MAINTAINING WATER QUALITY ON FRINGING REEFS WITH EMPHASIS ON TOURIST DEVELOPMENT

Kevin E Parnell

Geography Department
University of Auckland
Auckland
New Zealand

Abstract

It is in the interest of tourist operators and government bodies to maintain water quality 'on fringing reefs and management practices which will maintain water quality should'be implimented. Collecting and interpreting data on fringing reef hydrodynamics and sedimentation to enable appropriate management decisions to be made is generally beyond the capability of individual operators, and very expensive.

Modelling water circulation in Pioneer Bay, Orpheus Island shows circulation to be tidal, with bay flushing rates generally greater than 90%. The effect of secondary circulation in the lee of headlands is shown to be important in establishing the nature of the circulation. The model is then applied to a number of other bays in which resorts are situated. Methods are presented which may enable water quality deterioration to be avoided in resort bays if basic hydrodynamic data are collected, and appropriate management practices adopted.

Introduction

The management of a natural resource such as the Great Barrier Reef involves the manipulation of that resource so as to optimise its long term value to man (Burton, 1983). The process of resource management usually involves the development of an informal or formal management plan.

Being in the zone of influence of land based activity and runoff, problems associated with freshwater runoff (with associated pollutants) and sedimentation may be important. Tourist development on continental islands may lead to a number of potentially damaging situations requiring management.

The legislative framework

Any attempt to apply scientific findings to management situations must consider the institutional and legislative framework which covers the region of interest. In the Great Barrier Reef region the responsibilities of the authorities involved in management are not always clear.

The Great Barrier Reef Marine Park Act 1975 provides for the establishment, control, care and development of a marine park in the Great Barrier Reef region (Bates, 1983; Australian Environment Council, 1984). The system of federal government in Australia has complicated the administrative arrangements in relation to the Marine Park (Kelleher and Kenchington, 1982). The Great Barrier Reef Marine Park Act applies up to low water mark. The mainland and islands are controlled by state legislation, except where owned by the Commonwealth and this control is extended by the Coastal Waters (State Title) Act 1980 which vests title to the seabed over the three mile territorial sea in the State, but is subject to the continuing operation of the Great Barrier Marine Park Act (Brazil, 1981).

This situation results in an area of uncertainty around islands (including cays) and the mainland coast, which is of particular importance to the control and management of fringing reefs. Around each island is a 3 mile belt of territorial sea to which State legislation may apply although the Great Barrier Reef Marine Park Act applies to low water mark, even on the mainland (Brazil, 1981). The management of fringing reefs and island resorts (which are frequently established by lease within a Queensland National Park (Ogilvie, 1981)), situated on high islands within the Marine Park is, therefore, complicated by this legal uncertainty. A functional approach (Brazil, 1981) based on consultation and co-operation which ignores artificial jurisdictional lines is needed. To this end, the Queensland Government enacted the Marine Parks Act (1982) which largely mirrors the Great Barrier Reef

Marine Park Act (1975) providing for the setting apart of tidal lands and tidal waters as Marine Parks (Australian Environment Council, 1984). Although the jurisdictional uncertainty remains, the, cooperative approach adopted by both State and. Federal governments appears to provide some solution to the legislative complications.

The provisions of the Clean Waters Act 1971-1982 which prohibits the indiscriminate, uncontrolled dumping or discharge of waste water and other polluting matter, cover GBR waters under state jurisdiction. The Great Barrier Reef Marine Park Act covers similar situations in areas under its jurisdiction.

Both the Commonwealth and Queensland have accepted the' desirability of having environmental impact assessment procedures to review any developments which may affect the environment., It is unclear whether environmental impact assessment in the Great Barrier Reef Marine Park comes under the jurisdiction of the Environment Protection (Impact of Proposals) Act 1974, or provisions of the Great Barrier Reef Marine Park Act. It is clear, however, that significant developments within the Marine Park will be subject to review, and that it is likely that any proposal will be reviewed by the Great Barrier Reef Marine Park Authority. Queensland, however, has adopted a decentralised system of administrative responsibility for environmental impact assessment, with no specific legislation, and oversight by no one department. Each department is required to assume responsibility for environmental impact assessment with respect to its area of activities and responsibilities (Australian Environment Council,' 1984). Environmental impact assessment on islands within the Marine Park is within the control of the State. A potential area of conflict, however, may come from developments on islands which cause no significant damage to the island environment, but which transfer damage to the marine environment. The management of fringing reef environments with particular reference to resort development must involve the cooperation of federal and state institutions, and resort operators.

The modelling process for management

There are many different approaches to modelling, but all have the overall objective to describe the system accurately, while simplifying it so that the model is substantially less complex than the system itself. The most basic approach is the development of a conceptual model which may be based on logic alone or on empirical evidence. The conceptual model is an essential prerequisite for further study, being merely an extension of the scientific method.

Model development for both research and management should be based on the most relevant attributes (or variables) for the particular problem being examined with "irrelevant, distracting or unknown attributes" (Bell, 1983) being excluded. Various parts of the system should be modelled separately, so that as many variables as possible can be eliminated where they are not relevant. The real world is too complex for practical treatments of complete systems (Bell, 1983). This approach means that the models developed can be used to answer specific problems with relative ease. Complete system models, although useful to and useable by the specialist are not generally useful to the environmental manager. It is recognised that models which are easy to conceptualise, treating few variables at a time, are likely to be less complete than larger models which do not need to approximate as many variables but the techniques may be used in more situations, being easier to use and less costly.

The object of all hydrodynamic models is to be able to predict the concentration of a substance at all points and at all times, this being governed by the way the substance disperses. Solution of the equation

$$C=C(x,y,z,t),$$

where x,y and z are space coordinates and t is instantaneous time is therefore the ideal, but no available model can achieve this. However, many management considerations only need approximations, which can be achieved by simplification, with the reduction in the number of dimensions that must be considered. This is usually achieved using spatial and temporal averaging

techniques. A coastal embayment, which normally does not have unidirectional water flow, has many advection axes and different rates of dispersion caused by the combination of all forcing mechanisms (such as wind, tide, freshwater flow). Consideration of all sites within the bay at once is unnecessarily complex, and not needed for most management applications. Consideration of subsections of the bay system (both temporal and spatial) separately enables the development of models based on consideration of simple problems rather than on one three dimensional problem, which is very difficult to solve. The result is a cluster of models which identify individual mechanisms but which may be used in any combination.

The first step in the development of the model' cluster is the identification of all forcing mechanisms, and the resulting water movements. Simplification of the conceptual model follows with the removal of all mechanisms which have minimal effect. The models may be developed from theorywhen it is available, but where systems are poorly understood an empirical approach is necessary. Small scale experiments are then undertaken to study the effect of each forcing mechanism, at a number of sites in the bay, and at a number of times. Specific questions, such as bay flushing, which necessarily involve the entire bay, are also studied by means of separate experiments.

Models are developed within either a Eulerian or Lagrangian reference frame. The Eulerian approach is most common, with the spatial grid being fixed. The Lagrangian approach has a spatial grid which is fixed to the water, and therefore contracts and expands to follow the water movement. Field studies can be similarly classified, with data collection either being Eulerian with data being collected at specified locations; or Lagrangian, with a parcel of water being labelled and followed as it disperses. Field studies can use both approaches concurrently.

The development of models, the direct examination of water movement and the determination of the behaviour of pollutants often involves the labelling of a parcel or parcels of water (either naturally or artificially) and following the dispersing parcel through time, either by sampling the labelled parcel or by measuring concentration at various points on a known grid. A great number of artificial tracers are

available but fluorescent dyes (particularly Rhodamine WT) are generally the most appropriate for management studies. Analysis of concentration is achieved using a filter fluorometer or spectrofluorometer. Reviews of the technique can be found elsewhere (Wilson, 1968; Smart and Laidlaw, 1977; Parnell, 1982, 1984).

The density of fluorescent dye solutions are higher than sea water. The density can be adjusted using methanol or fresh water to reduce the density to that of seawater, freshwater or to a value required to simulate an injection of a contaminant, and using glycerine to increase density. The ability to simulate an injection of a solution of a particular density is particularly useful in the modelling of contaminant behaviour. The release of dye with a density less than that of seawater enables the surface circulation to be modelled.

The study location

The islands studied all lie in the Central Section of the Great Barrier Reef Marine Park, from Dunk Island in the north to the Whitsunday Islands in the South. All study sites have extensive fringing reef development, and are subject to broadly similar climatic and tidal influences. Pioneer Bay, Orpheus Island (Figure 1) was chosen as the site for model development as it was representative of many of the bays in which resorts are, or potentially may be, located. It demonstrates a number of features desirable for resort development such as flat land suitable for building, a sandy beach, a potential water supply, a sheltered anchorage, reasonable access to outer reefs and hills suitable for walking tracks. Its lee side location, the nature of the reef flat, the offshore depths and the defining headlands are also characteristic of bays in which resorts have located. Other situations examined were Hazard Bay on Orpheus Island, and the resort bays of Hamilton, Long, South Molle and Dunk Islands.

Pioneer Bay is one of a number of bays on the highly indented western side of Orpheus Island, with a 400m wide reef flat which is completely exposed during spring low tides. The outer band of living

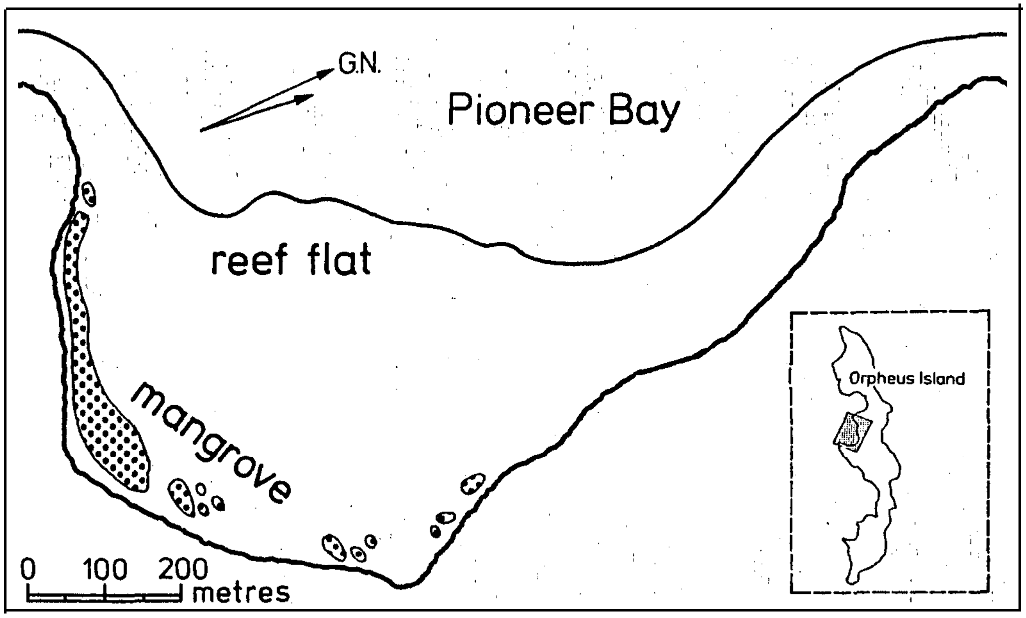

Figure 1 Pioneer Bay, Orpheus Island

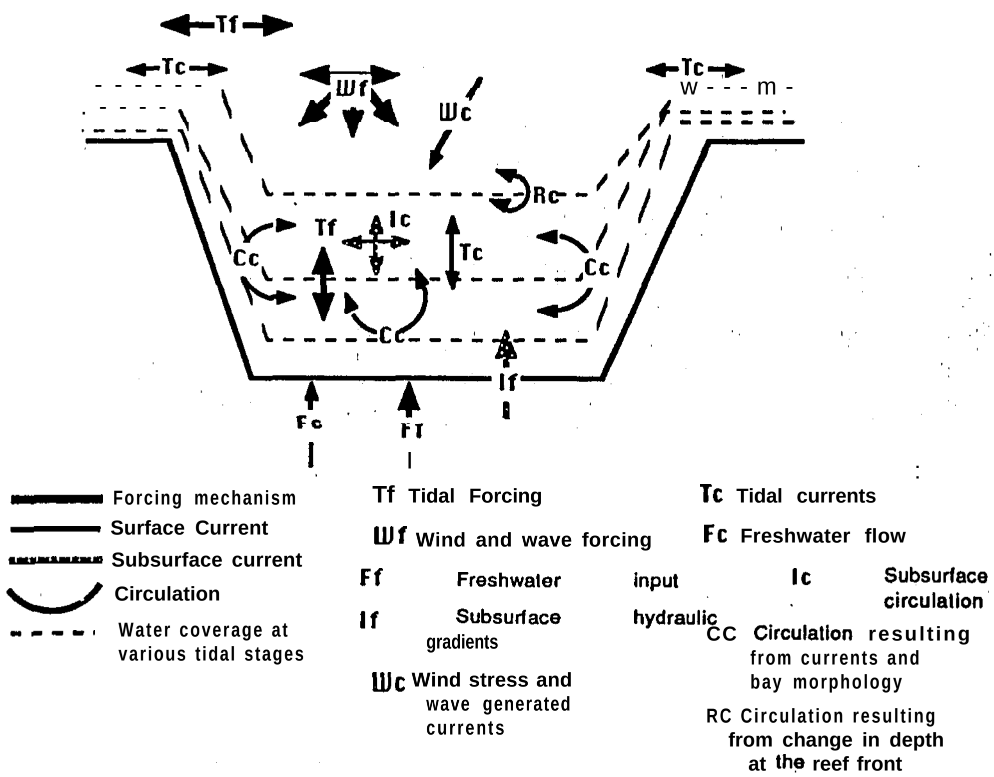

Figure 2 Conceptual model of water circulation in Pioneer Bay

coral is flanked by 100m of rubble with some living colonies. The inner reef flat consists of fine to very fine sand and coral debris with some dead microatolls. An area of mangrove is situated on the southern inner reef flat, with isolated specimens elsewhere. The beach in the centre of the bay rises steeply from the reef flat into a dissected vegetated beach ridge sequence about 100m wide. The northern and southern shores of the Bay are predominantly composed of small boulders (10 to 20 cm in diameter), with considerable accumulations of coral clasts above high tide mark. The catchment of Pioneer Bay rises steeply to 156m with six small ephemeral streams flowing into a depression behind the bay at each end of the ridge. During periods of heavy rainfall water percolates through the ridge sequence discharging onto the beach and into the reef flat framework.

The reef front is highly indented, with the base at 5m below Chart Datum (CD). The sea floor slopes gently to 15-25 m well offshore. Pioneer Bay is sheltered from the predominant southeast and easterly winds. Only for a short period during the summer months when winds have a westerly component is the bay exposed. Even during such periods, waves are small as the fetch is short due to the proximity to the mainland. At most times of the year the bay is calm, even during very windy periods.

Pioneer Bav - Modelling

The generating forces which operate and may cause water movement within Pioneer Bay are illustrated in Figure 2. The most important generating forces which must be considered are wind, waves and tides. Additionally, freshwater inflow and hydraulic gradients within the reef framework must be considered.

The principal tidal currents stream across the bay, north on the ebb tide and south on the flood. Velocities are usually highest off the southern bayhead. Additionallv, tidal currents are required to move water into and out of the bay. The combination of these currents is the most dominant influence on bay circulation. Representative current diagrams for one site near the mouth of the bay are in

Figure 3. It is apparent that tidal streaming is out of phase with the tide. With a similar tidal range velocities are lower on the ebb tide than on the flood.

A number of tracer studies using fluoroescent dyes were undertaken in order to determine the circulation pattern which results from the interaction of forcing mechanisms. The experiments were carefully designed to give data on velocity and direction of water movement at sites of interest under a' variety of tidal conditions, and to indicate where 'olcl'water may accumulate. For much of the work, Eulerian type data would have been impractical to collect as water velocities are often near the lower limit of measurement of commonly used current meters, and in order to study circulation at the small scale, the number of instruments needed would have been prohibitive. Dye data can, however, be used to estimate velocity. A generalised circulation,, based on these experiments is illustrated in Figure 4. Experiments indicated that. there was a zone of accumulation of 'old water near the northern beach.

The particular feature which makes the bay with a fringing reef different from other coastal embayments is the dramatic change in water depth at the reef front. There is a general upwelling at the reef front indicated at all stages 'of tide. There is preferential upwelling in small crevices in the reef front, but there is no evidence of preferential movement into larger embayments. Water coming off the reef flat remains near the surface for a considerable distance.

Estimates of flushing are generally made using volume exchange models. The term "flushing time" and its counterpart "residence time", are used in many ways, but, normally describes either average residence time of a particle in the system, or the amount of time it takes to'remove a proportion of the water or tracer, and are usually measured in tidal cycles: To determine flushing time for management the bay extent is defined, and the bay partitioned. Detailed bathymetric analysis enables volume to be calculated. Tidal measurements must be made 'or estimated. An approximation to an even distribution of dye over the bay'is achieved by dividing the bay into segments and injecting'dye as a slug at the centre of, each segment, the amount of which is proportional to the segment volume.

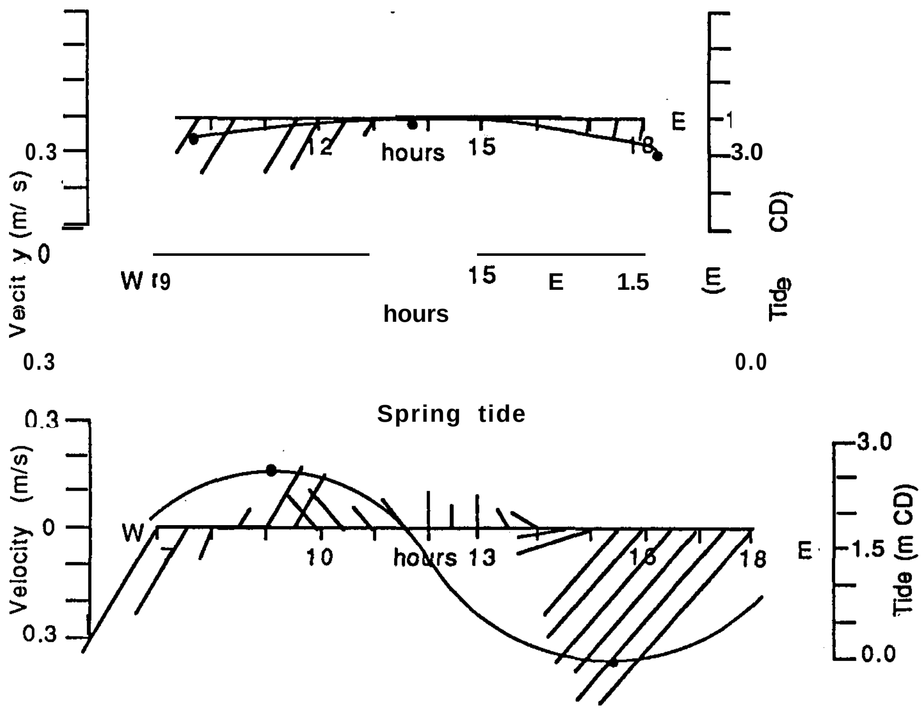

Figure 3 Water velocities and tidal data at the bay mouth on spring and neap tides

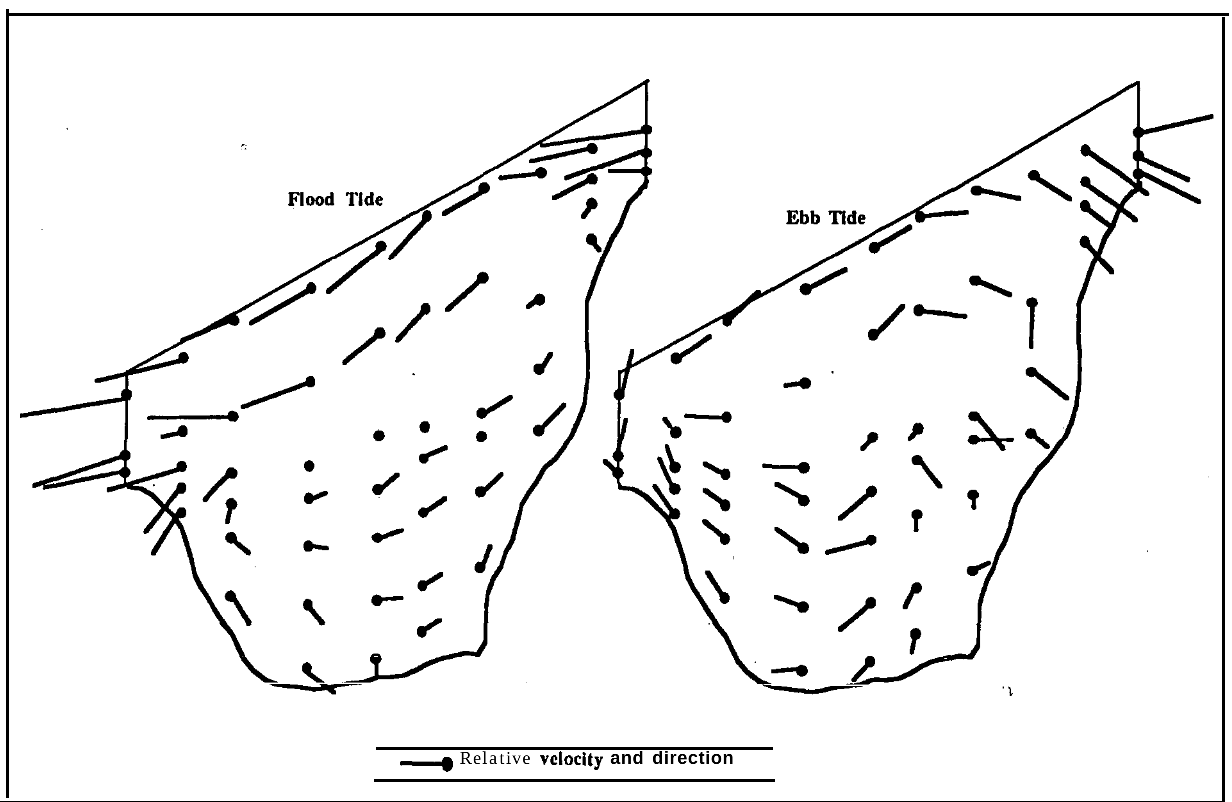

Figure 4 Generalised circulation, Pioneer Bay

Alternately, for the answer to a more specific' problem, dye' can be injected at a' point, or as a line source. The results of experiments in Pioneer Bay indicated that 92% of the water in the bay at one high tide was removed on the average tide, with most of the water remaining being concentrated along the northern shore. The total proportion of dye removed over two tidal cycles was 99.5%. This indicated that the exponential model of decay (which is generally applied to estuary situations) may apply to the bay situation.

As a comparison bay volume was modelled to determine flushing time Over the period of the bay flushing experiment, using an average value for high and low water volumes, T (residence time)= 4.12 tidal cycles. This compares with T= 1.08 established using fluorescent dye. Although the bay flushing experiment using dye may slightly underestimate T because some dye will be present below the minimum detectable limit, it is clearly much less than T predicted using the standard volume exchange model. This is because bay circulation is superimposed on the volume exchange required by the vertical tidal movement. Because much of the water within a bay is stored seaward of the reef front if the bay did not have well developed circulation it would have a long residence time approaching 4.12 tidal cycles for the average tide.

The circulation in Pioneer' Bay is a result of many forcing mechanisms and residual currents associated with them. Circulation is predominantly tidal, with the combined effect of eddying in the lee of the headlands, and diverging flow caused by tidal streaming against the opposing shore causing flow within the bay to be opposite in direction to flow across the bay. The southern shore is at a higher incident angle to the tidal stream than the northern shore,' and this combined with the requirement to move water into and out of the bay, ensure higher velocities along the southern shore than along the northern shore. At a smaller scale, freshwater inflow, boundary effects and the effects of topography (particularly at the reef front) cause local modification to the overall pattern, and cause differing velocities in the vertical. The effect, of wind for most of the year is minimal, but the effect' for the small period of the year when the bay is exposed is unknown.

The movement and distribution of sediment over the reef flat and offshore can be explained in terms

of source and the predominant bay circulation. Most of the sediment on the reef flat has a local origin, with sediment from the catchment, and coral and shell fragments from the reef flat and slope contributing to the offshore sediment facies. The importance of bioturbation to the movement of sediment through the system was noted.

Modelling investigations - other bays

Circulation in bays in which resorts are located (Brammo Bay Dunk Island, Happy Bay Long Island, Bauer Bay South Molle Island, Catseye Bay Hamilton Island and Hazard Bay Orpheus Island) was studied (Figure 5). It was found that the most important factor in determining the nature of the small scale hydrodynamics and bay flushing was the nature of secondary circulation established as a result of the relationship between the ebb and flood tidal streaming and the bay shape.

Happy Bay Long Island has a similar aspect and tidal streaming to Pioneer Bay. On the ebb tide strong eddy circulation is developed in the lee of the southern bayhead, but because of the long northern shore it is not reinforced by water being deflected into the bay at the northern bayhead. On the flood tide, water moves into the bay from the north, and leaves the bay around the southern bayhead with only slight eddy circulation along the northern shore. Similar patterns exist in Brammo Bay, and in Catseye Bay (except that the tidal streaming is east-west). The extent of eddy circulation is directly related to the angle the bayheads form with the prevailing tidal stream. The circulation in Bauer Bay is complicated by the presence of Mid Molle and North Molle Islands, which has the effect of lengthening the bay on its western side. Again, an eddy circulation is evident, but the primary mechanism is the diversion of water against the opposing headland, as opposed to the eddying effect in the lee of a headland. Hazard bay is much less indented than the other bays and the circulation within the bay is dominated by the tidal streaming, illustrating the importance of bay shape on circulation.

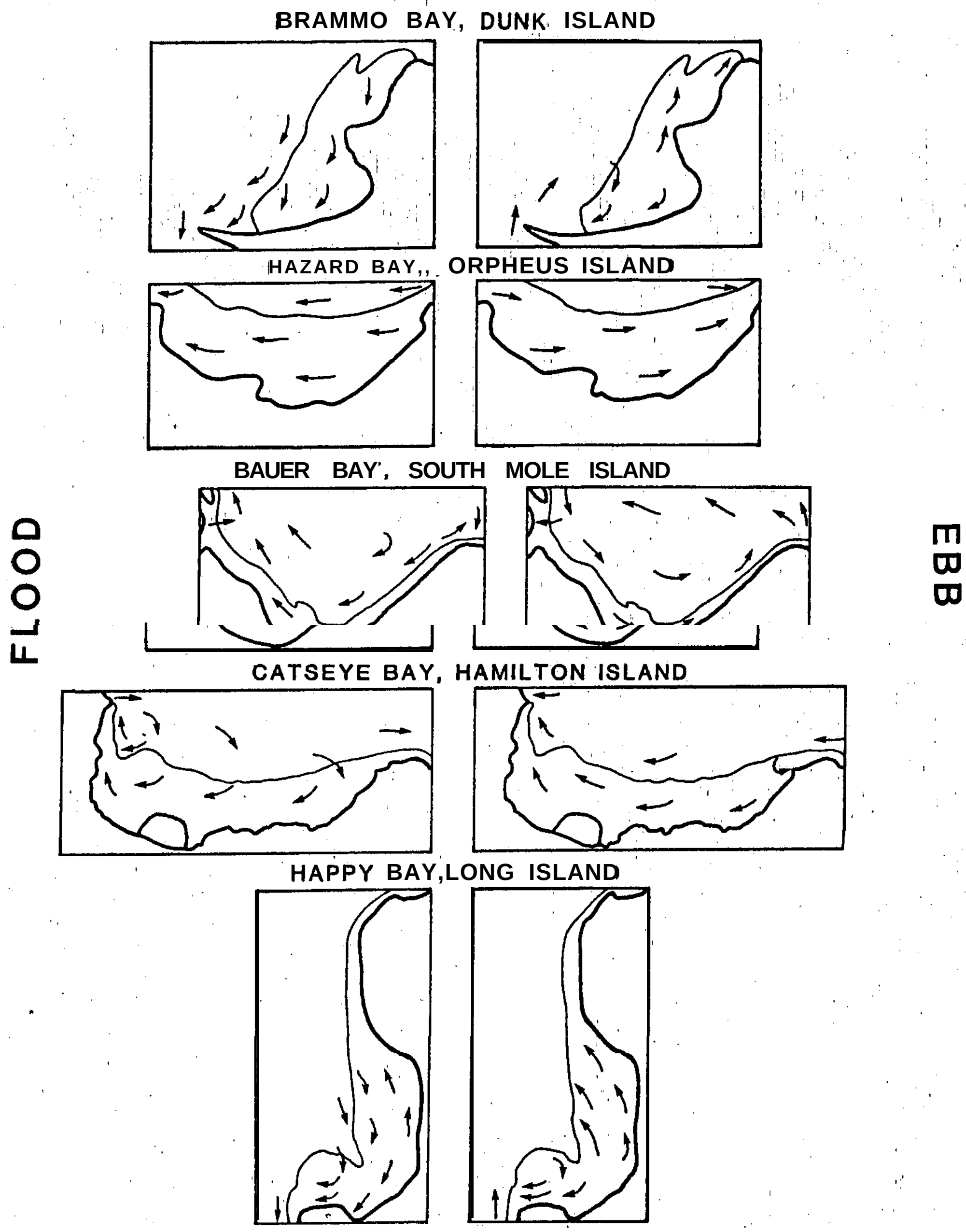

Figure 5 Generalised circulation in five resort bays

Water aualitv management problems

The two principal causes of water quality deterioration in the vicinity of resorts are caused by the impact of wastewater (including freshwater) discharge and associated increases in sediment discharge onto the reef, and by changes in the hydrodynamics and sediment movement due to engineering works.

The study bays illustrate a number of these problems. Evidence from Hazard Bay, shows that a channel across the reef flat, perpendicular to the dominant water flow is trapping sediment moving along the coast in both directions. The direction and velocity of flow in the channel is altered, and there is potential during periods of high winds for- the removal of substantial quantities of beach sediment into the channel and off the reef flat. The long term effect of the construction of a watersport enclosure in Catseye Bay is as yet uncertain, but there were indications of a change in sedimentation along the beach and accross the reef flat. The problem of retaining sand on the beach is illustrated in Bauer Bay, where beach sand is continually being removed and deposited off the reef flat. In two resort bays substantial quantities of silt was observed to be flowing onto the reef flat during periods of heavy rainfall. This is likely to be a problem in all bays with resort development and is potentially damaging to reef communities. It was found that reef flat sediment in resort bays contained substantially more terrigenous material than sediment in similar undeveloped bays.

A summary of management techniques

There are a number of techniques which can be used by the non-specialist to assist in the interpretation of bay hydrodynamics and assist is management decisions. Ideally information should be gathered before wastewater discharge or engineering works begin, but the methods described may assist in minimising the impact of present situations.

Well designed small scale tracer studies can lead to the understanding of where individual parcels of water move. If a number of these experiments are conducted, a model of bay circulation can be

derived using the data and basic equations. This can then be used to predict circulation at other sites and times.

There are a number of techniques which are available to examine the movement and flushing of introduced pollutants. The characteristics of a tracer can be made to resemble that of a pollutant and injected at the site of a potential outfall as a slug; or continuously over a period of time. The effect of a single injection can then be measured using concentration data, or by integrating the concentration curve with respect to time at any site of interest, the ultimate or equilibrium concentration at the site of a continuously injected contaminant can be estimated (the superimposition principle). At a larger scale bay flushing can be estimated using a volume exchange model (which is likely to give'a very conservative estimate of total flushing), or by introducing a tracer at a number of points within the bay in proportion to water volume, and monitoring its removal. If the flushing of a particular segment of the bay is required, the experiment can be confined to the area of interest.

Sedimentation patterns can be monitored by examining the potential sources of sediment, and relating this to bay circulation. Velocities and directions established using tracer data (or model data) can then be used to predict sediment distributions, with rates established using sediment transport equations. The possible effects of increased sediment input or of engineering works can then be examined.

Conclusions

The study of bay hydrodynamics involves a cluster of models (Figure 6). Models of water volume and flushing, and studies of boundary effects, the effect of the change in 'topography at the reef front on circulation, and the study of other small scale factors such as water movement within the reef framework, are used to further refine the circulation model which is derived from a number of well designed Lagrangian tracer experiments.

Data from a number of lee side fringing reef bays indicates that the nature of bay circulation is

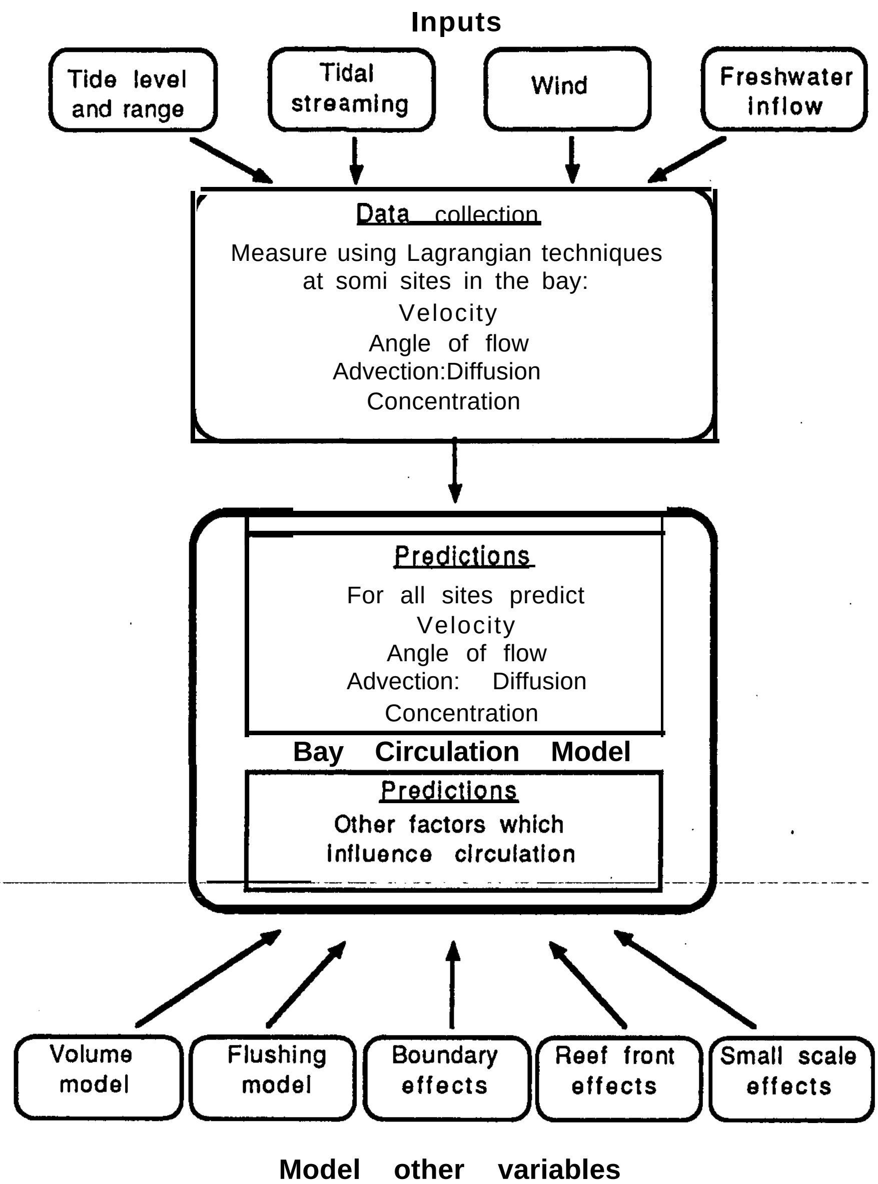

Figure 6 Bayhead fringing reef modelling, model cluster

determined by &relationship between tidal streaming and bay morphology. The' extent of eddy circulation is related to the extent of bay indentation. "Where eddy circulation is established bay flushing (and hence removal of pollutants) is high. Velocities within bays are variable and must be, considered when changes in sediment supply are envisaged. Once a hydrodynamic model for the whole or part of a bay is obtained, the likely impacts of wastewater discharge or engineering work can be determined.

Although the legislative framework within which management decisions must be made is unclear, it is to the benefit of government, resort operators and visitors that water quality be maintained. 'Major studies are expensive and generally need to be undertaken by specialist personnel. Although such studies are both useful and necessary, reasonable quality information which can be used in many management situations can be obtained inexpensively by non-specialists using, Lagrangian tracer techniques.

Acknowledgements

I' would like to acknowledge the assistance given me by resort managers in the fieldwork stages of this study. Financial assistance was provided by' the Great Barrier Reef Marine Park Authority and the Queensland Co-ordinator General.

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