Flushing study of the Monkey Mia lagoon, Western Australia, during 19-22 September 1996

A collaborative project between the Marine Conservation Branch, Midwest Region and Gascoyne District of the Department of Conservation and Land Management and the Department of Environmental Engineering of the University of Western Australia

Field Programme Report MM - 01/96

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CONTENTS

Tide predictions and boating guide of Western Australia”. Westprint, Western Australia).

SUMMARY

This field programme report presents details of the planning and proposed field work for a study of the flushing characteristics of the Monkey Mia lagoon and adjacent waters during 19-22 September 1996. A grid of 31 sites will be visited repeatedly during the field period in order to establish the flushing behaviour of the lagoonal waters under the influence of tides, winds and density gradients during typical early-spring conditions. The study follows on from the preliminary field survey of the Shark Bay Marine Reserves Monitoring Programme (SBMRMP), conducted in April 1996, and during which salinity-temperature data were collected at selected sites within the study region (see D'Adamo, Colman and Pobar, 1996; D'Adamo and Pobar, 1996). The results of the study will serve as a contribution to the SBMRMP by developing a better understanding of the Monkey Mia region of the Shark Bay Marine Park with particular reference to the Monkey Mia lagoon. The information will provide a better technical basis from which to assess the potential for contaminant accumulation in the Monkey Mia lagoon. The objectives of the study are consistent with the recommendations of recent studies which have highlighted the need to improve the understanding of the hydrodynamics of the lagoon and wider waters of the bay (Environmental Protection Authority, 1989; Trayler and Shephard, 1993; Murex Consultants Pty. Ltd., 1994; CALM, 1994).

The study is being coordinated by the Marine Conservation Branch of the Department of Conservation and Land Management (CALM) and conducted in collaboration with CALM's Midwest Region and Gascoyne District offices and the Department of Environmental Engineering of the University of Western Australia (DEEUWA). The study will form the basis of a student Honour's project at the DEEUWA. Field assistance is being provided by the Department of Fisheries, Carnarvon.

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Direction

- Kieran McNamara **-** Director, Nature Conservation Division, CALM.
- Dr Chris Simpson **-** Manager, Marine Conservation Branch (MCB), Nature Conservation Division, CALM.
- Greg Leaman **-** Manager, Midwest Region, CALM.

CALM Regional/District collaboration

- Geraldton Region **-** Ron Shephard, Programme Leader, Nature Conservation.
- Gascoyne District **-** Paul Brown, Manager; Brad Barton, Operations Officer.

University of Western Australia collaboration

- Department of Environmental Engineering **-** Dr Greg Ivey and Dr Charitha Pattiaratchi.

Funding and resources

- Funding of $10,000 has been provided by the World Heritage Unit of the Commonwealth Department of the Environment, Sports and Territories.
- In kind resources comprising scientific supervision, logistical support, instrumentation and staffing have been provided by the Marine Conservation Branch and Gascoyne District, CALM.
- In kind resources comprising scientific supervision, computing resources and instrumentation have been provided by the Department of Environmental Engineering, University of Western Australia.
- Logistical support in the form of vessels and field staff have been provided by the Department of Fisheries, Carnarvon

1 INTRODUCTION

1.1 Aim

The aim of the study is to develop a better understanding of the general hydrodynamics of the Monkey Mia region of the Shark Bay Marine Park with particular reference to the Monkey Mia lagoon.

The results will also be used to assess whether a follow-up summer study of the hydrodynamics of the lagoon is required to provide a more detailed understanding of the seasonal characteristics of the hydrodynamics of the lagoon.

1.2 Background

1.2.1 General

Monkey Mia is located on the eastern side of the Peron Peninsula in Shark Bay, Western Australia (Figure 1). The lagoon has a high conservation status and is situated within the Monkey Mia Recreation Zone of the Shark Bay Marine Park. The high numbers of tourists (>80000 per year) that come to view dolphin feeding in the lagoon results in it being a high revenue earning attraction and an opportunity to promote the conservation value of dolphins and other flora and fauna of the Bay by means of public awareness and education. Careful management of the pressures that can accompany high usage is required, with an adequate understanding of the mixing and transport of water and contained substances, as emphasised by recent studies (Environmental Protection Authority, 1989; Trayler and Shephard, 1993; Murex Consultants Pty. Ltd., 1994; CALM, 1994).

In the Shark Bay Marine Reserves Draft Management Plan 1994 (Department of Conservation and Land Management, 1994) the physically protected nature of Shark Bay was highlighted in discussions relating to circulation and exchange. It was emphasised that "Water temperature, circulation patterns and salinities have a major impact on the distribution of habitats and the biology of individual species. A comprehensive understanding of these variables is essential for effective management of the marine park". To that end a major recommendation of the draft management plan was to "Encourage research into water circulation, salinity and temperature fluctuations in Shark Bay and utilise this information in marine reserve management and assessment of proposed developments in, and affecting, the marine reserves". The objectives of this proposed study are consistent with these recommendations.

The proposed study will contribute to the environmental management of the lagoon by providing a more detailed understanding of the manner and rate at which water, and contained substances, are flushed from the lagoon out to the more open waters of Shark Bay under a range of oceanographic conditions. The climate of Shark Bay during late winter-early spring is characterised by prolonged calms interrupted by occasional storms, and during calms the effect of wind-driven mixing and advection is less than during storms. The information will provide a better technical basis from which to assess the potential for contaminant accumulation in the Monkey Mia lagoon. This will allow a better basis from which to manage the potential increase in contaminant inputs to the dolphin feeding area and surrounding waters as usage of these waters increases over time.

1.2.2 Past hydrodynamic studies

Monkey Mia

No specific studies of the hydrodynamics of the Monkey Mia lagoon have been conducted to date although the issue of flushing was highlighted as important in the context of pollution management and conservation by recent environmental studies (Environmental Protection Authority, 1989; Trayler and Shephard, 1993; Murex Consultants Pty. Ltd., 1994; CALM, 1994), as discussed above.

This field study follows an initial salinity-temperature and habitat survey of the Monkey Mia lagoon and adjacent nearshore waters conducted on 18 April 1996 as part of the preliminary survey of the Shark Bay Marine Reserves Monitoring Programme (see D'Adamo, Colman and Pobar, 1996; D'Adamo and Pobar 1996). The salinity temperature data from that survey showed there were significant salinity and temperature differences between the lagoon and adjacent waters. The mean salinity in the lagoon was greater than 42 pss whereas the salinity of near-surface water 3-5 km offshore was about 39.5 pss. The lagoonal temperature was about 25.5 °C compared to about 24.5 °C further offshore.

Shark Bay

Shark Bay is subjected to large rates of evaporative salinity increases and restricted exchange with the adjacent ocean and as a result is predominantly hypersaline. Salinities have been found to range from oceanic (approximately 35 pss) in the northern areas of the Bay to hypersaline (up to approximately 72 pss) in the southernmost areas, such as Hamelin

Basin and L'haridon Bight. The approximate north-south direction in the salinity gradient is present throughout the year. Water temperatures range from about 16 ^{o}C in winter to about 26 ^{o}C in summer, with the greatest seasonal fluctuations occurring in the southern areas of the Bay. The main factor that restricts exchange is the blocking effect of sills between the central portions of the Bay (such as Faure Sill near Monkey Mia) and the lower southern reaches. In addition, the presence of Bernier and Dorre Islands to the north of Dirk Hartog Island presents a further physical barrier to exchange with the ocean. These and other general physical characteristics of Shark Bay have been comprehensively described in Logan and Brown (1986) which contains information on the climate, bathymetry, sea level history, geomorphology, geology, benthic habitats, salinity, temperature, broadscale flow patterns and exchange. Logan and Brown (1986) analysed long-term records of salinity, temperature and currents, and considered the data in conjunction with evaporative, bathymetric, tidal and wind effects, to calculate a salt budget and estimate a residence time of order 8 months for water in the Hamelin Pool/Faure Sill area.

More detailed studies of the hydrodynamics of Shark Bay are currently being conducted by Mr Murray Burling, a M. Eng. Sc. student at the Department of Environmental Engineering of the University of Western Australia (supervised by Drs Charitha Pattiaratchi and Greg Ivey). Mr Burling is analysing oceanographic data and applying a three-dimensional barotropic numerical model to the Bay (Burling and Pattiaratchi, 1995a, b). Mr Burling's analyses have highlighted the vertically and horizontally stratified salinity and temperature (and therefore density) structure of the Bay, including the region offshore of Monkey Mia. Circulation in the Bay is strongly influenced by wind and tidal effects, however Burling and Pattiaratchi's (1995a, b) preliminary data analyses suggest that the density stratification and Coriolis force (due to the Earth's rotation) provide important influences on the nature of wind and tidal driven flows. Burling and Pattiaratchi (1995a, b) also suggest that characteristic horizontal density gradients in the Bay are sufficiently strong to drive density currents of significance to the overall circulation.

Mr Alan Pearce of the CSIRO Division of Oceanography is undertaking analyses of NOAA-AVHRR sea-surface temperature imagery for Shark Bay and adjacent oceanic waters to determine the seasonal characteristics of basin-wide SST structures and the influence of the Leeuwin Current (Cresswell and Golding, 1980; Cresswell, 1990; Pearce, 1990) on the hydrodynamics of Shark Bay.

1.3 Collaborations

This study was initiated following discussions between the Marine Conservation Branch, Midwest Region and Gascoyne District. The work will be conducted as a joint exercise between CALM's Marine Conservation Branch (MCB) (contacts: Chris Simpson, Nick D'Adamo), Midwest Region (contacts: Greg Leaman, Ron Shephard) and Gascoyne District (contacts: Paul Brown, Brad Barton) and the University of Western Australia's Department of Environmental Engineering (DEEUWA). Nick D'Adamo is the Field Team Leader for the study. Logistical support has been provided by the Monkey Mia Visitor Centre (contact: Brian Nicholson).

Discussions between MCB and DEEUWA have resulted in an agreement to conduct the study as a collaborative exercise between CALM and DEEUWA, with the involvement a fourth year honours student in the data processing and preparation of a data report. Supervision will be shared by Drs Greg Ivey and Chari Pattiaratchi of DEEUWA and Nick D'Adamo of MCB. Terms for the collaboration are presented in Section 8 of this proposal.

2 SURVEY GRID, METHODS AND EQUIPMENT

2.1 Site and grid details

Figure 2 presents the bathymetry of the lagoon and adjacent waters and also the grid of salinity-temperature monitoring sites, with the dashed line indicating the boundary of what is referred to as the "inner grid" of sites. The coordinates of the sites are listed in Table1.

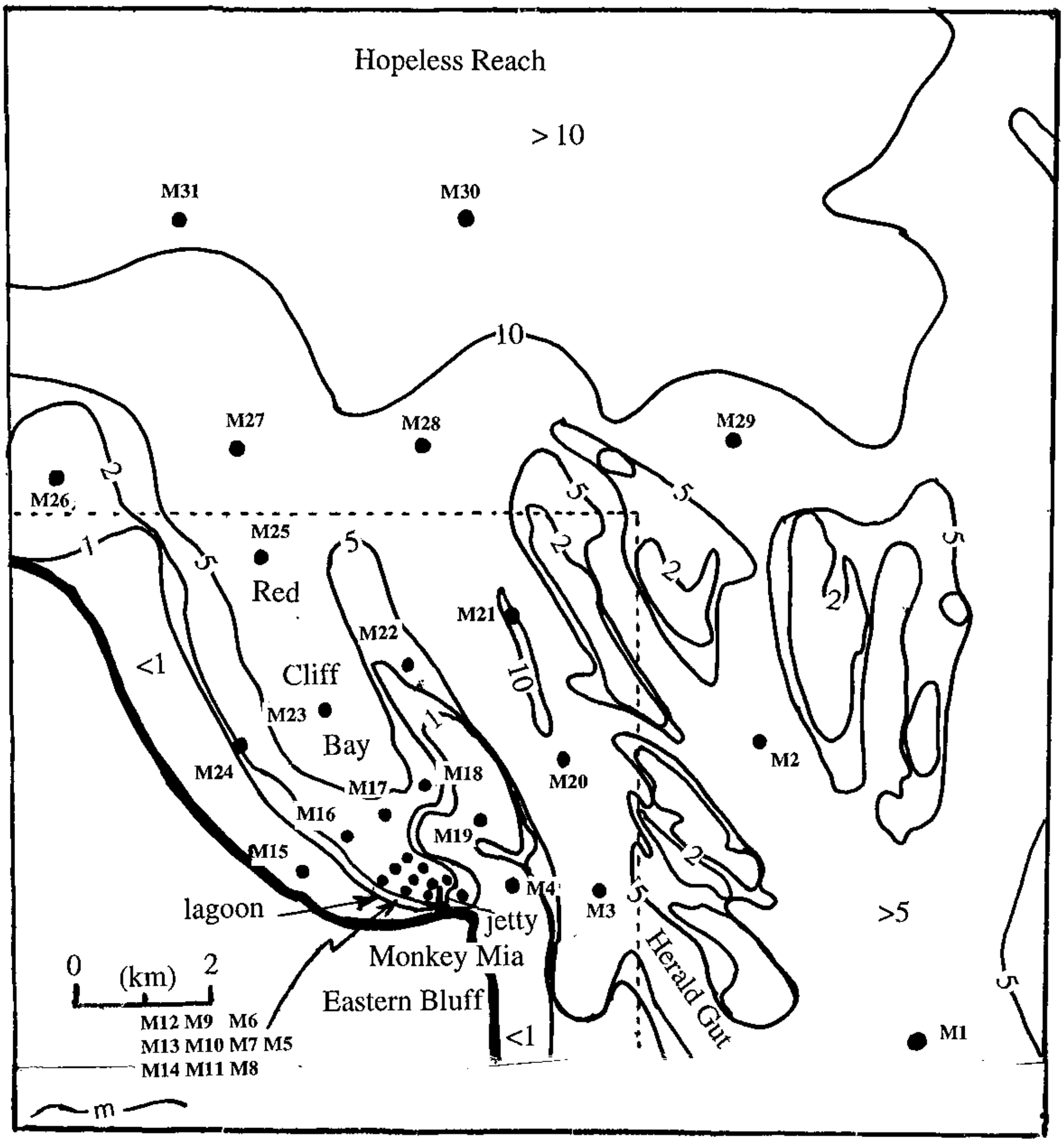

Figure 2 Proposed salinity-temperature profiling sites and detailed bathymetry of the Monkey Mia lagoon and its surrouding waters. The "inner grid" lies within the dashed line.

Table 1 Site coordinates.

SITE	LATITUDE	LONGITUDE	COMMENT
M1	25° 48.65	113° 47.25	
M2	25° 46.23	113° 45.80	
M3	25° 47.45	113° 44.35	INNER GRID
M4	25° 47.45	113° 43.55	INNER GRID
M5	25° 47.58	113° 43.10	INNER GRID
M6	25° 47.40	113° 43.00	INNER GRID
M7	25° 47.44	113° 42.88	INNER GRID
M8	25° 47.52	113° 42.82	INNER GRID
M9	25° 47.28	113° 42.75	INNER GRID
M10	25° 47.40	113° 42.66	INNER GRID
M11	25° 47.48	113° 42.62	INNER GRID
M12	25° 47.20	113° 42.60	INNER GRID
M13	25° 47.30	113° 42.50	INNER GRID
M14	25° 47.41	113° 42.39	INNER GRID
M15	25° 47.30	113° 41.63	INNER GRID
M16	25° 47.00	113° 42.05	INNER GRID
M17	25° 46.85	113° 42.40	INNER GRID
M18	25° 46.60	113° 42.75	INNER GRID
M19	25° 47.00	113° 43.25	INNER GRID
M20	25° 46.40	113° 44.00	INNER GRID
M21	25° 45.20	113° 43.50	INNER GRID
M22	25° 45.60	113° 42.57	INNER GRID
M23	25° 46.00	113° 41.80	INNER GRID
M24	25° 46.28	113° 41.05	INNER GRID
M25	25° 44.75	113° 41.20	INNER GRID
M26	25° 44.13	113° 39.35	
M27	25° 43.85	113° 40.98	
M28	25° 43.82	113° 42.68	
M29	25° 43.78	113° 45.52	
M30	25° 42.00	113° 43.00	
M31	25° 42.00	113° 40.40	

The bathymetric relief and prominence of the sill that envelopes the lagoon is highlighted in the aerial photo of Figure 3. As shown, the bathymetry of the lagoon and adjacent waters of Red Cliff Bay is characterised by a relatively deep basin of approximately 4-6 m (with respect to chart datum, which is approximately the level of lowest astronomical tide) surrounded to the south by land, and to the east and north by a relatively shallow sill of less than about 1 m depth. The approximate dimensions of the inner lagoon area (within the 1 m contour) are 1500 m X 900 m in the NW-SE and SW-NE directions, respectively. The wider semi-enclosed area, containing a portion of Red Cliff Bay, has dimensions of approximately 2800 m X 2200 m (within the 1 m contour). A series of approximately parallel channels and sills are situated offshore of the lagoon and Red Cliff Bay.

For the purposes of this proposal the inner lagoonal area will be referred to as the Monkey Mia lagoon, or otherwise simply as the 'lagoon', and the broader area which contains the 'lagoon' and the remaining part of Red Cliff Bay will be referred to as Red Cliff Bay. The wider waters of Shark Bay will be referred to as Shark Bay, or otherwise simply as the 'Bay'.

2.2 Contingency for adverse weather conditions

In the event of foul weather and the decision by the skipper to rule out offshore monitoring on safety grounds, then the programme will revert to monitoring of sites within the immediate confines of the Monkey Mia lagoon. Decisions of this nature are to be made by consultation between the Field Team Leader, Nick D’Adamo, and the skipper. Another possible alternative would be to station the vessel off the end of the jetty and perform repeated CTD profiling of the water column at that point to determine the temporal variation of the mean salinity-temperature characteristics in response to strong wind conditions.

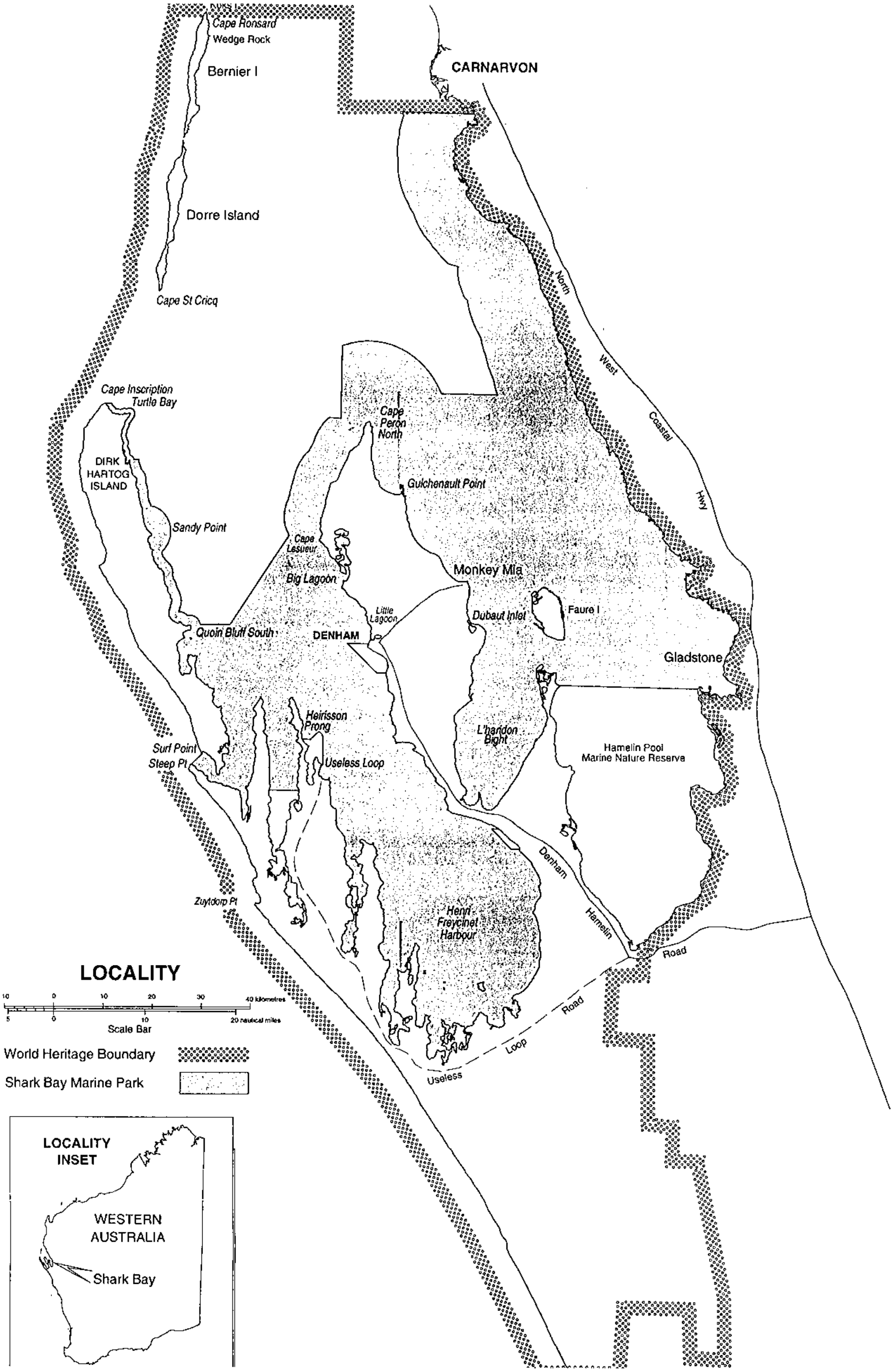

Figure 1 Locality diagram of Monkey Mia and boundaries of the Shark Bay Marine Park and Shark Bay World Heritage area

Figure 3 Aerial photo of the Monkey Mia lagoon and Red Cliff Bay

With respect to safety considerations, the skipper of the vessel reserves the right to alter field activities due to foul weather.

2.3 Methods

The period of the hydrodynamic field survey was chosen to coincide with neap tides and early spring meteorological conditions anabling a likelihood of encountering calm periods interrupted by occasional storms. Measurements will be at a sufficiently high temporal resolution so as to capture the influence of the dominant factors of tides, winds and density effects. The general techniques of repetitive basin-scale salinity-temperature (ST) profiling in conjunction with direct current measurements (using current meters and/or drifter drogues) will be used. Water level variation and meteorological parameters will also be monitored.

The objective of the ST monitoring is to detail the three-dimensional salinity-temperature-density structure as it changes due to mixing, circulation and exchange. Changes in the salinity, temperature and density structure can be interpreted to infer vertical mixing and horizontal motions. Complementary in situ flow measurements will enable the inferred flow patterns to be directly verified.

The acquisition of regional satellite imagery will assist in understanding first, the role of broadscale processes in introducing water to the Monkey Mia-Faure Sill region and second, the fate of water that leaves the lagoonal area and enters the wider waters of the Bay. To this end, the strategic measurement of salinity-temperature fields in waters offshore of Monkey Mia, between Peron Peninsula and the mainland, should provide valuable insight to the wider circulation patterns when considered in conjunction with a time series of regional SST images

2.3 Equipment

2.3.1 Salinity-temperature monitoring

A high resolution conductivity-temperature-depth (CTD) probe will be used (from the Centre for Water Research, University of Western Australia). The CTD probe acquires data in free fall mode at 50 Hz reading directly to an onboard computer. The sensors return salinity, temperature and depth data at accuracies of 0.001 pss, 0.001 ^{o}C and 0.001 m, respectively. A demonstration of the operation of the CTD probe was held on 14 August 1996 at the Department of Environmental Engineering of the University of Western Australia (UWA). This was conducted by Mr Terry Smith of the Centre for Water Research (UWA).

CALM will provide 4 temperature loggers for deployment within the lagoon and wider surrounding waters of the Bay. These loggers collect time-series data of water temperature variation over relatively wide spatial scales, and would thereby provide data that could be used to assist in the calibration and validation of barotropic and baroclinic numerical models of the hydrodynamics of the Bay (Burling and Pattiaratchi, 1995a, b).

2.3.2 Current measurements

Four cross-vane drifter drogues will be deployed at selected times to measure flow. The drogue vanes will be square and 2x2 m^2 in cross-section. The general approach will be to deploy the drogues within the lagoon after the completion of an ST grid circuit and then periodically fix their positions by differential GPS for a period of 5-10 hours during the ST monitoring.

In addition, CALM will explore the possibility of deploying fixed point current meters (Neil-Brown ACM-2) under a collaboration between the Department of Environmental Protection, CALM, and the Department of Fisheries. Continuous current meter records would serve as valuable calibration and validation data for the application of three-dimensional barotropic and baroclinic models (Burling and Pattiaratchi, 1995a, b). In addition, the data would assist in understanding the hydrodynamic response of the wider waters of the Bay to winds, tides and density effects. A better understanding and predictive ability of circulation within Shark Bay would assist greatly in assessing the impacts of proposed commercial activities such as aquaculture.

2.3.3 Water level

The period of the field survey has been planned to coincide with neap tides. Tidal variation at Monkey Mia approximately reflects that at Carnarvon and extracts from the Tide Tables for Carnarvon and Denham are presented in Appendix I.

2.3.4 Meteorological data

The closest Bureau of Meteorology site is at Denham, Shark Bay. The following parameters are read from instruments and recorded to data sheets every third hour of the day, beginning at 0000 hours but excluding 2100 hours: wind speed and direction at 10 m, air temperature, cloud cover, visibility, barometric pressure, relative humidity. Data will be obtained from the Bureau of Meteorology, Perth.

3 FIELD PROGRAMME

The field work is planned to span a total of 5 days through consecutive tidal cycles (predominantly semi-diurnal) with the objective of capturing periods of relatively weak ($\leq$ 5 m s^{-1}) and, if the opportunity arises, strong (~ 10 m s^{-1}) winds. Measurements will involve basin-scale salinity-temperature profiling, with complementary current measurements, water level and meteorological data collection. Satellite imagery of sea-surface temperature (SST) and water colour for the Shark Bay region will also be acquired in order to gain an insight into broad-scale circulation patterns that may be evident from changes in the SST structure.

A total of 31 CTD profiling sites (Figure 2) have been chosen to cover both the Monkey Mia lagoon area and the surrounding waters of Red Cliff Bay and Shark Bay (see Figure 2 and Table 1). This overall grid is referred to as the 'major' grid. A more focussed grid of 23 sites (concentrating on the Monkey Mia lagoon) has been selected from the major grid and these sites lie within the dashed line of Figure 2. This smaller grid is referred to as the ‘inner’ grid. The field programme will be structured in three Phases (1, 2 and 3, respectively), as follows.

Phase 1

During Phase 1 it is proposed that the inner grid of 23 sites be visited intensively 4 times per day over two consecutive days, but with the additional stations that complete the major grid added to the circuit once per day (say as the first ST circuit of each day). Table 2 presents the field itinerary for Phase 1, including planning and travel arrangements. This will enable any changes in the lagoon's salinity, temperature and density fields to be captured at a temporal resolution consistent with the time scales of the major forcings (i.e., tides, density currents, wind events). In addition, the detailing of the broader salinity field should enable the changes within the lagoon to be related to any exchange processes that occur between the lagoon and adjacent waters.

Table 2. Field itinerary for Phase 1 of the survey, including travel and planning arrangements to Denham.

Date	Field day	Time	Activity or circuit	Principal investigator	Field officer	Skipper
14-8-96		0900	CTD probe demonstration at UWA			
To be advised		0700	Depart Perth, travel to Denham in CALM vehicle			
	1	0630-1130	Major grid	N D'Adamo	CALM officer	DoF skipper 1
	1	1230-1600	Inner grid	N D'Adamo	CALM officer	DoF skipper 1
	1	1630-2000	Inner grid	N D'Adamo	CALM officer	DoF skipper 2
	1	2030-2400	Inner grid	N D'Adamo	CALM officer	DoF skipper 2
	2	0630-1130	Major grid	N D'Adamo	CALM officer	DoF skipper 1
	2	1230-1600	Inner grid	N D'Adamo	CALM officer	DoF skipper 1
	2	1630-2000	Inner grid	N D'Adamo	CALM officer	DoF skipper 2
	2	2030-2400	Inner grid	N D'Adamo	CALM officer	DoF skipper 2

Phase 2

After Phase 1 it is envisaged that the monitoring be reduced to two major grids per day until the end of day 5 of the programme or until the occurrence of a mixing event due to strong winds (of order 10 m s^{-1}). A typical field itinerary for these days is given in Table 3.

Table 3. Typical field itinerary for Phase 2 of the survey

				investigator		
	3, 4 or 5	0630-1130	Major grid	N D'Adamo	CALM officer	DoF skipper 1
	3, 4 or 5	1200-1730	Inner grid	N D'Adamo	CALM officer	DoF skipper 1

Phase 3

In the event of the occurrence of a strong mixing event the field programme will return to the routine of Phase 1 during and after the mixing event in order to capture the temporal and spatial characteristics of mixing and flushing caused by strong winds (of order 10 m s^{-1}). A typical field itinerary for these days is given in Table 4.

Table 4. Typical field itinerary for Phase 3 of the survey , including return travel.

Day	Time	Activity or circuit	Principal investigator	Field officer	Skipper
3, 4 or 5	0630-1130	Major grid	N D'Adamo	CALM officer	DoF skipper 1
3, 4 or 5	1230-1600	Inner grid	N D'Adamo	CALM officer	DoF skipper 1
3, 4 or 5	1630-2000	Inner grid	N D'Adamo	CALM officer	DoF skipper 2
3, 4 or 5	2030-2400	Inner grid	N D'Adamo	CALM officer	DoF skipper 2
To be advised	0700	Depart Denham, travel to Perth in CALM vehicle.			

A possible follow-up survey may be conducted during strong wind conditions in summer to capture the hydrodynamic response of the lagoon to strong SSW winds.

4 SAFETY

All safety procedures relating to navigation and associated onboard procedures will be the responsibility of the skipper of the vessel. Scheduled communications and reporting to land-based stations will be conducted according to Department of Fisheries protocols and coordinated by the skipper.

As stated in Section 3, above, alterations to field procedures based on safety aspects related to weather conditions are the responsibility of the skipper. Decisions to modify the field programme will be made by consultation between Nick D’Adamo (Field Team Leader) and the skipper.

5 DATA PROCESSING AND REPORTING

The following sequence outlines the minimum level of processing, analysis and reporting that will follow the field survey.

- A data report containing all edited data and associated plots and contours. This is to be produced as the requirement of a summer vacation scholarship, funded from the project budget (see Section 8, below).

- An interim report, based on a preliminary analysis of the data, describing the major hydrodynamic mechanisms. This will draw on the data report and will be principally produced by Nick D’Adamo in collaboration with Drs Ivey and Pattiaratchi and the student.

- A final report on the results of the study, containing details of mixing, circulation and flushing analyses. This will be produced as a 4th year Honour’s report.

6 BUDGET

The budget has been framed within the context of a collaboration between CALM and DEEUWA, with the participation of a 4th year Honours student at DEEUWA. Table 5 presents the budget details.

Table 5. Budget

Item	**Comment**	**Cost**	
		From budget	**In kind**
Preparation	CALM - Principal Investigator 15 days		**In kind**
	Technical support and field report	$420	
Supervision	CALM		**In kind**
	DEEUWA		**In kind**
Field personnel	CALM - Field officer	$1280	**In kind**
	Dept of Fisheries Boatman 1		**In kind**
	Dept of Fisheries Boatman 1		**In kind**
CTD meter hire	CALM - 5 days @ $150/day	$750	
	DEEUWA - 5 days @ $150/day		**In kind**
Vessel hire	Dept of Fisheries (nominal)		**In kind**
Vessel costs and and monitoring infrastructure	Dept of Fisheries	$400	
	CALM	$200	
Preparation of 4 drogues	CALM	$200	
Differential GPS Hire	CALM - 2 days @ $100/day	$200	
Car	CALM - 8 days	$800	
Accommodation	CALM - 1 week @ $100	$100	
Other	CALM - Allowances, equipment transport, insurance	$250	
Temperature loggers	4 X $325	$1300	
Consumables	CALM	$400	
Technical assistant (post-survey)	CALM	$320	
Data processing	CALM - student summer vacation scholarship at DEEUWA	$2800	
Cost of scientific publication	CALM - Diagrams etc	$200	

Sub total		**$9820**
Contingency	10%	$982
TOTAL (from budget)		**$10802**

7 FUTURE WORK

7.1 Field surveys

Depending on the range of meteorological and hydrodynamic conditions encountered, further field studies may be required to complement the results of this study. For example, it may be required that a specific hydrodynamic study be conducted during characteristic summer conditions to investigate the role of prevailing south-southwesterly winds in the mixing, circulation and flushing of the lagoon.

In addition, it may be possible to increase the scale of this or future studies if other interests (e.g., environmental protection, aquaculture, fisheries, shipping) were to provide collaborative support to increase the spatial scale and field programme of the study. For example, the deployment of current meters and broader scale salinity-temperature monitoring would contribute to a greater understanding of the circulation of Shark Bay. The data would provide process information and data for modelling. In addition, baseline monitoring of sediment quality would provide a valuable baseline data set for long-term monitoring of the lagoon.

7.2 Modelling

Although numerical modelling of the hydrodynamics is not within the scope of this proposal it is recommended that the results of the field exercise be considered for use in numerical modelling of the hydrodynamic behaviour of these waters under a wide range of oceanographic and meteorological conditions. It remains to be seen how important density effects are relative to wind and tidal effects in the hydrodynamics of the lagoon and wider Bay waters. However, with the existing knowledge that there can be strong vertical and horizontal salinity, temperature and therefore density gradients throughout Shark Bay, including the Monkey Mia area, then it would seem appropriate to consider, in the first instance, the application of baroclinic numerical models. The models should incorporate the dynamical effects of wind stress, tides, density currents, Coriolis force, and thermal fluxes at the water surface (e.g., heating, cooling, evaporation). A number of baroclinic models exist for such a purpose. These include the Princeton Ocean Model which has been successfully applied to Cockburn Sound and the adjacent coastal waters off Perth during strongly stratified conditions (Simpson *et. al*., 1996) and the HAMSOM model which has been successfully applied to Perth's coastal waters (Pattiaratchi *et. al.*, 1995) and is currently being applied to Shark Bay (pers. comm., Murray Burling, University of Western Australia).

8 DATA OWNERSHIP AND COLLABORATION PROTOCOLS

All data will remain the property of CALM. Data collected in collaboration with another organisation or agency may, upon agreement with CALM, be used for non-commercial scientific purposes by the collaborator, with due acknowledgement to CALM, and with due consideration (by consultation with CALM) to the inclusion of CALM personnel in authorship. Within the collaborative arrangement between the DEEUWA and CALM the following separation of obligations and responsibilities apply.

Proposal

Motivation and objectives	CALM
General methodology	CALM
Planning	CALM
Core funding	CALM

Field survey - resourcing

Personnel	CALM//FISHERIES
ST meter	DEEUWA
Weather station	CALM
Vessel	CALM/FISHERIES
Other equipment	CALM

Interim report on hydrodynamics	CALM/DEEUWA
Thesis or technical report	DEEUWA (student)/DEEUWA and CALM supervision
Scientific paper or technical publication	CALM/DEEUWA (incl. student)

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APPENDIX 1 **Predicted tides at Carnarvon and Denham, Western Australia. (Source: "1995-96 - Tide predictions and boating guide of Western Australia". Westprint, Western Australia).**

CARNARVON

LAT 24° 53' S LONG 113° 37' E TIME ZONE–0800

TIMES AND HEIGHTS OF HIGH AND LOW WATERS

SEPTEMBER – 1996

	Time	m		Time	m		Time	m		Time	m
1	0050	1.35	9	0157	0.69	17	0046	1.28	25	0245	0.53
	0644	0.16		0800	0.99		0702	0.15		0850	1.15
SU	1315	1.23	MO	1506	0.38	TU	1330	1.09	WE	1525	0.29
	1854	0.26		2141	0.89		1859	0.38		2145	1.10
2	0125	1.35	10	0306	0.61	18	0113	1.29	26	0340	0.37
	0728	0.17		0903	1.04		0740	0.16		0954	1.21
MO	1401	1.13	TU	1543	0.34	WE	1409	1.02	TH	1602	0.27
	1929	0.32		2212	0.96		1930	0.43		2224	1.21
3	0200	1.32	11	0346	0.51	19	0141	1.28	27	0424	0.22
	0814	0.21		0953	1.10		0821	0.19		1047	1.24
TU	1447	1.01	WE	1614	0.30	TH	1456	0.95	FR	1638	0.27
	2002	0.40		2240	1.04		2002	0.49		2301	1.30
4	0234	1.26	12	0421	0.42	20	0215	1.25	28	0505	0.10
	0903	0.28		1034	1.14		0911	0.25		1135	1.24
WE	1537	0.91	TH	1643	0.28	FR	1555	0.87	SA	1714	0.28
	2036	0.48		2307	1.10		2041	0.56		2337	1.36
5	0312	1.18	13	0453	0.34	21	0301	1.19	29	0545	0.04
	1000	0.35		1112	1.17		1015	0.32		1221	1.21
TH	1635	0.82	FR	1710	0.28	SA	1709	0.82	SU	1748	0.31
	2110	0.56		2332	1.17		2130	0.63			
6	0359	1.10	14	0524	0.26	22	0413	1.13	30	0012	1.39
	1108	0.41		1145	1.18		1145	0.37		0626	0.02
FR	1746	0.77	SA	1736	0.29	SU	1836	0.82	MO	1304	1.15
	2151	0.64		2357	1.22		2259	0.69		1824	0.36
7	0508	1.02	15	0556	0.21	23	0548	1.08			
	1234	0.45		1219	1.17		1332	0.37			
SA	1917	0.76	SU	1802	0.31	MO	2002	0.88			
	2324	0.71									
8	0640	0.98	16	0021	1.26	24	0059	0.66			
	1414	0.43		0629	0.17		0730	1.09			
SU	2055	0.81	MO	1253	1.14	TU	1440	0.33			
				1830	0.34		2101	0.98			

CARNARVON

LAT 24° 53' S LONG 113° 37' E TIME ZONE–0800

TIMES AND HEIGHTS OF HIGH AND LOW WATERS

OCTOBER – 1996

	Time	m		Time	m		Time	m		Time	m
1	0045	1.37	9	0251	0.57	17	0042	1.36	25	0335	0.27
	0706	0.04		0844	0.92		0725	0.04		0955	1.07
TU	1347	1.08	WE	1457	0.45	TH	1410	1.04	FR	1528	0.43
	1859	0.41		2116	1.02		1909	0.53		2145	1.32
2	0117	1.31	10	0330	0.46	18	0115	1.33	26	0416	0.13
	0746	0.10		0938	0.98		0805	0.10		1046	1.12
WE	1430	1.00	TH	1530	0.42	FR	1459	0.99	SA	1606	0.44
	1934	0.48		2148	1.10		1948	0.58		2224	1.39
3	0147	1.24	11	0402	0.34	19	0151	1.27	27	0455	0.04
	0827	0.18		1022	1.05		0851	0.18		1132	1.14
TH	1516	0.93	FR	1601	0.41	SA	1556	0.95	SU	1644	0.45
	2010	0.54		2217	1.18		2036	0.63		2301	1.42
4	0218	1.14	12	0433	0.23	20	0241	1.18	28	0533	–0.02
	0911	0.27		1100	1.09		0946	0.28		1215	1.13
FR	1610	0.87	SA	1631	0.40	SU	1702	0.93	MO	1720	0.47
	2049	0.61		2245	1.25		2142	0.68		2336	1.41
5	0254	1.05	13	0505	0.14	21	0353	1.07	29	0611	–0.03
	1003	0.36		1135	1.12		1059	0.38		1255	1.11
SA	1715	0.84	SU	1700	0.41	MO	1813	0.96	TU	1757	0.50
	2142	0.67		2314	1.31		2322	0.68			
6	0346	0.95	14	0538	0.07	22	0537	0.99	30	0010	1.38
	1111	0.44		1211	1.13		1229	0.44		0647	0.00
SU	1830	0.84	MO	1730	0.43	TU	1918	1.03	WE	1335	1.08
	2318	0.71		2342	1.35					1834	0.54
7	0533	0.88	15	0612	0.03	23	0134	0.59	31	0042	1.32
	1245	0.48		1247	1.12		0724	0.97		0723	0.05
MO	1945	0.88	TU	1800	0.45	WE	1353	0.45	TH	1415	1.04
							2015	1.12		1911	0.58
8	0142	0.68	16	0012	1.37	24	0247	0.43			
	0729	0.87		0647	0.01		0849	1.01			
TU	1411	0.47	WE	1327	1.09	TH	1445	0.44			
	2038	0.94		1833	0.49		2101	1.23			

DENHAM

LAT 25° 56' S LONG 113° 32' E TIME ZONE–0800

TIMES AND HEIGHTS OF HIGH AND LOW WATERS

SEPTEMBER – 1996

	Time	m		Time	m		Time	m		Time	m
1	0245	1.07	9	0931	0.89	17	0244	1.03	25	0426	0.65
	0943	0.45		1803	0.41		1002	0.37		1045	1.03
SU	1509	1.02	MO			TU	1522	0.93	WE	1604	0.47
	2114	0.51					2045	0.60		2335	0.89
2	0321	1.09	10	0035	0.70	18	0310	1.07	26	0542	0.54
	1038	0.43		0415	0.63		1051	0.38		1150	1.04
MO	1553	0.92	TU	1043	0.90	WE	1602	0.88	TH	1845	0.48
	2123	0.54		1843	0.40		2100	0.63			
3	0357	1.09	11	0033	0.73	19	0341	1.10	27	0015	0.96
	1130	0.43		0511	0.57		1142	0.39		0654	0.44
TU	1638	0.83	WE	1141	0.92	TH	1649	0.83	FR	1246	1.04
	2135	0.57		1914	0.40		2121	0.65		1912	0.51
4	0431	1.07	12	0043	0.77	20	0419	1.12	28	0053	1.02
	1224	0.44		0600	0.51		1235	0.42		0758	0.36
WE	1726	0.74	TH	1228	0.94	FR	1747	0.77	SA	1335	1.01
	2147	0.59		1941	0.41		2146	0.67		1928	0.53
5	0508	1.03	13	0101	0.82	21	0509	1.11	29	0129	1.06
	1324	0.46		0645	0.46		1337	0.44		0850	0.31
TH	1828	0.67	FR	1307	0.96	SA	1907	0.73	SU	1419	0.97
	2200	0.61		2001	0.44		2215	0.69		1945	0.55
6	0550	0.99	14	0124	0.88	22	0613	1.09	30	0202	1.09
	1435	0.46		0732	0.42		1452	0.46		0936	0.29
FR	2022	0.63	SA	1341	0.97	SU	2057	0.73	MO	1500	0.92
	2204	0.62		2015	0.47		2300	0.71		2007	0.56
7	0645	0.95	15	0150	0.94	23	0736	1.05			
	1554	0.45		0822	0.39		1609	0.46			
SA			SU	1414	0.97	MO	2206	0.76			
				2023	0.51						
8	0801	0.91	16	0216	0.99	24	0132	0.73			
	1708	0.43		0913	0.38		0919	1.03			
SU			MO	1446	0.95	TU	1714	0.46			
				2034	0.56		2253	0.82			

DENHAM

LAT 25° 56' S LONG 113° 32' E TIME ZONE–0800

TIMES AND HEIGHTS OF HIGH AND LOW WATERS

OCTOBER – 1996

	Time	m		Time	m		Time	m		Time	m
1	0235	1.08	9	0440	0.60	17	0230	1.16	25	0625	0.44
	1019	0.29		1033	0.78		1039	0.29		1159	0.90
TU	1541	0.86	WE	1714	0.51	TH	1600	0.90	FR	1715	0.63
	2033	0.58		2307	0.79		2028	0.72		2327	1.08
2	0308	1.06	10	0534	0.52	18	0306	1.17	26	0718	0.33
	1100	0.32		1138	0.81		1123	0.33		1253	0.92
WE	1622	0.80	TH	1749	0.52	FR	1650	0.87	SA	1745	0.64
	2059	0.60		2332	0.85		2104	0.74			
3	0340	1.03	11	0621	0.44	19	0350	1.15	27	0007	1.12
	1141	0.35		1226	0.85		1208	0.38		0805	0.26
TH	1707	0.74	FR	1815	0.54	SA	1752	0.84	SU	1338	0.92
	2124	0.63		2359	0.91		2146	0.76		1816	0.64
4	0413	0.98	12	0705	0.38	20	0442	1.10	28	0045	1.13
	1221	0.39		1302	0.89		1256	0.45		0847	0.22
FR	1808	0.70	SA	1833	0.57	SU	1914	0.84	MO	1418	0.91
	2151	0.65					2245	0.78		1849	0.65
5	0450	0.93	13	0028	0.97	21	0546	1.03	29	0119	1.13
	1305	0.43		0747	0.32		1350	0.51		0925	0.22
SA	2000	0.68	SU	1335	0.92	MO	2025	0.86	TU	1457	0.89
	2219	0.67		1853	0.60					1923	0.66
6	0537	0.87	14	0057	1.03	22	0045	0.78	30	0154	1.11
	1400	0.46		0830	0.29		0715	0.94		1000	0.24
SU	2146	0.69	MO	1408	0.94	TU	1453	0.56	WE	1533	0.87
	2258	0.69		1914	0.63		2115	0.91		1958	0.67
7	0651	0.80	15	0128	1.08	23	0400	0.70	31	0226	1.08
	1515	0.49		0912	0.27		0914	0.89		1032	0.28
MO	2237	0.72	TU	1442	0.94	WE	1553	0.60	TH	1610	0.84
				1935	0.67		2201	0.97		2033	0.69
8	0318	0.67	16	0158	1.13	24	0521	0.57			
	0859	0.77		0955	0.27		1049	0.89			
TU	1624	0.50	WE	1519	0.93	TH	1639	0.62			
	2246	0.75		1959	0.70		2245	1.03			

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