The Behaviour and Future of the River Murray Mouth

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Executive Summary

A study of the River Murray Mouth has been undertaken with a view to assessing the likely effects of Mouth closure and the management options that are available to prevent closure. The study has concentrated on using water level data collected at Goolwa and Tauwitchere Barrages to derive a model of the Mouth behaviour and to relate this to the predicted flow over the barrages. The model has been used by Close (2002) to assess a number of management options, especially in regard to how additional flows might be best used.

Based on the work undertaken during the study a number of conclusions can be drawn.

1. In recent years the Mouth has been observed to silt up and approach closure on a number of occasions, with a large flood tidal delta forming inside the Mouth. The build-up inside the Mouth is believed due to a combination of inadequate river flows and nearshore coastal processes related to the wave and tide climate. Engineers and managers have no control over the latter.

2. Historically, the lower lakes (Lakes Alexandrina and Albert) were kept fresh by adequate river flows. During extended droughts evidence shows that the lakes became saline. It is believed that river flows were sufficient to maintain lake level close to the current level maintained by the barrages.

3. Closure of the Mouth should be avoided to prevent flooding, ecological damage, damage to tourism and to maintain the RAMSAR listed Coorong, fishing, and the conservation significance of the area.

4. The ratio of tidal energy in the 12 hour tidal components between Goolwa Barrage and Victor Harbor (R) provides a useful indicator of the state of the Mouth in terms of its size. It was found that this indicator was not valid during periods of high river flow. The nature of the error means it would be significant when the model is forecasting the peak openings, but not have an effect on the highly restricted state of the Mouth that was the focus of the study.

5. It is possible to model the relative Mouth opening in terms of river flow. This model can be written: \( R_t = 0.8 R_{t-1} + 0.0002 F_{t-2} \) (\( R^2 = 0.46 \)) where \( R_t \) = relative tidal energy in month \( t \) and \( F_{t-2} \) = flow in GL per month two months previously. Use of the model by Close (2002) allows a number of conclusions to be drawn:
   
   - substantial reductions in the risk of Mouth closure can be achieved by maintaining flow through the Mouth more often;
   - a combination of an increase in South Australia’s entitlement flow by 2,000 ML/d and the use of the barrages to maintain a steady release reduces the percentage of years at risk of Mouth closure from 31.5% to 7.4%;
   - providing a larger flow once a year appears to be a less effective strategy for keeping the Mouth open;
   - increasing South Australia’s entitlement increases the degree of regulation across the rest of the River Murray with consequential adverse environmental impacts;
   - increasing South Australia’s entitlement adversely affects the water supply security to water users;
   - using the barrages to regulate outflows may also have adverse local impacts.

6. It should be noted that the current emphasis on the mouth opening should not be taken to mean that keeping the mouth open will maintain the environment of the lagoons and environs around the mouth. A Mouth closure may be an easily identified state, but the build-up occurring in the mouth region, the deterioration of the Tauwitchere Channel and reduction in the level of tidal flows to the Coorong should be of more concern.
Acknowledgments

The flow data used in this study were supplied quickly and efficiently by Mr Andy Close of the Murray-Darling Basin Commission. The tide data were supplied by The Department of Environment and Heritage, South Australia.
Introduction

Recent concerns about the state of the River Murray Mouth have renewed interest in its behaviour, and in particular what measures might be taken to maintain an effective opening. For much of 1999 the Mouth was observed to move steadily towards a total closure as excess sediment built up the flood tidal delta, restricting flows, water exchange and navigation. The situation at the Mouth in early 2000 is shown in Figure 1.1. The photograph shows a severely restricted Mouth with a series of well defined channels crossing an extensive flood tidal delta.

![River Murray Mouth, taken on February 29, 2000.](image)

Current understanding of tidal inlets would indicate that the state of the Mouth depends on two factors: river flows and the coastal climate. The key elements of the coastal climate are wave energy, littoral transport, and tides. Given the micro-tidal conditions and the domination of wave energy on the coast the large flood tidal delta is to be expected (Hayes, 1991, Harvey, 1996). The tendency for inlets of this type to close periodically has been observed in many seasonally open inlets both in Australia and around the world (Australian Parliament Senate Standing Committee, 1981; Bally, 1987; Ranasinghe and Pattiaratchi, 1999). In this respect the situation at the Murray Mouth is not unexpected, although it should be stated that closure would be a radical departure from normal behaviour. The key questions are:

- Is Mouth closure avoidable? And if so, what is the best way to achieve this?
- Should Mouth closure be avoided?

In order to provide answers to these questions the aims of the current study were to:

1. Derive a modelling indicator for the Murray Mouth so that its health and state could be taken into account when management decisions that could affect the area were being taken.

2. Set out the historical behaviour of the Mouth and lower lakes (Alexandrina and Albert) so that the current situation could be viewed in a proper perspective.

3. Describe the consequences of total Mouth closure.

These aims will be addressed in subsequent chapters where the emphasis is on the derivation of a quantitative model of the Mouth behaviour.
2 A Brief History of the River Murray Mouth

The River Murray Mouth is located near Goolwa in South Australia (Figure 2.1). Although the river channel has been fixed in its position between Points Sturt and McLeay, and the Narrung Narrows for the last 780,000 years the position of the Mouth has varied over a range of approximately 6 km during the last 3,000 years and over 1.4 km in the last 160 years (Bourman and Murray-Wallace, 1991; Harvey, 1996).

Figure 2.1 Location of the Murray Mouth in relation to the lower lakes (Alexandrina and Albert) and The Coorong.

According to Barnett (1995) the general layout of the River Murray Mouth was finalised around 6,000 years ago when sea level rises and the subsequent formation of sand barriers (Sir Richard and Younghusband Peninsulas) enclosed the lower lakes (Alexandrina and Albert) and the Coorong. Based on sediment cores taken in Lake Alexandrina Barnett was able to provide a description of the lakes over the last 7,000 years. This is shown in Table 2.1. A key conclusion of the work is that for much of its history the river flows have been sufficient to keep the lower lakes fresh, and at a pool level that was similar to that maintained by the barrages (pers. comm. Bourman, 2001).

Table 2.1 Condition in and around lower lakes and Murray Mouth.

<table>
<thead>
<tr>
<th>Period</th>
<th>General Description</th>
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</thead>
<tbody>
<tr>
<td>(BP = Before Present)</td>
<td></td>
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<tr>
<td>7,000 – 6,000 BP</td>
<td>Sir Richard and Younghusband Peninsulas yet to form. Lakes Alexandrina and Albert</td>
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<tr>
<td></td>
<td>essentially part of an open estuarine system.</td>
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<tr>
<td>6,000BP – 1940 approx.</td>
<td>Formation of sand barriers encloses lower lakes. Extended periods of fresh water to</td>
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<td></td>
<td>estuarine conditions but with wide fluctuations in salinity. When fresh, Lake</td>
</tr>
<tr>
<td></td>
<td>Alexandrina was probably fresher than at present.</td>
</tr>
<tr>
<td>1940 approx.- present</td>
<td>Construction of barrages led to freshwater conditions. It should be noted that the</td>
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<td></td>
<td>term freshwater takes into account of an annual salt load of 595,000 tonnes (Bourman</td>
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<td></td>
<td>and Barnett, 1995).</td>
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</table>
In the last 170 years the Mouth has intermittently deposited and removed significant volumes of sediment on the landward side in the form of flood tidal deltas. The size of the Mouth has varied from being several hundred metres wide during heavy flood flows to a situation where it closed completely at low tides in April 1981. The Mouth, at the time of the closure in 1981, is shown in Figure 2.2. It is evident that the blockage involved not just a plug of sand in the Mouth, but an extensive flood tidal delta that had built up over the preceding months.

![Figure 2.2 River Murray Mouth in April 1981 showing full blockage at the Mouth and restriction of water exchange between the Goolwa (left) and Tauwitchere (right) Channels.](image)

Low flows and their effects, however, are not a recent phenomenon. The plan to construct the series of locks and weirs that are now an integral part of the river system was formulated and put into action after the drought of 1914 when the river had shrunk to a series of pools (DEHAA, 1999). In the 1930s low river flows led to salt water intrusions into Lakes Alexandrina and Albert. What has changed is the frequency at which the low flow events occur. According to unpublished data from the MDBC the median annual flow is now 27% of what it was under natural conditions. Thomson (1994) found that at the Mouth low flows (less than 5000 GL/year) occurred 7% of the time under natural conditions but 66% of the time under regulated conditions. At the Mouth, high flows (greater than 25,000 GL/year) occurred 5% of the time under natural conditions and 2% of the time under regulated conditions. Thomson also points out that it is not just the flow that has been removed but the fact that the annual spring high flow events are either much lower or fail to occur at all.

Following closure the Mouth was opened artificially in July 1981 and the opening maintained by winter river flows. Based on observations at the time it was suggested that flows of 25,000 to 30,000 ML/day were required to maintain and expand the artificial opening. This then led to the estimate that 20,000 ML/day for four weeks should restore a severely restricted Mouth to a healthy state. This figure has been quoted ever since (Harvey, 1988; Bourman and Barrett, 1995).

To illustrate the change in flows Figure 2.3 shows the predicted flows at the Murray Mouth under natural and regulated conditions for a ten year period. The flow predictions, supplied by MDBC, were based on a computer simulation that uses known river flows at a lock some distance from the Mouth and takes into account water extractions, losses due to seepage and evaporation, barrage operation and lower lake levels. The predictions are necessary because the actual flow over the barrages is not measured. In the figure the general reduction in flow is evident, as is the reduction in the peaks that would normally have occurred on an annual basis.
The change in the annual cycle of flows is best illustrated in Figure 2.4 redrawn from Thomson (1994) which shows the median flow at the Murray Mouth under natural and regulated conditions. Under current conditions the spring peak in flows is seen to occur earlier with a significantly reduced flow rate.
3 Issues Related to Mouth Restriction and Closure

The importance of maintaining the Murray Mouth opening has been set out in a number of papers and reports (Australian Parliament Senate Standing Committee, 1981; Murray Mouth Advisory Committee, 1983, Murray Mouth Advisory Committee, 1987; Harvey, 1988). The primary reasons have been listed as:

- prevent ecological damage to the Coorong;
- maintain the habitat in the RAMSAR listed Coorong area;
- prevent flooding of towns, shack sites and agricultural lands around Lakes Alexandrina and Albert;
- prevent damaging the local tourist industry;
- maintain the fishing industry in the Coorong;
- maintain the conservation significance of the Mouth area and Coorong;
- maintain water quality in the Coorong and adjacent channels.

The issues that have been listed come up commonly in discussions of seasonally open inlets. For example Ranasinghe et al. (1999) list navigation and water quality as the two primary reasons for aiming to maintain seasonally closed inlets. Bally (1987) listed local flooding, recreation and fishing as the main reasons for artificially opening a seasonal inlet in South Africa.

It should be stressed that while seasonally open tidal inlets are common around the world, the River Murray Mouth has, until recently, had sufficient river discharge to maintain an opening. It would represent a significant change in the river environment if the Mouth were to move to one that was closed frequently or open only seasonally.

In addition to the reasons given to prevent closure, experience gained during the re-opening of the Mouth in 1981 indicates the benefit of maintaining an effective opening in preference to allowing the situation to deteriorate until an urgent remedy is required. According to Harvey (1983) the re-opening took two attempts to effect. On the first, on 8 July 1981, a 3 metre wide channel 300 metres long was constructed between the Coorong Lagoon and the sea using two front-end loaders and a grader. The resulting flows were insufficient to maintain the channel and it silted up and closed. On 16 July a second channel from the Goolwa Channel to the sea was formed and, with sufficient flows (7,000,000 ML over four months), was able to form a viable mouth. From this point of view efforts should be directed towards a long-term management of the Mouth rather than a short-term view that concentrates on planning for the next closure.

In the next chapter a description of the Mouth opening is given together with results from simulations that were run to assess Mouth opening and stability.
Estimating Mouth Opening

The River Murray Mouth, its position and size, has been the subject of investigation and study since the days of colonisation in the 1830s. However, proper study of the size has been hampered by a lack of quantitative data. While there have been a number of surveys of the Mouth region the area does not lend itself to easy measurement.

To overcome this lack of specific detail Walker and Jessup (1992) used the tide data collected from Victor Harbor (outside the Mouth), the Goolwa Barrage (inside the Mouth) and the Tauwitchere Barrage (inside the Mouth) to determine an effective Mouth opening. The reasoning behind this idea was that the sediment build-up in the Mouth would act to restrict the free flow of tidal waters from the ocean into the channels leading to the barrages. Any restriction would be reflected in a reduced tidal amplitude at the barrage locations. Examples of the comparison for two periods, one (Figure 4.1) in 1982 when the Mouth had been cleared by river flows and the other in 1981 just prior to the most recent closure (Figure 4.2) when the Mouth was severely restricted show this effect clearly.

The tides serve as a reliable estimate of the Mouth opening for the majority of the time when the river flows are small. Once flows increase there is a damping of the tidal signal inside the mouth which means that the relative tides no longer reflect just the mouth restriction. An example of this is shown in Figure 4.3. The river flow is shown to elevate the water level at the Goolwa Barrage and there is also some damping of the tidal signal. It was not possible to take account...
of this in the model and the phenomenon would be responsible for some of the scatter shown in the comparison of measured and modelled data in Figures 4.6 and 4.7. The nature of the error means it would be significant when the model is forecasting the peak openings, but not have an effect on the highly restricted state of the Mouth that was the focus of the study.

Figure 4.3 Tides recorded at Victor Harbor and Goolwa Barrage during October 1990. The damping of the tidal signal at Goolwa Barrage is likely due to the river discharge rather than restrictions at the Mouth. The river flow, based on MDBC estimates was 2,658 GL/month.

Although tidal amplitude gives an excellent visual measure of the tidal variation, any noise in the signal can distort the estimates significantly. For this reason tidal energy (determined by spectral analysis) was selected as a measure of the tidal signal. The tides at the Mouth have a number of components but the most significant are due to the influence of the sun and the moon and have periods around 12 hours and around 24 hours. For the study tidal energy was defined based on the 12 hour tidal components of the tidal energy at both Victor Harbor and Goolwa Barrage. The 12 hour components were used since the filtering of signals by the Mouth should be frequency dependent, and to ensure that a comparison of energy was being undertaken at a period clearly associated with flows through the mouth. A sample energy spectrum is shown in Figure 4.4. The relative tidal energy, $R$, was defined where $E = \text{tidal energy in 12 hour components at location inside and outside the Mouth.}$

$$R = \frac{E_{\text{inside}}}{E_{\text{outside}}}$$  \hspace{1cm} (1)

Figure 4.4 Sample tidal energy spectrum for the Goolwa Barrage tide gauge. The two principle tidal components at periods of 24 hours (frequency $= 0.04$ cycles/hour) and 12 hours (frequency $= 0.08$ cycles/hour) are clearly identified.
A scatter plot of the relative tidal energy calculated using the 12 hour and 24 hour tidal energy components is shown in Figure 4.5. Given the nature of the data the scatter is not considered unreasonable and it is believed that the 12 hour tidal energy component or the 24 hour component could be used with equal confidence.

Based on this, $R$ should vary between 0 (complete closure leading to no tides inside Mouth) to 1 (complete opening leading to full transmission of tides to barrages). If there was some form of tidal amplification inside the mouth it would be possible to have an $R$ value that exceeded 1, and in the analysis there were a few instances where this was found to occur. An alternative explanation is that it could be due to slight variations in the spectral analysis estimates.

Walker and Jessup (1992) used the relative tidal energy factor $R$, as a measure of Mouth opening and attempted to model the variation of $R$ in terms of the monthly river flow. A reprint of Walker and Jessup (1992) is included in Appendix A. Recent analysis on the updated data set that includes information from 1976 to 2000 has derived a revised expression:

$$R_t = 0.8 R_{t-1} + 0.0002 F_{t-2} \quad (R^2 = 0.46) \quad (2)$$

where $R_t$ = relative tidal energy in month $t$;
$F_t$ = flow over barrages in GL in month $t$; ($F_{t-2}$ = flow two months previously).

The relationship explains much of the variation in the opening of the Mouth but does not attempt to predict the total behaviour since this would require taking into account the coastal processes. It has been observed by Culver (quoted in Australian Parliament Senate Standing Committee, 1981) that in addition to low flows, calm seas and reduced tides appear necessary for a complete closure. These calm conditions may not occur often. Harvey (1996) quoted work that indicated the area had swell waves greater than 2 metres in height for 68% of the time and that for a similar percentage of the time the locally generated sea would have added 1 metre in height to the waves.

It is also important to note that the model does not attempt to simulate the physical processes of tidal flows, river flows, sediment transport and morphological development. The model is empirical, based on a set of observations and therefore confined to situations similar to those under which the data were collected to develop the model.

A comparison between the actual Mouth opening based on the tidal analysis (Equation 1) and that predicted by Equation 2 is shown in Figure 4.5. The comparison is reasonable. Gaps in the measured signal are due to missing tidal data at Goolwa Barrage. It should be noted that the application of the model over the first two months requires the use of some estimated values (since the prediction of $R_t$ requires $R_0$ and $F_{-1}$) so the predictions are less reliable but the importance of the initial conditions is soon diluted and does not affect the bulk of the predictions.
A scatter plot of the modelled and measured data is shown in Figure 4.6. The $R^2$ value of 0.46 reflects the level of scatter that the plot exhibits, although given the underlying assumptions of the model and the complexity of the physical situation this is considered satisfactory.

The relationship described in Equation 2 was based on tide data at the Goolwa Barrage as it was felt that the Goolwa Channel would not provide significant loss of tidal transmission since the channel was wide and deep and therefore any loss of tidal signal could be attributed to the Mouth area.

Having determined that Equation 2 allows a reasonable prediction of the Mouth opening to be made the model was used in a long term simulation to predict the relative Mouth opening over a longer time scale under both natural and regulated conditions. The predicted Mouth opening under predicted natural flows (using the MDBC modelling tools) is shown in Figure 4.7. Since the model was derived under conditions where the barrages were in place it is not possible to estimate the true natural behaviour in the absence of the barrages so in the figures the values shown for the period 1900 to 1940 are artificial.
Figure 4.7 Predicted Mouth opening based on predicted natural flows (ignoring regulation and diversions). Note: the method of analysis assumes barrages in place for total duration of simulation.

A number of features are evident in Figure 4.7. The Mouth, even under natural flows, would have become congested and may even have approached closure on a number of occasions. However, on average the opening would have been sufficient to pass most of the tidal signal and there would have been few times when the relative tidal energy would have been below 20%. In contrast the prediction of Mouth opening under current regulated conditions is shown in Figure 4.8.

Figure 4.8 Predicted Mouth opening based on predicted regulated conditions (structures, diversions and barrages). Note: the method of analysis assumes barrages in place for total duration of simulation.

Comparison of the two predictions illustrates the effect that diversions and regulation are likely to have had on the Murray Mouth. The situation can be illustrated further by plotting the relative opening as histograms. This is done in Figure 4.9 for the natural situation and in Figure 4.10 for the regulated condition.

Two features are evident in the plots. The average opening under natural conditions is significantly larger than under the current regulated conditions, and the regulated river tends not to have the larger relative Mouth sizes than would have been expected under natural conditions.
Figure 4.10 Histogram of relative Mouth opening based on long term (100 year) simulation under natural conditions.

Figure 4.11 Histogram of relative Mouth opening based on long term (100 year) simulation under current regulated conditions.
5 Behaviour of the Goolwa and Tauwitchere Channels

The tidal data from the two barrages were used to determine the long-term trends in tidal conveyance for the Goolwa and Tauwitchere Channels. The situation for Tauwitchere is shown in Figure 5.1. It is evident from the figure that in addition to a significant variation in time there is a trend for decreasing tidal signal at Tauwitchere Barrage, particularly after 1990. It appears that the channel is being affected in the long-term by a consistent build-up of sediment inside the Mouth and the ability of the channel to pass tidal flows is being reduced. This is of serious concern given that the Tauwitchere Channel is the gateway to the Coorong.

![Figure 5.1 Relative tidal energy at Tauwitchere based on data from Tauwitchere Barrage. Gaps are due to missing water level data.](image)

Results of a similar analysis for the Goolwa Channel (Figure 5.2) indicates that there has also been a reduction since 1990 although it is not as marked as that experienced at Tauwitchere. It is also evident that the tidal transmission in the Goolwa Channel is much greater than that in the Tauwitchere Channel. This is perhaps not surprising since the channel is used for much of the discharge from the lakes and represents an efficient channel to the ocean.

![Figure 5.2 Relative tidal energy at Goolwa based on data from Goolwa Barrage. Gaps are due to missing water level data.](image)
6 Issues Related to Flow Scenarios and Management Options

It is clear from the preceding chapters that there is a problem developing at the River Murray Mouth. River flows have decreased and this has led to increased sedimentation inside the Mouth. This in turn has restricted flow through the Mouth and led to excessive siltation in the Tauwitchere Channel that leads to the Coorong.

As shown in Chapter 4 it is possible, using river flows predicted by MDBC and Equation 2, to predict the relative Mouth opening. This work, which enables various management options to be evaluated, has been undertaken by MDBC personnel and is reported elsewhere (Close, 2002).

When evaluating the options there are a number of other issues that must be considered in addition to the predicted effect on the Mouth opening. The sudden release of freshwater from the barrages influences not only the Mouth but also the Coorong. According to Dr David Paton (pers. comm., 2001) a sudden release is deleterious for bird and plant life in the Coorong as the flows tend to elevate water levels significantly and flood areas that are sensitive to water level. The benefits of using water to maintain the mouth must also be balanced against the those that would accrue from the provision of flow volumes for other environmental concerns such as floodplain health.

The changes at the Mouth have been linked to the construction of the barrages and a possible course of action would be to remove the barrages and return the Mouth to its ‘natural state’. Harvey (1996) quotes estimates of tidal prism that indicate that the construction of the barrages reduced the flow by around 90%. This would have a significant effect on the size of the Mouth under normal conditions. Unfortunately removing the barrages does not address the real problem: the lack of river flows. The micro-tidal wave dominated coastal environment means that the River Murray Mouth is likely to have excessive sedimentation inside the Mouth area and in the past the tendency to close would have been balanced by the consistent pattern of river flows flushing sediment from the Mouth. Culver (quoted in Australian Parliament Senate Standing Committee, 1981) believed that overall the effects of the barrages have not been deleterious although he did note that the tidal prism would have been larger had the barrages not been constructed. Since the model (Equation 2) was derived from data collected while the barrages were in place it was not possible to use it to model the effect of removing the barrages.

It should be noted that the current emphasis on the mouth opening should not be taken to mean that keeping the mouth open will maintain the environment of the lagoons and environs around the mouth. The results of determining the relative tidal index for the Tauwitchere Barrage have highlighted the long-term degradation that is occurring in the Tauwitchere Channel. This in turn would be adversely affecting the tidal exchange in the Coorong. If and when the mouth closes it will not be the start of a problem, it will be a point well along the way to severe damage and significant change. The final closure may be an easily measured key point, but it should not be thought of as the key problem.
7 Summary and Conclusions

A study of the River Murray Mouth has been undertaken with a view to assessing the likely effects of Mouth closure and the management options that are available to prevent closure. The study has concentrated on using water level data collected at Goolwa and Tauwitchere Barrages to derive a model of the Mouth behaviour in terms of the predicted flow over the barrages. The model derivation followed earlier work by Walker and Jessup (1992) but used additional tide data not available at the time of the initial study.

Based on the work undertaken during the study a number of conclusions can be drawn.

1. In recent years the Mouth has been observed to silt up and approach closure on a number of occasions, with a large flood tidal delta forming inside the Mouth.

2. The build-up inside the Mouth is believed due to a combination of inadequate river flows and nearshore coastal processes related to the wave and tide climate. Engineers and managers have no control over the latter.

3. Historically, the lower lakes were kept fresh by adequate river flows. During extended droughts evidence shows that the lakes became saline. It is believed that river flows were sufficient to maintain lake level close to the current level maintained by the barrages.

4. The annual median flow is 27% of what it was under natural conditions.

5. Closure of the Mouth should be avoided to prevent flooding, ecological damage, damage to tourism and to maintain the RAMSAR listed Coorong, fishing, and the conservation significance of the area.

6. The ratio of tidal energy in the 12 hour tidal components inside and outside the Mouth (R) provides a useful indicator of the state of the Mouth in terms of its size. It was found that this indicator was not valid during periods of high river flow. The nature of the error means it would be significant when the model is forecasting the peak openings, but not have an effect on the highly restricted state of the Mouth that was the focus of the study.

7. It is possible to model the relative Mouth opening in terms of river flow. This model can be written:

   \[ R_t = 0.8 R_{t-1} + 0.0002 F_{t-2} \]  
   \[ (R^2 = 0.46) \]  

   where \( R_t \) = relative tidal energy in month \( t \) and \( F_{t-2} \) = flow in GL per month two months previously. Use of the model by Close (2002) allows a number of conclusions to be drawn:

   - substantial reductions in the risk of Mouth closure can be achieved by maintaining flow through the Mouth more often;
   - a combination of an increase in South Australia’s entitlement flow by 2,000 ML/d and the use of the barrages to maintain a steady release reduces the percentage of years at risk of Mouth closure from 31.5% to 7.4%;
   - providing a larger flow once a year appears to be a less effective strategy for keeping the Mouth open;
   - increasing South Australia’s entitlement increases the degree of regulation across the rest of the River Murray with consequential adverse environmental impacts;
   - increasing South Australia’s entitlement adversely affects the water supply security to water users;
   - using the barrages to regulate outflows may also have adverse local impacts.

8. It should be noted that the current emphasis on the mouth opening should not be taken to mean that keeping the mouth open will maintain the environment of the lagoons and environs around the mouth. A Mouth closure may be an easily identified state, but the build-up occurring in the mouth region, the deterioration of the Tauwitchere Channel and reduction in the level of tidal flows to the Coorong should be of more concern.
8 References


Appendix A – Reprint of Walker and Jessup (1992)

Reprint of “Analysis of the Dynamic Aspects of the River Murray Mouth, South Australia” by Walker and Jessup. Published in Journal of Coastal Research Volume 8, Number 1, 1992, Pages 71-76
Analysis of the Dynamic Aspects of the River Murray Mouth, South Australia

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ABSTRACT


Much of the work on tidal inlets carried out to date has been devoted to the determination of time-independent equilibrium criteria for the inlet dimensions. The relationships have generally been defined in terms of tidal prism, inlet velocity, littoral transport and mouth area. In the case of the River Murray Mouth it has been found that river flows play a major role in maintaining the inlet, and that the inlet dimensions are directly affected by the magnitude of those flows. The emphasis of the present study has been to utilise Time Series Analysis techniques to analyse and quantify the dynamic aspects of the inlet behaviour. The work presented includes results of the analysis leading to the identification of a linear system between the river flows and the mouth restriction. It is proposed that the use of Time Series Analysis has enabled a clear understanding of the role of river flow in maintaining the inlet to be gained and has provided a tool which is proving useful in managing the mouth.

ADDITIONAL INDEX WORDS: Tidal inlet, Time Series Analysis, river mouth management.

INTRODUCTION

The River Murray, Australia's main river system, travels a distance of some 2,500 km and drains an area of over 1,000,000 km² before it makes its way to the sea in South Australia near the coastal town of Goolwa, 100 km southeast of Adelaide. The mouth and environs are shown in Figure 1.

Immediately prior to entering the sea the river flows through a large freshwater lake, Lake Alexandrina. Lake Alexandrina also supplies water to an adjacent freshwater lake, Lake Albert. In an effort to keep the lakes fresh and to allow the discharge of fresh water to be regulated, a series of barrages were completed in the early 1940's. Prior to the construction of the barrages saline water had been known to travel as far as Murray Bridge, 113 km upstream of the mouth.

The fact that Australia is so arid and the river has a low run-off, considering the size of its catchment, means that the flows entering the lakes are often not sufficient to keep pace with diversions and evaporation. There are often long periods when no fresh water at all is discharged over the

Figure 1. Murray Mouth and environs. Barrages are shown as bold lines. The location of the Goolwa Barrage water level recorder is shown as "a", and the Victor Harbor tide station as "b".
barrages. In 1979–1981, for example, a period of 19 months passed when the barrages remained effectively closed. This lack of river flow meant that the mouth was then deprived of its fresh flushing water and it proceeded to shoal and close. It was subsequently re-opened with the aid of human intervention, and, with the benefit of quite high winter flows, was able to stay open naturally. The closing of the mouth raised a number of concerns including the possibility of flooding around Lakes Alexandrina and Albert, the effects on water quality in the nearby coastal lagoons (the Coorong), and the impact on the local fishing industry. The closure highlighted the fact that a better understanding of the mouth behaviour would be required if further closures were to be avoided. This paper contains the results of a study that was undertaken to investigate the effects of the river flows on the mouth size. The approach taken was statistical, rather than one concentrating on the physics of the mouth behaviour. It is hoped that a future study of the area will focus more thoroughly on the latter.

**EQUILIBRIUM CRITERIA FOR TIDAL INLETS**

There is a wealth of literature concerning the stability of tidal inlets. The emphasis, however, to date has been on studying inlets that were in some form of equilibrium, and determining the parameters to describe that equilibrium. Bruun and Gerritsen (1958), O’Brien (1969), Bruun et al. (1974), Bruun (1978) and others have proposed various quantities that have been chosen to describe inlet stability. The more frequent have been inlet area, tidal prism, inlet velocity and the rate of littoral drift. Nearshore wave energy has also been suggested by Bruun (1968) and O’Brien (1969) as relevant when inlet closure is being considered. River flow, where present, has been assumed to be of lesser significance, due to the generally lower flow rates and shorter durations when compared with the tidal flows. Escoffier and Walton (1979), however, investigated the effect of river flow on the stability of simple inlets and derived relationships that included such flows.

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Figure 2. Tidal energy in the 12 hour band for Victor Harbor—1981.

Figure 3. Tidal energy in the 12 hour band for Goolwa Barrage—1981.
The situation at the Murray Mouth had been investigated by applying many of the stability criteria. Although these provided some confirmation as to the state of the inlet, none of the methods was able to be used to predict the changing mouth dimensions and therefore its flushing characteristics for the waters of the adjacent coastal lagoons.

ESTIMATION OF MOUTH RESTRICTION

Although there have been a number of surveys of the mouth area taken over the years, the information on its own was insufficient to allow any relationships between the mouth dimensions and the river flows to be determined. The South Australian Engineering and Water Supply Department (E&WS) has collected continuous water level data at three of the barrages, Goolwa, Mundoo and Tawitcherie (both upstream, in the lakes, and downstream, on the ocean side), over the last decade.

There is also a tide recording station at Victor Harbor which is near Goolwa and some 25 km from the mouth. The data from this station are collected and analysed by the Tidal Laboratory, Flinders Institute for Atmospheric and Marine Sciences at Flinders University, on a routine basis. The raw data from this station were obtained from the Tidal Laboratory for the period 1981–1984. The relative tidal amplitude between the records taken at the Goolwa Barrage and the Victor Harbor gauge was found to give the best indication of the relative restriction of the mouth.

The tide data were digitized in hourly intervals and it was found that the 12 hour spectral component of the tidal energy gave a useful measure of the tides. Figure 2 illustrates the spectral energy for the Victor Harbor Tide Station while Figure 3 shows the results for the Goolwa Barrage Water Level Recording Station. The use of the spectral components filtered out much of the short period waves that were present at the barrage gauges due mainly to wind effects.

To specify the capacity of the mouth to pass the total tidal component, an energy ratio factor, $R$, has been defined:

$$ R = \frac{E_b}{E_o} $$

(1)

where $E_b$ is the tidal energy inside the mouth and $E_o$ the tidal energy in the ocean adjacent to the inlet. The energy ratio, $R$, should vary between 0.0 (complete restriction) and 1.0 (no restriction). Figure 4 shows the calculated values for 1981 based on the Goolwa and Victor Harbor data.

It is evident in the plot that there was considerable variation in the capacity of the mouth to pass the total tidal component. This method of analysis assumes that the mouth can be considered as a simple inlet where all the restriction will be in the inlet throat and not in the adjoining channels leading to the water level recording stations. This is a simplification of the actual situation but based on surveys of the mouth the assumption is considered reasonable in this case.

RELATIONSHIP BETWEEN MOUTH RESTRICTION AND RIVER FLOWS

The reason for the variation in mouth restriction becomes clear if the restriction is compared with the estimates of flow over the barrages for the same period. This is illustrated in Figures 5 and 6 where the data are plotted monthly for the years 1981–1984. It can be seen that there appears to be a direct relationship between the mouth restriction and the river flow. Time Series Analysis allowed the form of this relationship to be determined.
To enable the analysis to proceed two data sets were prepared, one containing the monthly barrage flow estimates and the other the average monthly mouth restriction. There were 48 data points in each set. It was unfortunate that such a large timestep as a month had to be used but the flow estimates, which were provided by the E&WS, were only available on a monthly basis.

TIME SERIES ANALYSIS

Time Series Analysis is a method of analysing a continually changing phenomenon where a position of stability may never be reached. Time Series Analysis can be used where two time series can be regarded as related, due to the fact that one can be considered as an input to a system and the other the output from that system. It is the identification of such a system between the river flows and the mouth restriction that was the major task of the study. Details of the methods described here can be found in Box and Jenkins (1976). A simpler introduction to the subject is presented in Chatfield (1984).

The analysis was conducted using an in-house statistical package based on the algorithms provided in Box and Jenkins (1976). The PEST (Parameter ESTimation) computing package from the Key Centre for Statistical Sciences, Melbourne, Australia was also used. No doubt there are numerous other sources of programs and packages that would carry out the required analysis.

The barrage flow data were analysed and the resulting model can be written:

\[
F_t = 1.550F_{t-1} - 0.640F_{t-2} + Z_t \\
(±0.120) \quad (±0.120)
\]

\[
- 0.301Z_{t-1} - 0.629Z_{t-2} \quad (±0.160) \quad (±0.160)
\]

where F represents the flow over the barrages, the subscripts refer to time (in months), and Z is a white noise (random) time series. Shown also are the standard errors. The 95% confidence limits for the coefficients are 1.96 times the standard errors. It is evident that the coefficients are generally at better than this level of confidence. This model was used to filter the input (flow) and output (mouth restriction) series to remove any autocorrelation. The cross correlation of the filtered
series was then determined. The Box-Jenkins approach allows this information to be parameterized so that the relationship can be described more compactly.

The resulting model can be written:

$$R_t = 0.734R_{t-1} + 0.000132F_{t-3} + N_t$$

(3)

\[
\pm 0.070 \quad \pm 0.000020
\]

where $R_t$ is the mouth restriction at time $t$ (where $t$ is in months) and $F$ is the river flow in Gt/month. $N_t$ represents the noise in the system. It should be noted that since $R$ varies between 0 and 1 and $F$ can be of the order of 2,000 the two quantities on the RHS of the equation will be of the same order, and therefore of equal importance.

It is evident that the degree of restriction $R$ for a particular month is based on the restriction from the previous month and on the river flow from two months previously. There is therefore a basic lag in the system of 2 months. The performance of the model can be illustrated by looking at numerical forecasts generated using the model. The first check is shown by calculating one month forecasts. For each month the flow and mouth restriction values are assumed known and the next month’s mouth restriction is calculated based on Equation 3. The results of this are shown in Figure 7. In the plot the vertical bars are the numerical predictions of Equation 3 and the solid line is the observed mouth restriction. It is evident that the model accounts for most of the observed variation in the mouth restriction. Note that the mean has been removed from the series. This is a precondition of the method of analysis used. Actual predictions could be generated by adding back in the calculated mean.

The derived model can be used to predict further ahead than one month. This is illustrated in Figure 8 where the mouth restriction was forecast 24 months ahead. Use of the model can be seen to give reasonably good predictions of the behaviour up to two years in advance. This of course assumes that the river flow could be predicted as far ahead as this. In the case of the Murray two years is excessive but certainly three month flow predictions would not be unreasonable. Due to
the lag in the behaviour of the mouth the model is capable of predicting what the mouth restriction will do in the following five months.

SUMMARY AND CONCLUSIONS

A method for analysing the dynamic aspect of tidal inlets using Time Series Analysis has been presented. The method has proved useful in deriving the relationship between river flows and the mouth restriction at the Murray Mouth in South Australia. The method is a statistical one which determines and quantifies the relationships without attempting to explain them. It is anticipated that the results of this study will be useful in predicting future mouth closures and in developing a barrage operation strategy which would assist in avoiding such events.

It is hoped that future work will include an investigation of the importance of the littoral processes on the mouth and a phenomenological study of the inlet which will seek to investigate the factors behind the behaviour of the inlet and flow systems that have been determined as part of this work.

LITERATURE CITED


□ RÉSUMÉ □

La plupart des travaux sur les goulets de marée effectués jusqu'à ce jour, ont été consacrés à la détermination de critères d'équilibre des dimensions du goulet, indépendants du temps. Les relations avaient généralement été définies en termes de prisme littoral, vitesses dans le goulet, transport littoral et surface de l'embouchure. Dans le cas de l'embouchure de la rivière Murray, il a été montré que les débits jouaient un rôle essentiel dans le maintien du goulet, et que les dimensions de celui-ci étaient directement affectées par leur magnitude. La présente étude tente d'utiliser des techniques d'analyse de séries temporelles pour quantifier les aspects dynamiques du comportement d'un goulet. On y trouvera les résultats de l'analyse conduisant à l'identification d'un système linéaire entre le débit fluvial et le rétrécissement de l'embouchure. L'utilisation de l'analyse de séries temporelles a permis une bonne compréhension du rôle du débit fluvial dans le maintien du goulet et a fourni un outil permettant l'aménagement de l'embouchure.—
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□ ZUSAMMENFASSUNG □

Viele der bisherigen Arbeiten über gezeitenbeeinflußte Seegatten dienten der Bestimmung zeitunabhängiger Kriterien für einen Gleichgewichtszustand der Gattdimensionen. Die Bezugsgrößen wurden generell in Ausdrücken wie Gezeitenprisma, Einlaufgeschwindigkeit, Küstentransport und Mündungsgebiet definiert. Im Falle der Mündung des Murray zeigte sich, daß der Abfluß des Flusses eine Hauptrolle bei der Erhaltung des Gatts spielt und daß die Dimensionen des Gatts unmittelbar von der Größe dieses Abflusses abhängen. Der Schwerpunkt der vorliegenden Studie war es, die Zeitreihen-Analysetechnik zu benutzen, um die Dynamik des Gatts zu analysieren und zu quantifizieren. Die Untersuchung stellt die Ergebnisse dieser Analyse dar und erarbeitet eine lineare Beziehung zwischen Abfluß und Mündungsdimension. Es wird deutlich, daß die Anwendung der Zeitreihenanalyse auf ein klares Verständnis der Bedeutung des fluvialen Abflusses für die Erhaltung des Gatts führt und daß sie sich als ein nützliches Instrument zur Erhaltung und Bearbeitung des Mündungsgebietes erwies.—
Helmut Brückner, Geographisches Institut, Universität Düsseldorf, Germany.