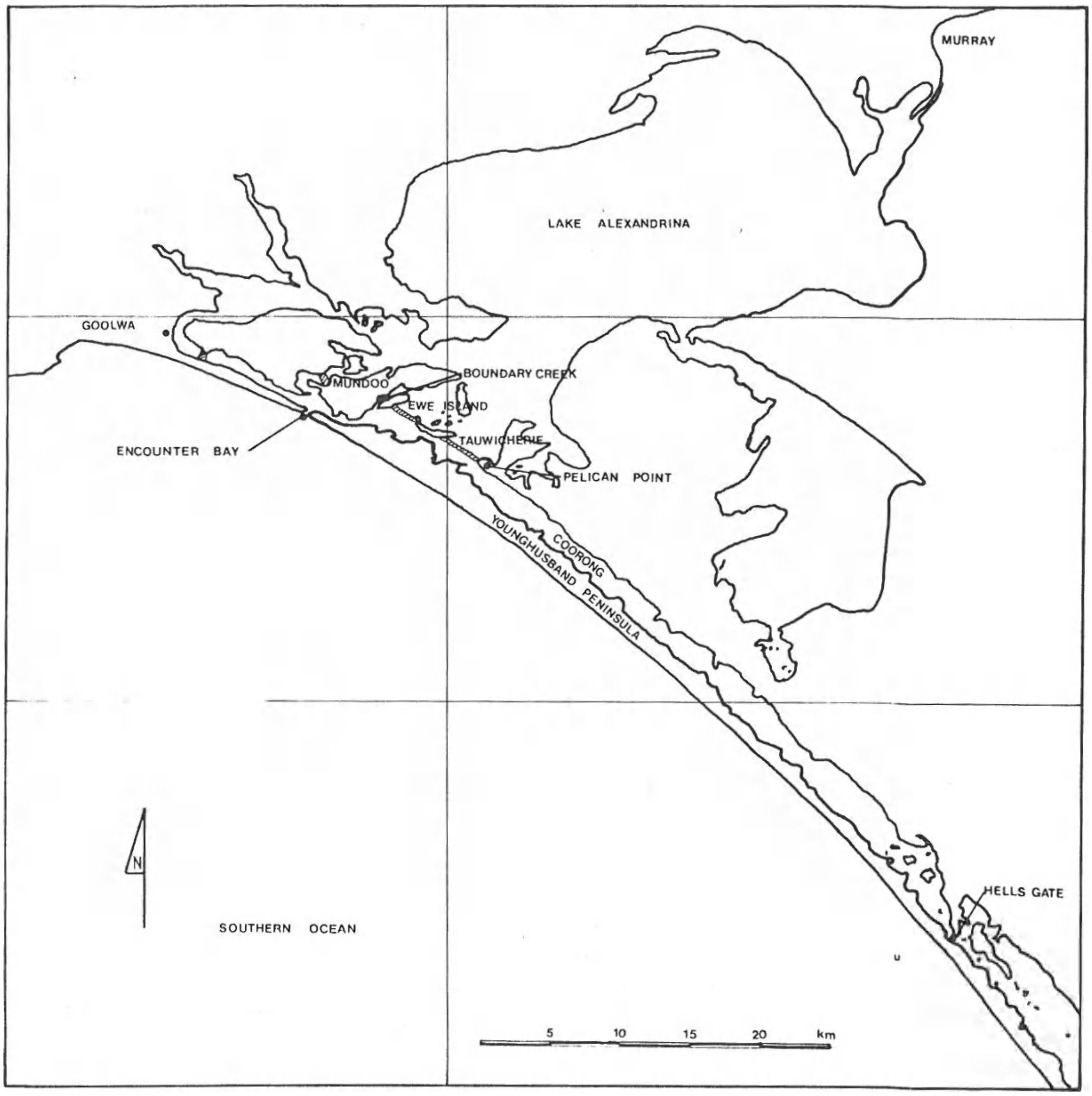

Figure 2. Murray Estuary

tide data were obtained from continuously recording stations at Pelican Point and Victor Harbor, respectively (Figure 2).

PREVIOUS WORK

In the past, physical measurements in the Coorong and the Murray estuary were confined to spot readings and recording of water levels. Geologists concerned with a modern formation of carbonate sediments (von der Borch (1965), Brown (1965)) and two of the author's students (Clarke (1965), Noye (1970)) in applied mathematics conducted intermittent programmes between 1960 and 1970 in the Coorong. However, at no time were events in the Coorong considered to be related to those in the Murray, and this aspect has remained an open question until this investigation.

Measurements near the mouth of the Murray go back as far as 1876. They are admirably summarized in Major Johnston's Report to the South Australian Government in 1913 which marks the beginning of realistic plans for the River Murray barrages. To the author's knowledge, no current measurements were taken after Major Johnston's visit (Radok and Stefanson (1975)).

WATER AND SALT BALANCE OF THE COORONG [25.5.–1.6.1974]

Ten minute readings of current speed and direction decomposed along the Coorong or across Tauwicherie Barrage (Figures 2 and 3) show clearly that the dilution process in the Coorong depends on the fluvial discharge from the Murray and the ocean tides. Southeasterly flows (into the Coorong and away from the Murray Mouth) at Pelican Point occurred or strengthened in the wake of high tides. As will be seen later, the flows across individual barrages varied greatly from day to day, and at times the tides did not exert their influence at Pelican Point. Larger flows through other channels might have been the reason for such disruptions.

At Hells Gate, the records cover a shorter period. Here, wind makes an important contribution so that there is no simple relationship between the currents there and at Pelican Point and the tides at the river mouth. However, on 30.5.1974, a reversal of the southeasterly flow direction at Pelican Point at 0320 seems to have induced at Hells Gate a decrease of southerly flow and eventually a reversal of direction at 1730. These figures yield a first estimate of the rate at which disturbances propagate along the Coorong which is up to 2 m deep. Certainly, current records offer much better means of detecting changes in flow conditions than water level recorders, which have been used exclusively in the past.

For the period 28.5.–30.5.1974, an estimated $3{\cdot}10^6\ m^3$ of water entered South Lagoon daily through Hells Gate. During these days, the salinity there fell from 51·5 to 24·8‰. By 9.6.1974, it had risen again to about 50‰.

The temperature–salinity (T–S) diagram (Figure 4) presents all salinity and temperature data taken at depths ranging from 0·5 to 2·0 m in the North Lagoon. It displays the presence of three water masses: Murray River water near the surface, Coorong deep water near the bottom and Hells Gate

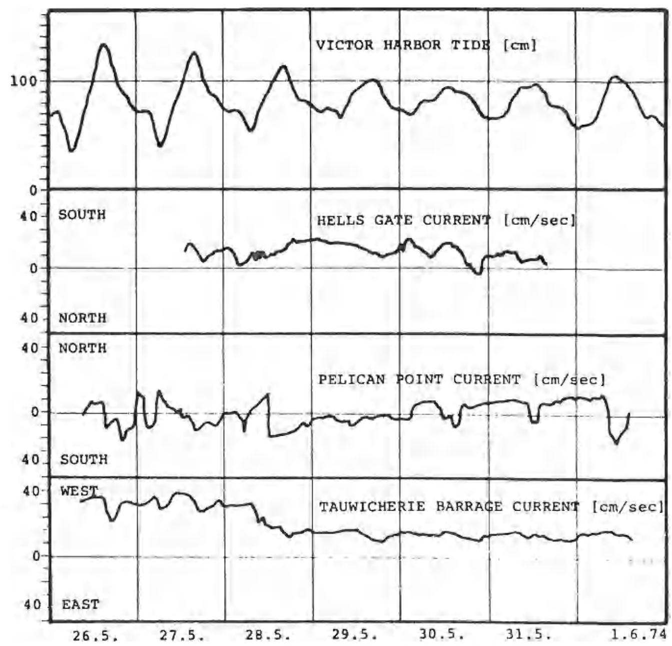

Figure 3. Dominant currents and predicted tides

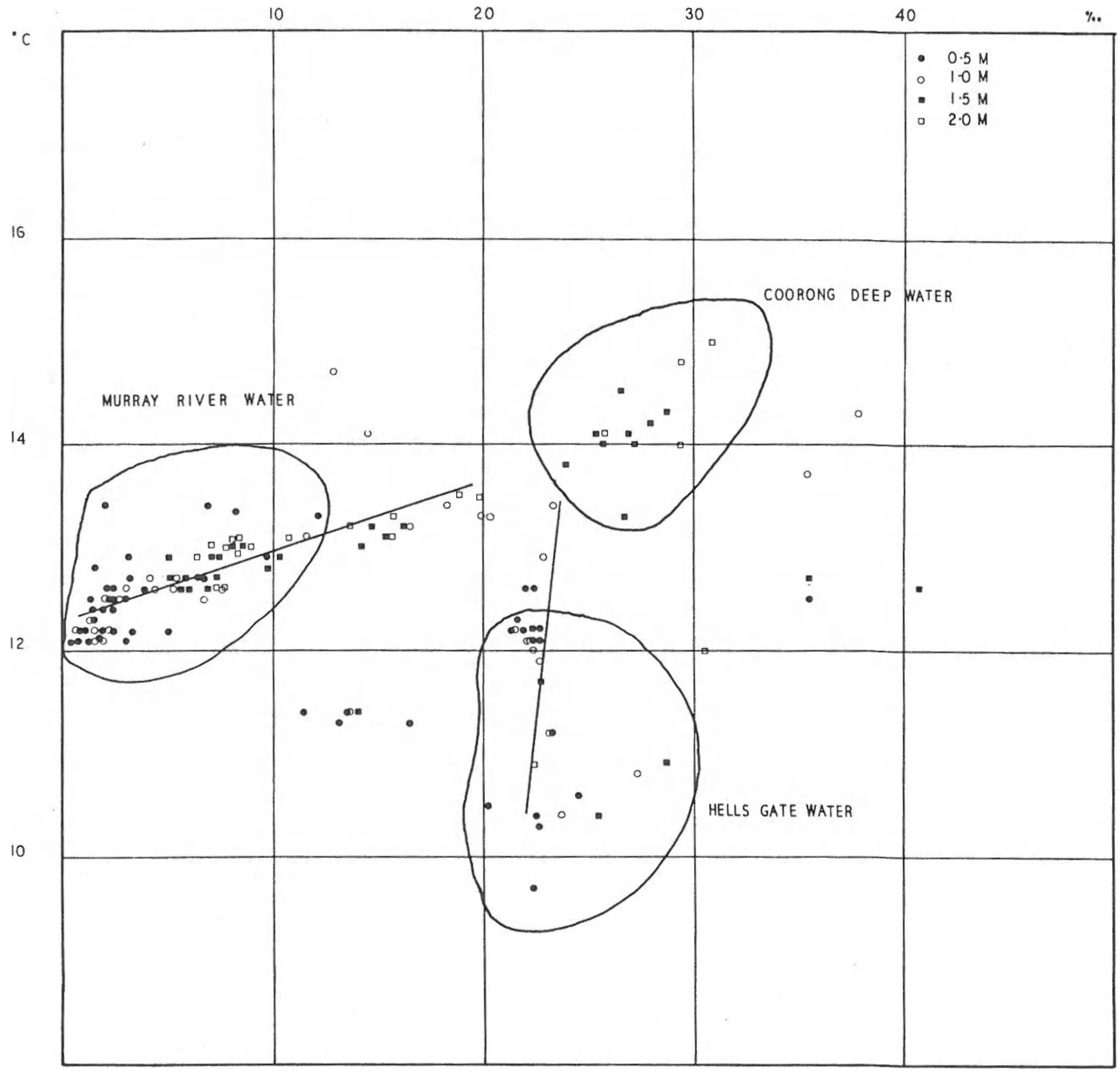

Figure 4. Temperature-salinity diagram for North Lagoon

water (from the South Lagoon). This stratification of the North Lagoon with its depth of 2 m persisted throughout the period of observation and suggests that the Coorong offers unique possibilities for studies of internal waves, the formation of a thermocline, the effects of atmospheric conditions, etc. on stratified media.

Longitudinal distributions of salinity of water samples collected along the entire length of the Coorong on separate days are shown in Figure 5. They display propagation of diluting water masses and yield diffusivities of an order of 10^5 cm^2/sec, i.e., in the range observed in the open ocean.

The distributions of major elements dissolved (Figure 6) show that there is an overall trend towards the composition of sea water. For example, a ratio of 2:1 between chlorine anions and sodium cations

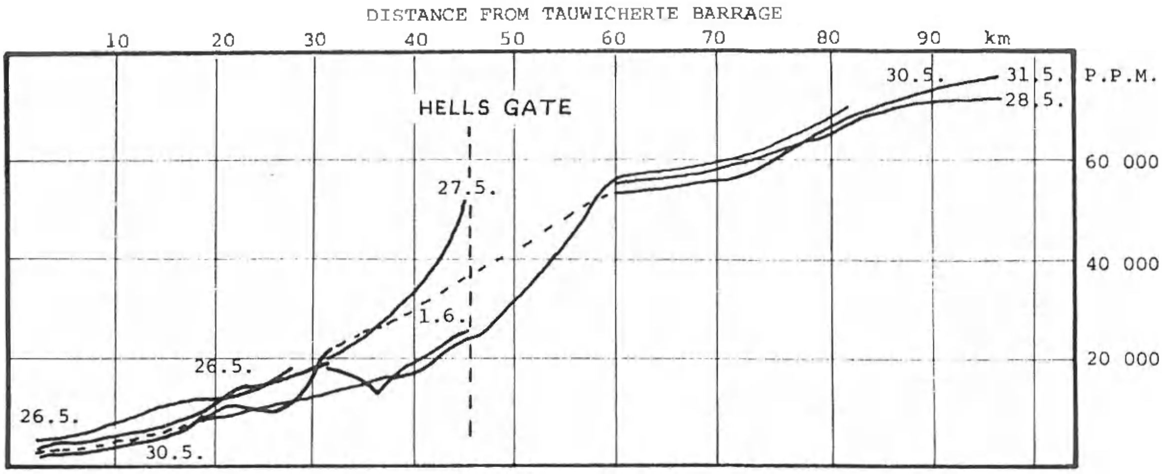

Figure 5. Salinity changes along Coorong

is maintained (Dietrich (1963)). These figures, based on small numbers of samples, reinforce the mechanical evidence that the salt in the Coorong originated from the sea. Unless the Murray is in flood, tides and mean sea level changes drive sea water into the Coorong. High evaporation rates during summer raise the salinity to values ranging from 35‰ at the Murray Mouth to over 80‰ at the Southern end. During floods, the Coorong takes the overflow which cannot be handled by the river mouth, owing to high tides and mean sea levels, and its salinity is reduced.

A logical consequence of this work was a detailed study of the flooding dynamics of the Murray which began on 15.6.1974. Unfortunately, deployment of current meters in the river mouth presented insurmountable difficulties. Measurements at the barrages offered an alternative which actually gave better insight into the sedimentation processes of the Murray in flood.

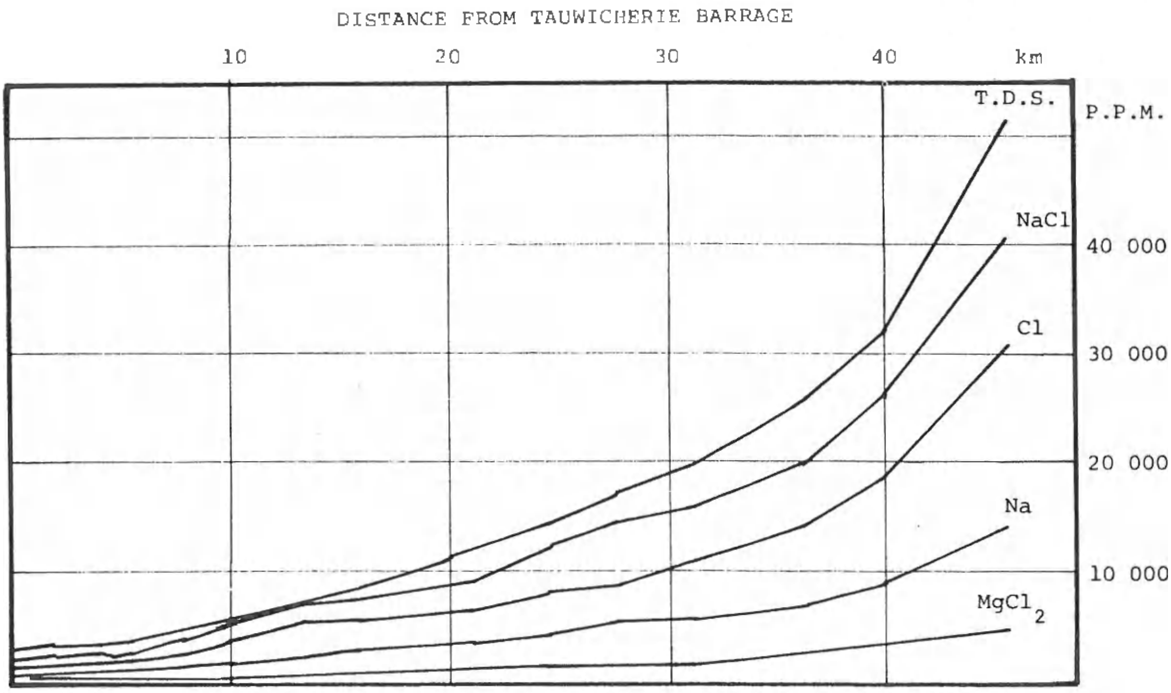

Figure 6. Total dissolved solids (TDS), NaCl, Cl, Na and $MgCl_2$ in North Coorong

FLOODING DYNAMICS OF THE RIVER MURRAY [15.6.–13.7.1974]

Half hourly readings of current speed and direction were obtained from instruments suspended from the barrage structures across the five channels (Figure 2). Two instruments were deployed each at Tauwicherie and Ewe Island Barrages after current profiles along all barrages and in depth had shown that single instruments would provide satisfactory monitors except at those barrages. From 6.7.–8.7.1974, all recorders were set to take readings every 5 min, in order to isolate high frequency phenomena.

Consider first the high frequency data for 7.7.1974 when there occurred flow reversals at all barrages [Figure 7]. This day was characterized by high tides in excess of predicted values. A first major inward flow at South Ewe Island Barrage was preceded by three short lived reversals at Tauwicherie South at 0925, 0950 and 1025. At North Ewe Island, the flow reversed at 1055, at Boundary Creek and Goolwa at 1100 and 1115, respectively. Finally, at the northern and southern ends of Tauwicherie Barrage, flow reversals were recorded at 1230 and 1315, respectively. Outward flows were resumed

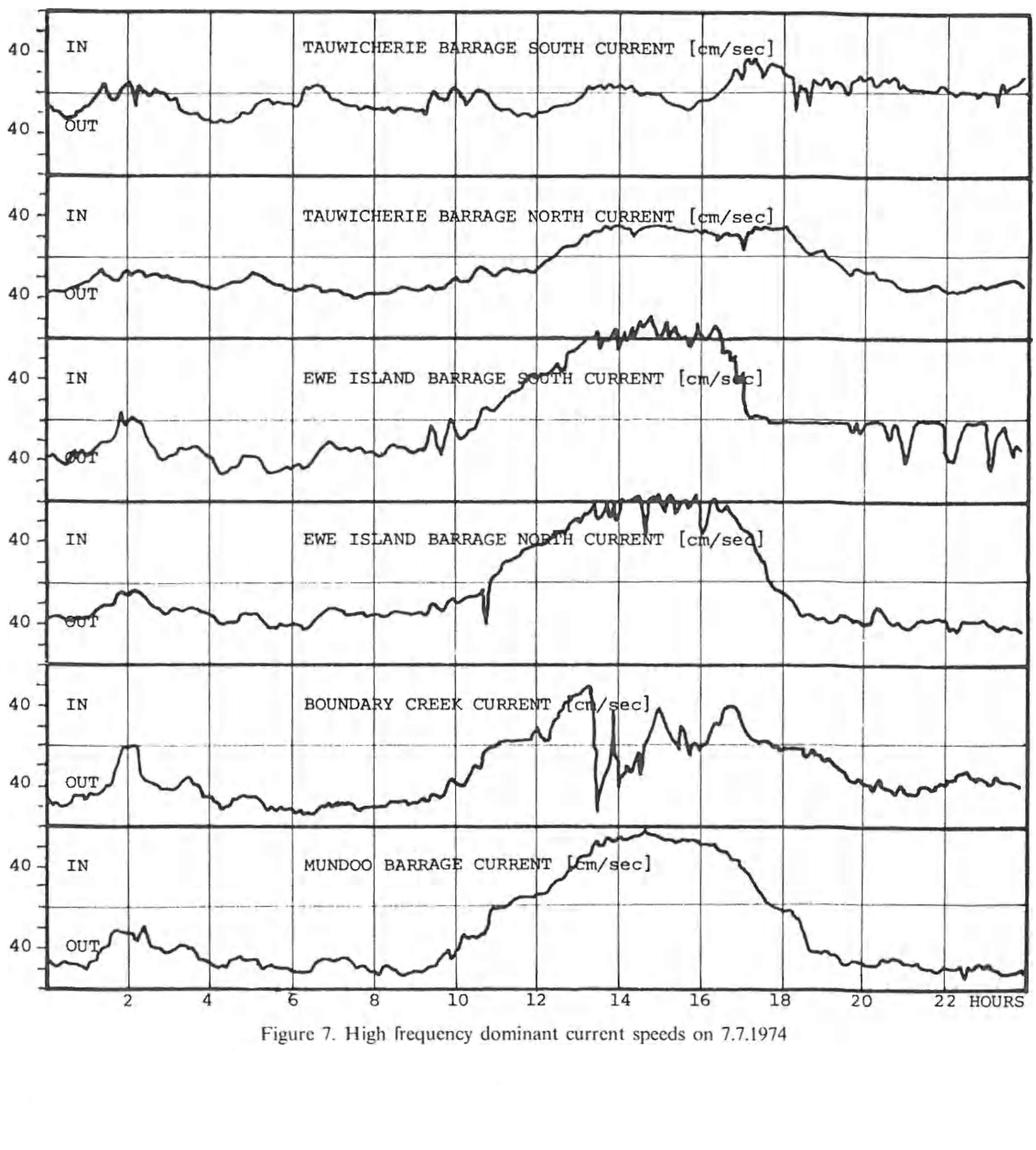

Figure 7. High frequency dominant current speeds on 7.7.1974

at Ewe Island South at 1740, at Boundary Creek at 1745, at Mundoo Island at 1755 and Tauwicherie North at 1910. At Tauwicherie South, inward flow continued until 1050 on 8.7.1974.

Certain sections of the records shown in Figure 7, for example those at Ewe Island South and Boundary Creek between 30^{00} and 60^{00} hours, raise the question of presence of seiches. Averaged spectra of all records yielded peaks at 5.33, 3.55, 3.04, 2.37, 1.85, 1.58, 1.01 and 0.52 hours. Spectrum analysis of the current data taken earlier at Hells Gate and Tauwicherie Barrage divulged at strong peak at 5.5 hours which could thus be identified with the fundamental seiching period of the North Lagoon. Correlation of the Ewe Island records strengthened the signals at 3.71, 1.47 and 0.53 hours which therefore become associated with the natural periods of oscillation of Lake Alexandrina and its bays. Probably, seiching of a local bay might have induced the short lived flow reversals at Tauwicherie South on 7.7.1974.

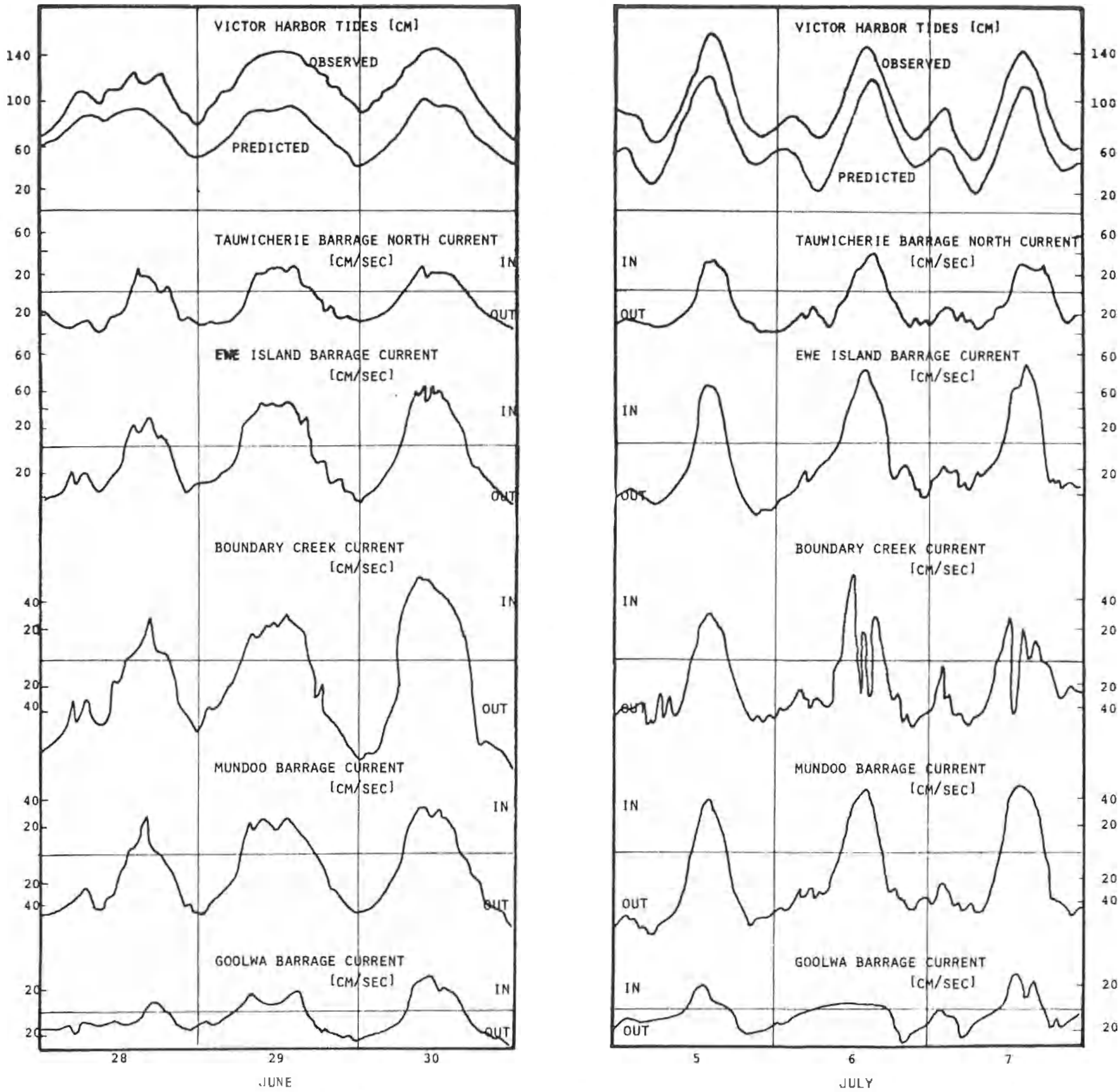

Figure 8. Major flow reversals in Murray Estuary

The major flow reversals encountered during the period of observations in the Murray channels are displayed by Figure 8 together with the tides in Encounter Bay. The first set [28.6–30.6.1974] occurred near neap tides, the second [5.–7.7.1974] near spring tides. In both cases, observed tidal heights were well in excess of predicted values.

Along Australia's south coast, meteorological tides exceed often astronomical tides. Observations in the South Australian Gulfs have shown that these phenomena are common along the entire coast with very little delay and are displayed conveniently by computation of filtered daily mean sea levels. As a consequence, the conclusion has been drawn that these effects are global and result from weather action over the Southern Ocean rather than from local winds. Their influences on coastal erosion and water renewal in the Gulfs, the Coorong and Port Phillip Bay near Melbourne is critical.

Table I. Daily water transports through Murray estuary

Date	June 16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Transports in 10^4 m^3															
Goolwa	2380	2119	1441	259	1581	1714	1980	1808	1860	236	257	1037	1523	644	931
Mundoo	137	124	87	38	3	3		152	156	134	121	113	94	35	42
Boundary Creek	136	119	80	42	57	52	110	132	140	133	113	106	77	35	44
Ewe Is. Nth.	1348	1209	812	−31	960	770	1184	1379	744	744	1174	978	803	165	188
Tauwicherie North	3300	2554	2128	682	2253	2789	2905	3390	3462	2976	2664	2504	1850	822	985
Totals	7300	6125	4548	990	4854	5328	6179	6861	6362	4223	4329	4738	4347	1701	2190
Blanchetown	6200							6700							7500

Date	July 1	2	3	4	5	6	7
Transports in 10^4 m^3							
Goolwa	2664	2091	2314	2382	1025	914	684
Mundoo	171	201	209	218	113	58	66
Boundary Creek	126	55	65	58	49	61	57
Ewe Is. Nth.	1735	1896	2259	2331	940	236	221
Tauwicherie North	3168	3884	4484	4673	2013	1383	1228
Totals	7864	8127	9331	9662	4140	2652	2256
Blanchetown							8600

Next, consider the water transport through the channels. Table I indicates that major day to day variations occurred in the transport through individual channels as well as in the total transport. The order of magnitude of the latter correlated reasonably with estimates based on river levels at Blanchetown, 270 km up river from Lake Alexandrina. These variations are induced by a wide range of phenomena including global weather action, astronomical tides, land and sea breezes, seiching of Coorong and Lake Alexandrina. Further measurements are required to isolate each of these phenomena (Krause, per. comm.).

Finally, spectral correlation of water and air transports at the Murray Mouth will be of interest. Figure 8 shows the spectral distributions of three hourly transports which display clearly the importance of weather systems (5–10 days) and astronomical (12–24 hours) forces. Again, the time series were too short to obtain better resolution.

CONCLUSIONS

The complex nature of the air–sea–river interactions in the estuary of the River Murray in flood has been exposed. In 1910, it was suggested that 'the plains of the Murray Basin have been the result of the silting up of a large arm of the sea which had its opening into the ocean in the neighbourhood of the present mouth of the Murray' and which extended several hundred kilometres into the continent. The measurements of this study suggest a process by which this silting up could have taken place.

Obviously, the major transport of sediment which accompanies the conditions described has led in the recent past to the establishment of the islands between Lake Alexandrina and the Coorong and is now silting up both these lakes. The length of the active Coorong is determined by the magnitude of recent floods of the Murray, tidal and sea levels at the river mouth. Huge quantities of material are gradually transported down the Murray by these floods and eventually carried through the mouth to be deposited on the shelf, where they lay the foundations for the next peninsula on which the ocean waves raise dunes at right angles to prevailing winds. The nature of the base of the Younghusband Peninsula confirms this process which has been repeated a number of times.

This interaction between prevailing winds and river flooding conditions has probably induced formation of similar estuarine geometries elsewhere. For example, the Vistula (Weichsel) and the Niemen (Memel) near Kalinigrad (Königsberg) near the Baltic Sea flow into the Zalew Wislany (Frische Haff) and Kursiu Marios (Kurische Haff), respectively. Probably these were formed by similar processes. During normal conditions, the mouth of the river is shaped and established firmly. During flooding, its waters spread behind dunes built by ocean waves on a base established gradually by sedimentation through fluvial discharge outside the river mouth.

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