Bay *wash*

Main picture: A Landsat image of Port Phillip Bay in November 1993, after heavy rain, shows the Yarra River plume spreading down the eastern side of the bay. The Great Sands region is visible inside the bay's southern entrance.
Above: The Yarra River, a major source of nitrogen entering the bay.

At the entrance to Port Phillip Bay lies a menacing stretch of water known as The Rip. From Point Nepean, the western tip of Victoria's Mornington Peninsula, The Rip can be viewed in all its fury, writhing above a deep gorge in the sea floor.

Beyond The Rip stand the lighthouses of Point Lonsdale and Queenscliff, sentinels of the opposite shore. When seen on a map, this entry to the bay seems oddly undersized, as though a vengeful lunge of the sea thwarted nature's plan for a lake. For most ships only 300 m of the entrance is navigable: a hazardous welcome to Melbourne.

Satellite images of the bay reveal an added peril beyond this narrow gateway. Just inside the heads is the Great Sands region, a flood tide delta of extensive sand bars and shallows dissected by deeper channels. The 4000 or so ships entering the bay each year bound for Melbourne or Geelong are guided through The Rip and Great Sands by local pilots, experienced ship-masters wise to the bay's tides, contours and whims.

As well as governing the passage of ships, the bay's unique bathymetry greatly restricts water exchange with Bass Strait. Estimates of flushing times vary from near zero at The Rip, to 260 days in the middle of the bay and about 350 days in the Geelong arm of Corio Bay (see diagram). This means that whatever flows in from the catchment has a long stay.

More than three million people live and work in the bay's catchment. The associated annual input of nitrogen from rivers, creeks, drains, sewage effluent and the atmosphere averages 7000 tonnes. Most of this total enters the bay as inorganic nitrogen, in the form of ammonia and nitrate. A major source of nitrogen is the Werribee sewage treatment plant, another is the Yarra River.

Between 1992 and 1996, an intensive study was conducted to determine the effects of these inputs, and to provide a scientific basis for managing the bay and its catchment. The Port Phillip Bay Environmental Study, designed and managed by CSIRO and funded by Melbourne Water, involved more than 47 individual research tasks. These were contracted to 29 state, national and international agencies and institutions.

A four-year ecological study of Melbourne's Port Phillip Bay has exposed a complex collection of mud-dwellers whose antics keep the water healthy and clean. **Bryony Bennett** reports.

The study found that despite these high inputs to the bay, nitrogen levels in the bay waters are much lower than in comparable bays and estuaries around the world. Phytoplankton levels – measured via chlorophyll *a* pigment – also are relatively low. Chlorophyll *a* commonly exists in Port Phillip Bay at one to two micrograms per litre, occasionally rising to 10. Similar water bodies elsewhere contain up to 50 micrograms or more.

This is good news for the bay's health. Most shallow water bodies with high nitrogen inputs and low flushing rates are at risk of eutrophication: excessive growth of a few dominant phytoplankton species. When this happens, the water becomes green and cloudy and seagrasses die from lack of light. Oxygen consumed during the plant's decay and the respiration of animals then exceeds the supply of oxygen from the atmosphere. Only bacteria that live on dead organic matter survive. These 'anaerobic' bacteria use carbon, sulfur and nitrogen compounds instead of oxygen to produce energy. The by-products are methane (marsh gas), hydrogen sulfide (rotten egg gas) and ammonia: all toxic to higher life forms.

Eutrophication is a state to be avoided. And so far it has been, thanks to the bay's oligotropic (low-nutrient) status. An explanation for the apparent vanishing of nitrogen in the bay waters had been sought in earlier studies. But it wasn't until the Port Phillip Bay Environmental Study that the phenomenon was understood.

A research task completed early in the study used purpose-built chambers to measure chemicals released from the bay sediments. The chambers were lowered onto the bay floor, effectively sealing off a quantity of water and sediment. Oxygen probes measured oxygen consumption over time, and water samples from the chambers were analysed for changes in their chemistry. Nitrogen was found to be released at levels much lower than expected, providing the first clue that processes occurring in the sediments must be taking up the nitrogen, thereby protecting the bay from eutrophication.

Another research task revealed the enormous magnitude and diversity of benthic (bottom-dwelling) fauna in the bay. It prompted a suggestion that benthic fauna might play a key role in nutrient turnover. Testing this theory required a deeper knowledge of the participants and processes in the bay's nutrient cycle.

Nutrients entering the bay are utilised by phytoplankton and other plants which are in turn consumed by zooplankton. Some nutrients are recycled, but most fall to the bay floor as faecal residues or dead algal cells. There they are taken up by invertebrates or single-celled algae (microphytobenthos), or decomposed by bacteria. Either way, the basic elements are converted back to their original inorganic forms of carbon dioxide, ammonia, nitrate, phosphate and silicate.

In many water bodies, these inorganic forms would diffuse upwards into the water and be recycled. If this recycling of ammonia and nitrate were to happen bay-wide, the ecosystem would rapidly become eutrophic. Water exchange with the ocean via Bass Strait would be too slow to prevent nitrogen accumulation. In Port Phillip Bay, however, nutrient recycling is limited by a series of processes occurring in the sediments which ultimately remove ammonia and nitrate from the water column as nitrogen gas.

Port Phillip Bay is mostly clear and shallow – the average depth is 13 m – so light penetrates through to the sea floor. Such conditions promote the proliferation of microphytobenthos, mostly diatoms, which glean inorganic nutrients from the sediments.

The sediments also house several hundred species of benthic invertebrates, or deposit feeders, which burrow some 50 centimetres in search of food. This expands the area of interface between the water column and the sediments, enabling oxygen to permeate the murky depths. As well as 'irrigating' the sediments with oxygen, the deposit feeders help to mix ammonia and nitrate into usually anaerobic sediments, and their faecal pellets encourage the presence of bacteria. These activities are known collectively as bioturbation.

Ammonia, upon reaching an oxygenated zone, is oxidised by bacteria to nitrate (nitrification). The nitrate diffuses into zones of low oxygen where other

More than 400 megalitres a day of treated sewage effluent enters the bay from the Western Treatment Plant at Werribee. The Port Phillip Bay Environmental Study recommended finding cost-effective ways of reducing ammonia loads from this source.

bacteria convert it to inactive nitrogen gas (denitrification). The nitrogen gas diffuses up into the water and eventually back to the atmosphere. Denitrification accounts for 80-90% of the nitrogen removed from the sediments and in so doing controls the degree of eutrophication in the bay. The bay's nitrogen cycle is almost entirely balanced by this process.

In a system devoid of bioturbation, anaerobic processes would dominate, because the aerobic zone would extend only a few millimetres into the sediment. Ammonia would not be nitrified, and its concentration would be much higher in the water column.

Research during the Port Phillip Bay Environmental Study found that burrows dug by one particular group of deposit feeders alone, the Callianassids, or ghost shrimps, increased the water-sediment interface by at least 8%. This adds up to an extra 8.6 km2 of interface below the sediment surface baywide. In effect, the deposit feeders build and maintain the bay's kidneys and lungs, keeping the system clean, and alive and breathing.

Clearly, protecting these hidden components of the bay ecosystem is vital to maintaining water quality. Given this need, an associated finding of the Port Phillip Bay Environmental Study offers cause for concern. Research by the Museum of Victoria found that benthic invertebrate numbers in the bay declined between 1969-73 and 1996. In addition, the proportion of filter feeders increased (from 23% to 33%) at the expense of deposit feeders (down from 71% to 55%).

The problem with this trend is that filter feeders rarely burrow. A shift towards filter-feeders at the expense of deposit feeders will result in a lower burrow surface area, and a consequent decrease in the mixing of oxygen, bacteria and ammonia through the sediments. Because these processes promote nitrification and denitrification, any further shift towards filter feeders may be detrimental to the bay.

These findings emphasise the need to monitor benthic populations on an ongoing basis. Bioturbation effects and rates can be investigated via experiments, but if population densities are not available for a system, baywide extrapolations cannot be made. With no warning system in place, the chances of repairing the bay's vital organs would be slim.

Defining the danger zone

Results of the diverse field surveys and experiments conducted during the Port Phillip Bay study have been integrated in a mathematical model that simulates physical and ecological processes occurring in the water column and sediments. The Port Phillip Bay model, developed by scientists from CSIRO's Division of Marine Research, can predict the critical nutrient loading at which eutrophication of the bay is likely to occur.

The most sensitive indicator of the trophic state of the bay is the nature of nitrogen release from the sediments. In the main bay, denitrification is the dominant process. As explained earlier, this is the desirable state. In some places, however, such as Hobsons Bay at the mouth of the Yarra River, nitrogen is released in the form of ammonia. This is not desirable and is an indication that the sediment system has been overloaded.

Denitrification efficiencies are maximised at intermediate nitrogen loads. The biomass of benthic invertebrates increases as water column production increases, but only up to a point. Benthic communities become depauperate, burrowing species disappear and bioturbation ceases if the sediment surface is too heavily loaded with decomposing organic material so that anoxia results. Under these circumstances, nitrogen is buried rather than denitrified and there is a significant release of ammonia to the water column. Also, there are major changes to the bacterial flora of the sediments.

The model estimates the critical catchment load at which sedimentary anoxia would begin as somewhere between double and treble the present loadings: about 17 000 tonnes of nitrogen a year. This is the irreversible point at which permanent eutrophication of the bay would occur.

Clearly it is desirable to maintain denitrification efficiency in the bay. This will ensure the long-term health and stability of the bay and provide some cushion against unforeseen extreme events. To achieve this, the Port Phillip Bay study team recommended a precautionary reduction in total nitrogen loads of about 1000 tonnes per year, particularly in the loads from the Yarra River and major creeks and drains in the urban area.

The potential benefits of such a strategy were illustrated during the 1994 drought when inflows from the Yarra River, creeks and drains were greatly reduced. During this time the bay became more oligotrophic and chlorophyll concentrations dropped to the lowest

MAFRI Queenscliff

A research task completed early in the study used purpose-built chambers to measure chemicals released from the bay sediments. Nitrogen was found to be released at levels much lower than expected, providing the first clue that processes occurring in the sediments were protecting the bay from eutrophication.

Sticky solution casts light on shrimps

A 40 centimeter-long resin cast of a *Biffarius arenosus* burrow. The ghost shrimp digs the burrow to find food. At the same time, it mixes oxygen, nutrients and bacteria through the sediments.

The ghost shrimp, *Biffarius arenosus*. This and other deposit feeders play a vital role in preventing nitrogen overload in Port Phillip Bay.

A cross-section of a block of sediment showing ghost shrimp burrows. The light brown sediment near to the burrows is oxic, the black sediment is anoxic.

FIONA BIRD has mud on her Goretex jacket. It's been there since 1994, offering a graphic reminder that her field work at Warneet on the muddy shore of Victoria's Western Port Bay, took place in the chill of winter.

Bird is close to completing a PhD. Her special subject is the feeding and burrowing ecology of *Biffarius arenosus*, a three-centimetre-long ghost shrimp that, believe it or not, shares with several hundred other benthic invertebrate species the cleaning contract for Port Phillip Bay (see main story).

Ghost shrimps, or Callianassids, make up about 8% of Port Phillip Bay's benthic invertebrate biomass. Early in the Port Phillip Bay Environmental Study it was suspected these critters might play a key role in preventing nitrogen overload in the bay waters. Most research on ghost shrimps, however, had concentrated on tropical species. Little was known about the locals.

Bird's task was to discover just what they did in all that mud, and their effects on the ecosystem. But how do you spy on a burrow? Tell-tale piles of rubble on the muddy surface belied their location; the challenge was to see inside.

This Bird achieved by waiting until the tide went out, placing on top of the burrows plastic cups with the bottoms cut out, pouring in epoxy resin and waiting . . . for two days. The technique took a bit of perfecting, but eventually yielded browny-yellow casts of ghost shrimp burrows, complete with U-shaped entry chamber, nobbly bits where the shrimps 'somersault' around corners, and a spiralled section that probably maximises food access, without impinging on the neighbours.

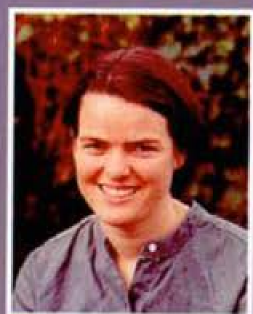
The casts gave Bird an idea of the shrimp's activities and territory. Next she needed to know what it ate. Under the microscope she identified in the shrimp's gut contents sand grains, seagrass cells, and, well, some 'brown gunk'. Further analysis also revealed the presence of seagrass epiphytes, algae that grow on seagrass blades.

Because the shrimps eat from inside the burrow, however, the source of the seagrasses and epiphytes was probably bacteria that had decomposed them in the sediments.

The next question was how the presence of the shrimps and their burrows changed the nature of the bay sediment. If the burrows increased bacterial numbers by oxygenating the sediments, nutrient cycling no doubt would be affected. Bird collected samples of the burrow wall and surface sediments, and of anoxic sediment between the burrows. She found that the burrow wall contained oxidising conditions similar to the surface sediments. There was little difference in bacterial numbers between the sediment types, but this may have been because bacteria on the sediment walls were being eaten by the shrimps.

Bird's findings supported the theory that deposit feeders such as ghost shrimps helped to prevent nitrogen overload in the bay. By enhancing the mixing of nutrients, oxygen and bacteria in the sediments, the ghost shrimp creates conditions under which two vital processes occur. The ammonia is oxidised by bacteria to nitrate, then converted by other bacteria to nitrogen gas.

Further research by Bird and her colleagues at the Museum of Victoria, and measurements taken during associated study of Port Phillip Bay, reveal that burrows potentially enhance the movement of these products from the sediments to the overlying water by up to 3.5 times. Without burrows, nitrogen removal from the bay waters would be slow indeed.



Fiona Bird: unravelling the secret life of ghost shrimps.

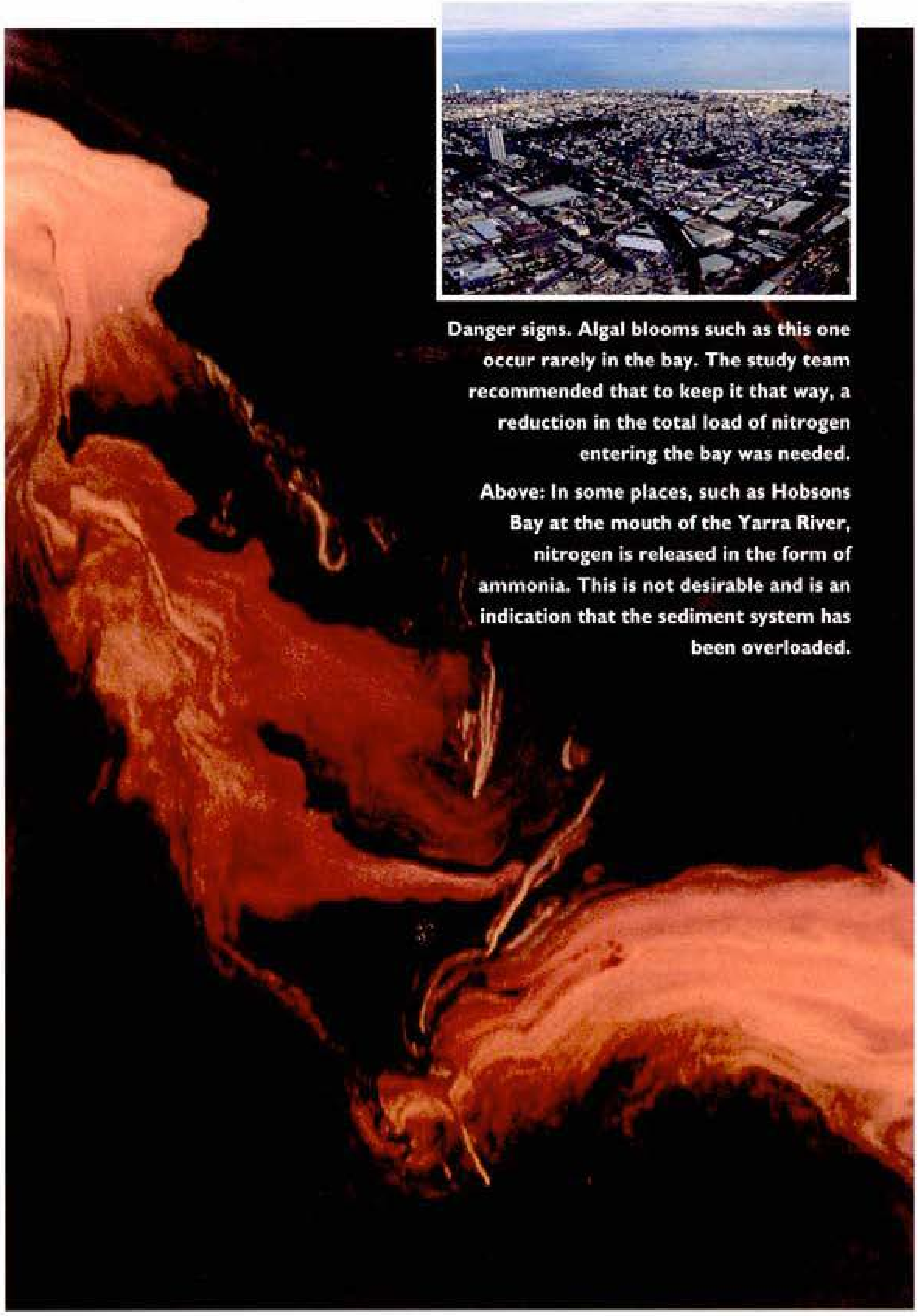
levels for years. The abundance of algae around the margins of the bay also dropped. Reduced storm inflows and urban runoff clearly can have a marked effect on the primary production and water quality of the bay.

The Port Phillip Bay study team concluded that a reduction in the total nitrogen load to some 6500 tonnes a year would rapidly show sustained improvements in water quality. At the very least, present levels should not be exceeded. They should certainly never be allowed to reach double present loadings.

Finally, the study team recommended that the bay be seen as an integral part of the entire regional development plan for the Melbourne. In the longer term, the key to the bay's successful management would be to develop models linking the bay to the city and its catchments. This would enable the impact of water supply, sewage and catchment management options to be objectively assessed, thus ensuring that dubious welcome to Melbourne entails no more than a rough ride through the gate.

More about the bay

The *Port Phillip Bay Environmental Study Final Report* was published by CSIRO in 1996. The report costs $60 plus $8 postage and is available from CSIRO Publishing (03) 9662 7500, fax (03) 9662 7555, email: sales.publish.csiro.au. Melbourne Water has a summary of the Port Phillip Bay Environmental Study on the Internet at http://www.melbwater.vic.gov.au



Danger signs. Algal blooms such as this one occur rarely in the bay. The study team recommended that to keep it that way, a reduction in the total load of nitrogen entering the bay was needed.

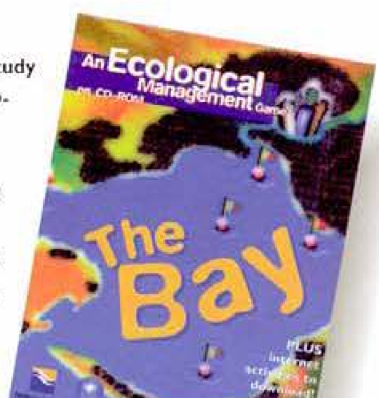
Above: In some places, such as Hobsons Bay at the mouth of the Yarra River, nitrogen is released in the form of ammonia. This is not desirable and is an indication that the sediment system has been overloaded.

abstract

A four-year ecological study of Melbourne's Port Phillip Bay, managed by CSIRO, has identified the importance of benthic flora and fauna in promoting nitrification and denitrification in the bay sediments. These processes facilitate the conversion of nitrogen to nitrogen gas, preventing eutrophication, despite high sewage and stormwater inputs. A predictive model developed during the study will be used to help manage the bay and its catchment.

Keywords: Coastal waters; Sea bed; Catchment areas; Nutrient cycling; Nitrification; Water quality; Benthic fauna; Environmental management; Port Phillip Bay

Now it's your turn!



Lessons learned during the Port Phillip Bay Environmental Study have contributed to an 'ecological management game' on CD-ROM. *The Bay* challenges users to manage five ecological disasters over a 10-year period, randomly selected from 19 bay-threatening adventures. They include freak storms, algal blooms dying penguins, disappearing beaches and oil spills. Guidance is given by Alex, a marine scientist, and Diatoma, a computer that monitors everything entering the bay system.

By working through the scenarios in *The Bay*, users learn about interpreting data, the impact of humans on the environment, the significance of biodiversity, and describe the effects of a change to one element in a food chain. The CD-ROM is intended for people aged about eight and older. It costs $69.95 plus $8 postage and is available from CSIRO Publishing (contact details above). A teachers kit, containing background information and activites to complement the CD-ROM, can be added for $9.95.