extremity of the country where the continental slope comes closest to the coast. They are readily accessible to visitors from Perth and until recently have been heavily fished.

The Houtman Abrolhos Islands, situated some 400 km north from Perth, are the most southerly reefs of the Indian Ocean and are one of the most interesting coral reefs of Australia. Although they form the southern distribution limit of most Western Australian coral species, the corals show few signs of environmental stress and in some areas they form the most luxuriant communities to be found on any Australian reef. Curiously, *Acanthaster* has never dispersed to these islands although it has reached the Solitary Islands and Lord Howe Island in the east. In other areas, corals grow with the kelp and *Sargassum* in an extraordinary mixture of the tropical and temperate. The islands themselves are covered with shacks used seasonally by rock lobster fishermen and have little natural scenic value.

The value of the Great Barrier Reef

The GBR is arguably the most valued part of Australia's natural inheritance. Its importance to life on this planet, and its intrinsic value to future Australians is beyond measure. Unlike most of the other great natural wonders of this earth, the GBR has nothing of the robustness we naturally associate with vast and apparently pristine regions. It is only a veneer of life on limestone foundations, and that veneer is fragile and as sensitive to environmental degradation as any other ecosystem. It is the challenge of the future to preserve that veneer for all time, and do so in the face of human usage that appears likely to undergo an exponential increase.

Some would place the value of the GBR to individual Australians second only to its value to world heritage. Most Australians, and indeed most educated people from any country who take an active interest in global issues, would place a high value on the conservation of the GBR. This value, I believe, is part of our national and international culture and is thus difficult to describe and impossible to define.

It is clear that Australian coral reefs in general are currently only at the dawn of international tourism. The GBR, as no other reef region in the world, offers true wilderness areas, still largely unexplored, of vast proportions. So far, the remoteness of these regions have preserved them almost completely from the tourist industry. How long this will last is guess-work, for future projections of tourist numbers and activities are inevitably prone to error because of the difficulty of predicting technological advances in transport and accommodation (such as high-speed aluminium catamarans and floating hotels) not to mention international economics.

At this time, most of the reef tourist industry is catering for a combination of speed and ease of access. In these respects there are many other places in the Indo-Pacific which effectively compete with the GBR. In perhaps a decade or less, this appears certain to change as better informed visitors demand more personal experience, more adventure and better access to remoteness and the unknown. In a decade or so beyond that, the place Australia will have in the global conservation of coral reefs will create management issues that can only be imagined at present.

In October, 1981, the Great Barrier Reef was inscribed of the World Heritage List having satisfied all criteria set out in Article 2 of the World Heritage Convention: an example of a major stage in the earth's evolutionary history; an outstanding example of geological processes, biological evolution and human-environment interactions, a place with unique, rare and superlative natural phenomena, a place which provides habitats for rare and endangered species of plants and animals.

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CREATING A CAPTIVE CORAL REEF ECOSYSTEM

Martin S Jones

Introduction

The Great Barrier Reef stretches over 2000 km along the north east coast of Australia covering an area of 350,000 km^2 (Figure 1). The Reef contains more than 2,900 individual reefs, 900 islands and has a great diversity of animals and plants. The Reef is managed by the Australian Government through the Great Barrier Reef Marine Park Authority (GBRMPA). To support the management and educational roles, the Authority operates a living coral reef aquarium and interpretive facility.

The Aquarium, which has been open since June 1987, is part of a complex on the bank of Ross Creek in Townsville, which contains shops, a branch of the Queensland Museum, the Magnetic Island Ferry Terminals and offices for the GBRMPA. The centre was built with Commonwealth Bicentennial funding and money from the Queensland Government, private enterprise and the Townsville community.

In addition to having plenty of sunshine (necessary to grow a coral reef) Townsville has the advantage of being a centre for tropical marine research. The Australian Insti-

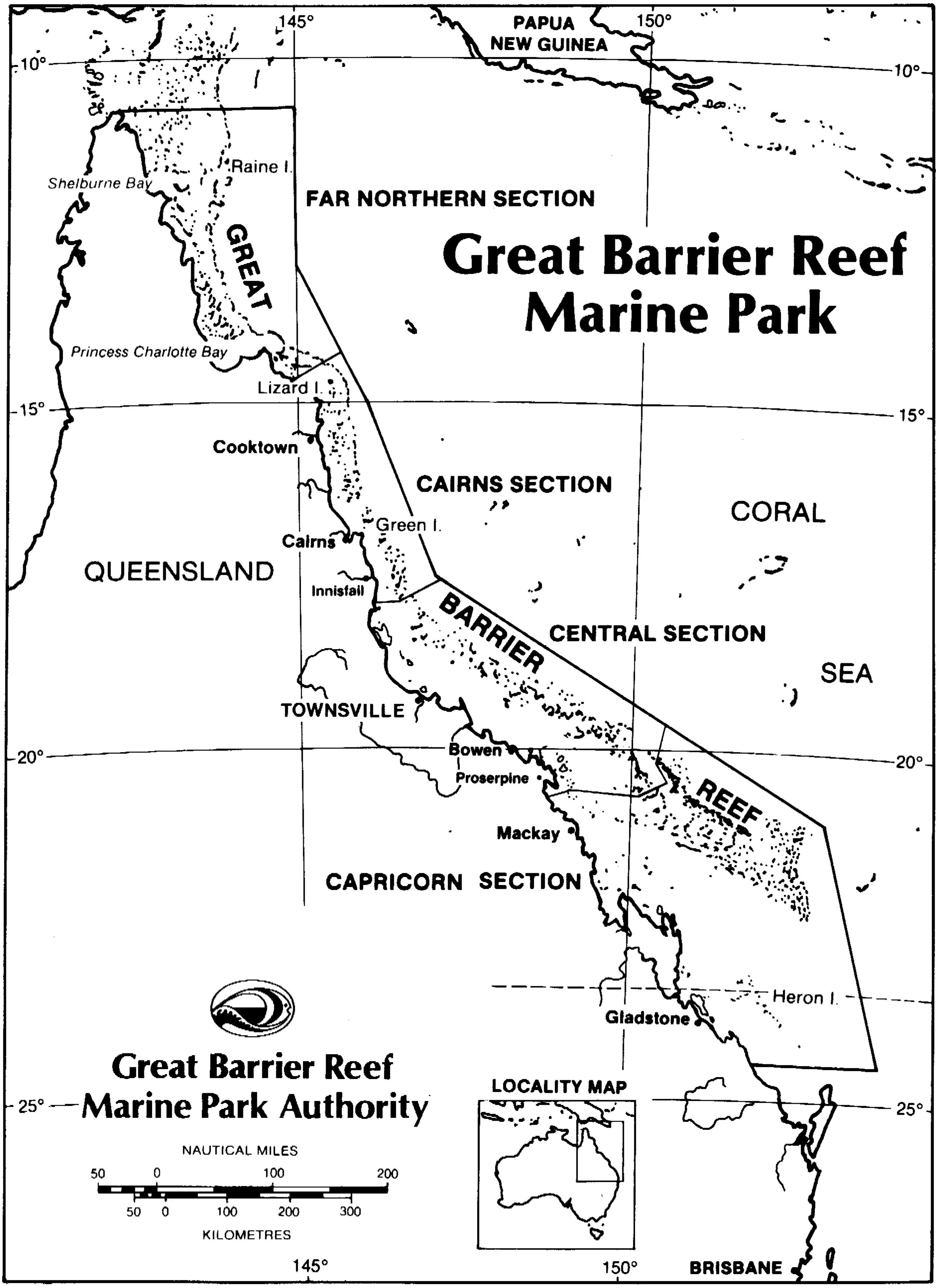

Figure 1 Map of the Great Barrier Reef Marine Park

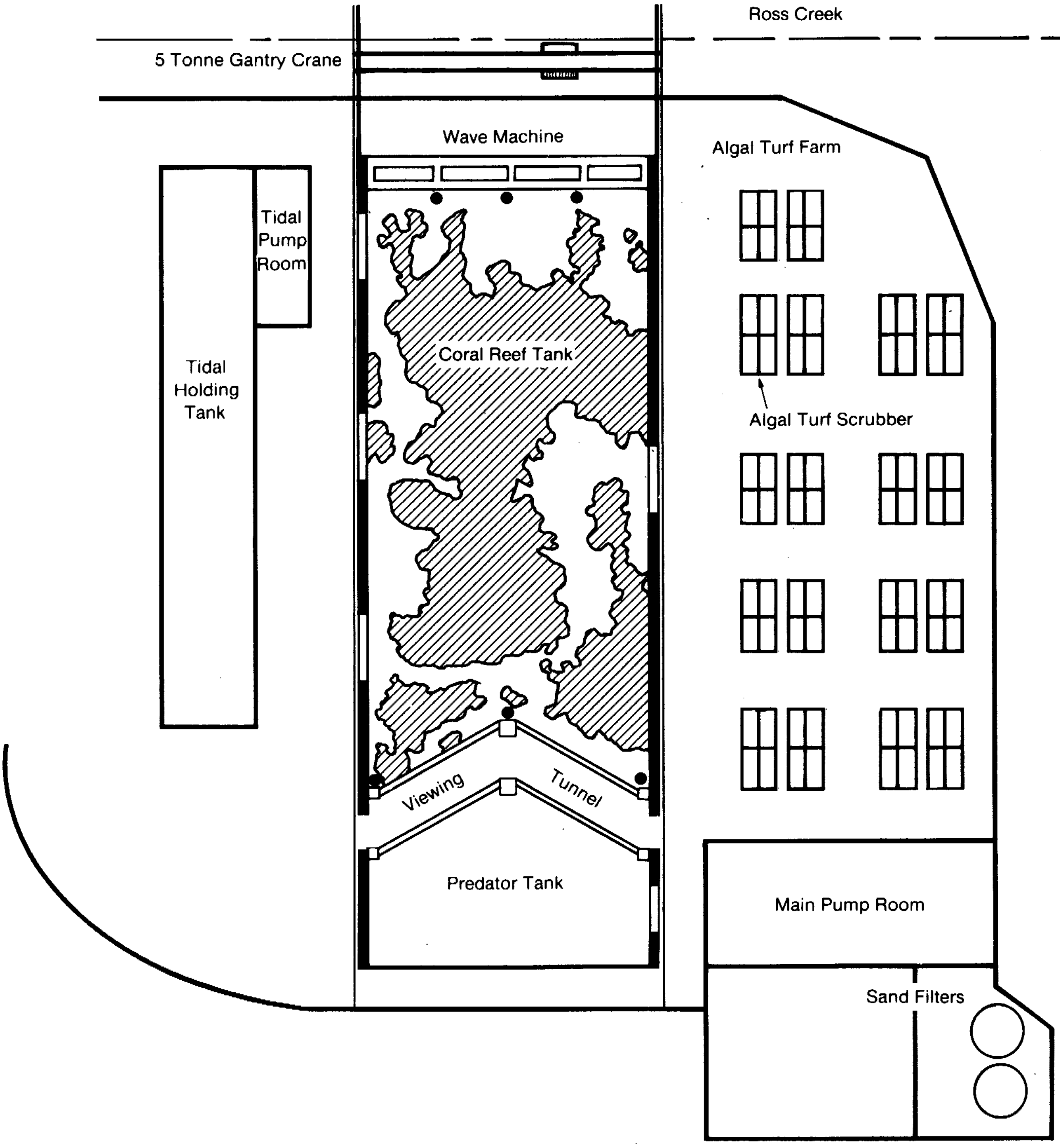

Figure 2 Plan of the Aquarium

tute of Marine Science, the GBRMPA and the Department of Marine Biology, James Cook University, are all located in the region.

The aquarium

As the quality of the water in nearby Cleveland Bay was considered unsuitable the Aquarium Coral Reef Exhibit is run on a closed circuit process with all seawater recycled through a purification process based on marine plants.

The 2,50,000 litre Coral Reef Exhibit tank is 17 m wide, 38 m long and 5 m deep with a four chambered wave machine at one end. At the opposite end a 20 m walk-through acrylic tunnel separates the reef exhibit from the 750,000 litre predator exhibit tank (17 m wide,10 m long and 5 m deep). Next to the coral reef, and under the observation area, there is a tidal holding tank with a capacity of approximately 750,000 litres. The unique algal turf farm, where the water purification occurs[1], occupies the roof of the interpretive area on the opposite side of the reef exhibit (Figure 2).

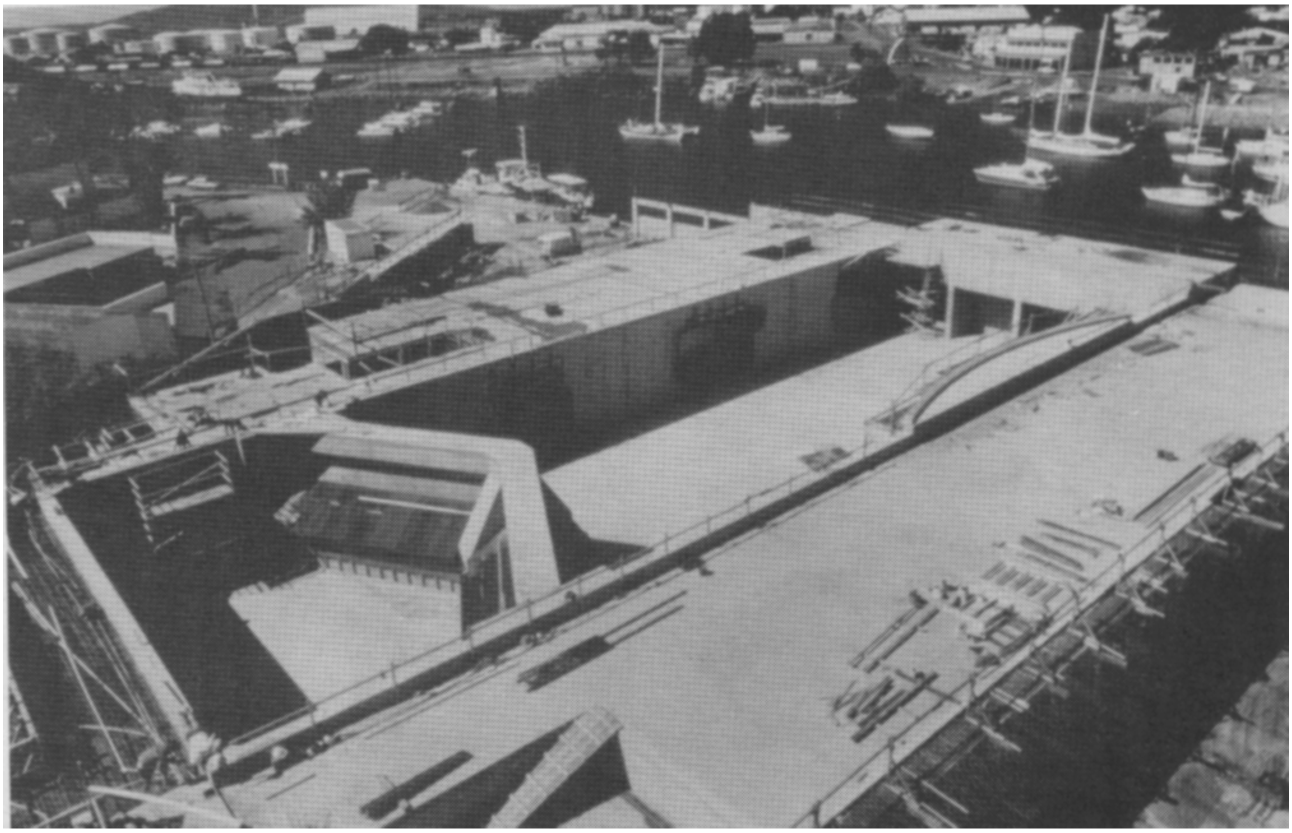

Figure 3 The Aquarium under construction

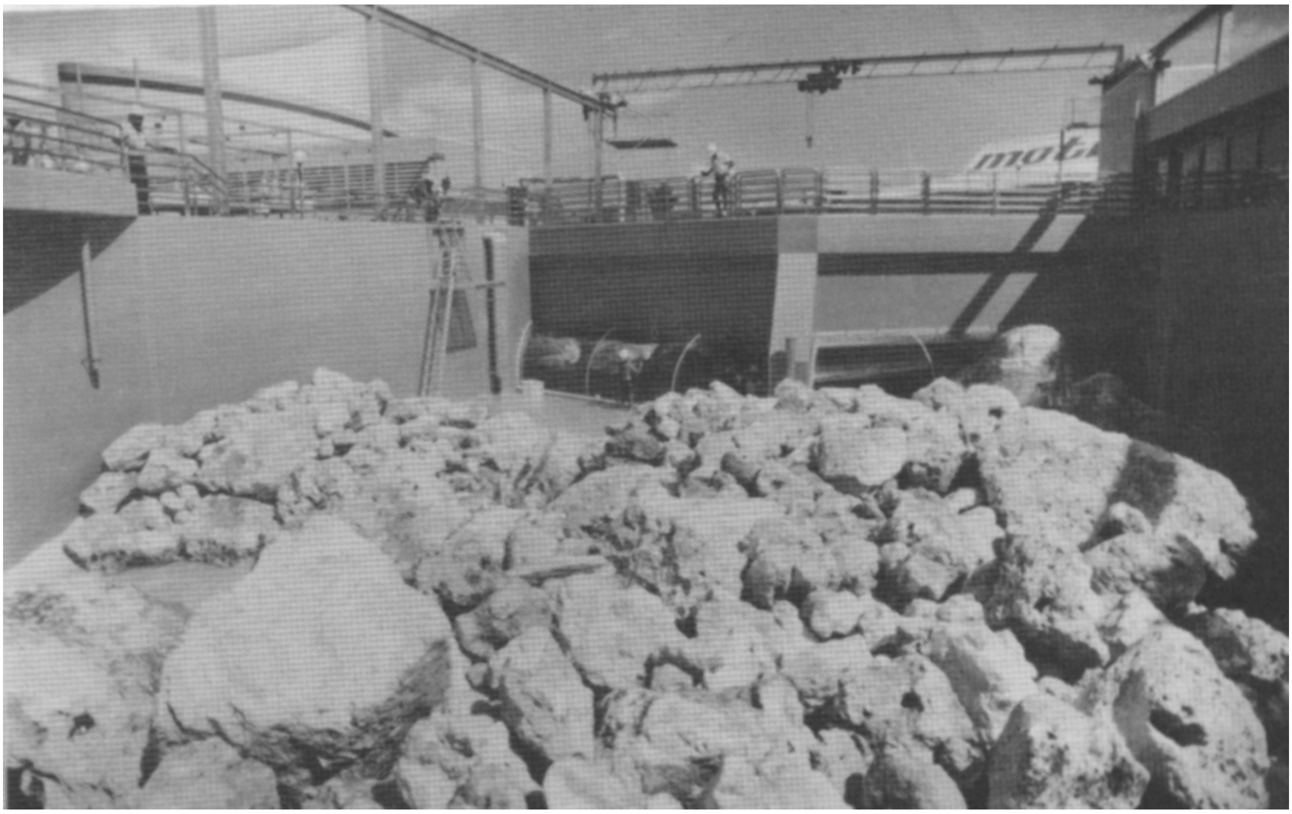

Figure 4 The Aquarium reef under construction

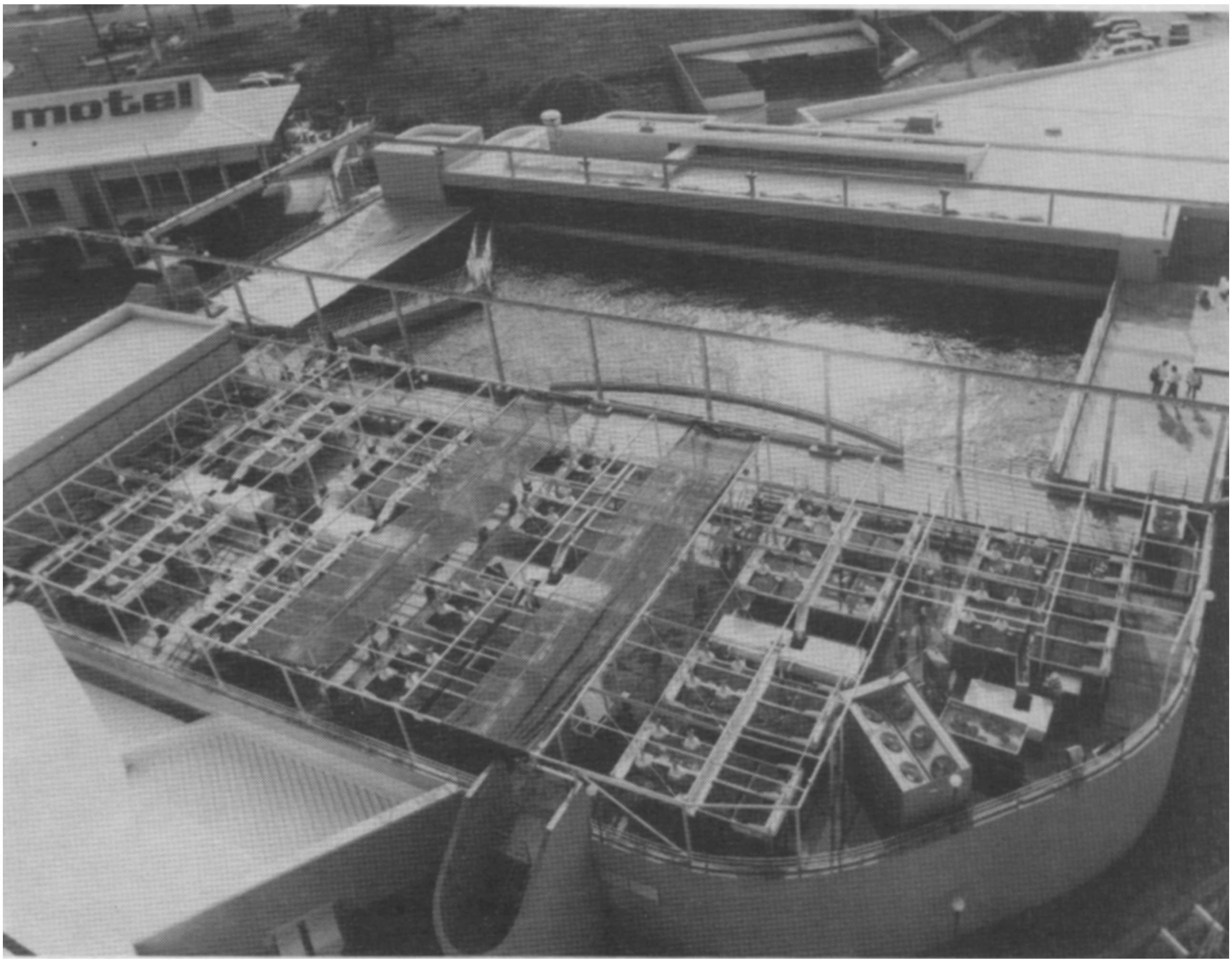

Figure 5 An aerial view of the completed Aquarium

The main interpretive area contains 15 smaller aquaria, a shop, a 200 seat theatre and static and video displays. A classroom and laboratory for school and other groups, a large Touch Pool and other exhibits are located on an enclosed observation deck overlooking the main tanks. Exhibit preparation areas, staff offices and a mechanical workshop are on the ground floor beside the Tidal Holding Tank.

Adjacent to the predator tank, is the main pump room. This houses the main circulation and filtration pumps for the coral reef and predator exhibits, together with the deionised water supply system and the scuba compressor. Two large sand filters and two freshwater reservoirs for filter backwashing are housed behind the pump room at street level. A 5 tonne gantry crane traverses the width and length of the coral reef and predator tanks and reaches over Ross Creek to allow servicing and stocking the main tanks.

The aquarium coral reef

Our understanding of how a reef functions has been largely derived by studying whole reefs or by taking reefs apart and investigating the various components. The job of trying to put a functioning coral reef together is a little different. It is rather like trying to put a jigsaw together with several important pieces missing.

The site for the Aquarium on the banks of Ross Creek was a former mangrove forest. To support the 4,000 tonnes of seawater and the weight of the concrete structures approximately 200 piles, each with a design load of 125 tonnes, were driven through more than 10 metres of soft mud to reach a hard foundation of clay and rock.

As draining the tank would kill much of the resident plant and animal life the tank housing the unique closed-cycle coral reef had to be designed to withstand the effects of seawater for 50 years.

A special high strength, low water/cement ratio mix of concrete was used. This concrete was pre-cooled with liquid nitrogen, to minimise cracking during curing, before pouring the foundations and tank walls. Conventional reinforcing steel was used, covered with twice the normal

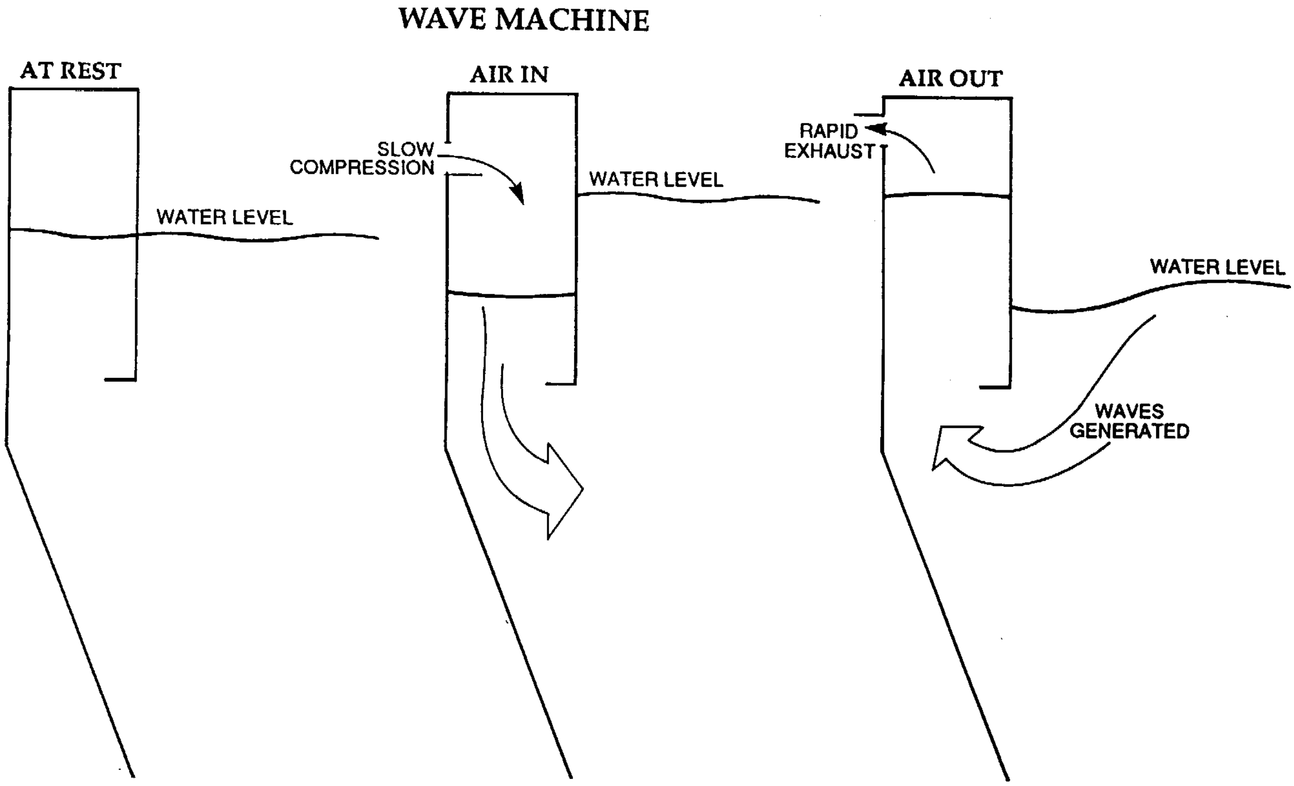

Figure 6 Diagram of the wave machine

depth of concrete, with stainless steel plates at the main tank joints. The internal tank walls were coated with non-toxic epoxy paint to give a smooth finish, reduce leaching of lime from the concrete and to ensure waterproofing.[2]

The principal feature of the Aquarium is a 20 m long acrylic viewing tunnel. In addition there are 5 flat viewing windows, each approximately 3.5 x 4 m, which provide a good view to the remainder of the coral reef exhibit. Construction of the Aquarium was completed on schedule in December 1986 leaving 6 months for stocking and fitting out before opening.

Building the coral reef exhibit started with dredging some 200 tonnes of coral sand, under permit, from the lagoon of Flinders Reef. A sand layer about 0.5 m thick was laid as the foundation. The basic reef shape was then constructed from 700 tonnes of coral boulders obtained from an excavation for a harbour development at Hayman Island in the Whitsunday Islands group (Figure 4). The tank was then filled with seawater, collected well offshore to ensure starting with unpolluted seawater and transported by barge to the Aquarium.

Waves and currents

The structure and biological activity of coral reefs are largely determined by the water motion due to waves, tides and currents and the chemical composition, temperature and salinity of seawater. As far as possible the physical and chemical environment of the Great Barrier Reef have been replicated in the Aquarium coral reef exhibit.

Waves are created by a pneumatic wave machine (Figure 6). For generating waves, producing a trough is just as good as producing a crest. At rest the water level in the wave machine chambers is the same as the water level in the coral reef exhibit. In the first stage of the wave generation cycle, compressed air is blown into the chamber and depresses the water level. At the end of the compression cycle a large valve opens allowing the compressed air to escape rapidly. The water level in the chamber rises swiftly drawing in water from the reef tank effectively generating a trough. This trough is propagated along the tank and reinforced by the next wave generation cycle depending on the timing and volume of air delivered to the 4 wave chambers.

The wave machine is capable of generating a 2 m wave, which gives spectacular results at the tunnel end of the tank! The wave height used is typically 0.25 to 0.75 m in contrast to the Great Barrier Reef itself where wave heights are 1 to 4 m and considerably larger during cyclones. The great advantage of the wave machine is that there are no moving parts in contact with seawater so corrosion, maintenance and contamination of the tank are kept to a minimum. Fish, soft corals and the larger marine plants sway back and forth in the realistic surge generated by the wave machine.

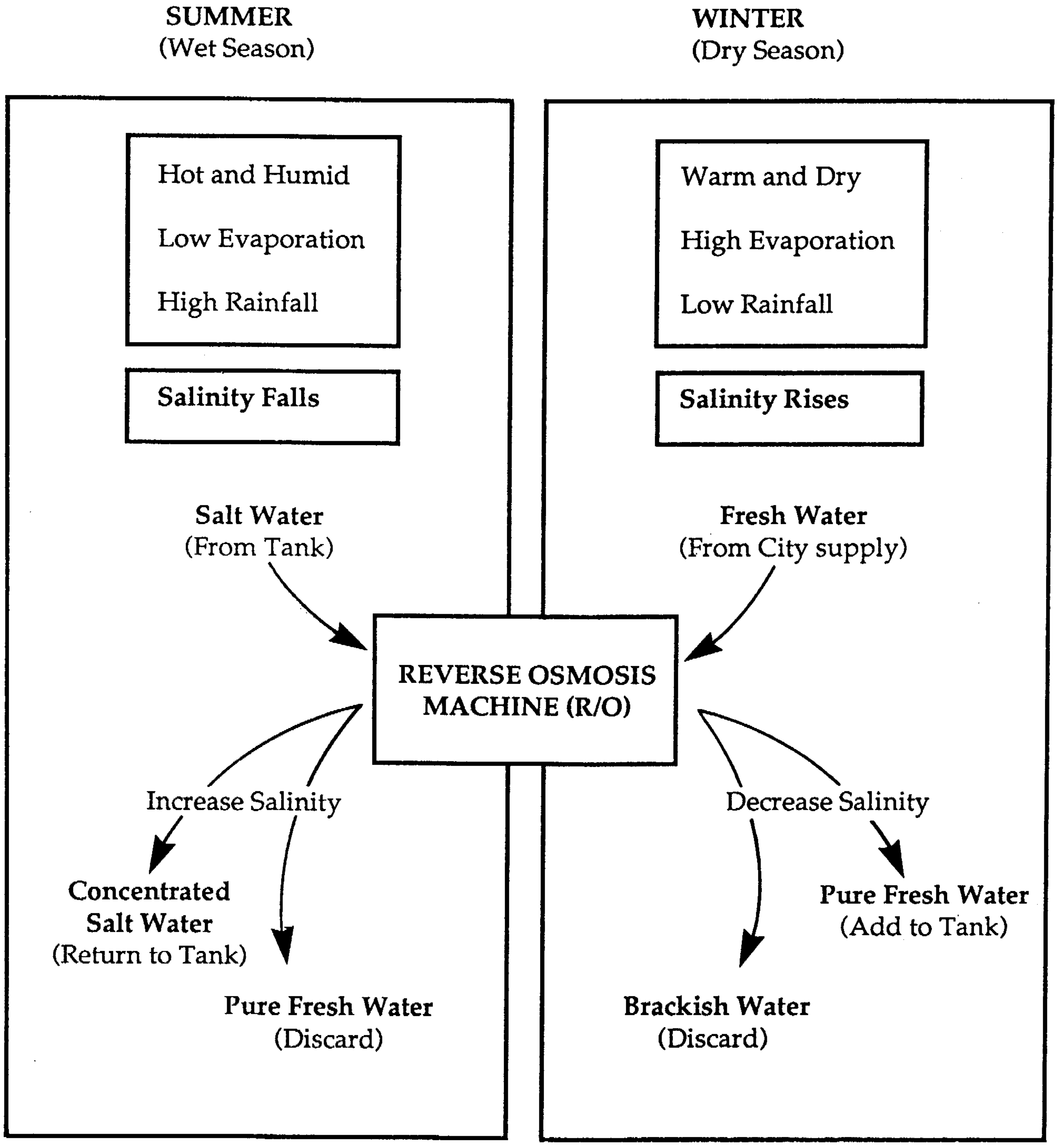

Figure 7 Diagram of salinity control using reverse osmosis

Sediments

As on the GBR, fine sediments are generated by physical and biological processes in the coral reef exhibit. Wave action suspends these sediments and prevents the undesirable effects of them accumulating on the corals and other substrate. Suspended sediments produced on the Great Barrier Reef are normally transported away from the reef by tidal and wind generated currents to settle in the deeper parts of the ocean. In combination with wave action, currents ensure good mixing and facilitate gas and nutrient exchange. A constant current is maintained across the reef in the tank by drawing water from the tunnel end, pumping it through a sand filter to remove suspended material and returning it to the wave machine end of the tank at 90 l sec^{-1}. The sand filter substitutes for the deep ocean in removing the sediments generated in the Aquarium reef.

Life processes in the sea and on reefs generate materials that gather on the water surface as films, scum or slicks. In the ocean these materials are dispersed they but will accumulate in any contained situation. Water constantly overflows from the Aquarium reef exhibit to the tidal holding tank taking these materials with it and dispersing them in the water, leaving a clean surface to facilitate gas exchange. The facility for generating tides to 0.5 m in the Coral Reef Tank has not been routinely used as the change in wave pattern with different water levels reduces visibility in the tank.

Temperature and salinity

Townsville has a climate with warm dry winters and humid hot summers, often involving torrential rains associated with cyclones. The great volume of the sea surrounding the Great Barrier Reef greatly reduces the effect of these sudden changes in air temperature and rainfall. It is generally considered that 30° C is the upper limit for Pacific corals and the phenomenon of "coral bleaching" throughout the Pacific, during high surface water temperature events, is attributed to this.[3] The Aquarium reef has a relatively small water volume and responds rapidly to changes in air temperature, humidity and rainfall. The summer maximum water temperature in the Aquarium reef, is controlled by a combination of refrigeration, shading and evaporative cooling.

Evaporative water losses are highest during the dry winter months and the salinity of the tank rises. During the humid summer periodic heavy rain dilutes the tank seawater and the salinity falls. Both of these conditions are compensated for by using a reverse osmosis machine. During winter the city water supply is purified to the exacting Aquarium standards required (removal of tannin based discolouring compounds, residual chlorine, iron and trace nitrogen and phosphorus nutrients) by passing it through the reverse osmosis treatment. During the summer the tank seawater is passed through the same reverse osmosis machine with the pure extracted fresh water being discarded and the concentrated brine returned to the tank to increase the salinity (Figure 7).

Metabolism of the aquarium reef

Scaling down the Great Barrier Reef to recreate a representative portion in the middle of a city requires close attention to more than replicating the natural physical conditions where coral reefs grow. The maintenance of water quality is critical.

The normal life processes on a reef, as in any living system, start with plants (primary producers) converting inorganic material to living matter by photosynthesis. Animals eat the plants in one form or another and produce organic wastes. These are reduced to inorganic materials by bacteria and are again available for plants. On a global scale this all balances out with sunlight providing the energy at the plant level to maintain a continuous cycle. The differential between primary production at any 2 points in the ocean is dependent on the availability of sunlight and inorganic nutrients. Tropical seas are usually almost devoid of nitrogen and phosphorus nutrients compared to the generally richer temperate and polar waters.

Paradoxically coral reefs, with their great variety and abundance of life forms, thrive in the low fertility tropical oceans. Low dissolved nutrient levels limit the growth of phytoplankton in the water column resulting in very clear water. The great transparency of reef water allows plenty of light to reach the bottom dwelling community. Tightly associated animal and plants such as corals with their symbiotic microscopic plants (zooxanthellae) facilitate direct relocation of basic nutrients and food without the inefficient step of transfer through the ocean.

Scaling down such a system inevitably results in distortion. In the case of the Great Barrier Reef Aquarium, distortion results from the requirement to present as large an area of reef as possible within the tank. In such a closed system the plant/animal ratio is weighted in favour of the animals and more wastes are being produced by the animals than are able to be converted by the plants and ultimately the level of nitrogen and phosphorus nutrients in the water increase.

Apart from adding small amounts of plankton or plankton substitutes, no animals are artificially fed. The Coral Reef Exhibit is a closed system and little water is exchanged with the adjacent ocean. Most closed system aquaria are based on bacterial degradation of metabolic wastes, similar to a basic sewage system. Ammonium compounds are degraded first to nitrites and finally nitrates. The nitrate level is then controlled by regular water changes.

To keep corals in captivity one needs water with a very low nutrient level, less than 50 ppb (parts per billion) nitrate.[4] In the Aquarium coral reef nutrients are generally between 5 and 60 ppb nitrate.[5] Increases exceeding 100 ppb can follow perturbations such as substantial specimen additions or extensive cloudy periods, particularly if accompanied by heavy rain. Higher than normal levels of some nutrients appear to be toxic to some species of corals (particularly *Acropora* species) and also promote the growth of macro-algae that out-compete corals for living space. The solution is to increase the area of plants, not make them available as food to the animals in the system, and harvest them, thereby removing the surplus inorganic nutrients. This is what the algal turf system does.[1]

Algal Turf Scrubbers

Although Townsville is an area of very low level pollution, the aerial addition of nutrients is significantly higher than on the reef, particularly as the Aquarium is in the lee of the main loading facilities for for a relatively large port. The effect of aerial nutrient additions from rain and dust is enhanced by the relatively high surface area of the

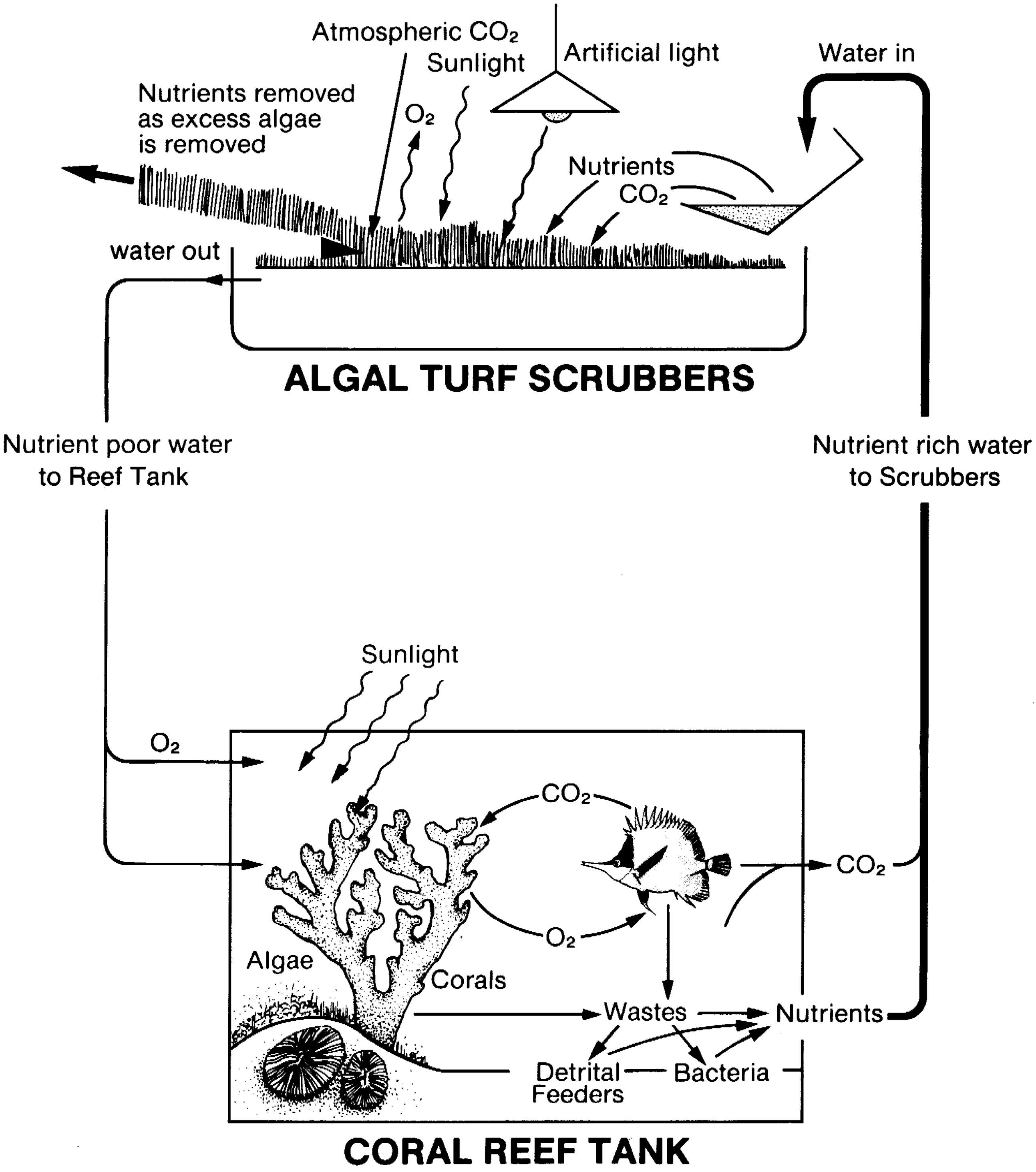

Figure 8 Diagram of the algal turf scrubber

aquarium reef and associated turf farm to the volume of the tank. There is also the, as yet undetermined, contribution of bacterial nitrogen fixation.

The algal turf system simulates the process that occurs on the weather side of coral reefs as the waves break against the reef and cross the reef top. In this area of turbulent mixing behind the breakers, a zone of short dense actively growing algae normally develops.

The system used by the Aquarium, is quite simple and consists of a shallow tray with two removable coarse mesh screens and a tip bucket at one end. Seawater is delivered to the tip bucket, which tips several times per

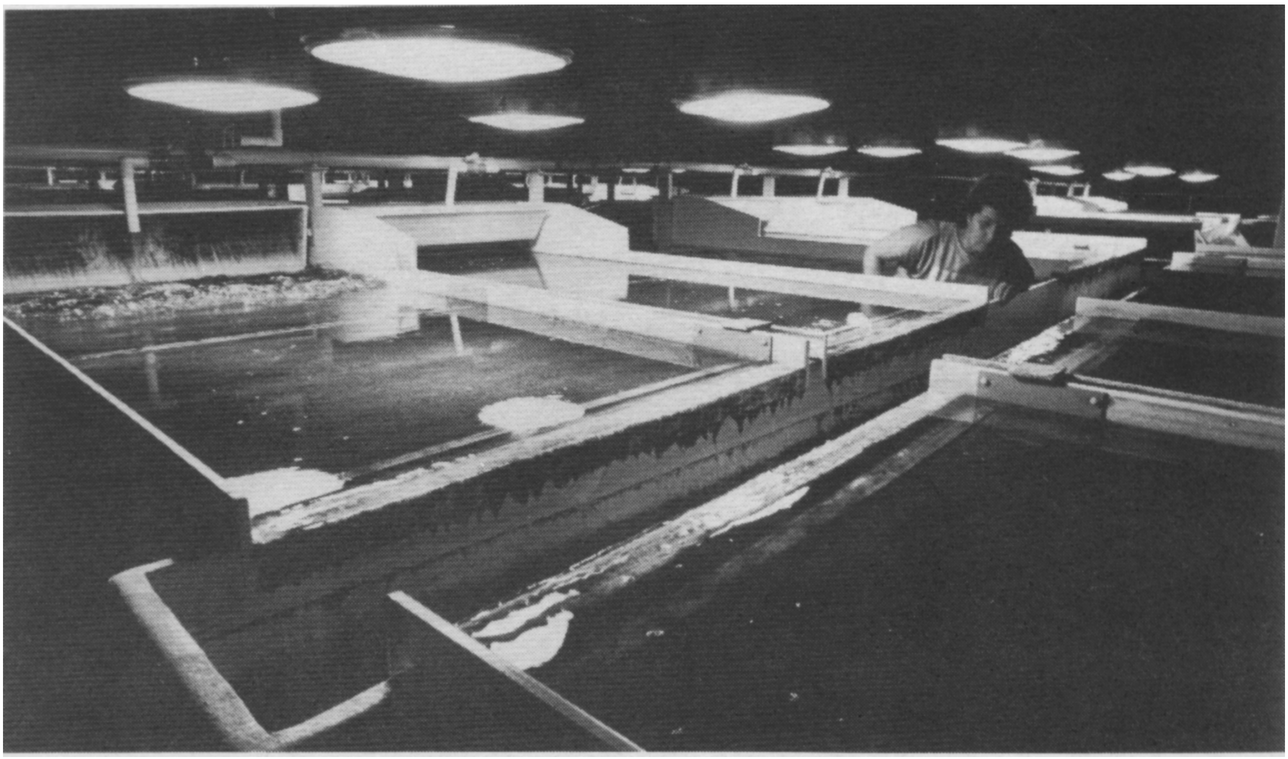

Figure 9 The algal turf scrubber at night

minute, causing a series of waves to rush across the screens. This water turbulence provides good mixing and facilitates gas exchange and nutrient uptake.

Algae in the process of growing on these screens take up nutrients. The algae, with the incorporated nutrients, are regularly scraped from the screens and discarded, effectively removing the inorganic waste from the tank as plant tissue. After passing over the screens the water runs into a settling bin and back to the tank. Artificial light, at an intensity of about half noon summer sunlight, supplied by forty 1 kw metal halide lamps is used at night and on cloudy days. Each algal turf screen has 18 hours illumination per day which increases the growing period and the rate of nutrient removal from the coral reef exhibit seawater (Figure. 9).

The distinguishing feature of the Great Barrier Reef Aquarium is the ability of the algal turf system to maintain water with a much lower nutrient level than conventional systems, some 1,000 fold lower for nitrate. This brings the nutrient concentration close to natural conditions.

The algal turf system provides other benefits. The process of photosynthesis removes carbon dioxide from the seawater thus maintaining the pH (Figure 10). Similarly the seawater oxygen levels are maintained without the need for supplementary aeration. Algae require trace amounts of various metals for compounds such as their photosynthetic pigments, these include heavy metals which may be toxic for reef organisms if allowed to accumulate in the water. Thus the algal turf system controls some trace metals[6] as well an inorganic nutrients.

Evolution of the aquarium reef

The tank was gradually stocked, over a 6 month period, beginning with establishing a diverse plant community. Large quantities of algal covered coral rock, most containing sponges, crabs, worms, sea urchins and other invertebrates, were carefully collected from the Great Barrier Reef and introduced to the tank. As the marine plants became established, herbivorous fish (mainly parrot fish and surgeon fish) were added, followed by herbivorous invertebrates (trochus and sea urchins). After about 3 months some omnivorous fish, hard and soft corals, giant clams, starfish and molluscs were added. Finally a small number of carnivorous fish and detritus feeding organisms such as holothurians and stromb shells were added.

Coral Reproduction

In the first year of operation, the corals spawned in the tank. This was significant as the generally accepted view is that if animals reproduce in captivity the environment must be right.

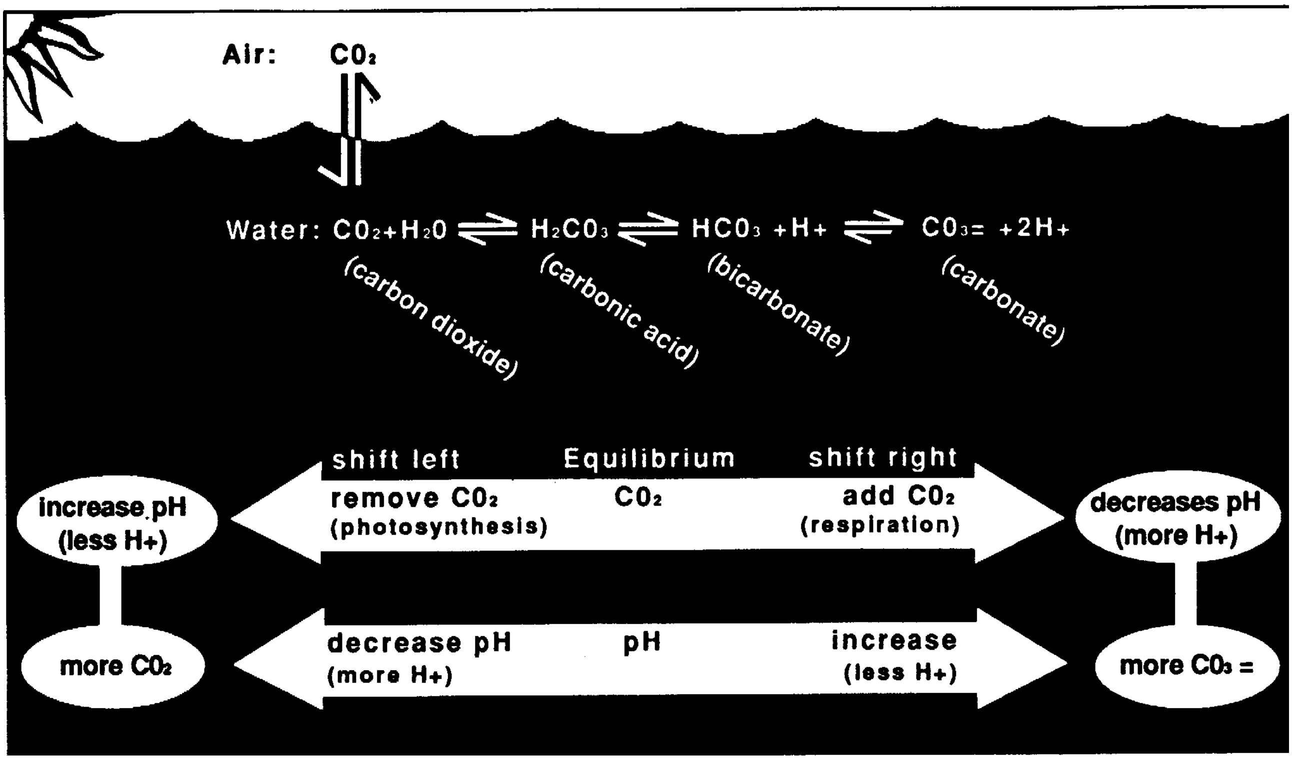

Figure 10 Diagram of the photosynthesis cycle. The pH and CO_2 content of sea water are linked by this reaction system. A change in pH or CO_2 will shift the equilibrium of these reactions. This buffering system helps maintain a relatively constant pH in the ocean.

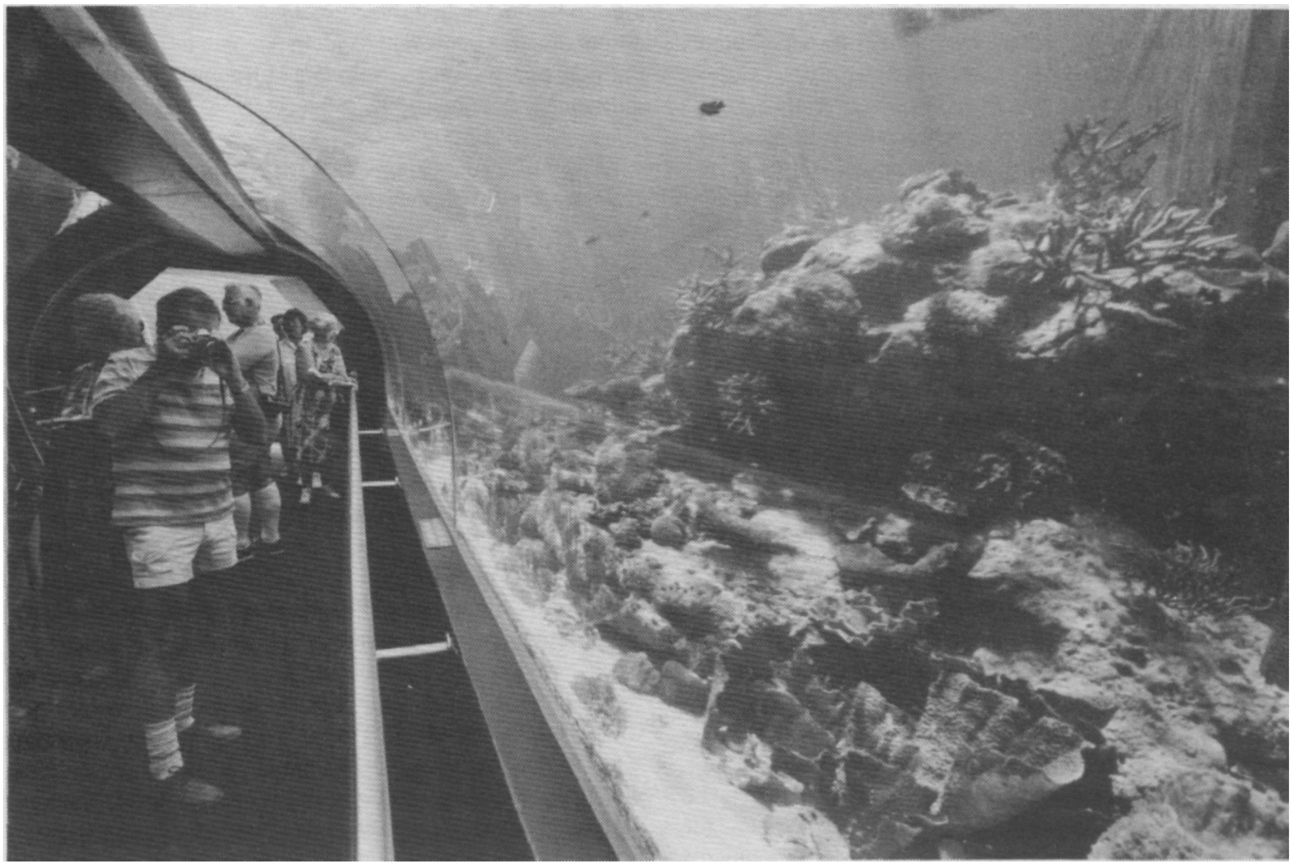

Figure 11 The Aquarium reef from the acrylic tunnel

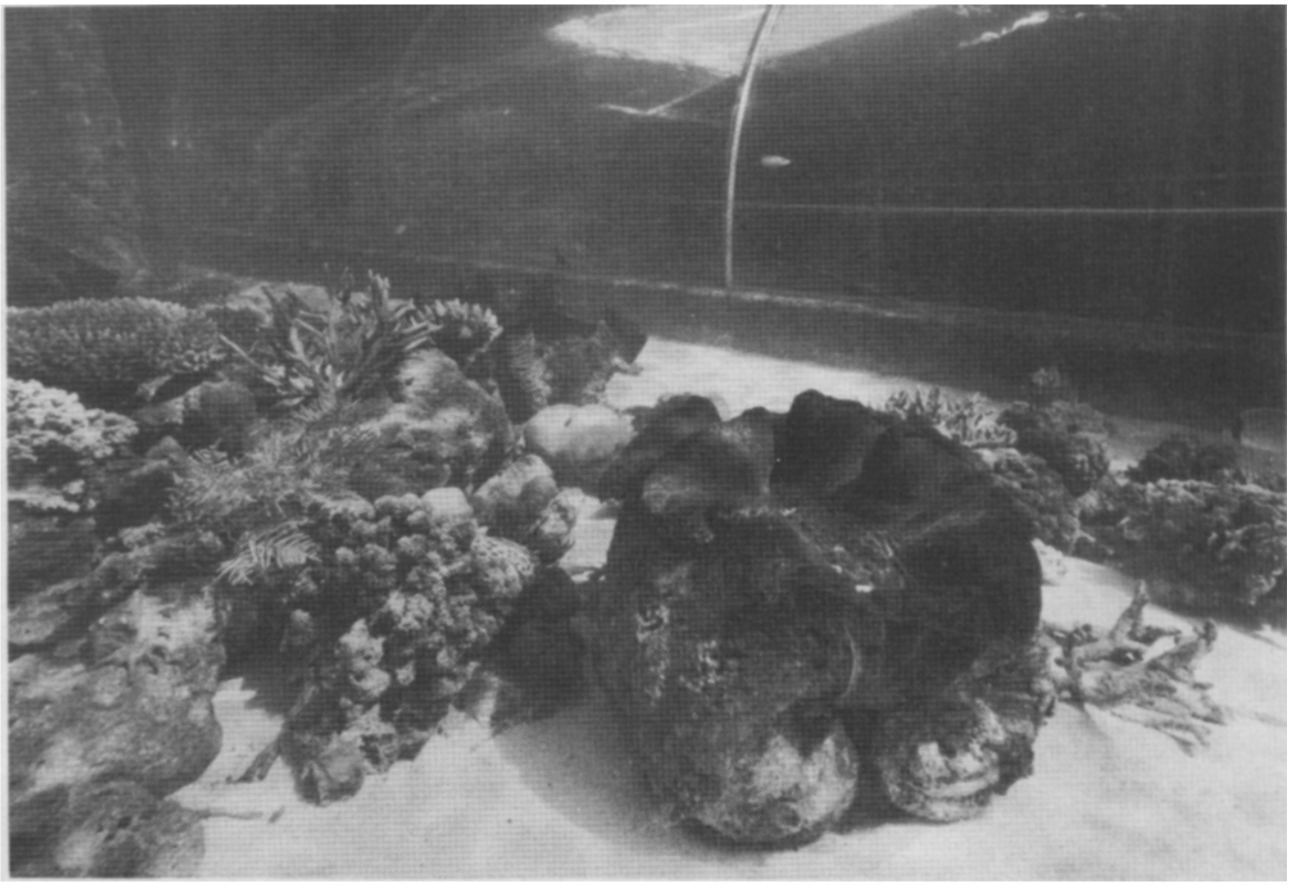

Figure 12 The finished Aquarium reef

Recruitment of corals, that is survival and growth from a successful spawning, is another matter. Coral larvae spend periods varying from 1 day to several months, depending on the species, drifting with the plankton. In the Coral Reef Exhibit young coral larvae are likely to be consumed by the pumps, trapped in the filters or plunged into the darkness of the tidal holding tank. Only one juvenile *Pocillopora* sp coral has, so far, successfully recruited. It had only a brief life before being consumed whole, probably by a coral eating parrot fish.

The tank now contains some 1,500 colonies of hard coral of 100 species, 700 soft coral colonies, 300 sea urchins, 400 molluscs and several thousand fish. No disease problems have developed, possibly as a result of the natural diet and environment. Many species of fish display courtship behaviour (parrot fish, *Chromis sp, Abudufduf sp,* anemone fish) and so far the catfish, *Plotosus anguillaris*, have reproduced in the tank. Other animals, giant clams, sea urchins, holothurians, trochus and spider shells, also spawn regularly in the tank.

Natural Disasters

Few projects go according to plan; and stocking the Aquarium has been no exception. A massive bloom of microscopic algae, turned the seawater a bright green immediately after the initial filling of the Coral Reef Exhibit tank. This was a comparable phenomena to the phytoplankton bloom that occurred in that section of the GBR lagoon affected by Cyclone Winifred.[7] The cyclone resuspended the sea floor sediments and liberated the stored nutrients. Filling the tank with sea water had dissolved and released the nutrients in the layer of dry coral sand. In both cases the abnormally high nutrient situation was taken advantage of by the rapidly growing phytoplankton. The solution was to pump out the phytoplankton (and nutrient) laden water and start again.

One thing was immediately apparent after successfully filling the tank. The reef structure that had looked so impressive through the curved tunnel windows in air, was not nearly as majestic in water. The curved tunnel windows, combined with the different refractive indices of water and acrylic, caused a foreshortening effect on the seascape. Rock moving, now more difficult under water, was continued until an appropriate seascape was produced.

At 6 months, as the tank was approaching full stocking level, a bloom of macro-algae covered the walls and all bare rock surfaces threatening to choke out the corals and filling the tank with unsightly floating algal fragments. Just as weeds initially flourish in freshly tilled earth the availabil-

Figure 13 A diver working in the Aquarium reef

ity of the fresh clean rock and wall surfaces provided opportunities for colonising macro-algae. This growth on the walls was probably encouraged by phosphate compounds (used in all paints) leaching out of the epoxy coating on the walls. For several weeks, teams of divers worked all day mechanically removing the profuse growth. Providing the right mix of herbivorous fish and invertebrates has ameliorated but not entirely resolved the situation. Unfortunately, sea urchins can not be trained to climb the walls to where they are needed to control the algal growth.

The reality of the need for careful management of coral reef systems can best be demonstrated by a simple calculation of the consequences of a diver succumbing to the temptation to urinate in the tank. Under normal circumstances one would expect these minor lapses in etiquette would not matter! At the normal parts per billion level operational level for nutrients in reef systems, this may not be so. The average human excretes 30 g of urea day^{-1}. Urea converts rapidly to ammonia and then to nitrate in the marine environment. One excretory event of say 5 g of urea would be sufficient to raise the nitrogen concentration of 200 m^3 of ocean water to over 10 ppb. This is well above normal ocean water levels.[8]

Fine Tuning

Fine tuning of the community structure of the Aquarium coral reef continues today, 5 years after its inception. Callianassid shrimps and goat fish are added to turn over and clean the sand. Predatory fish are collected to correct the behaviour of anemone and other damsel fish straying too high in the water column. We add territorial herbivorous fish to inhibit overgrazing by other animals and make regular small additions of plant and animal material to maintain diversity and make up for the depredations of the carnivores. No animals in the Aquarium reef are artificially fed, however zooplankton are routinely collected from Cleveland Bay adjacent to Townsville and added to the Coral Reef Exhibit as a substitute for the natural planktonic food available to a coral reef but removed by the sand filtration system in the Aquarium. When we are unable to collect zooplankton brine shrimps or other substitutes are used.

Figure 14 A diver vacuuming surplus algae in the Aquarium coral reef exhibit

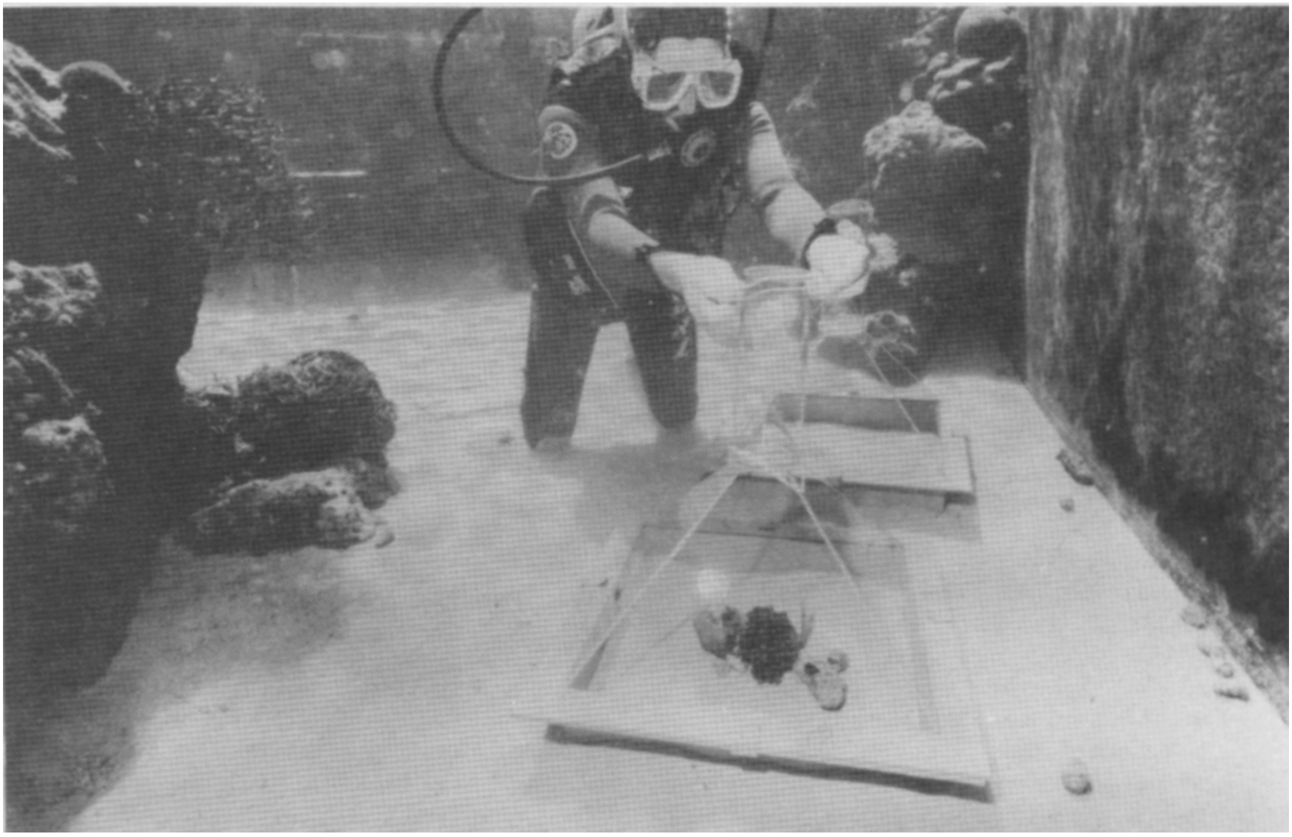

Figure 15 A diver sampling the new benthic zooplankton community of the Aquarium reef.

Reef research

The coral reef exhibit is a ideal research tool. Our research effort at the Aquarium is applied to determining the optimum conditions for the growth of our captive coral reef. The reputation of corals as difficult animals to keep in the home aquarium are well deserved. They are fussy about their surroundings compared to reef fish which have wider environmental tolerances. Corals are the focus of our research activities as we learn about ways to improve coral survival in our tank. Investigations completed or underway at the Aquarium have examined: development of a test for nutritional state of corals, the effects of oil on corals, the light regime in the tank[9] and a comparison of the benthic plankton community of the Great Barrier Reef with the Aquarium coral reef (Figure 15).

Conclusions

Ultimately education is the key to public support for the conservation and wise use of natural resources. The Great Barrier Reef Aquarium provides a readily accessible window on the reef and a wide range of educational experiences and interpretive services. Reproducing a section of the Great Barrier Reef on land, as a self supporting natural ecosystem, was a difficult and exacting task. Our Coral Reef Exhibit is unique in but costly to maintain in terms of skilled labour for operation, maintenance, collecting and monitoring and electricity costs. A captive coral reef ecosystem, for demonstrating and interpreting processes and issues affecting the Great Barrier Reef, is a powerful public education facility for assisting the work of the GBRMPA.

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MANGROVES IN TROPICAL REGIONS ADJACENT TO THE GREAT BARRIER REEF

Joe Baker

I speak on behalf of Alistar Robertson and his colleagues of Program 1 (Coastal Processes and Resources) of the Australian Institute of Marine Science (AIMS). They have established world leadership in understanding of the ecology of tropical mangrove ecosystems. I hope to communicate some of the excitement of this research.

Mangroves are often regarded as small and insignificant trees growing on the coastal fringe. Many people believe they are confined to the tropics. However, there are mangroves in the gulf systems of South Australia. In Western Port and other sections of southern Australia mangroves are common. As one moves up the New South Wales coast, mangroves become more plentiful and more diverse in form until we come to the North Queensland region. At our study site on Hinchinbrook Island there are more than 35 different species of mangrove trees. Mangroves are not confined to the tropical regions but the greatest diversity of mangrove species does occur in the tropics.

What are mangroves? The origin of the word "Mangroves" has been analysed by one of the leaders of mangrove research, Dr Marta Vannucci, in work conducted for UNESCO and with the International Society for Mangrove Ecology. She says:

"I finally concluded that the word mangrove would be African. The word was learned by the Portuguese on the west African coast by the early XV century. In fact, in discussing the fortifications to be made at Cacheu, which is present day Guinea-Bissao ,(Anon. Fortificacao de Cacheu, c. 1600, courtesy M.E. Bandeira Santos, C.E.H.C.A. Lisbon, pers. comm.) on the Guinea coast, "mangue sticks" (paus de mangue) are mentioned as being normally used to