MARINE MANAGEMENT SUPPORT:
MIDWEST

SUMMARY OF SCIENTIFIC RESULTS OF THE FLUSHING STUDIES OF THE MONKEY MIA LAGOON AND THEIR IMPLICATIONS FOR MANAGEMENT

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A collaborative project between the CALM Marine Conservation Branch, CALM Midwest Region, the University of Western Australia and University of New South Wales

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Prepared by N D'Adamo
Marine Conservation Branch

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Marine Conservation Branch
Department of Conservation and Land Management
47 Henry St
Fremantle, Western Australia, 6160

SUMMARY

This report presents an overview of the key results from oceanographic studies of flushing behaviour in the Monkey Mia lagoon and adjacent waters conducted during September 1996 and April 1998 by CALM under World Heritage Property Area funding. The Universities of Western Australia and New South Wales collaborated with CALM to assist in both data processing and modelling of circulation and dispersion patterns. The two field data sets were used to guide the choice of models, test their performance and help prepare them for predictive simulations of the dispersion and flushing of contaminants introduced into the lagoon and adjacent waters under typical wind and tide conditions.

The studies were motivated by the need for managers to have a better technical understanding of the potential threats to the conservation values of the lagoon posed by introduced contaminants, such as: accidental and deliberate spills from vessels (sullage containing nutrients and pathogens, hydrocarbons from re-fueling facilities, onboard tank spillages and engine exhausts), wastes from boat maintenance activities, seepage of contaminated interstitial water (fertilizers and pesticides from lawns and gardens), water-borne marine pests and contaminants from remote but hydrodynamically linked sources (eg aquaculture and shipping from around the bay) and substances such as suntan lotions (see Murex Consultants, 1996). The key results are as follows:

- Effective tools, ie computer-based models, have been implemented, tested and made available for managers to use in understanding and predicting the circulation and dispersion of contaminants in the lagoon under varied wind and tide conditions.
- The following flushing characteristics apply for a mass introduced into the area between the shore and main seagrass sill, under common meteorological and hydrological conditions:
    - ◊ Most (greater than about 50%) of the released mass remains in the area during the first 12 hours after release, with dispersion weakest for nearshore point discharges.
    - ◊ After about 2 days the introduced mass is almost completely expelled to Red Cliff Bay or to the adjacent channels where transport and dispersion are then relatively rapid.
- In terms of the introduction of contaminants, via accidental or deliberate discharges, the following factors are the most important in determining flushing and dispersion rates:
    - ◊ The exact location of the introduction.
    - ◊ The nature of the release (ie whether it is a point source discharge or an evenly spread line of discharge).
    - ◊ The time at which the introduction occurs with respect to tidal phase.
    - ◊ The direction and strength of the prevailing wind field during the first 12 hours after release.

A review of waste management practices and a sediment contaminants survey are recommended in the light of the relatively restricted lagoonal flushing indicated by the field and model results.

BACKGROUND

The Monkey Mia lagoon is one of Western Australia’s most important ecotourism icons. It provides an idyllic setting for human interaction with dolphins, and visitation numbers are currently running at about 80000 per year, rendering this attraction important from both an educational and economic point of view. Even the most conservative estimates of its economic value to the State would result in a figure of tens of millions of dollars per year. Concern related to the harmful effects of anthropogenically introduced contaminants dates back to the late 1980’s, when leachates from septic tanks were implicated in the disappearance and death of dolphins (Environmental Protection Authority, 1989). This concern subsequently motivated investigations into the nutrient and microbiological status of the lagoonal waters (Environmental Protection Authority, 1989; Trayler and Shephard, 1993) which, in conjunction with a recent study by Murex Consultants Pty. Ltd (1996), have highlighted the need for careful management of the pressures that accompany high usage at Monkey Mia. Interestingly, the practices of sullage discharge within the lagoon, jetty or shore-based boat re-fueling and boat maintenance (eg hull scraping) still occur within relatively close proximity of the dolphin interaction area. This stems from the historical belief amongst users and managers that tidal flushing is relatively rapid. The results presented in this report allow this assumption to be re-assessed on the basis of the first comprehensive hydrodynamic study of the area. A compelling case is made for a review of waste management practices in the Monkey Mia lagoon.

THREATS

The potential threats to the conservation values of the lagoon posed by introduced contaminants can be summarised as

- Accidental and deliberate spills from vessels (sullage containing nutrients and pathogens, hydrocarbons from re-fueling facilities, onboard tank spillages and engine exhausts).
- Seepage of contaminated interstitial water (fertilizers and pesticides from lawns and gardens).
- Contaminants entering the water as a result of boat maintenance practices (eg hull scraping).
- Water-borne marine pests and contaminants from remote but hydrodynamically linked sources (eg aquaculture and shipping from around the bay).
- Substances such as suntan lotions.

STUDY APPROACH

The successful World Heritage Property Area funding applications for the 1996 and 1998 flushing studies were motivated by the requirement to have a better understanding of the hydrodynamic characteristics of the area in order to enable the correct choice, calibration and validation of numerical hydrodynamic models of the lagoon. Modelling is required for the prediction of flushing and concentration fields of substances, such as contaminants, contained in the water. Numerical models are important management tools because, once adequately calibrated and validated for specific scenarios, they can provide a generic ability to predict the transport and dilution of substances in water through long time frames and over large spatial scales, thereby enabling a wide range of scenarios to be investigated without the need for repeated intensive and costly field investigations to address each individual case.

The first field study was conducted by the Marine Conservation Branch of CALM (D'Adamo, 1996) in collaboration with the University of Western Australia during 19-22 September 1996 and involved extensive salinity-temperature profiling and temperature logging throughout the lagoon, Red Cliff Bay and adjacent waters. A data report was produced by Blyth *et al* (1997) and this was followed by hydrodynamic analyses, modelling and interpretations performed as an Honours study by Blyth (1997).

The second field study was conducted during 19-23 April 1998 by the Marine Conservation Branch of CALM and involved extensive drifter-drogue tracking (yielding current patterns), temperature profiling and in-situ meteorological measurements in the lagoon and Red Cliff Bay. A data report was produced by Hunt and D'Adamo (1998) and this was complemented by hydrodynamic analyses, modelling and interpretations in Luketina *et al* (1998).

These field studies have provided the first intensive characterisation of the hydrodynamics of the lagoonal waters and have enabled computer-based hydrodynamic models to be implemented, tested and run for specific management related scenarios.

TECHNICAL RESULTS

Climate

The climate of the area has been summarised by Logan and Brown (1986) and the Australian Bureau of Statistics (1989). The area has a semi-arid to arid climate experiencing hot, dry summers and mild winters. Summer minimum and maximum air temperatures average between about 20 ^{o}C and 30 ^{o}C, respectively, and winter temperatures between about 10 ^{o}C and 20 ^{o}C. Temperatures have been recorded to be as high as 48 ^{o}C in summer and as low as about 2 ^{o}C in winter. Evaporation is high, averaging about 2600 mm per year with a maximum rate in summer and a minimum in winter. This compares to average annual rainfall of about 230 mm per year, most of which falls during May-July but with occasional heavy falls due to the passage of cyclonic depressions in summer and autumn.

The annual wind climate is dominated by southeast tradewinds reinforced by south-southwesterly sea-breeze winds mainly during spring to early autumn, as is typical for the west coast of Western Australia. The normal diurnal wind pattern during summer to early autumn consists of fresh southeasterly winds in the morning followed by stronger south-southwesterly sea-breezes during the afternoon and night. Burling and Pattiaratchi (1995) analysed year long wind records from Denham and Carnarvon and these indicate that from spring to early autumn winds are commonly south-southwesterly at speeds of about 7.5-12.5 m s^{-1} and winds become more variable in direction from mid-autumn to winter and weaken in strength with speeds commonly less than about 7.5 m s^{-1}.

Occasional cyclones from the Timor Sea region can influence Shark Bay from summer to mid-autumn (Logan and Brown, 1986) with associated wind velocities of up to about 50 m s^{-1}. There are on average about two cyclones per year in the northwest regions of the state.

The eastern gulf has a characteristic longitudinal salinity gradient where salinities increase from about 40 pss near Cape Peron to about 50 pss near L'Haridon Bight; as a comparison, oceanic salinity is about 35 pss. This gradient is known to persist throughout the year and the relatively strong north-south gradient zone in the region off Monkey Mia was named the 'Faure Salinocline' by Logan and Brown (1986). The tides oscillate this salinity gradient back and forth in the along-gulf direction, with the central portion of the gradient passing through the Monkey Mia lagoon, as shown by broad-scale salinity fields recorded over consecutive tidal cycles in September 1996 (Blyth *et al*, 1997; Blyth, 1997). These data revealed how during ebbs high salinity water enters the lagoon via the sill region as a well mixed front, thereby displacing relatively low salinity resident lagoon water northwards. The data indicate that this process can force most of the lagoonal water out into Red Cliff Bay. However, upon the turn of the tide, flood flows force low salinity water back into the lagoon.

Another interesting feature revealed by the changing salinity fields was the occurrence, on more than one occasion, of a localised zone of high or low salinity within Red Cliff Bay, just inside (ie shoreward) of the sandbank. The significance of such peaks and troughs in the salinity field is that they may represent localised zones of re-circulation and poor localised flushing.

Measurements of the vertical salinity structure along a centreline transect beginning in the sill region and progressing out into Red Cliff Bay show that ebb flows are generally well-mixed vertically, whereas relatively low salinity (and therefore buoyant) flood flows that enter the lagoon have a tendency to overshoot denser resident lagoon water, thereby causing a vertically stratified (ie layered) salinity structure. The main point to note here is that there can be short periods of vertically stratified water in the lagoon, thereby raising the possibility of trapping of bottom water at these times.

With respect to the effectiveness of flushing by the ebb-flood cycling the main issue is the proportion of ebb outflows that re-enter the lagoon during each ensuing flood. To address this uncertainty clusters of cross-vane drifter drogues were deployed in the lagoon during the April 1998 survey and tracked as they were moved by wind and tidal currents. The clusters released within the lagoon near the dolphin interaction area tended to propagate out towards Red Cliff Bay during ebbs only to return to near the point of release with minimal spreading during the ensuing flood. If one uses the drogue-cluster as a proxy for a load of contaminant released at the same point then this would suggest that dispersion is restricted and flushing is poor because a significant proportion of the originally released mass has returned to the point of release with minimal lateral spreading. Other drogue clusters released near the shore indicate that during the first tidal cycle the cluster is driven parallel to the shore with minimal offshore spreading.

Key results from the modelling studies

The usefulness of the field data lies in the insight that they have given in identifying key broad-scale circulation processes and in providing guidance to the choice of models. Following the analyses of the field data, models were run to simulate broad-scale circulation patterns and the dispersion behaviour of contaminants released at various points around the field domain. Blyth (1997) performed initial model runs and, based on Blyth's (1997) work and the results of the 1996 and 1998 field studies, Luketina *et al* (1998) undertook a more detailed modelling study. A precis of the results of the two modelling studies is given below.

University of Western Australia

Blyth (1997) ran a three-dimensional model at the University of Western Australia using the 1996 data set (Blyth *et al*, 1997) as guidance. Some of the key results from that modelling exercise are summarized as follows:

- Broad-scale circulation fields indicated good circulation through the lagoon during fully established ebb and flood flows, consistent with the recorded movements of broad-scale salinity fields. However, at a finer scale Blyth's (1997) modelling produced evidence of re-circulation in the Red Cliff Bay region adjacent to the offshore sand bank, which is also consistent with the field data results.
- Current speeds within the lagoon are typically less than about 0.25-0.5 knots during fully established flood or ebb flows, whereas corresponding flows in the adjacent channels, such as Herald Gut, reach up to 1-2 knots. These model predictions are broadly consistent with recorded flows.
- Preliminary flushing estimates, based on the release of particles spread throughout the lagoon region suggested that it would require about 2 days for 70 percent of the injected mass to be effectively flushed from the system and a further 3 days for the remaining 30 percent to be expelled.
- Mass injected as a cluster near the shorelines of Monkey Mia and Red Cliff Bay tended to travel shore-parallel with minimal dilution for a number of tidal cycles prior to eventually moving offshore and escaping out to the

University of New South Wales

Luketina *et al* (1998) reviewed both the results of the field surveys (1996 and 1998) and Blyth's (1997) modelling and applied a model from the University of New South Wales tailored to take account of the key physical processes that were shown to be critical to the flushing behaviour of the lagoon by the previous studies. To represent the introduction of contaminants, Luketina *et al* (1998) injected 21000 neutrally buoyant particles as both nearshore clusters and as evenly spread lines between the shore and offshore bank. The clusters are analogous to say a concentrated spill from a stationary vessel, whereas a line release is analogous to say the introduction of contaminant from a row of vessels. The key results from Luketina *et al* (1998) are as follows:

- Clusters released near the shores of either Red Cliff Bay or Monkey Mia oscillated back and forth parallel to the shore with minimal offshore spreading for the first 12 hours. Another 36-48 hours was generally required before significant dispersion and effective flushing from the lagoon occurred.

- Particles released along straight lines (across Monkey Mia lagoon or Red Cliff Bay) were more quickly flushed from the system than cluster releases.

- The most poorly flushed scenarios resulted during windless conditions involving cluster releases (representing point source discharges) and the most unfavourable release positions were those near the shore and within the lagoonal region near the dolphin interaction area.

- The flushing of the injected particles was highly sensitive to the timing of the release and prevailing wind conditions.

    ◊ Mass released as a cluster in the lagoon at high water (with no wind) was initially driven out to Red Cliff Bay during the first ebb only to return during the ensuing flood tide with minimal dispersion.
    ◊ Mass released as a nearshore cluster in Red Cliff Bay at low water (with no wind) was initially driven into the lagoon by the first flood, where it was trapped with minimal dispersion for up to 2 days.

- The presence of wind significantly improved flushing.

- In general, the following flushing characteristics applied for a mass introduced into the lagoonal area between the shore and main seagrass sill, under common meteorological and hydrological conditions:
    ◊ Most (greater than about 50%) of the released mass remained in the area during the first 12 hours after release, with dispersion weakest for nearshore point discharges.
    ◊ After about 2 days the introduced mass was almost completely expelled to Red Cliff Bay or to the adjacent channels where transport and dispersion was then relatively rapid.

- In terms of the introduction of contaminants, via accidental or deliberate discharges, the following factors were the most important in determining flushing and dispersion rates:
    ◊ The exact location of the introduction.
    ◊ The nature of the release (ie whether it is a point source discharge or an evenly spread line of discharge).
    ◊ The time at which the introduction occurs with respect to tidal phase.
    ◊ The direction and strength of the prevailing wind field during the first 12 hours after release.

CONCLUSIONS

Field and model studies of circulation and dispersion patterns have been successful in providing managers with a better technical understanding of the key oceanographic processes operating to move and mix water (and therefore contained substances, such as contaminants) in the Monkey Mia lagoon and adjacent waters.

Based on the understanding acquired from the field studies, effective tools (ie computer-based models) have been implemented, tested and made available for managers to use in understanding and predicting the circulation and dispersion of contaminants in the lagoon under varied wind and tide conditions.

The following flushing characteristics apply for a mass released into the area between the shore and main seagrass sill, under common meteorological and hydrological conditions:

- Most (greater than about 50%) of the released mass is likely to remain in the area during the first 12 hours after release, with dispersion weakest for nearshore point discharges.
- After about 2 days the mass is almost completely expelled to Red Cliff Bay or to the adjacent channels where transport and dispersion are then relatively rapid.

In terms of the introduction of contaminants, via accidental or deliberate discharges, the following factors are the most important in determining flushing and dispersion rates:

- The exact location of the introduction - with mass introduced in the lagoonal region near the dolphin interaction area generally taking the longest to be flushed. However, it is to be noted that mass released near the shore further to the northwest may enter the lagoon under flood tides to thence be trapped in that region for extended periods of time (up to 48 hours).
- The nature of the release (ie whether it is a point source discharge or an evenly spread line of discharge) - with cluster releases tending to resist spreading more than line releases.
- The time at which the introduction occurs with respect to tidal phase - with the following two cases being of critical importance to overall flushing:
  - ◊ Mass released as a cluster in the lagoon at high water (with no wind) was initially driven out to Red Cliff Bay by the first ebb only to return during the ensuing flood tide with minimal dispersion.
  - ◊ Mass released as a nearshore cluster in Red Cliff Bay at low water (with no wind) was initially driven into the lagoon by the first flood, where it was trapped with minimal dispersion for up to 2 days.

- The direction and strength of the prevailing wind field during the first 12 hours after release - with the presence of winds generally enhancing flushing.

RECOMMENDATIONS

A review of waste management practices is recommended in the light of the relatively restricted lagoonal flushing indicated by the field and model results. The following issues should be considered as part of the review.

- The threat of nutrient enrichment and microbiological contamination (by pathogens) as a result of accidental or deliberate wastewater discharges in the lagoon.
- The risk of contamination as a result of accidental or deliberate spillages of fuel during re-fueling at the end of the jetty or along the shores of Monkey Mia and Red Cliff Bay.
- The risk of contamination from hydrocarbons that enter the water via engine exhausts.
- The risk of contamination as a result of boat maintenance practices at the jetty (eg hull scraping).
- The threat of nutrient enrichment and pesticide contamination due to leachates (from lawns and gardens) via the flow of interstitial groundwater to the shores of Monkey Mia or Red Cliff Bay.
- Potential environmental threats due to contaminant plumes that may be derived from nearshore activities such as aquaculture and shipping at sites to the northwest of the lagoon and driven into the lagoon under unfavourable wind and tidal conditions.
- The threats posed to water quality and marine fauna by suntan lotions introduced in the wading zone of the dolphin viewing area.

In view of the relatively restricted flushing that has been identified to be a characteristic of the lagoon a sediment survey is recommended to determine whether there has been any contamination of the sediments.

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