GOVERNMENT OF WESTERN AUSTRALIA

DAWESVILLE CHANNEL

MONITORING PROGRAMME

TECHNICAL REVIEW REPORT

Submitted to
THE WATER AND RIVERS COMMISSION

Prepared by
D.A. LORD & ASSOCIATES PTY. LTD.

Plate 1: Macroalgal accumulations' at Coodanup, Peel Inlet

Plate 2: Macroalgal harvesting in Peel Inlet.

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Background

The construction of the Dawesville Channel was a major environmental management measure undertaken as part of a three-part State strategy (the Peel Inlet and Harvey Estuary Management Strategy) to improve the environmental health of the Peel-Harvey Estuarine System (PHES). The two other components of the Peel-Harvey Management Strategy were a catchment management program to reduce nutrient inputs to the PHES, and harvesting of macroalgal accumulations from the shores of the system. The Minister for Transport, Waterways (now the Minister for Water Resources) and Agriculture are the proponents of the three-part State strategy, and are legally bound to carry out ministerial conditions and proponents' commitments that were set in 1993 and combined with previous conditions set in 1989 to the satisfaction of the Environmental Protection Authority (EPA).

The PHES is a broad shallow water body with a large catchment, strongly seasonal river inflow and, prior to opening of the Dawesville Channel, limited exchange with oceanic waters. Nutrient enrichment of the PHES resulted in large accumulations of macroalgae and massive blooms of the toxic blue-green microalga *Nodularia spumigena* during the 1980s, the former largely in Peel Inlet and the latter largely in Harvey Estuary. This proliferation of algae was attributed to high levels of nutrients in run-off from the coastal plain portion of the PHES catchment.

Opened in April 1994, the Dawesville Channel connects the PHES to the ocean close to the junction of the Peel Inlet and Harvey Estuary. The Channel was constructed with the principal aim of increasing tidal flushing, thereby enhancing nutrient transport from the PHES in winter and improving marine exchange in summer. However, it was recognised that there would be profound changes to the physical, chemical and biological characteristics of the system over both the short and long terms, and that some negative impacts would result. A five-year monitoring program was therefore approved by the State Government to determine the success of the overall management strategy, but particularly how well the Channel was achieving the purpose for which it was designed and to ensure that positive and negative environmental impacts associated with it were properly understood and managed.

The overseeing, coordinating and reviewing of the numerous projects associated with the Dawesville Channel Monitoring Programme (DCMP) are the responsibility of the Peel-Harvey Senior Officers Group (SOG), comprising representatives of the proponent ministers and led by the Water and Rivers Commission (WRC). The SOG is supported by the Peel-Harvey Project Managers Group (PHPMG), which brings together all the government departments undertaking monitoring. The SOG commissioned a review of the monitoring of the PHES, with the aim of assessing and reporting on changes to its water quality and biology since the opening of the Dawesville Channel.

This Technical Review Report involved reviewing and analysing the results from the 32 monitoring projects associated with the DCMP. An interpretation and summary of the results was conducted, particular emphasis being given to trend analysis (comparisons with pre-channel conditions). The performance of the Dawesville Channel was also assessed in terms of the environmental health of the PHES. The main focus of this report is on the results of the first two years of the DCMP, but later data are referred to where appropriate.

Predicted effects of the Dawesville Channel

The physical, chemical and biological changes to the PHES expected with the opening of the Channel were:

- increased astronomic tidal fluctuations (from 15% to 50% of oceanic tide);
- a less variable and more marine salinity regime (i.e. salinities around 35 ppt) except during periods of river flow in winter;
- shorter and less frequent periods of low oxygen levels in estuarine waters;
- increased water clarity and lower concentrations of nutrients, particularly in Harvey Estuary;

- unfavourable salinities for the growth of *Nodularia* (*Nodularia* spores germinate at salinities less than 15 ppt, and growth is poor at salinities greater than 30 ppt);
- a possible increase in macroalgal accumulations in the *short-term* but less macroalgal growth in the *long-term*;
- a more favourable (i.e. less variable) environment for most estuarine biota;
- less favourable conditions for some species of waterbirds;
- increased mosquito populations due to an increase in the frequency of tidal inundation of mosquito-breeding areas (i.e. tidal saltmarsh).

On the whole, impacts on the human community were expected to be largely beneficial, especially the expected improvements in water quality and reduction in *Nodularia* blooms. There was, however, concern that the increased mosquito populations would result in an increased risk of contracting Ross River virus (RRV) or Barmah Forest virus (BFV) via mosquito bites. Both of these viruses can cause seriously debilitating diseases in humans.

Limitation of the Technical Review

Data from post-Channel monitoring covered two years of below- average rainfall (1994 and 1995) and one year of average rainfall (1996). The influence of the Channel in a year of above-average rainfall has therefore not been assessed. Furthermore, the effects on some components of estuarine biota, particularly fringing vegetation, may take many years to develop.

Interpreting the effects of the Dawesville Channel on some components of estuarine ecology was compromised due to the lack of baseline (pre-Channel) data. The main components thus affected were riverine phytoplankton, fringing vegetation and waterbirds. Fisheries, mosquitos and arbovirus ecology were, to a lesser extent, also affected. Conversely, impacts on estuarine sediments and benthic invertebrates could not be determined due to lack of post-Dawesville Channel data.

Effects of the Dawesville Channel

The following comments are made with the above limitations in mind.

Hydrodynamics

Prior to the opening of the Dawesville Channel, the daily mean tidal range in the Peel Inlet and Harvey Estuary averaged 17% and 15% of the ocean tides respectively (DMH 1993), high-tide levels in the Estuary lagging behind those in the Inlet by approximately 3 hours. Measured tidal ranges in the Inlet and the Estuary after the opening of the Dawesville Channel were 48% and 55% of the ocean tides, respectively, and Harvey Estuary experienced high tide approximately 43 minutes *before* the Peel Inlet.

Sediment erosion/accretion within the Dawesville Channel has been relatively minor, and a small floodtide delta developed at the channel entrance to Harvey Estuary. Due to the increased tidal range, the intertidal area is greater and the inundation regime of the intertidal areas changed such that the upper intertidal areas were submerged more frequently but for reduced periods and, similarly, the lower intertidal areas were exposed more frequently but for reduced periods.

A significant horizontal salinity gradient was observed along the length of the Harvey Estuary during summer. Relatively marine salinities (about 35 ppt) prevailed close to the Dawesville Channel and hypersaline conditions (up to 48 ppt) occurred towards the south end of the Estuary, which suggested that the level of water exchange from the Estuary to the ocean was very near to the minimum required for adequate mixing. The Peel Inlet exhibited relatively little variation in water structure, which suggested that the water exchange within it was satisfactory.

Sediments

Sediment phosphorus stores played an important role in sustaining macroalgal accumulations and *Nodularia* blooms prior to the opening of the Dawesville Channel. A large proportion of the phosphorus carried in winter river inflow was taken up by blooms of phytoplankton (microscopic free- floating algae) — usually diatoms — and, when the diatom blooms died and settled to the sediment surface, part of the phosphorus store trapped in decaying organic matter was released and became available for the growth of macroalgae and *Nodularia* in spring and summer.

Over the years the store of phosphorus in the sediments accumulated, and under conditions of low oxygen levels this sediment phosphorus was released into the water column. The sediments became an important *in- situ* source of phosphorus, complementing the external sources (the rivers) and helping to maintain nuisance levels of algal growth during years of lower nutrient input (i.e. lower catchment run-off). Prior to the opening of the Dawesville Channel, sediment total phosphorus concentrations in Harvey Estuary were two to four times greater than in Peel Inlet, and a greater proportion was 'biologically available' (i.e. available for uptake by algae).

The Dawesville Channel was expected to cause a gradual decline in sediment phosphorus stores in the PHES by enhancing nutrient transport during periods of winter run-off, thereby reducing both the diatom blooms and the subsequent loading of the sediment with phosphorus. Preliminary post-Channel monitoring indicates that the sediment stores of nitrogen and phosphorus are similar to 1982-89. A more comprehensive survey will be undertaken in December 1998.

Nearshore marine environment

The breakwaters constructed for the Dawesville Channel were expected to alter patterns of erosion and accretion along the Dawesville coast. Sediment bypassing (i.e. the transfer of sand from areas of accretion to areas of beach erosion) from the south to the north of the Channel was carried out on three occasions after its opening. Sediment accretion occurred on the beaches to the south in 1995 but the rate of accretion appeared to slow in 1996. The beaches to the north generally experienced erosion between 1992 and 1994, accretion between 1994 and 1995 and a period of minor erosion till March 1997.

The Dawesville coastline has no outer barrier reef system, and it therefore receives the full impact of ocean swell all year round as well as the high energy conditions associated with winter storms. Environmental impacts on the nearshore marine environment were expected to be minimal because the characteristically high-energy conditions of the nearshore area — particularly during winter — would ensure rapid dispersion and dilution of estuarine waters. Available water quality data appeared to confirm this, while impacts on nearshore reef macroalgal communities were further minimised because the greatest outflow of estuarine water occurred in winter, when the algae were effectively scoured off reef surfaces due to storms.

Water quality

The predicted effects of the Channel on estuarine water quality were largely confirmed. Salinities in the PHES were still low during periods of winter river run-off, but marine salinities were rapidly reestablished (by the end of spring) and maintained until the onset of the next winter rains. Periods of deoxygenation were rare in waters close to the Dawesville Channel, less frequent (than in pre-Channel times) in waters in the middle of Peel Inlet and Harvey Estuary, but relatively unchanged in the southern Estuary and eastern Inlet. Estuarine waters were also less turbid during spring, especially in the Estuary.

The most dramatic effect of the Channel was on phytoplankton biomass as expressed by chlorophyll a levels. Winter blooms of diatoms were smaller (less than 50 µ/L of chlorophyll a) and of shorter duration, and no *Nodularia* blooms occurred in Peel Inlet or Harvey Estuary. Chlorophyll a levels remained below 10 µg/L for most of the year except during winter diatom blooms. The reduction in phytoplankton biomass resulted in corresponding decreases in the levels of organic nitrogen and organic phosphorus in estuarine waters (i.e. in the nitrogen and phosphorus present in phytoplankton), and therefore in levels of total nitrogen and total phosphorus. A further effect was that Peel Inlet and Harvey Estuary were very similar in terms of water quality.

Although water quality in the PHES was greatly improved, it appears to have declined in the lower reaches of the Murray and Serpentine Rivers, particularly the latter. It was not possible to determine the level of decline due to the scarcity of pre-Channel data on river water quality; nonetheless *Nodularia* blooms occurred in the Serpentine River from late spring to the end of summer in 1994/95, 1995/96 and 1996/97, and it was necessary to erect warning signs declaring it unsafe for swimming and fishing on a number of occasions. Blooms of dinoflagellates also occurred during summer and autumn in the Serpentine and — to a far lesser extent — the Murray, including the potentially toxic species *Alexandrium minutim* in the Murray in February 1996. Blooms of the Haptophyte microalga *Prymnesium*, which can be lethal to fish, were also recorded for the first time in the Serpentine in April/May 1997. These changes may not all be due to the opening of the Channel, as catchment monitoring studies indicated that nutrient inputs to some parts of the Serpentine may have increased.

There were no data on chlorophyll a levels or phytoplankton species for the lower reaches of the Harvey River.

Macroalgae

Prior to the opening of the Dawesville Channel, large accumulations of macroalgae were a feature of Peel Inlet, and consisted largely of recognised 'nuisance' species of the green algae *Chaetomorpha*, *Ulva* and *Enteromorpha*. Nutrients and light were the main factors affecting their growth, with *Chaetomorpha* more competitive during periods of lower nutrient conditions and *Ulva* and *Enteromorpha* more competitive when nutrient levels were higher. Estimated total macroalgal biomass was generally in the range 5000-20,000 tonnes, although it reached 60,000 tonnes in 1979. Maximum macroalgal biomass was generally attained in late summer/early autumn, the amount being strongly linked to water clarity over the summer period.

There were concerns that the opening of the Dawesville Channel would actually cause an increase in macroalgae accumulations in the short term, due to the expected improvement in water clarity while the nutrient status of the Peel Inlet was still relatively high due to accumulated phosphorus stores in the sediments. The possibility was also raised of improved light conditions causing increased macroalgal growth in the Harvey Estuary, in the deeper waters of the estuarine system generally, and in the lower reaches of the Murray and Serpentine Rivers. In the long-term, the ongoing reduction in phosphorus availability was expected to cause a decline in macroalgal accumulations.

Following the opening of the Dawesville Channel, total macroalgal biomass in Peel Inlet was around 15,000 tonnes in spring 1994 and summer 1994/95, remained around 5000 tonnes until autumn 1996, but declined to about 3000 tonnes in spring 1996 and 2000 tonnes in summer 1996/97. The proportion of red and brown algae, which are more indicative of low nutrient conditions, also exceeded that of green algae in the summer of 1996/97. There was increased macroalgal growth in the Harvey Estuary, but levels were still an order of magnitude less than those in Peel Inlet.

Both 1994 and 1995 were years of low rainfall and low nutrient input, and the levels of macroalgal biomass were not significantly different to those measured in years of low rainfall before the opening of the Channel. However, 1996 was a year of average rainfall, yet macroalgal biomass was the lowest on record. The predicted short-term increase in macroalgal biomass did not occur, although a year of high rainfall has yet to be experienced. Available data indicated that the amount of nutrients available for macroalgal growth in Peel Inlet was less and the nutrient status of the PHES was declining.

Seagrasses

Seagrass beds usually have a higher abundance and diversity of estuarine fauna than bare sand, and this is attributed to a combination of greater habitat complexity (and therefore more ecological niches to exploit), greater protection from predators, calmer conditions (due to the wave- baffling effect of dense macrophyte stands) and a more abundant food supply. The proliferation of algae in the PHES in the 1970s and 1980s caused the widespread loss of seagrasses, but effects on fauna were mitigated because the ecological functions of the macroalgal accumulations were similar to those of seagrasses.

As a group, seagrasses are intolerant to eutrophication, as they are effectively shaded out by the proliferation's of macroalgae, epiphytes (algae that grow attached to seagrasses) and phytoplankton that develop in nutrient-enriched conditions. Seagrasses are also quick to die back if salinities fall below about three- quarters of marine levels. Hence the presence of seagrasses in the PHES was often sporadic as well as sparse, depending on both the amount of winter river run-off and the level of algal growth.

Prior to the opening of the Dawesville Channel the most common seagrass in the PHES was the small species *Halophila ovalis* (paddle weed), which is more tolerant of low salinities and low light supply (and therefore turbid waters) than other species. Small beds of less tolerant species occurred in or near the Mandurah Channel, where conditions were more marine, while the aquatic angiosperm *Ruppia megacarpa* (duck weed) was also common in the shallow waters of south-east Peel Inlet. Ruppia is not a seagrass in the strictest sense, as it flowers on top of the water rather than under water, but it is usually included as one; it has an extremely broad range of salinity tolerance.

The opening of the Dawesville Channel was expected to be beneficial to seagrasses due to the less variable salinity regime, maintenance of marine salinities for longer periods and improved water clarity. The only deleterious effect predicted was the loss of stands of *Ruppia* from the shallow margins of south-east Peel Inlet, which would be regularly exposed because of increased tidal fluctuations.

The results of post-Channel monitoring generally confirmed the above predictions. *Halophila* stands in Peel Inlet consistently maintained high biomass in summer and autumn (and in deeper water), and stands expanded in the northern half of Harvey Estuary. *Halophila* was also recorded for the first time in deeper waters of the Estuary, and patches of seagrass species that require marine salinities were found near the eastern entrance of the Dawesville Channel. However, it was not possible to determine whether losses of *Ruppia* had occurred from tidally exposed areas in the Inlet, as no sites were monitored in these areas.

Fringing vegetation

Fringing vegetation plays an important role in the ecology of estuaries by supporting extensive food webs, acting as a biological filter for waters discharging into the estuaries and providing habitats for waterbirds. Fringing vegetation (often called salt marsh) in the PHES occupies the upper part of the tidal zone from about mean water level to just above extreme high- water mark. Assessment of historical changes in fringing vegetation around the PHES based on aerial photographs established that it was extremely dynamic and variable, with different areas undergoing losses due in many cases to degradation caused by human use and expansion.

Very little on-ground monitoring of fringing vegetation was carried out before the Channel was opened. Post-Channel monitoring consisted of the following components:

- monitoring of salt marsh at various locations around the PHES to detect changes in species distribution due to changes in tidal levels, frequency of inundation and salinity;
- monitoring of seasonal freshwater wetlands in the Austin Bay Nature Reserve, which have rare freshwater aquatic plants in areas that were thought might be susceptible to ingress of salt water during storm surges;
- monitoring of riverine vegetation, river bank tree health and *Typha* patch dynamics along the lower 4 km of the Harvey River, in order to detect any changes due to the expected increase in penetration of salt water upstream with the tidal change and the more marine salinities.

At the saltmarsh sites monitored there were no consistent patterns in changes of species cover from 1994 to 1995. Similarly, there were no changes in seasonal freshwater wetlands in the Austin Bay Nature Reserve other than those consistent with year- to-year variations in environmental conditions, and there was no evidence of saltwater intrusion. Nor did the monitoring of the riverine transects show an immediate effect of the influence of increased salinity; however, given the nature of the vegetation it could be expected that any change would be gradual. Overall, the monitoring results emphasised the dynamic and variable nature of fringing vegetation, but no clear effect attributable to the Dawesville Channel was apparent. Clear trends may take several more years to emerge.

Fisheries

The PHES is the most important commercial estuarine fishery (by weight of catch) in Western Australia, and it is also heavily utilised for recreational fishing. Approximately 60 fish species were documented as occurring in the PHES before the opening of the Dawesville Channel, the majority of these being marine species that entered the system as juveniles during the summer months.

No fish kills were recorded in the PHES in post-Channel monitoring, and this was attributed to the absence of *Nodularia* blooms and the reduced periods of low oxygen in estuarine waters. Water quality improvements were equally beneficial for the small benthic invertebrates (worms, crustaceans and molluscs) that are the favoured food of most species of fish.

Data indicated that the Dawesville Channel resulted in a far earlier recruitment of juvenile western king prawns and juvenile crabs into Harvey Estuary, and their retention therefor a far longer period. The maximum densities of prawns and crabs in the Estuary were far higher than in pre-Channel years. However, these crustaceans left the estuary at a smaller size than before the opening of the Channel, which may simply be because the it allowed a much more rapid return to the ocean.

Marine species of fish such as gobbleguts (*Apogon rueppellii*) and six- lined trumpeter (*Pelates sexlineatus*) were less abundant than before the opening of the Channel. As these species are associated with macroalgae, this apparent decline may be related to the decline in macroalgae in recent years. Marine species of fish penetrated further south into the Harvey Estuary and fish densities were higher in this region.

Commercial catch per unit effort (CPUE) data indicated a higher abundance of cobbler, sea garfish, Australian herring and western sand whiting since the opening of the Dawesville Channel, and little change in the abundance of sea mullet, yellow-eye mullet, tailor and King George whiting. However, commercial catches of western king prawns declined dramatically even though prawns were still abundant. Large numbers of prawns were observed emigrating out through the Dawesville Channel (rather than the Mandurah Channel), where strong currents make it very difficult for commercial fishers to use their beamtide trawls.

Waterbirds

The PHES is an internationally significant habitat for waterbirds, as recognised by its listing as a Wetland of International Importance under the Ramsar Convention. Tens of thousands of waterbirds gather on the PHES each year, and over 80 species have been recorded, 27 of which are listed on the Japan Australia Migratory Birds Agreement (JAMBA) and the China Australia Migratory Birds Agreement (CAMBA).

Waterbird communities vary considerably throughout the year. Resident species are present all year round, whereas migratory species inhabit the PHES mainly in spring and summer. Prior to the opening of the Dawesville Channel the PHES was considered somewhat unusual in that it had large populations of resident waders (e.g. the banded stilt), which usually prefer non-tidal waters. The system was also particularly favourable to small species of waders, due to the extensive areas of extremely shallow waters that persisted for many days. The shallow areas were believed to be very important for pre-migratory fat deposition in late summer/early autumn, as feeding opportunities between the PHES and Shark Bay are limited at this time of year. The PHES also regularly supported larger numbers of pelicans than any other water body in the southern half of the State, was one of only two pelican breeding sites south of Shark Bay, and was one of the most significant habitats for black swans in Western Australia.

Post-Channel monitoring of waterbirds included regular surveys of all waterbird species, with special attention directed towards specific concerns about Channel effects. These concerns included: pelican nesting activity and success; numbers of pelicans; numbers of black swans; salinity changes and waterbird use in the upper Harvey Estuary, Harvey River Delta and lower Harvey River; numbers of banded stilts; and the effect of increased inundation on three major roosting sites at Herron Point Ford, Point Birch and Nirimba Cay.

Although data on the surveys of all waterbird species are still being processed, strong impressions were gained that: little egrets (*Egretta garzetta*) were more numerous and widespread (reflecting a general trend in south western Australia); there was no decline in numbers of eastern curlew (*Numenius madagascariensis*), a species rarely observed elsewhere in southwestern Australia; and curlew sandpipers (*Calidris ferruginea*) were far less abundant, although it was uncertain whether this was due to channel effects or variations in numbers migrating to Australia.

A previously successful summer breeding site for pelicans (*Pelecanus conspicillatus*) on Nirimba Cay was lost due to inundation, and there was no pelican breeding on Creery and Boodalan Islands, in this case due to excessive disturbance (boating activity, people, dogs, foxes). Despite this, pelican breeding on Boundary Island in the last three years was apparently sufficient to maintain total pelican numbers. However, black swan (*Cygnus atratus*) numbers appeared to decline. The reasons for this are unknown, but may include variations in the abundance and distribution of the *Ruppia* and certain algae on which swans feed, and this is being investigated.

Public health issues

The region around the PHES was identified as having a severe saltmarsh mosquito problem as early as 1985, and was known to be a major focus of RRV and BFV. Mosquito control throughout the Peel Region was (and still is) undertaken jointly by the Health Department of Western Australia (HDWA) and the Peel Region Contiguous Local Authority Group (CLAG), and consisted of the following components:

- application of aerial larvicide-coated sand dropped from a helicopter between September and April (HDWA) (the warmer months of the year are the period of most prolific growth of mosquitoes as well as the highest potential interaction with humans);
- monitoring of mosquito larvae in salt marshes every two to three days to determine appropriate times to apply larvicides (CLAG);
- adult mosquito and virus surveillance (HDWA via the Department of Microbiology at the University of Western Australia) to determine the effectiveness of the mosquito control measures; public education (HDWA).

Further work to improve exchange in inundated areas, not easily treated with larvicide, is planned by the Health Department. This will be an expensive and complex exercise because the damage lines (runnelling) must be kept small to minimise adverse environmental impacts.

Aerial application of larvicide as a mosquito control measure commenced in 1988/1989, but it was not necessary on a frequent and widespread basis until after the Dawesville Channel was opened.

The mosquito *Aedes camptorhynchus* was the major vector of RRV and BFV in the Peel Region prior to the opening of the Channel. It breeds in salt marsh and brackish wetlands, predominantly from winter through to spring. *Aedes camptorhynchus* comprised about 70% of the total adult mosquito population in the Peel Region prior to the opening of the Dawesville Channel, and was the main species targeted by larvicide application. *Aedes vigilax* also carried RRV in the Peel Region, although to a lesser extent. It is known as the summer saltmarsh mosquito because it breeds in salt marshes in the warmer months, and is considered a nuisance species even aside from potential RRV infection because it is a vicious biter and can travel long distances.

Mosquito larvae control measures undertaken by HDWA and CLAG intensified after the opening of the Channel, and changes in adult mosquito populations were hard to ascertain as the number of larvicide applications increased at least threefold. Nonetheless, larger numbers of adult *Aedes camptorhynchus* were detected in the summer of 95/96, when a major outbreak of RRV also occurred, and there was a marked increase in the numbers of adult *Aedes vigilax* each summer despite the massive increase in larvicide application. *Aedes vigilax* may now be the major vector of RRV in the Peel Region. The number of RRV cases each year was also consistently significantly higher.

Social and economic uses

After the opening of the Dawesville Channel, members of the public noted the improvement in water quality and the absence of *Nodularia* blooms in the PHES. There were far fewer complaints about weed accumulations, and therefore far less macroalgal harvesting was carried out. However, there were reports from concerned residents about discolouration of the water due to phytoplankton blooms in the Serpentine and Murray Rivers in summer. There was also a major outbreak of RRV in the Peel Region in the summer of 1995/96, and elevated levels of RRV activity in the spring/summer of 1994/1995 and 1996/1997.

Despite concerns about riverine water quality and RRV, there was little apparent impact on the social and economic uses of the PHES. To a large extent this can be attributed to an effective social impact and public information program. This pro-active approach ensured that most community concerns were effectively dealt with in the first 12 months after the opening of the Channel. The program is due to continue until the end of 1998, and although it is now mainly concerned with addressing public information needs, appropriate management procedures remain in place to deal quickly and effectively with any major social impact that might arise.

Conclusions

Conditions prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the PHES had only limited tidal exchange with marine waters via the narrow 5 km-long Mandurah Channel. Seasonal changes in salinity were extreme:

- almost freshwater conditions occurred during periods of winter river run-off;
- salinities gradually increased via tidal exchange during spring and early summer;
- hypersaline conditions (greater than marine salinity) developed in late summer and autumn due to the effects of evaporation.

Poor exchange with marine waters resulted in a high level of retention of nutrients from catchment run-off, and this nutrient enrichment resulted in large accumulations of macroalgae in Peel Inlet in summer and autumn, and massive *Nodularia* blooms in Harvey Estuary in late spring/early summer.

The salinity regime in Peel Inlet was less variable than in Harvey Estuary. The Inlet had higher salinities than the Estuary during winter and spring; marine salinities re-established one or two months earlier (e.g. by the end of December instead of the end of January); and the degree of hypersalinity was less in late summer and autumn. Deoxygenation of bottom waters in Peel Inlet mostly occurred during periods of stratification, although *Nodularia* blooms spreading out from the Estuary affected both oxygen levels and turbidity in the western part of the Inlet. Unlike the Estuary, water clarity in the Inlet was sufficient to allow the growth of extensive stands of macroalgae in summer and autumn, and macroalgal uptake of nutrients helped to maintain low levels of organic nutrients and chlorophyll a in the water column during these seasons.

Water quality was particularly poor in Harvey Estuary due to its physical and chemical features, particularly its greater distance from the Mandurah Channel and phosphorus-rich inflow from the Harvey River. The Estuary was generally less saline (except in autumn), was more prone to salinity stratification, was more turbid (due to both *Nodularia* blooms and continued resuspension of fine sediments by wind-driven waves), was more nutrient enriched and had higher levels of chlorophyll a than Peel Inlet (due to *Nodularia* blooms). Deoxygenation of bottom waters in the Estuary also occurred during periods of stratification, during and after *Nodularia* blooms, and after their collapse. Periods of severe deoxygenation in turn caused the death of benthic invertebrates and fish.

The variable salinity regime and periods of poor water quality in the PHES were tolerated by few species of aquatic plants and invertebrates, but these species were nonetheless highly productive due to the nutrient-enriched conditions. The high productivity of both aquatic plants and invertebrates in turn helped maintain large populations of fish and waterbirds.

The region around the PHES was identified as having a severe saltmarsh mosquito problem almost ten years before the Dawesville Channel was opened. Inundation of salt marshes and wetlands fringing the PHES in winter and spring (during periods of catchment run-off) provided favourable conditions for breeding of the mosquito *Aedes camptorhynchus*, the main vector of RRV and BFV in the Peel Region.

Observed effects of the Dawesville Channel

The observed effects of the Dawesville Channel were largely as predicted, although it should be noted that in the first two years after its opening rainfall was below average. Tidal fluctuations in the PHES increased to about half of oceanic levels, resulting in increased tidal flushing and rapid re-establishment of marine salinities after the cessation of river run-off. Water quality improved, particularly in the Harvey Estuary, where periods of stratification and deoxygenation were shorter and less frequent, *Nodularia* blooms were absent and turbidity during spring was less. In contrast to pre-Channel years, water quality in Harvey Estuary was very similar to that in Peel Inlet.

The more stable salinity regime and improved water quality in the PHES resulted in an increased number of species of aquatic plants and animals, particularly those requiring marine salinities. These were also able to stay in the PHES for a larger part of the year. Compared to the salinity regime and resident biota of pre-Channel years, the PHES was more like a sheltered marine embayment for much of the year.

Macroalgal populations appeared to decline, seagrass distribution and production increased, and little effect on fringing vegetation was observed. Biological productivity remained high, based on the numbers of fish, crabs, prawns and waterbirds present. Numbers of black swans appeared to decline, possibly as a result of loss of preferred food sources (*Ruppia* and certain species of macroalgae).

Effects of winter outflow from the Dawesville Channel on the adjacent marine environment were minimal due to rapid dispersion and dilution of estuarine waters in the high-energy conditions characteristic of the nearshore area in winter. There does, however, appear to be a deterioration in the water quality of the lower reaches of the Murray and Serpentine Rivers, particularly the latter. Whether the changes in river water quality were largely due to the influence of the Dawesville Channel or the result of nutrient accumulation over years remains unclear.

The increased tidal amplitude exacerbated the mosquito problem due to increased frequency of inundation of tidal salt marshes, particularly in summer. Numbers of adult saltmarsh mosquitoes in summer — especially the species *Aedes vigilax* — increased significantly despite a threefold increase in the number of aerial larvicide applications.

From the human perspective the Dawesville Channel resulted in:

- enhanced amenity due to improved water quality;
- fewer complaints about odours from macroalgal accumulations;
- improved business development opportunities (this may also be viewed as detrimental, depending on personal viewpoints);
- an earlier crab season, with increased numbers of crabs;
- adverse effects on the commercial prawn fishery due to the inability of commercial fishers to catch prawns moving out to sea via the Dawesville Channel — actual prawn numbers in the PHES did not appear to decline;
- some increase in stratification and depletion of oxygen in the lower reaches of the Serpentine and Murray Rivers which may have enhanced blooms of phytoplankton in summer and autumn, including some toxic species — problems were more severe in the Serpentine River where nutrient concentrations, coming from the catchment, were higher and on occasions it was necessary to close the river to swimming and fishing;
- increased summer mosquito populations and mosquito-borne viral diseases of humans, with the associated effects of increased nuisance from biting mosquitoes (especially the vicious biter *Aedes vigilax*), increased risk of transmission of RRV and BFV, and a far greater level of aerial applications of mosquito larvicide.

Overall, the Dawesville Channel can be viewed as largely beneficial to the ecology of the PHES, but may have contributed to some deterioration of the ecology of the lower reaches of the Serpentine and Murray Rivers. From the human perspective the Channel can be viewed as either beneficial or detrimental, depending on the relative importance attached to the mosquito problem and to the decreased amenity of the lower reaches of these two rivers.

It is again emphasised that the above assessment was based on two (and in some cases three) years of data. A full assessment of the impacts of the Channel must include the long-term responses of the biological community, including natural population variations, and incorporate years of average and above-average rainfall.

1. Introduction

The Peel-Harvey Estuarine System (PHES) is located 75 km south of Perth in south-western Australia, and consists of two interconnected shallow lagoons, the Peel Inlet and the Harvey Estuary (Figure 1.1). The system is connected to the ocean by the Mandurah Channel, a narrow 5 km-long inlet which restricts tidal exchange. Nutrient enrichment had resulted in large accumulations of macroalgae and blooms of the toxic blue-green microalga *Nodularia spumigena*, the former largely in Peel Inlet and the latter largely in Harvey Estuary.

The construction of the Dawesville Channel was a major environmental management measure undertaken as part of a three-way State strategy to improve the environmental health of the PHES. The Channel was constructed to increase tidal flushing. The other parts of the management strategy included a catchment management program to reduce nutrient inputs to the PHES and harvesting of macroalgal accumulations from the shores of the system. The Ministries of Transport, Waterways (now the Ministry of Water Resources) and Primary Industries are the proponents of the Peel Inlet and Harvey Estuary Management Strategy, and are legally bound to carry out to the satisfaction of the Environmental Protection Authority Ministerial conditions and proponents' commitments that were set in 1993 and combined with previous conditions set in 1989 (see also Chapter 10).

Opened in April 1994, the Dawesville Channel connects the PHES to the ocean close to the junction of the Peel Inlet and Harvey Estuary (Figure 1.1). It is 2.5 km long, 200 m wide and from 4.5 to 6.5 m deep, and it was constructed with the principle aim of enhancing nutrient transport from the PHES.

It was recognised that the Channel would cause profound changes to the physical, chemical and biological characteristics of the system over both the short and long terms, and that some negative impacts would result. The five-year Dawesville Channel Monitoring Program (DCMP) was therefore approved by the State Government to determine how well the Channel was achieving the purpose for which it was designed and to ensure that positive and negative environmental impacts associated with its construction were properly understood and managed.

Overseeing, coordinating and reviewing the numerous projects associated with the DCMP are the responsibility of the Peel-Harvey Senior Officers Group (SOG), comprising representatives of the proponent Ministers and led by the Water and Rivers Commission (WRC). The SOG is supported by the Peel-Harvey Project Managers Group (PHPMG), which brings together all government departments undertaking monitoring. A subgroup of the PHPMG, led by the WRC, was also established to consider social impacts and public information needs associated with construction of the Channel, and this team liaises closely with the PHPMG.

The SOG has commissioned a review of the DCMP, with the aim of assessing and reporting on changes to the ecology of the PHES since the opening of the Channel.

1.1 Environmental setting

The PHES is arguably one of the most intensively studied and extensively managed estuaries in the world (Kinhill Engineers 1988; Humphries & Ryan 1993; Waterways Commission 1992, 1994). The following section provides a brief summary of its main environmental features, the background to the 'algal problem' and the legal framework of the three-part State strategy undertaken to overcome it.

1.1.1 Location, climate and geomorphology

The PHES is located 75 km south of Perth on the western edge of the Swan Coastal Plain. The region has a Mediterranean climate, characterised by mild wet winters and hot dry summers, with an average annual rainfall of 880 mm (James & Dunn, 1996).

The Harvey Estuary is a long shallow (less than 2.5 m deep) coastal lagoon that is connected at its northern end by the Grey Channel to the shallow (less than 2 m deep) nearly circular basin of Peel Inlet (Figure 1.1). The Harvey Estuary is 61 square kilometres in area and the Peel Inlet somewhat larger at 75 square kilometres(over half of which is wide peripheral platforms that are less than 0.5 m deep. The basins are of similar volume: Harvey Estuary 56 and Peel Inlet 61 million cubic metres (Hill *et al.* 1991).

The PHES has two connections to the ocean, the 2.5 km-long Dawesville Channel at the northwestern end of Harvey Estuary and the 5 km-long Mandurah Channel at the northern end of Peel Inlet (Figure 1.1). Sand accumulation occurs at both channel mouths due to longshore sediment transport, and regular sand bypassing programs are required to keep the channels open.

1.1.2 Catchment land use

Run-off from the total catchment area of 11,378 square kilometres enters the PHES via three rivers and 15 agricultural drains. The rivers are the Murray, the Serpentine and the Harvey (Figure 1.1). Approximately 95% of the run-off occurs between May and October (Rose 1994).

The Harvey catchment has been extensively cleared and drained for agriculture. Irrigated pastures in the southeast portion support a major dairy industry and some intensive horticulture, while clover-based pastures in the central and western portions support beef cattle, sheep and hay production (WRC 1996). The Murray catchment contains mostly wheat and sheep farms. The Serpentine catchment has undergone the least clearing for agriculture, but there are some productive horticulture and grazing areas and hobby farms associated with the outer Perth suburbs (WRC 1996). Waters from the largely pristine forested catchment of the Serpentine have been diverted for potable water supplies.

1.1.3 The Peel-Harvey Estuarine System

Estuaries are characterised by seasonal and spatial differences in the salinity of their waters, and are also naturally enriched due to the accumulation of nutrients and sediments from catchment runoff. Few species of animals and plants are adapted to the changing salinities of estuarine waters, but those that are benefit from the nutrient-enriched conditions, and estuaries are usually extremely productive (Day 1981; McComb 1995).

The PHES is a broad shallow waterbody with a large catchment, strongly seasonal river inflow and, prior to the opening of the Dawesville Channel, limited exchange with oceanic waters. Like all estuaries it is an accumulation site for sediments and nutrients.

The natural enrichment of estuaries is a slow process, which gives the biota time to change and adapt. However, rapid changes in nutrient inputs can produce extreme responses in estuarine biota, such as massive algal blooms.

The PHES and its catchment have been highly modified over the last 160 years. These changes have altered the flushing characteristics of the PHES and greatly increased the amount of nutrient inputs (James & Dunn 1996). The major changes are as follows:

- large-scale clearing of land, principally for agriculture (clearing for timber and mining industries has also occurred, and in more recent years for urban development;
- water management practices, such as swamp drainage, dam construction, river diversion, dredging, removal of sandbars and modification of river mouths;
- massive increase in nutrients (especially phosphorus) in catchment run-off, associated with agricultural land use.

The shallow waters of the PHES support extensive stands of macroalgae and some seagrass, and these plants, in combination with a high phytoplankton productivity, support large populations of small invertebrate animals. The high plant and invertebrate productivity is the basis of a food chain that supports large numbers of waterbirds, fish, crabs and prawns. The fringing vegetation and the shallow intertidal flats are also important feeding and shelter areas for waterbirds. The PHES has the largest professional and recreational estuarine fisheries in Western Australia and it is one of the most important estuarine habitats for waterbirds in south-western Australia, particularly for summer migrant species whose breeding-grounds are in the northern hemisphere (McComb *et al.* 1995).

The PHES is also an important recreational and tourism resource due to a combination of its biological features, sheltered waters, scenic surrounds and close proximity to the Perth metropolitan area. There is considerable recreational use of the system, the most popular being passive recreation (e.g. walking), prawning, crabbing, fishing and boating (O'Brien *et al.* 1994).

1.1.4 The algal problem

The algal problem in the PHES is relatively recent, and its onset has been linked to clearing of extensive areas of deep grey sandy soils on the coastal plain catchment in the 1960s and 1970s and subsequent application of phosphate fertilisers in these areas (Hodgkin *et al.* 1980). Phosphorus was readily leached from the sandy soils of the catchment, and this led to a considerable increase in phosphorus inputs to the PHES, particularly from the Harvey River (James & Dunn 1996) and also from the Serpentine River, which drains effluent from intensive piggeries and feedlots.

The earliest account of superphosphate fertiliser from farms being washed into the PHES by the winter rains appeared in the Mandurah Fisheries Inspector's Annual Report for 1957 (WWC, DoT & WADA 1994). Ten years later the Shire of Murray started complaining about the accumulation of algae on the shores of the Peel Inlet and the smell from decomposing algae and, in 1970, a massive bloom of the toxic alga *Nodularia* occurred in the Serpentine River. The problem intensified in 1978 with the appearance of the first large-scale bloom of *Nodularia* in Harvey Estuary (*Nodularia* blooms had occurred in the Harvey Estuary in 1973 and 1974, but aroused little comment: Hodgkin *et al.* 1985).

Most of the phosphorus entering the PHES is associated with catchment run-off in winter, and a complicated sequence of nutrient cycling events was responsible for the algal problem. Prior to the opening of the Dawesville Channel a large proportion of the phosphorus carried in winter river inflow was taken up by phytoplanktonic diatom blooms. When these died and settled to the sediment surface, at least part of the phosphorus store trapped in decaying organic matter was released and became available for the growth of macroalgae and *Nodularia* in spring and summer.

Over the years the store of phosphorus in the sediments also accumulated, and under conditions of low oxygen levels this sediment phosphorus was released into the water column. The macroalgal accumulations and *Nodularia* blooms also caused low oxygen conditions, causing further release of phosphorus from sediments. Oxygen is consumed by living plants during the night, and the decomposition of decaying plant material also consumes oxygen. The sediments became an important in-situ source of phosphorus, complementing the external sources (the rivers), and helping to maintain nuisance levels of algal growth during years of lower nutrient input (i.e. lower catchment run-off).

1.2 Scope of the technical review

The Technical Review covered the following tasks:

- a review and analysis of available data collected before the opening of the Dawesville Channel;
- a review and analysis of the results from the 32 monitoring projects associated with the DCMP;
- an interpretation and summary of those results, with particular emphasis given to trend analysis (comparisons with pre- Channel conditions); assessment of the performance of the Channel in terms of the environmental health of the estuary.

The main focus of the Technical Review was on the results of the first two years of the DCMP, but later data were considered where available and appropriate.

1.3 Study approach

The basis of the Technical Review was the 32 projects associated with the DCMP. Most of these were in various stages of completion, though some had not been initiated. A description of the projects is presented in Table 0.1, along with the relevant management agencies and organisations responsible for their implementation.

DCMP project reports were reviewed where available, and discussions were held with project team personnel. In some cases it was necessary to inspect raw data. Information was also accessed in unpublished material and scientific theses, and the scientific literature was examined for descriptions of environmental conditions in the PHES before the construction of the Dawesville Channel.

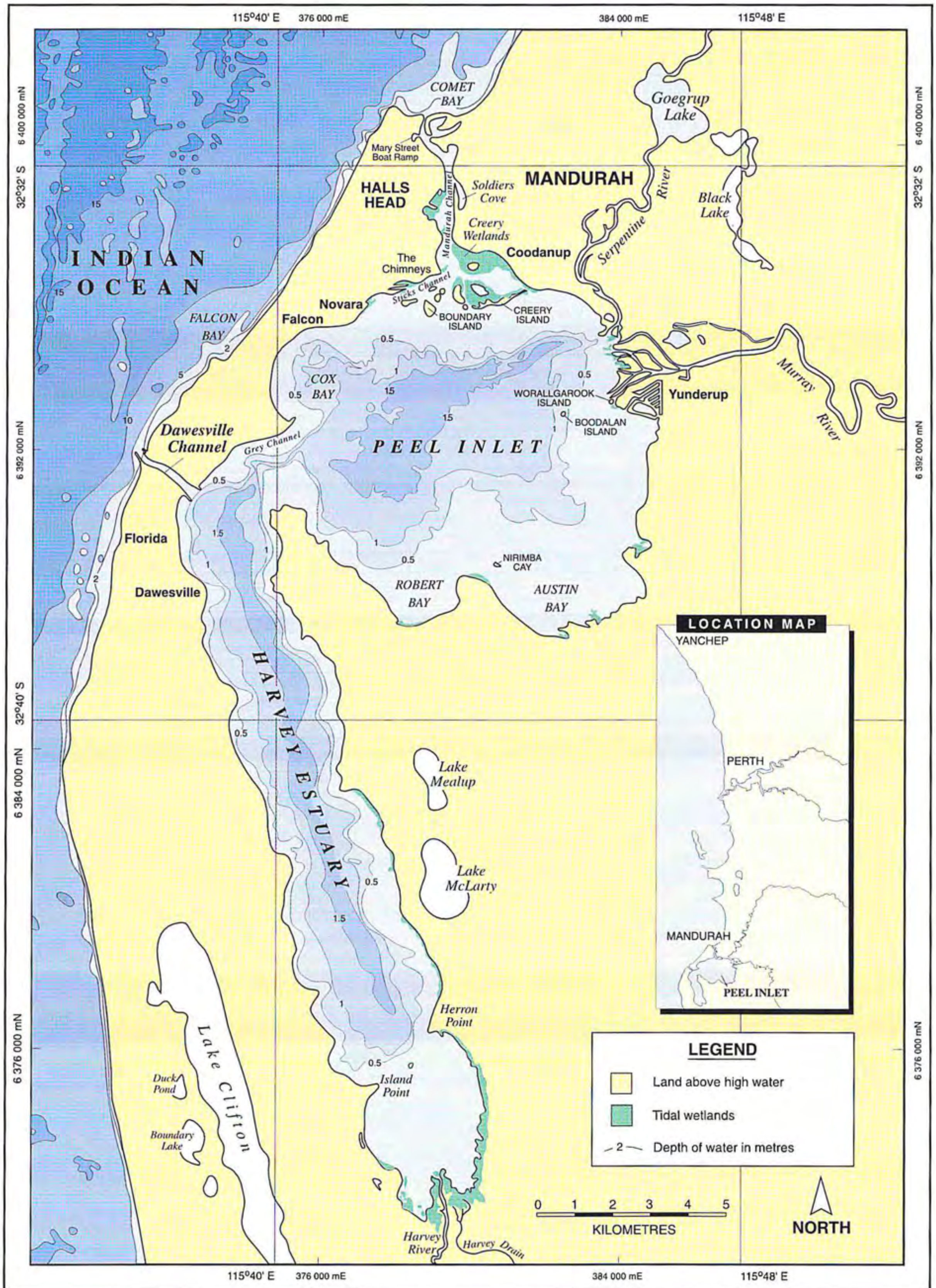
Table 1.1 Projects associated with the Dawesville Channel Monitoring Program

Project	Agency Responsible for Project		Description	Status
	Management	Implementation		
Hydrodynamics				
Tidal Monitoring	DoT	DoT	Monitor tidal levels through the PHES.	Datum levels have been established. Monitoring of five tide gauges continues; monitoring of three draingauges ceased.
Estuarine Processes: Hydrodynamics	WRC	WRC	Review literature and available data onestuarine hydrodynamics and assess changes.	Not initiated.
Channel Exchange Characteristics	DoT	DoT	Describe exchange characteristics of Dawesville Channel, characteristics Mandurah Channel and Grey Channel.	Limited analysis of the channel flow No further measurements or analysis planned.
Inundation Assessment	DoT	DoT	Examine the frequency, duration and extent of shoreline inundation around the PHES.	Pamphlet and report completed. No further investigations planned.
Drains and Flood Levels	WRC	WRC/WC	Assess flood levels for planning and examine flood intrusion into drains flood intrusion into drains.	Pamphlet and report completed. No further investigations planned.
Sediments				
Estuarine Processes Sediments	WRC	WRC	Conduct historical review of estuarine sediment characteristics and compare with pre-Channel sediment characteristics.	Commenced February 1998. To conclude June 1999.
Riverine Management: Sediments	WRC	WRC	Make preliminary investigations of post-Channel riverine sediment characteristics.	Draft report completed. A further study under way, to conclude conclude June 1999.
Nearshore Marine Areas				
Nearshore Water Quality	DoT	DoT	Monitor nearshore water quality conditions in the vicinity of the Dawesville Channel.	Report completed.
Topographic/ Hydrographic Surveys	DoT	DoT	Conduct topographic and hydrographic surveys of the coastline adjacent to the Mandurah Channel, the Dawesville Channel and Grey Channel.	Draft report completed. Nearshore surveys to continue annually; Channel and estuary surveys due in three years.
Nearshore Habitat Survey	DoT	Botany Dept, UWA	Monitor nearshore macroalgae and seagrass communities in the vicinity of the Dawesville Channel.	Report completed.
Water Quality				
Catchment Audit Programme	WRC	WRC	Measure and estimate catchment nutrient loads entering the PHES.	Report on 1990-1992 data available. Data report for 1993-1997 being completed.

Project	Agency Responsible for Project		Description	Status
	Management	Implementation		
Riverine Management: Water Quality	WRC	WRC	Monitor river water quality through physico-chemical and phytoplankton parameters.	Draft report completed.
Dawesville Channel Groundwater	DoT	DoT	Monitor groundwater levels and salinities in the vicinity of the Dawesville Channel to determine the influence of dewatering during Channel construction and the re-establishment of a freshwater lens.	Reports completed. Monitoring ceased in May 1995.
Historical Review of Water Quality	WRC	PsyPh Scientific Data Analysis	Review and analyse available data on estuarine water quality (includes the following data sets:1948-1951 CSIRO and 1977-1993 Chemistry Centre).	Report completed.
Estuarine Processes: Spatial Variability	WRC	MAFRL/Peel-WRC	Examine the spatial variability in water quality characteristics within the PHES to determine the suitability of sampling locations.	Report completed.
Estuarine Water Quality	WRC	MAFRL/Peel-WRC	Monitor estuarine water quality through physico-chemical and phytoplankton monitoring.	Annual reports for 1994-1995, 1995-1996 and 1996-1997 completed.
Salinity Profile Surveys	CALM	CALM	Conduct depth surveys of salinity within the Harvey River and delta complex to determine impacts on peripheral vegetation and hence impact on birds.	Awaiting report.
Estuarine Flora				
Macroalgae/ Seagrass	WRC	MAFRL	Monitor seasonal and annual changes in macroalgae and seagrass abundance in the PHES.	Annual reports for 1994-1995, 1995-1996 and 1996-1997 completed.
Estuarine Processes: Peripheral Vegetation Using Remote Sensing Data	WRC	Dept Env. Science Murdoch Uni.	Assess the suitability of a remote sensing technique (Digital Mosaic Spectral Variation) for monitoring peripheral vegetation.	Report completed.
Vegetation and Habitat Survey	CALM	CALM	Establish baseline and historical vegetation changes in CALM Reserves.	Draft report available.
Samphire Vegetation Survey	WRC	Peel Preservation Group	Limited study of samphire salt marsh habitats around the PHES.	Report completed.
Estuarine Fauna				
Estuarine Processes: Review of 1985-1987 Shallow Water Fish Communities	WRC	WRC	Review shallow water fisheries data in the PHES during mid to late1980s.	Draft report available.

Project	Agency Responsible for Project		Description	Status
	Management	**Implementation**		
Estuarine Processes: Shallow Water Benthic and Fish Communities	WRC	WRC	Conduct limited monitoring of shallow water benthic and fish communities. Also includes bird surveys.	Draft report being prepared.
Recruitment, Distribution and Emigration of Crabs and Prawns in the PHES	FWA	Dept Biol. Sci., Murdoch Uni.	Survey recruitment, distribution and emigration of crabs and prawns in the PHES.	Interim report available.
Recruitment, Distribution and Emigration of Fish in the PHES	FWA	Dept Biol. Sci., Murdoch Uni.	Survey recruitment, distribution an and emigration of fish in the PHES.	Interim report available.
Commercial Fisheries Survey	FWA	FWA	Survey commercial fisheries catches.	Ongoing surveys; data always available.
Anglers' Survey	FWA	FWA	Study recreational fish catches at boat ramps	Study commenced in September 1996; some data available.
Creel Survey	FWA	FWA	Study recreational fish catches at Dawesville Channel and Mary Street boat ramp. Data from March 1994 to June 1996.	Report completed.
Bird Survey	CALM	CALM	Monitor bird populations around the PHES.	Draft report available.
Social and Economic Uses				
Social Impacts, Public Education and Public Involvement in Monitoring Changes	WRC	WRC	Identify the community groups likely to be affected by the construction of the Dawesville Channel, assess communities' concerns and provide recommendations. Prepare and coordinate videos, information pamphlets, topic sheets, media specials and community forums and assess public observations of changes in the PHES.	Ongoing
Public Health				
Mosquito Surveys and Isolation of Ross River Virus HDWA	HDWA	Dept of Microbiol., UWA.	Monitor mosquito breeding sites, mosquito populations and disease risk. Conduct larval control programs when required.	Ongoing
Macroalgal Harvesting (reduction of odours and clearing of navigation hazards)	WRC	WRC	Manage excess macroalgae in popular areas of the PHES.	Ongoing

Note: Organisations involved: Department of Conservation and Land Management (CALM), Fisheries Department of Western Australia (FWA), Department of Transport (DoT), Health Department of Western Australia (HDWA), Marine and Freshwater Research Laboratory, Murdoch University (MAFRL), Peel Office, South-west Region, Water and Rivers Commission (Peel-WRC), River and Estuaries Investigation Branch, Water and Rivers Commission (REI), University of Western Australia (UWA), Water Corporation (WC) and Water and Rivers Commission (WRC).



FROGGRAPHICS DAL-DAW 16/2/98

Auth: KH/BH · Date: 2/98	Water and Rivers Commission **Dawesville Channel Monitoring Programme** **Two Year Technical Review** **THE PEEL–HARVEY ESTUARINE SYSTEM**	Figure **1.1**

1.4 Document structure

The Technical Review comprises two documents: a summary report and a technical appendices document.

The following document is the summary report: Chapters 2-7 contain discussions of the physico-chemical and biological characteristics of the PHES before and after the opening of the Dawesville Channel; public health issues are discussed in Chapter 8; social and economic uses of the PHES are addressed in Chapter 9; estuarine management is the subject of Chapter 10; and conclusions are presented in Chapter 11. The technical appendices contain the more detailed material on which the summary report has been based.

2. Hydrodynamics

Prior to the construction of the Dawesville Channel, occasional dredging was conducted in the Mandurah Channel to maintain navigable waters. However, after the mid-1980s dredging of the latter was conducted with the secondary aim of modifying the hydrodynamics (particularly flushing rates) in the PHES to ameliorate the adverse effects of severe nutrient enrichment. The Dawesville Channel was constructed with the primary aim of increasing the marine flushing of the PHES.

The opening of the Dawesville Channel was intended to cause profound changes to the prevailing hydrodynamics within the PHES, including modifications to the tidal levels, water circulation and structure, exchange characteristics and extreme water levels. The influence of the Channel on these hydrodynamic processes is described in this chapter.

2.1 Tidal Levels

2.1.1 Prior to the opening of the Dawesville Channel

Before the opening of the Dawesville Channel the tidal water movements in the Peel Inlet were solely due to exchanges through the Mandurah Channel. Tidal fluctuations in the Harvey Estuary were due to exchanges with the Peel Inlet via the Grey Channel, which resulted in a substantial attenuation and lag in water-level variations. The daily mean tidal range in the Peel Inlet and Harvey Estuary averaged 17% and 15% of the ocean tides respectively (Department of Marine and Harbours 1993), and daily high-tide levels in the Estuary lagged behind those in the Inlet by approximately 3 hours. The longer period (monthly and seasonal) tidal constituents were not attenuated by the Mandurah Channel, and hence caused corresponding changes in the estuarine water level (DoT 1996).

2.1.2 Predicted effects of the Dawesville Channel

The effects of the Dawesville Channel on tidal levels within the PHES were predicted using detailed modelling (DMH 1993), which indicated a marked increase in the amplitude of tidal oscillations in both the Peel Inlet (45%-50% of the ocean tide range) and Harvey Estuary (60%-70%). It was also predicted that the tidal range in the Estuary would be greater than the tidal range of the Inlet. The predicted changes are shown in Figure 2.1.

2.1.3 Observed effects of the Dawesville Channel

Following the opening of the Dawesville Channel the tidal ranges in the Peel Inlet and Harvey Estuary were 48% and 55% of the ocean tides respectively (Tremarfon 1997b). The opening of the Channel caused a phase change in the diurnal tidal constituents within the PHES such that the Estuary experienced high tide approximately 43 minutes *before* the Inlet (DoT 1996). The observed changes in the tidal regime were similar to the modelled changes; however, in the period following the opening of the Channel the ocean water levels were approximately 6 cm higher than those used in predictive modelling (Tremarfon 1997a). Hence, the water levels in the PHES following the opening of the Channel were slightly higher than predicted, the effect being more pronounced in the Harvey Estuary than in the Peel Inlet.

The increased tidal range in the PHES following the opening of the Dawesville Channel resulted in an increased intertidal area. The inundation regime of the intertidal areas also changed, such that the upper intertidal areas were submerged more frequently but for reduced periods; similarly the lower intertidal areas were exposed more frequently but for reduced periods.

2.2 Water circulation and structure

2.2.1 Prior to the opening of the Dawesville Channel

Water circulation in the PHES is largely controlled by river flows, tidal exchanges with the ocean and wind forces acting across the water surface. The main factor controlling vertical density differences is differences in salinity between oceanic, estuarine and riverine waters.

Prior to the opening of the Dawesville Channel, the Peel Inlet was generally more saline than the Harvey Estuary in winter and spring due to greater exchange of oceanic water in the Inlet via the Mandurah Channel. However, in summer and autumn the situation was reversed, due to a relatively high evaporation rate and the limited exchange with oceanic waters.

The PHES was generally well mixed in summer and autumn; however, despite the shallow depth the system could remain stratified for extended periods during calm periods in winter and spring (Hodgkin *et al.* 1985; Lukatelich & McComb 1989). During these periods oceanic and/or estuarine waters would move underneath the fresh river waters. Persistent strong winds could mix the water to a uniform salinity, but with the return to calm weather the stratified condition was rapidly re-established (Hodgkin *et al.* 1985). The Peel Inlet generally showed stronger stratification than the Harvey Estuary during winter as the marine water that entered from the Mandurah Channel formed a thin layer (often referred to as a 'saltwedge') underneath the relatively fresh river waters.

2.2.2 Predicted effects of the Dawesville Channel

The predicted, and intended, effect of the Dawesville Channel was to increase the exchange of estuarine and ocean waters and thereby produce a more consistent marine environment. As a result, episodes during which the estuarine waters remained either almost fresh or hypersaline were expected to decrease in intensity, frequency and duration (DoT 1996). In addition, the increased flushing was expected to reduce the duration of stratification during winter and early spring.

The opening of the Dawesville Channel was also predicted to cause localised increases in the rate of water movement within the PHES in the vicinity of the Channel, and perhaps near the narrow Grey Channel (Hodgkin *et al.* 1985). The increased current flow in the vicinity of the Dawesville Channel was expected to result in the development of a flood-tide delta in the Harvey Estuary (Hodgkin *et al.* 1985).

2.2.3 Observed effects of the Dawesville Channel

Observations of the water quality within the PHES following the opening of the Dawesville Channel have realised the prediction of more marine conditions with vertical stratification predominantly limited to the winter months (DoT 1996; see also Chapter 5). A flood-tide delta developed in the Harvey Estuary, as predicted.

A significant horizontal salinity gradient was apparent along the length of the Harvey Estuary during summer. Relatively marine salinities prevailed close to the Dawesville Channel and hypersaline conditions (up to 48 ppt) occurred towards the south end of the Estuary, which suggested that the level of water exchange from it to the ocean was very near to the minimum required for adequate mixing. The Peel Inlet exhibited relatively little variation in water structure, which suggested that water exchange within it was satisfactory.

2.3 Exchange characteristics

2.3.1 Prior to the opening of the Dawesville Channel

The PHES has a large ratio of basin surface area to channel cross-section, and therefore, despite being microtidal, strong tidal currents can occur through the Dawesville, Mandurah and Grey Channels. The residence times (number of days required for the water volume to be flushed to the ocean) for the PHES prior to the opening of the Dawesville Channel were determined by numerical modelling as 30 and 50 days for the Peel Inlet and Harvey Estuary respectively (Humphries & Ryan 1993).

2.3.2 Predicted effects of the Dawesville Channel

Predicted residence times for the PHES following the opening of the Dawesville Channel were approximately 10 and 17 days for the Peel Inlet and Harvey Estuary respectively (Humphries & Ryan 1993).

Modelling of the tidal current velocities through the Dawesville Channel indicated that the average peak tidal currents would be 1.03 meters per second for the flood tides and 1.13 m/s for the ebb tides (DMH 1993). The maximum flood and ebb tidal currents in the Dawesville Channel were predicted to be 1.90 m/s and 1.85 m/s respectively (DMH 1993).

2.3.3 Observed effects of the Dawesville Channel

Maximum flood and ebb tidal currents measured through the Dawesville Channel were slightly above the predicted flows, being 2.17 and 2.09 m/s respectively.

2.4 Extreme water levels

2.4.1 Prior to the opening of the Dawesville Channel

Extreme water-level conditions in the PHES are largely controlled by river flood inputs and/or storm surge events. Prior to the opening of the Dawesville Channel, the majority of the extreme water levels were governed by river flows rather than storm surges: the narrow Mandurah Channel was a 'bottleneck' for river flood discharge, but also considerably attenuated the effects of ocean surge events. Extreme high water levels could take up to nine to ten days to return to tidal levels (DoT 1996).

2.4.2 Predicted effects of the Dawesville Channel

The Dawesville Channel was expected to allow floodwaters to more readily drain to the ocean and thus reduce the level and duration of river floods (Humphries & Ryan 1993), but also allow ocean surges to be more readily transmitted into the PHES. In contrast to pre-Channel conditions, it was expected that extreme water levels would be caused more by storm surge than river flooding (DoT 1996). Given that storm events may occur at any time of the year, whereas floods typically occur in winter, it was also expected that extreme water levels would occur over a wider portion of the year. In addition, it was predicted that the duration of peak water levels during a storm event would increase, as the first component of the water-level peak would be driven by oceanographic factors (tides and storm surge), and the second component would be due to river flows from the catchment areas (DMH 1987).

2.4.3 Observed effects of the Dawesville Channel

Observations since the opening of the Channel indicate that water levels did not exceed those historically recorded. The observed submergence and exposure statistics for intertidal areas in the Peel Inlet were similar to modelled predictions. However, for the Harvey Estuary the observed frequency and persistence of submergence were greater than predicted and frequency and persistence of exposure less than predicted: this was due to ocean levels after the opening of the Dawesville Channel being 6 cm higher than levels used in predictive modelling (see also Section 2.1).

3. Sediments

The principal importance of sediments in the ecology of the PHES is their role in phosphorus recycling, as they have the ability to both bind and release phosphate depending on the physical and chemical nature of the sediments and overlying waters (Hill *et al.* 1991). Prior to the opening of the Dawesville Channel, phytoplankton blooms (largely diatoms) absorbed phosphorus from the nutrient-rich waters in winter. Phosphorus bound up in organic material then settled onto the sediments: Hill *et al.* (1991) estimated that approximately 50% to 70% of the riverine phosphorus, predominantly as phosphate, was trapped in winter phytoplankton blooms. The collapse of the diatom bloom and subsequent decomposition resulted in conditions of low oxygen which caused high levels of phosphorus release from the sediment. Thus, the major source of phosphorus for both the *Nodularia* blooms and the macroalgal accumulations in the PHES was that released from the sediments (Lukatelich 1985).

The total phosphorus concentration in the sediments may be divided into organic and inorganic components. Organic phosphorus is ultimately converted to inorganic phosphorus via decomposition, and inorganic phosphorus may in turn be divided into apatite phosphorus and non-apatite phosphorus, apatite being a crystalline mineral of calcium phosphate and fluoride. Non-apatite phosphorus is considered to be the fraction of inorganic phosphorus that is 'biologically available', i.e. available for uptake by plants. The amount of non-apatite phosphorus and the potential for its release and recycling determines the contribution of the sediment phosphorus store to the overlying waters.

3.1 Estuarine sediments

3.1.1 Prior to the opening of the Dawesville Channel

The sediments in the PHES accumulated phosphorus because the riverine phosphorus inputs exceeded the phosphorus losses from the system. Sediment cores obtained from the Peel Inlet and Harvey Estuary indicated that the total and inorganic phosphorus concentrations in the surface sediments in the PHES had more than doubled over the past 100 years (Gerritse *et al.* submitted). Examination of the phosphorus concentrations in the sediment cores suggested that more than half of the phosphorus entering the PHES was flushed to the ocean. The contribution of anthropogenic phosphorus to the sediments accounted for 70% of the dissolved inorganic phosphorus and 20% of the total phosphorus in the Peel Inlet, while in the Harvey Estuary the corresponding figures were 25% and 15% approximately (Gerritse *et al.* submitted).

Regular sediment sampling between 1982 and 1989 (reported by Hill *et al.* draft A) indicated that the sediment mean annual total phosphorus concentrations in the Peel Inlet and Harvey Estuary ranged from 167-258 µg/g and 595-714 µg/g respectively. The proportion of total phosphorus as non-apatite phosphorus in the Inlet and the Estuary ranged from 20%to 43% and 35% to 52%, respectively. No clear trends were apparent from an examination of this eight-year time series of sediment phosphorus concentrations.

3.1.2 Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in an increase in the flushing of the waters of the PHES and thereby to reduce the proportion of phosphorus retained in the sediment. An ongoing loss of fine sediments suspended by wave action in Harvey Inlet was also expected, due to increased oceanic exchange. It was considered that a relatively modest increase in the summer flushing rate would rapidly deplete the sediment phosphorus storage, whereas even a significant depletion in the riverine phosphorus loading would have relatively little impact on the rates of phosphorus build up in the PHES (Kidby *et al.* 1984).

The increased flushing associated with the Channel was also expected to keep waters well oxygenated throughout most of the year. As sediment phosphorus release rates are an order of magnitude less under well-oxygenated conditions than under conditions of low oxygen, it was predicted that there would be a significant decrease in sediment phosphorus release (Lukatelich 1985).

3.1.3 Observed effects of the Dawesville Channel

Estuarine sediment samples have only been collected on one occasion, in February 1998. The preliminary results indicated that nutrient concentrations are similar to pre-channel years. A more detailed study is currently under way and will conclude in June 1999.

3.2 Riverine sediments

3.2.1 Prior to the opening of the Dawesville Channel

Phosphorus concentrations in Murray River sediments prior to the construction of the Dawesville Channel were highly variable. Two sites had total phosphorus concentrations of 665 µg/g (Ravenswood Hotel) and 742 µg/g (Pinjarra Road bridge) and a third site (at North Yunderup) 129 µg/g. In the Serpentine River the sediment total phosphorus concentration at three sites ranged from 142 to 259 µg/g; whereas the figure for a fourth site (downstream of Goegrup Lake) was 713 µg/g. Concentrations in sediments at two sites in Goegrup Lake were 284 and 685 µg/g. These values were similar to those of sediments in the PHES.

3.2.2 Predicted effects of the Dawesville Channel

No predictions of the effects of the Dawesville Channel on riverine sediment quality were found in the literature reviewed.

3.2.3 Observed effects of the Dawesville Channel

Sediment samples were obtained in January 1996 from the Murray and Serpentine Rivers and in Goegrup Lake, the total phosphorus concentrations being generally less than those observed by Hill (draft B) prior to the opening of the Dawesville Channel. The median concentration of total nitrogen in the Murray sediments was seven times lower than that of the sediments from the Serpentine. The latter were generally higher in total phosphorous concentration and much higher in total nitrogen concentrations than those of the other estuarine rivers (Water and Rivers Commission, draft). The heavy metal concentrations in both the Murray and Serpentine were low.

Examination of faecal sterols by Leeming (1996) indicated that groundwater, sourced from piggeries, was entering the Serpentine River via the Gull Road drain. This type of effluent, if untreated, is rich in phosphorus.

4. Nearshore marine areas

The breakwaters constructed for the Dawesville Channel interrupt longshore transport of sediments along the coast, and therefore affect shoreline stability. The Channel itself is also subject to silting up, and turbid, low-salinity and nutrient-rich estuarine water is discharged into the nearshore marine environment in winter and early spring. The effects of these changes are discussed in this chapter.

4.1 Shoreline and channel stability

4.1.1 Prior to the opening of the Dawesville Channel

Prior to the construction of the Dawesville Channel a series of investigations was conducted to estimate the quantity of coastal littoral drift, the most consistent estimate being that approximately 60,000 m^3 of sediment was moving from south to north each year (DMH 1987). It was considered that the majority was transported during occasional high wave-energy events, which could transport slugs of sediment of approximately 10,000-30,000 m^3.

The beaches to the north of the Channel site generally experienced erosion between 1992 and 1994.

4.1.2 Predicted effects of the Dawesville Channel

To incorporate large annual variations, and the potential for large short-term sediment movements, the southern breakwater of the Dawesville Channel was designed with a sediment trap to the south with a capacity of 85,000 m^3. To facilitate sediment bypassing to the north, two submarine pipes were installed across the Channel at the time of construction. A small breakwater was also constructed to the north of the Channel to prevent sediment incursion into it during periods of southerly longshore sediment transport.

Detailed analysis of the stability of the Dawesville Channel by the DMH (1987) indicated that a tapered channel with a stepped profile (6.5 m on the ocean side and 4.5 m towards the estuary side) would provide a satisfactory channel design.

4.1.3 Observed effects of the Dawesville Channel

Sediment bypassing from the south to the north of the Dawesville Channel was conducted on three occasions after the opening of the Channel. Sediment accretion occurred on the beaches to the south in 1995 but the rate appeared to slow in 1996. The beaches to the north of the Channel generally experienced accretion between 1994 and 1995 and a period of minor erosion till March 1997.

Sediment erosion/accretion within the Dawesville Channel was relatively minor; however, there was a general east-west gradient from maximum accretion on the ocean side (deeper section) of the Channel to maximum erosion towards the estuary side (shallower section). Changes in sediment distribution in the areas surveyed within the Harvey Estuary and Grey Channel were relatively minor.

4.2 Nearshore water quality

4.2.1 Prior to the opening of the Dawesville Channel

The Dawesville coastline has no outer barrier reef system and therefore receives the full impact of ocean swell all year round, as well as the high-energy conditions associated with winter storms. The nearshore waters of the Dawesville area are therefore naturally turbid (secchi depths typically less than 2 m) due to constant resuspension of sediments in the high wave-energy environment (Chase 1995; Montgomery 1995).

There was very little in the way of pre-Channel water quality data for coastal waters adjacent to the Dawesville area. A single baseline survey was carried out in March 1994 (Chase 1995) involving five inshore sites, five offshore sites and one site in the Channel. The results of this survey and other available data are presented in REF _Ref412966929 * MERGEFORMAT Table 0.1, and show the typical low nutrient status of local coastal waters.

Table 4.1: Available water quality data on coastal waters off Dawesville before the Dawesville Channel was opened

PARAMETER (all data in (g/L)	SEPTEMBER 1993	FEBRUARY 1994	MARCH 1994	
			Inshore sites	Offshore sites
Total phosphorus	14	5-14	22	20
Orthophosphate phosphorus	2.5-3.5	2-3	3	2.5
Total nitrogen	250-290	100-230	120	110
Nitrate+nitrite nitrogen	2-8	1-2	16.5	7.5
ammonium nitrogen	no data	3-6	45	16
chlorophyll a	0.2-0.4	0.2-0.7	1.4	0.8

4.2.2 Predicted effects of the Dawesville Channel

It was predicted that the estuarine water 'jet' from the Dawesville Channel in winter would discharge water up to 1 km offshore during ebb tides, and this, combined with longshore currents, was expected to ensure sufficient dispersion of estuarine waters to prevent excessive buildup of nutrients in nearshore waters (EPA 1988). Furthermore, it was anticipated that the phosphorus would be rapidly immobilised as it converted to apatite (Humphries & Ryan 1993). The DoT predicted that the Dawesville Channel would flush approximately 120 tonnes of phosphorus and 1000 tonnes of nitrogen from the Peel-Harvey system per year (DoT 1996).

4.2.3 Observed effects of the Dawesville Channel

The extent of the winter plume of estuarine waters was detected less than 2 km offshore and approximately 3 km north of the Dawesville Channel (DoT 1996). Nutrient levels in the offshore sampling sites were lower during the winters of 1994 and 1995 than in that of 1996 (Figure 4.1): this was attributed to lower rainfall and nutrient export from the catchment in 1994 and 1995 compared to 1996, as was evident in nutrient concentrations in Channel waters (Figure 4.2).

Water quality sampling sites were insufficient to resolve plume dispersion characteristics, but the rapid dilution and dispersion of the plume was evident in the difference in water quality between the Channel site and offshore sampling sites (Figures 4.1 and 4.2). Elevation of inorganic nutrient levels at the offshore sampling sites was clearly confined to periods of river discharge (Figure 4.1), and there was no indication of any buildup of nutrients (Latchford *et al.* 1997).

Calculations based on 1994/95 data indicated approximately 100 tonnes of total phosphorus and 900 tonnes of total nitrogen per year were exported, which agreed well with predicted values (DoT 1996).

4.3 Nearshore benthic habitats

4.3.1 Prior to the opening of the Dawesville Channel

The Dawesville nearshore benthic environment is characterised by an extensive complex of reefs and areas of bare sand. As for water quality, there was scant information on the benthic environment prior to the opening of the Dawesville Channel. Pre-Channel monitoring was limited to a series of aerial survey videos and an intensive two-day ground truthing exercise carried out in March 1994 (Walker 1994).

Reef macroalgae were considered the best biota for monitoring the effects of the Dawesville Channel on the nearshore environment, as they are fixed organisms (unlike plankton and fish populations) and respond to in-situ changes to the environment by showing conspicuous changes in community composition (Montgomery 1995). The upper surfaces of the reefs were covered by a diverse community dominated by red algae. Macroalgal community complexity was highest in March and May, prior to the onset of winter weather patterns, when all but the most resilient species were scoured from the reef surfaces (Montgomery 1995).

4.3.2 Predicted effects of the Dawesville Channel

It was recognised that discharge of estuarine water from the Dawesville Channel might expose marine algae to low salinity water and high nutrient levels, but there were also potential impacts due to changes in the nature of the substratum (deposition of organic material and a change in reef architecture due to accumulation of sediments in reef gullies and potholes) and increased turbidity due to suspended particulates in the water column. However, it was considered that environmental impacts on the nearshore marine environment would be minimal and acceptable (EPA 1988) because the characteristically high-energy conditions of the nearshore area(particularly during winter(would ensure rapid dispersion and dilution of estuarine waters.

4.3.3 Observed effects of the Dawesville Channel

For post-Channel monitoring, sites 0.5, 1.5 and 3 km north of the Channel were chosen as areas where environmental changes might occur, water movement in winter being predominantly northwards, while sites 0.5, 1.5 and 3 km to the south were considered 'control' sites. Results confirmed the predicted effects of the construction of the Channel. Data collected after two winters of relatively low river flow indicated there were no deleterious effects on the nearshore marine environment due to the outflow (Montgomery 1995; Montgomery & Walker 1996). Potential impacts were reduced because the greatest outflow of estuarine water occurred in winter, when the macroalgal communities were effectively scoured off reef surfaces due to winter storms. Furthermore, the hydrodynamics of the area ensured that little settlement of plume sediments occurred on reef surfaces.

5. Water quality

The water quality of the PHES depends largely on the amount of exchange with oceanic waters and the amount and quality of river inflow (Kinhill Engineers 1988). Therefore, although the main focus of this document is the impact on the PHES of increased oceanic exchange following the opening of the Dawesville Channel, changes in nutrient inputs from river inflow are also discussed in this chapter. The construction of the Channel also had localised effects on groundwater quality, and a brief account of these is included.

5.1 Catchment nutrient inputs

Water quality monitoring of catchment streams is the basis of an ongoing catchment nutrient audit required under ministerial conditions for the Peel Inlet and Harvey Estuary Management Strategy, and compliance is measured against interim targets set by the EPA for phosphorus input to the PHES (see also Chapter 10). The interim targets are:

"Annual phosphorus input to the system shall not exceed 85 tonnes in more than four years out of ten (on average) and shall not exceed 165 tonnes in more than one year out of ten (on average). (These are based on 60th and 90th percentile loads.)"

However, a recent critique by Wittenoom *et al.* (1998) points out that load-based compliance testing requires accurate measures of total catchment inputs, and this is impossible to achieve with either the past or present network coverage and sampling regimes of the PHES catchment monitoring program. Nor can the performance of the catchment management program be assessed from catchment nutrient loads or the validity of the original management targets tested (see ministerial conditions in Section 10.2.2). Wittenoom *et al.* (1998) recommend a change in the nature of the targets and compliance testing, and suggest trends in the nutrient concentrations of the waters of the catchment drainage network as an alternative performance indicator for the integrated catchment management program.

5.1.1 Catchment nutrient data pre-1989

Bearing the above comments in mind, in the period up to 1989 the DCE/EPA estimated that streamflow into the PHES catchment ranged from 370 to 1200 x 10^6 m^3, and total phosphorus input varied from 95 to 237 tonnes. Over this period the Harvey River contributed 30%-40% of stream inflow to the PHES, but between 50% and 75% of the annual phosphorus load. The Murray contributed large volumes of stream inflow, but had low nutrient concentrations and therefore contributed less total phosphorus. The Serpentine generally contributed less than 25% of stream inflow but its nutrient concentrations were much higher than those of the Murray, and its contribution to total phosphorus loads was therefore higher.

5.1.2 Catchment nutrient data post 1989

Water and Rivers Commission nutrient input data for 1990-95 were more reliable than estimates for earlier years. Available data, summarised in Table 0.1, indicate that over this period the relative importance of Harvey nutrient inputs to the PHES declined and those of the Serpentine increased.

Table 5.1 Available data on annual nutrient input for the PHES from 1990 to 1995. Total input includes contributions from ungauged areas.

YEAR AND PARAMETER	SERPENTINE	MURRAY	HARVEY	TOTAL INPUT
1990				
Volume of Runoff	55 x 10^6 m^3	219 x 10^6 m^3	153 x 10^6 m^3	594 x 10^6 m^3
Nitrogen Input	60 tonnes	145 tonnes	202 tonnes	643 tonnes
Phosphorus Input	8 tonnes	5 tonnes	30 tonnes	84 tonnes
Median Total Phosphorus Concentration	0.11 mg/L	0.02 mg/L	0.14 mg/L	not applicable
1991				
Volume of Runoff	152 x 10^6 m^3	334 x 10^6 m^3	240 x 10^6 m^3	1,045 x 10^6 m^3
Nitrogen Input	262 tonnes	286 tonnes	339 tonnes	1,442 tonnes
Phosphorus Input	41 tonnes	19 tonnes	65 tonnes	222 tonnes
Median Total Phosphorus Concentration	0.19 mg/L	0.01 mg/L	0.30 mg/L	not applicable
1992				
Volume of Runoff	157 x 10^6 m^3	389 x 10^6 m^3	179 x 10^6 m^3	1,019 x 10^6 m^3
Nitrogen Input	176 tonnes	368 tonnes	205 tonnes	1,223 tonnes
Phosphorus Input	42 tonnes	8 tonnes	34 tonnes	167 tonnes
Median Total Phosphorus Concentration	0.25 mg/L	0.01 mg/L	0.19 mg/L	not applicable
1993				
Volume of Runoff	54 x 10^6 m^3	279 x 10^6 m^3	132 x 10^6 m^3	518 x 10^6 m^3
Nitrogen Input	not available	not available	not available	not available
Phosphorus Input	10 tonnes	5 tonnes	20 tonnes	50 tonnes
Median Total Phosphorus Concentration	0.12 mg/L	0.01 mg/L	0.14 mg/L	not applicable
1994				
Volume of Runoff	67 x 10^6 m^3	not available	153 x 10^6 m^3	not available
Nitrogen Input	not available	not available	not available	not available
Phosphorus Input	17 tonnes	not available	39 tonnes	not available
Median Total Phosphorus Concentration	0.16 mg/Ls	not available	0.19 mg/L	not applicable
1995				
Volume of Runoff	74 x 10^6 m^3	not available	140 x 106 m^3	not available
Nitrogen Input	not available	not available	not available	not available
Phosphorus Input	22 tonnes	not available	38 tonnes	not available
Median Total Phosphorus Concentration	0.19 mg/L	not available	0.15 mg/L	not applicable

Compliance with the nutrient loads set out in the Ministerial conditions cannot be determined as yet, because the conditions are expressed upon a basis of ten years of data. It is noted that in the period 1990-93 phosphorus loads exceeded both the 60th percentile (85 tonnes) and 90th percentile (165 tonnes) loads of the conditions on two occasions.

The EPA (1988) also proposed interim targets for total phosphorus concentrations in rivers as follows:

- Serpentine River: 0.135 mg/L (50th percentile), 0.137 mg/L (90th percentile);
- Murray River: 0.046 mg/L (50th percentile), 0.047 mg/L (90th percentile);
- Harvey River: 0.104 mg/L (50th percentile), 0.107 mg/L (90th percentile).

The median concentrations measured for the Harvey and Serpentine Rivers in 1990-95 did not meet the EPA targets, but, as with the nutrient input targets, the validity of the water quality targets is unclear.

As noted previously, load-based compliance testing is effectively impossible because accurate estimates of total catchment inputs cannot be made. However, there are good long-term data sets for nutrient concentrations at a number of key sites in the PHES catchment monitoring program, and analysis of long-term trends in measured nutrient concentrations provides a far more reliable record of changes in catchment inputs than estimated loads. The WRC carried out a detailed statistical analysis of trends in total phosphorus (TP) and total nitrogen (TN) concentrations in PHES catchment waters monitored between 1983 and 1995 (Donohue *et al.* 1998), and some important findings were as follows:

- TP concentrations in the Harvey River fell by about 0.03 mg/L each year between 1982 and 1985, by about 0.01 mg/L annually between 1986 and 1989, and changed little between 1990 and 1995.
- There was an emerging trend of increased nutrient concentrations in the Serpentine River from 1992 (0.01 mg/L each year). It was not known whether this increase was from catchment inputs or increased sediment/water column nutrient cycling due to increased stratification in the river.
- The Murray River changed little between 1983 and 1995.
- TP concentrations in the Gull Road Drain, which drains into the Serpentine River, fell dramatically (by 2.1 mg/L per year) between 1985 and 1987, and there was an unconfirmed trend (i.e. one not statistically proved) of a slower decline (0.26 mg/L per year) between 1988 and 1995. However, concentrations remained extremely high and were a significant source of nutrients to the Peel Inlet.
- TP concentrations in the Meredith Drain, which drains into the Harvey River, changed little between 1982 and 1988, but fell by 0.05 mg/L each year between 1990 and 1995. It was noted that large-scale soil amendment programs were implemented to improve nutrient retention in the Meredith subcatchment in the early 1990s, and AgWA monitoring data also confirmed decreases in TP concentrations between 1990 and 1995, although there was little further change after 1995 (Rivers 1997).
- TP concentrations increased in Nambeelup Brook, which drains into the Serpentine River, by 0.04 mg/L each year between 1990 and 1995, and there was an emerging trend of increasing TP concentrations in the Mayfields Main Drain, which drains into Harvey Estuary.

At the time the Dawesville Channel was about to be opened the following changes in catchment practices had also been implemented:

- All major point sources in the catchment had put effluent management systems in place to the satisfaction of the EPA (Bradby 1997), which prevented 34 tonnes of phosphorus per year from entering the region's waterways.
- The amount of fertiliser applied in the catchment was reduced through market forces from 27,000 tonnes/annum in the late 1960s to 17,000 tonnes/annum by 1975, and further reduced to 9500 tonnes/annum by 1987 due to improvements in fertiliser use efficiency throughout the catchment.
- Considerable progress in Landcare (environmental repair) had been achieved.
- Wetland drainage had been severely curtailed.

Assessment of the effects of the Dawesville Channel on the present-day water quality of the PHES was therefore made bearing in mind that:

- all the major catchment management issues that had resulted in the original environmental deterioration of the PHES were well on the way to improvement; but
- nutrient inputs to Peel Inlet from the Serpentine River had apparently increased.

5.2 Groundwater

5.2.1 Prior to the opening of the Dawesville Channel

Studies of the groundwater in the immediate vicinity of the Dawesville Channel prior to its construction indicated that most of the shallow groundwater was brackish, with a series of thin freshwater lenses overlying this saline watertable (Owens 1992). These freshwater lenses were tapped by several private bores, the majority installed about 30 years ago, which were initially used for domestic water supply. Following the introduction of the reticulated water system to this region, the bores were principally used for watering domestic gardens.

5.2.2 Predicted effects of the Dawesville Channel

The Dawesville Channel was constructed by dry excavating, and dewatering was conducted using groundwater sumps at the ocean and estuary sites. It was anticipated that this dewatering process would disturb the freshwater lens and result in saltwater intrusion in the immediate vicinity of the Channel.

5.2.3 Observed effects of the Dawesville Channel

Observations of groundwater levels indicated that, during the dewatering phase of construction, they dropped approximately 2.5 to 4 m in the immediate vicinity of the Channel (Water Quality Monitoring 1995). However, they recovered to the pre-dewatering levels within approximately one month of the cessation of this operation. During dewatering the groundwater salinity generally increased from 1800-3000 mg/L to approximately 6000 mg/L total dissolved solids. Groundwater monitoring till May 1995 indicated that the salinity levels were slowly declining; however, in the majority of bores they were still higher than the pre-dewatering levels. The DoT currently subsidises the excess water bills of the affected residents, but it is intended that this subsidy will be discontinued soon

5.3 Estuarine water quality

5.3.1 Prior to the opening of the Dawesville Channel

Before the opening of the Dawesville Channel the PHES was poorly flushed with oceanic waters via the Mandurah Channel. Seasonal changes in salinity were extreme, ranging from almost fresh water during periods of winter river run-off to hypersaline (greater than marine salinity) in late summer and autumn due to evaporation. Because of the physical and chemical features of the Harvey Estuary (particularly its greater distance from the Mandurah Channel and the phosphorus-rich inflow from the Harvey River), it was less saline, more prone to stratification and deoxygenation, more turbid, more nutrient enriched and had higher levels of chlorophyll a (a measure of phytoplankton biomass) than Peel Inlet. Chlorophyll a levels in Harvey Estuary in late spring and early summer were often extremely high (200 μg/L or more) due to *Nodularia* blooms.

5.3.2 Predicted effects of the Dawesville Channel

The Dawesville Channel was predicted to allow more than three times greater exchange between the PHES and the ocean: in effect 10% of the estuary's volume would be flushed each day. The increased oceanic exchange was expected to result in a more stable salinity regime, closer to that of marine water for much of the year, with no periods of hypersalinity in late summer and autumn (EPA 1988; Humphries & Ryan 1993). The degree of oxygen depletion in bottom waters was also expected to be less severe and less frequent (particularly in Harvey Estuary) because of the regular inflow of well-oxygenated oceanic water (EPA 1988; Humphries & Ryan 1993).

The increased oceanic exchange was expected to result in a smaller winter diatom bloom, and therefore less loading of the sediments with organic matter from dying organisms. This effect, in combination with less deoxygenation of bottom waters (and therefore less sediment nutrient release) and salinities much less favourable for *Nodularia* (see Section 6.1.1), was expected to dramatically reduce *Nodularia* blooms during late spring and early summer (EPA 1988).

An improvement in water clarity was also predicted, particularly in Harvey Estuary, due to increased oceanic exchange and the expected decline in *Nodularia* blooms. The differences in water clarity between Harvey Estuary and Peel Inlet were also expected to lessen with time, due to both the decline in *Nodularia* blooms and the gradual depletion, through tidal exchange, of the fine sediments easily resuspended by wave action in Harvey Estuary.

5.3.3 Observed effects of the Dawesville Channel

Since the opening of the Dawesville Channel, water quality monitoring of the PHES has continued on a weekly to monthly basis, similar to pre-Channel monitoring. During both 1994 and 1995 the salinity regimes of Peel Inlet and Harvey Estuary were very similar, while surface salinities in the winter of 1996 were lower (Figure 5.1) due to greater river run-off (Wilson & Paling 1998). As predicted, marine salinities re-established far more quickly after cessation of winter run-off (by November). However, hypersaline conditions still occurred in autumn, although to a lesser degree than in pre-Channel years.

In winter and spring, surface salinities were lower than bottom salinities during ebb tides, but the salinity during flood tides approached that of bottom waters. Significant differences in nutrient concentrations in winter were also found, depending on whether measurements were taken during ebb tide or flood tide (Wilson *et al.* 1997a). Nutrient-rich lower salinity water was clearly not mi(ing with oceanic waters, ensuring rapid loss of nutrient-rich river inflow and a reduction in the periods of low salinities.

Hydrodynamic studies also indicated that during summer and autumn the incoming flood tide forced water in the Harvey Estuary towards the south, with little mixing between the ocean and estuary waters (Hart 1995). Evaporation therefore still resulted in hypersaline conditions, particularly at the southern end of Harvey Estuary: in effect there was a shift from vertical stratification to horizontal stratification in the PHES as a result of the construction of the Dawesville Channel (Hart 1995).

Compared to pre-Channel water quality there was a higher level of oxygenation in the bottom waters of the PHES overall (Figure 5.2). Available data indicated that the bottom waters close to the Dawesville Channel were well oxygenated throughout the year, while periods of deoxygenation in the central Peel and central Harvey areas were shorter and less frequent compared to conditions before the opening of the Channel, and were confined to winter and early spring. There was no apparent change in the level of deoxygenation in waters at the southern end of Harvey Estuary and the eastern end of Peel Inlet.

As predicted, levels of turbidity measured during spring were less than those in pre-Channel years, particularly in Harvey Estuary, due to the more rapid loss of turbid river water and to the absence of *Nodularia* blooms in late spring and summer (see below).

There was little difference between pre-Channel and post-Channel peak nutrient concentrations in winter months, as these were determined by concentrations in winter river inflow (Wilson & Paling 1998). There were, however, noticeable changes during the remaining months of the year, the main change being lower organic nutrient concentrations, particularly in Harvey Estuary, with corresponding effects on total nutrient concentrations (Figures 5.3 and 5.4). Peel Inlet and Harvey Estuary were very similar in terms of organic nutrient concentrations, which can be attributed to the absence of *Nodularia* blooms: if anything, the data suggested that the nutrient status of Peel Inlet was slightly higher than that of Harvey Estuary, at least with respect to nitrogen.

The most dramatic difference between pre- and post-Channel water quality in the PHES was in chlorophyll a concentrations (Figure 5.5). Chlorophyll a concentrations in Harvey Estuary were significantly lower, and levels were similar in Peel Inlet and Harvey Estuary (Wilson & Paling 1998). Mean chlorophyll a levels for both Peel Inlet and Harvey Estuary generally remained below 10 μg/L except in late winter/early spring 1995 and 1996: *Nodularia* blooms did not occur in either Peel Inlet or Harvey Estuary in those years. Both 1994 and 1995 were dry years and *Nodularia* blooms also failed to occur during some dry years before the Dawesville Channel was opened, but no *Nodularia* bloom occurred in late 1996 after a winter of moderate freshwater inflow. There were, however, *Nodularia* blooms in the Serpentine River, which affected chlorophyll a levels in the eastern side of Peel Inlet when river water moved downstream during ebb tides.

Water quality monitoring of the PHES is the basis of an ongoing audit required under ministerial conditions for the Peel Inlet and Harvey Estuary Management Strategy, and compliance is measured against the following interim target set by the EPA:

"Average phosphorus concentration in estuary water shall not exceed 0.02 milligrams per litre (29 µg/L) in nine years out of ten (on average)."

The interim target does not specify the sampling requirements or statistical procedures to be used in assessing compliance. Furthermore, it is unclear whether levels of orthophosphate phosphorus, organic phosphorus or total phosphorus are to be assessed. If the assumption is made that total phosphorus is intended, neither the median values for 1992 (82 µg/L in Peel Inlet, 136 µg/L in Harvey Estuary) — a year of low phosphorus input — nor those for 1995 (59.5 µg/L in Peel Inlet, 74 µg/L in Harvey Estuary) and 1996 (60 µg/L in Peel Inlet, 72 µg/L in Harvey Estuary) have ever fallen below the compliance target.

Monitoring of heavy metal levels in PHES waters is not part of the DCMP, but it is noted that data collected by AgWA showed that heavy metal levels in PHES waters frequently exceeded national water quality guidelines for environmental protection (ANZECC 1992), far more so than in the Murray and Serpentine Rivers (Rivers 1997).

5.4 Riverine water quality

5.4.1 Prior to the opening of the Dawesville Channel

Algal blooms were a feature of the Murray and Serpentine Rivers before the opening of the Dawesville Channel, with a massive bloom of *Nodularia* in the Serpentine River in 1970 considered the first sign that serious eutrophication problems were occurring in the PHES. Other than in 1992/1993, no consistent river water quality sampling program was undertaken, and some subsequent blooms may have occurred and gone unrecorded. *Nodularia* blooms were observed in the Serpentine in the late spring/summer of 1989/1990, late spring 1992 and early autumn 1994. ANZECC national water quality guidelines for inorganic and total nutrient concentrations in rivers (ANZECC 1992) were exceeded in the Serpentine between November 1992 and January 1993.

5.4.2 Predicted effects of the Dawesville Channel

It was recognised that the opening of the Dawesville Channel might not prove beneficial to the lower reaches of the rivers, as saline water would be carried further upstream by the increased tides, with stratification possibly stronger and earlier to develop; oxygen depletion would therefore occur for increased periods of time. Conditions of oxygen depletion were also predicted for the lower reaches of the rivers after any sudden inputs of fresh water from a storm during summer or autumn. As riverine sediments were believed to be nutrient-rich, the predicted conditions of oxygen depletion were expected to cause sediment nutrient release in the lower reaches of the rivers (PIMA 1994), which in turn would stimulate phytoplankton blooms. The expected phytoplankton blooms would in turn cause an increase in organic nutrient concentrations, leading to further enrichment of riverine sediments.

It was also predicted that *Nodularia* blooms would continue to occur in suitable regions (i.e. nutrient-rich, lower salinity waters) of the lower reaches of the rivers, and that conditions of strong salinity stratification and high nutrient levels might favour toxic species of dinoflagellates (see also Chapter 6).

5.4.3 Observed effects of the Dawesville Channel

Data collected since the opening of the Dawesville Channel indicated that strong salinity stratification and depletion of oxygen in bottom waters occurred in the Murray River except during periods of winter river flow, whereas stratification and oxygen depletion were not as well developed or prolonged in the Serpentine (Figure 5.6). Nutrient concentrations in the Serpentine were, however, generally much higher than in the Murray (Figure 5.7). From January 1996 to June 1997 inclusive, the Serpentine exceeded ANZECC's (1992) indicative ranges where eutrophication problems may occur for total nitrogen (100-750 μg/L) and total phosphorus (10-100 μg/L).

Nodularia blooms occurred in the Serpentine River from late spring to the end of summer in 1994/95, 1995/96, 1996/97 and 1997/98, and it was necessary to erect warning signs declaring it unsafe for swimming and fishing on a number of occasions. The bloom in 1996/97 — which followed a year of average rainfall — was particularly intense and extensive. In contrast, the late spring/summer of 1997/98 coincided with an El Nino Southern Oscillation (ENSO) event (which meant that coastal water levels were particularly low) and a low winter river flow; and data indicated that conditions in the Serpentine were the best since the opening of the Channel.

Overall, blooms appeared more pronounced after the opening of the Dawesville Channel (Water and Rivers Commission, draft; see also Chapter 6). In particular, the Serpentine experienced a similar pattern of algal succession to that of the PHES prior to the opening of the Channel, with a *Nodularia* bloom in late spring through to early autumn (Water and Rivers Commission, draft).

There were no water quality data for the Harvey River other than nutrient concentrations for the catchment monitoring sites and monitoring of salinity profiles undertaken by the Department of Conservation and Land Management (CALM) to check on effects of increased salinities on fringing vegetation and waterbirds (see Chapter 7). A full analysis of the results of the CALM surveys was not available, but there were preliminary indications of increased saltwater penetration upstream (Lane *et al.* 1997).

6. Estuarine flora

The Dawesville Channel was constructed specifically to achieve more rapid removal of nutrient-rich river inflow so that less algal growth (microalgae and macroalgae) would take place. It was expected also that the more marine-like salinities would be less favourable to *Nodularia*. As well, the attendant changes in water quality and tidal fluctuations were also expected to affect seagrasses and fringing vegetation. The DCMP includes monitoring of phytoplankton, macroalgae, seagrasses and fringing vegetation, and the effects of the opening of the Channel on these components of estuarine flora are discussed in this chapter.

6.1 Phytoplankton

Estuarine phytoplankton communities change throughout the year, as different species become more competitive under the prevailing conditions of light, temperature, salinity and nutrient supply (Day 1981). Diatoms usually predominate, but dinoflagellates become more competitive in warm, calm conditions. Certain species of blue-green algae, such as *Nodularia*, are independent of inorganic nitrogen concentrations in the water column (because they can fix atmospheric nitrogen), and are therefore favoured by high concentrations of inorganic phosphorus (Day 1981).

Phytoplankton 'blooms', defined here as chlorophyll a levels of greater than 20 µg/L, can be a natural feature in estuaries little affected by human activities (Day 1981). Changes in phytoplankton communities are only indicative of deteriorating environmental health when massive blooms occur regularly and for long periods, and/or the blooms are of toxic species of dinoflagellates or toxic blue-green algae such as *Nodularia* (McComb 1995). Both of these scenarios are associated with excessive nutrient enrichment.

Nodularia is known to be toxic to humans if ingested via contaminated shellfish (e.g. mussels, cockles and oysters), and some species of dinoflagellates (e.g. of the genus *Alexandrium*) produce paralytic shellfish poison, a neurotoxic group of protein-like compounds which can cause anything from skin rashes, dizziness and mucosal tissue inflammation up to death by respiratory failure in persons consuming contaminated shellfish (Hosja & Deeley 1994).

6.1.1 Prior to the opening of the Dawesville Channel

The first recorded indication that excessive nutrient enrichment was affecting the phytoplankton communities of the PHES was in 1970, when a massive bloom of *Nodularia* appeared in the Serpentine River. *Nodularia* blooms appeared in Harvey Estuary in 1973 and 1974, which were years of very high rainfall (Hodgkin *et al.* 1985). The first large-scale bloom appeared in Harvey Estuary in 1978, and it also drifted out into Peel Inlet (Hodgkin *et al.* 1985).

Nodularia akinetes (i.e. spores or seeds) lie dormant in sediments and germinate after several days of near-fresh salinities in warm water (Huber 1985). After germination, the organism is capable of growing well at salinities from 3 to 30 ppt, water temperatures from 16°C to 30°C and relatively low light levels, but does not grow well at marine salinities (35 ppt) (Huber 1985). In Harvey Estuary the conditions in late spring and early summer of high phosphorus levels, low salinities (around half to three-quarters of marine levels) and warm water temperatures (around 20°C) were particularly favourable to *Nodularia*.

Prior to the opening of the Dawesville Channel, blooms of diatoms occurred in the PHES in winter, although chlorophyll a values seldom exceeded 50 µg/L. Winter dinoflagellate blooms also occurred, particularly in Harvey Estuary. The winter blooms collapsed by spring, which was attributed to grazing by zooplankton, and the phytoplankton community was subsequently dominated by massive blooms of *Nodularia* (chlorophyll a values commonly greater than 100 µg/L and sometimes greater than 1000 µg/L), which appeared in late spring almost every year between 1978 and 1994. The only years in which *Nodularia* did not bloom were 1987 and 1990, which were years of low river flow and therefore had lower phosphorus inputs and reduced periods of favourable salinities for *Nodularia*.

Blooms of blue-green algae (mainly *Nodularia*) and dinoflagellates were also common in the Serpentine River in summer and autumn, while in the Murray blooms of diatoms and dinoflagellates were common in summer and autumn (WRC, unpublished data).

6.1.2 Predicted effects of the Dawesville Channel

With the opening of the Dawesville Channel the 'window' of favourable conditions for the germination of *Nodularia* (salinities less than 15 ppt combined with temperatures around 20°C) was expected to virtually disappear except in years of very heavy runoff (e.g. as in 1973 and 1974, when the Harvey River annual flow was around 400 million cubic metres). Furthermore, even if *Nodularia* blooms were initiated, their growth was expected to be retarded due to the rapid return to marine salinities with the cessation of river runoff. It was also predicted that the winter diatom bloom would be of lesser magnitude, because increased oceanic exchange would reduce the amount of nutrients available to the phytoplankton, and a significant proportion of the phytoplankton population would be lost to sea. As a result, there would be less loading of the sediments with organic matter when the diatoms blooms collapsed, and less release of phosphorus for the growth of *Nodularia* and other species of phytoplankton in spring and summer. Sediment phosphorus release to the water column was also expected to decrease due to reductions in periods of low oxygen levels.

It was predicted that the phytoplankton community in the PHES would become more dominated by marine species, but that *Nodularia* blooms would continue to occur in suitable regions of the lower reaches of the rivers.

6.1.3 Observed effects of the Dawesville Channel

No *Nodularia* blooms occurred in Peel Inlet or Harvey Estuary between 1994 and 1998 and phytoplankton biomass in the PHES — as measured by chlorophyll a levels — decreased overall (see Chapter 5). This suggested that the high nutrient levels associated with river inflow were rapidly lowered due to oceanic exchange. Diatoms dominated the phytoplankton communities in the PHES throughout the year, although the species previously typical of the winter diatoms were confined to a much shorter period and species more commonly found in marine salinities were prevalent (Chase 1995).

Although no *Nodularia* blooms occurred in Peel Inlet or Harvey Estuary, they occurred in the Serpentine River from late spring to the end of summer in 1994/95, 1995/96 and 1996/97. Blooms of blue-green algae (mainly *Nodularia*, but also *Anabaenopsis, Merismopedia, Oscillatoria, Anabaena* and *Microcystis*) and dinoflagellates (during summer and autumn) dominated in the Serpentine River, and blooms of the Haptophyte *Prymnesium*, which can be lethal to fish, also occurred in April/May 1997. In the Murray River diatom blooms predominated in summer and autumn, but the potentially toxic dinoflagellate species *Alexandrium minutim* was detected in moderate densities in February 1996.

The occurrence of dinoflagellate blooms in the lower reaches of the Serpentine River and — to a far lesser extent — the Murray River (including a potentially toxic species), and the continued occurrence of *Nodularia* blooms in the Serpentine, indicated that conditions favourable to toxic phytoplankton blooms occurred regularly in the lower reaches of these rivers. These changes may not all be due to the opening of the Channel, as catchment monitoring studies indicate that nutrient inputs to some parts of the Serpentine may have increased (see Section 5.1).

6.2 Macroalgae

Changing water salinities ensure that estuaries typically have far fewer species of macroalgae than coastal areas. Estuarine conditions favour euryhaline species of macroalgae (i.e. species that tolerate a broad range of salinities), the majority of which belong to two phyla: red algae (Rhodophyta) and green algae (Chlorophyta) (Day 1981). Brown algae (Phaeophyta) generally do not tolerate salinities less than marine levels. As with phytoplankton, the prevailing conditions of light, temperature, salinity and nutrient supply determine which species predominate. For example, red algae are generally more competitive under conditions of low light supply (i.e. turbid water) and marine salinities; some species of green algae are capable of extremely fast growth rates under conditions of high nutrient supply; and brown algae are favoured by conditions of low nutrient supply and marine salinities (Lavery *et al.* 1995).

6.2.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel large macroalgal accumulations were a feature of Peel Inlet

(Plate 1), but the number of species was low even by estuarine standards. This is because most species of macroalgae require a hard surface to grow on, and the predominantly sandy or muddy floor of the PHES offered few attachment sites. Furthermore, few species of macroalgae could tolerate the extremes of salinity that occurred in that environment.

Nutrient enrichment of the PHES affected both the species composition and the amount of macroalgae. Between the 1960s and the opening of the Channel the macroalgal community was dominated by different species of opportunistic green algae, mainly *Cladophora*, *Chaetomorpha*, *Ulva* and *Enteromorpha* (Lavery *et al.* 1995). Harvesting of macroalgal accumulations from the shores and shallows of Peel Inlet commenced in the 1970s, and harvesting of drifting wracks of algae using conveyor harvesters in deeper water (greater than half a metre) commenced in 1984 (Plate 2). This was originally carried out as a cosmetic exercise, but in later years was used as a management tool to minimise the development of large accumulations of macroalgae that might get washed ashore or block navigation channels (Rose, *pers. comm.*).

Large macroalgal accumulations, mainly of *Cladophora montagneana*, were first noticed in the Peel Inlet in the 1960s, and reached their highest levels in the 1970s. Measurements of macroalgal biomass and species composition in the PHES were carried out at least once a year between 1978 and 1994, with the exception of 1980 and 1983 (Lavery *et al.* 1995), and estimated total macroalgal biomass was generally in the range 5000 — 20,000 tonnes, although it reached 60,000 tonnes in 1979.

The initial appearance of the *Cladophora* accumulations was linked to above-average river flows coupled with high fertiliser applications in the catchment, and therefore high nutrient inputs, between 1963 and 1968. *Cladophora* dominated Peel Inlet until 1979, then underwent a dramatic decline in biomass (Lukatelich & McComb 1985).

From 1979 until the opening of the Dawesville Channel there were considerable fluctuations in macroalgal biomass, and one of *Chaetomorpha linum*, *Ulva rigida* or *Enteromorpha* species (principally *E. intestinalis*) would be dominant, with occasional periods of co-dominance (Lavery *et al.* 1995). Nutrients and light were the main factors limiting their growth (Lavery *et al.* 1995 and references cited therein), with *Chaetomorpha* more competitive during periods of lower nutrient conditions and *Ulva* and *Enteromorpha* during periods of higher nutrient availability. Maximum macroalgal biomass was generally attained in late summer/early autumn: although nutrient concentrations were more favourable for growth in spring, water clarity and salinity were seldom so. Total macroalgal biomass was strongly linked to water clarity over the summer period, with high macroalgal biomass recorded in years of high water clarity.

The influence of nutrient and light conditions in determining macroalgal abundance was less clear in the 1990s. River flows and nutrient inputs in 1991 and 1992 were average or above average, yet *Chaetomorpha* was dominant. The inference was that nutrient concentrations were declining more quickly after the cessation of winter runoff, and one potential explanation offered for this was improved flushing of Peel Inlet due to the dredging of the Sticks Channel in late 1987. After a low river flow in the winter of 1993, the macroalgal biomass in the summer/autumn of 1994 was the lowest recorded up till then, with *Chaetomorpha* dominant. The conclusion drawn was that the overall nutrient status of Peel Inlet had declined as a result of improved flushing and/or reduced phosphorus loss from the catchment due to the catchment management program, and that the low macroalgal biomass was due more to low nutrient supply than to light availability (Lavery *et al.* 1995).

6.2.2 Predicted effects of the Dawesville Channel

With the opening of the Dawesville Channel, the species richness (i.e. number of different species) of macroalgae present in the PHES was expected to increase due to increased recruitment of algal propagules from the ocean, improved water clarity and the more marine salinity regime (Lavery *et al.* 1995). While it was expected that *Chaetomorpha* would initially be dominant, the importance of red and brown algae in the macroalgal community was predicted to increase in the long term (Lavery *et al.* 1995).

Predictions of the effect of the Dawesville Channel on amounts of macroalgal accumulations were less certain. Originally it was anticipated that the expected improvement in water clarity — while the nutrient status of the Peel Inlet was still relatively high — would cause a continuation and even an increase in macroalgae in the short-term, but that the ongoing reduction in phosphorus availability would see a decline in the long-term (EPA 1988). The possibility was also raised of improved light conditions causing increased macroalgal growth in the Harvey Estuary, in the deeper waters of the estuarine system and in the lower reaches of the Murray and Serpentine Rivers (Waterways Commission 1994). However, the improved flushing of Peel Inlet due to dredging the Sticks Channel did not cause an increase in macroalgal growth (see Section 6.2.1); thus there was uncertainty about whether macroalgal levels in the short term would be as high as originally expected (Lavery *et al.* 1995).

6.2.3 Observed effects of the Dawesville Channel

After the opening of the Dawesville Channel *Chaetomorpha* was dominant from spring 1994 to spring 1996, but in the summer and autumn of 1997 red and brown algae comprised over 50% of total macroalgal biomass. The predicted increase in species richness of the macroalgal community occurred, while 1997 data indicated that the increased importance of red and brown algae (to total macroalgal biomass) was occurring sooner than predicted.

The majority of macroalgal biomass remained in the shallows of Peel Inlet, particularly the south-eastern shoreline. Large accumulations of *Chaetomorpha* and red algae also occurred near Island Point in Harvey Estuary up to autumn 1996, but these were not present from spring 1996 to autumn 1997: instead, accumulations of *Cladophora montagneana* occurred at a site 2 km further north of Island Point. Macroalgal biomass was low in the deeper waters of Peel Inlet and Harvey Estuary, and largely consisted of red algae.

Prior to the opening of the Dawesville Channel, macroalgal biomass generally peaked in late summer/early autumn. After the opening, peak biomass occurred in spring. This change was attributed to an improvement in water clarity during that season.

Total macroalgal biomass in Peel Inlet was around 15,000 tonnes in spring 1994 and summer 1994/95, remained around 5000 tonnes until autumn 1996, but declined to around 3000 tonnes in spring 1996 and 2000 tonnes in summer 1996/97 — the lowest ever recorded (Wilson *et al.* 1997b) (Figure 6.1). Both 1994 and 1995 were years of low rainfall and low nutrient input, and the levels of macroalgal biomass were not significantly different to those measured in years of low rainfall before the opening of the Channel. However, 1996 was a year of average rainfall, and macroalgal biomass was very low: the prediction that it might increase with the improved water clarity following the opening of the Channel was not realised. Available data indicated that the opening had decreased nutrient availability for macroalgal growth in Peel Inlet.

6.3 Seagrasses

Seagrasses are essentially marine plants, and they are quick to die back if salinities fall below about three-quarters of marine levels and/or turbidity is too high. A few species of seagrass are found in the more marine parts of south-western Australian estuaries, while quick-growing species such as *Halophila ovalis* often penetrate further into estuaries but are present intermittently, only becoming prolific in those months when marine salinities prevail and water clarity is suitable (Kirkman & Walker 1989).

As a group, seagrasses are also intolerant to eutrophication (Shepherd *et al.* 1989). The principal cause of their intolerance appears to be light-related: they are effectively shaded out by the proliferations of macroalgae, epiphytes (algae that grow attached to seagrasses) and phytoplankton that develop in nutrient-enriched conditions.

6.3.1 Prior to the opening of the Dawesville Channel

The most common seagrass in the PHES prior to the opening of the Channel was the small species *Halophila ovalis*, which is more tolerant of low salinities (down to about half marine salinity) and low light supply (and therefore turbid waters) than other species (Hillman *et al.* 1995). Small beds of the less tolerant *Zostera mucronata* occurred near the entrance of the Mandurah Channel and *Heterozostera tasmanica* near the Sticks Channel, where conditions were more marine. The aquatic angiosperm *Ruppia megacarpa* was also common, mainly in Austin Bay and Robert Bay. *Ruppia* is not a seagrass in the strictest sense — it flowers on top of the water rather than under water — but it is usually included as one: it has an extremely broad range of salinity tolerance, from essentially freshwater to hypersaline conditions.

Anecdotal evidence suggested that before the 1960s *Ruppia megacarpa* was prolific on the shallow fringes of both Peel Inlet and Harvey Estuary, and *Halophila ovalis* was common in the slightly deeper waters of the central basin of Peel Inlet (Kinhill Engineers 1988). With the appearance in the 1970s of large macroalgal accumulations and *Nodularia* blooms, the extent of *Halophila* and *Ruppia* in Peel Inlet apparently declined considerably, and seagrasses disappeared from Harvey Estuary.

6.3.2 Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in a number of changes favourable to seagrasses, including a less extreme salinity regime, maintenance of marine salinities for longer periods, improved water clarity and less algal smothering. Accordingly, it was anticipated that *Halophila* would expand its distribution, both *Halophila* and *Ruppia* would move into deeper waters, existing patches of Zostera and Heterozostera in and near the Mandurah Channel would expand, and *Heterozostera* beds would establish near the entrance of the Dawesville Channel. However, stands of *Ruppia* were also expected to disappear from the shallow margins of Austin Bay and Robert Bay, regularly exposed due to increased tidal fluctuations.

6.3.3 Observed effects of the Dawesville Channel

Results of seagrass monitoring carried out after the opening of the Dawesville Channel generally confirmed the above predictions. *Halophila* stands in Peel Inlet consistently maintained high biomass in summer and autumn, and stands in the northern half of Harvey Estuary expanded. The presence of *Halophila* in deeper waters of the Harvey Estuary was also recorded for the first time, and patches of *Heterozostera tasmanica* established near the entrance of the Dawesville Channel. Stands of *Ruppia* were still present in Austin Bay, but it was not possible to determine whether there were losses from the shallow fringes, as no sites were monitored in these areas.

6.4 Fringing vegetation

In the PHES the fringing vegetation (often called salt marsh) occupies the upper part of the tidal zone from about mean water level to just above extreme high-water mark. The PHES has only three areas of extensive fringing vegetation: on either side of the Mandurah Channel (which includes the Creery wetlands, Plate 3), along the eastern side of Peel Inlet and around the Harvey delta. Only a narrow fringe of wetland exists elsewhere. Narrow fringing marshes also border the Serpentine River, including Goegrup Lake (Plate 4) (McComb *et al.* 1995).

Salt marshes are usually typified by well-defined zones, each with its characteristic species composition. The two main factors influencing the distribution of saltmarsh plants are usually the salinity of foreshore waters and the level of inundation by tidal and flood water. The most influential factor is tide, which usually sets the upper and lower limits of the fringing vegetation. As the elevation of the marsh surface increases, the frequency of flooding tides decreases, and salt marsh is often divided into two zones: the lower (or intertidal) marsh, which is flooded almost daily, and the upper (or high) marsh, which is flooded irregularly (McComb *et al.* 1995).

6.4.1 Prior to the opening of the Dawesville Channel

A comprehensive study based on aerial photographs taken between 1957 to 1994 on the salt marshes of the PHES and the Serpentine River was carried out before the opening of the Dawesville Channel (McComb *et al.* 1995). This study found that they were extremely dynamic and variable. Between 1957 and 1994 the general trends for the whole study area were:

- a significant loss of saltmarsh area between 1965 and 1986, consisting of a rapid decline between 1965 and 1977 (due to permanent breaching of the Mandurah Channel) and a slower rate of loss between 1977 and 1986 (due to human disturbance);
- an arrest in the loss of salt marsh area between 1986 and 1994.

Exceptions to the general trends were the Harvey delta and Austin Bay areas, which showed steady increases in salt marsh cover between 1977 and 1994, and the Lakes area (including Goegrup Lake), which showed a marked decline in area between 1986 and 1994. The rate of loss in the Lakes area also appeared to be increasing, but the cause of the decline was not clear. The main *qualitative* change was a continuing decline in the cover continuity of the Creery wetlands between 1957 and 1994. The Creery wetlands is the largest single area of salt marsh in the PHES, and it clearly showed increasing damage from human access, particularly in the form of vehicle tracks.

6.4.2 Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in an increased intertidal area, with the upper intertidal areas submerged more frequently but for reduced periods, and the lower intertidal areas exposed more frequently but for reduced periods. Salinities would also be more marine for most of the year, and periods of hypersalinity in late summer and autumn were expected to disappear.

The response of fringing vegetation to the predicted changes in salinity levels and/or inundation patterns was expected to be one of gradual change (i.e. over periods of years) in species composition and in the extent of the zone occupied. These changes in inundation patterns were expected to have little effect on the lower salt marsh, the majority of which was already inundated regularly for most of the year. The *Sarcocornia* species that dominate the lower marsh are furthermore very resilient, and were unlikely to be adversely affected by increased tidal energy. With regular inundation predicted to occur at slightly higher elevations, it was also anticipated that the *Sarcocornia* complex would extend its distribution landwards, and this would be noticeable over a wider area in the flatter marshes. There was also the possibility that these plants would be adversely affected by macroalgal smothering, due to increased tidal range and frequency, if macroalgal populations increased in the short term (McComb *et al.* 1995).

6.4.3 Observed effects of the Dawesville Channel

Very little on-ground monitoring of fringing vegetation was carried out before the Dawesville Channel opened; afterwards a monitoring program was undertaken that consisted of the following components:

- monitoring of salt marsh at various locations around the PHES on Department of Conservation and Land Management (CALM) land;
- monitoring of seasonal freshwater wetlands in the Austin Bay Nature Reserve which have rare freshwater aquatic plants in areas that were thought might be susceptible to ingress of salt water during storm surges;
- monitoring of riverine vegetation, river bank tree health and *Typha* patch dynamics along the lower 4 km of the Harvey River to detect any changes due to the expected increase in penetration of salt water upstream as a result of the tidal change and the more marine salinities.

In addition to the monitoring program, a study was undertaken using airborne Digital Multi-Spectral Video (DMSV) to map the peripheral vegetation of the PHES and Serpentine and Murray Rivers (Glasson *et al.* 1996). This remote sensing technique was investigated as a potentially useful tool for the documentation and analysis of changes to fringing vegetation since the opening of the Channel. Unfortunately, DSMV proved unsuitable for detailed mapping of large areas: the technique produced massive data sets that were difficult to store and manipulate, and mosaicing of video images to complete a composite scene was extremely time-consuming.

The results of salt marsh monitoring did not indicate any consistent pattern in changes in species cover from 1994 to 1995 (Gibson 1997). The historical review of aerial photography described in Section 6.4.1 (McComb *et al.* 1995) indicated that there were steady increases in salt marsh cover at Austin Bay and the Harvey delta between 1977 and 1994, and the data obtained to date has been consistent with this trend. There was also little change in seasonal freshwater wetlands in the Austin Bay Nature Reserve other than that consistent with year-to-year variations in environmental conditions, and there was no evidence of saltwater intrusion. Similarly, the monitoring of the riverine transects showed no immediate effect of the influence of increased salinity, however, given the nature of the vegetation any change could be expected to be gradual.

Overall, monitoring results did little other than emphasise the dynamic and variable nature of fringing vegetation: no clear effect attributable to the Dawesville Channel was apparent, although clear trends may take several more years to emerge (Gibson 1997). Interpretation of the effect of the Channel on fringing vegetation was severely hindered by the lack of baseline (i.e. pre-Channel) data (Gibson 1997). In future years there will be considerable difficulty in differentiating the influence of the Dawesville Channel on fringing vegetation from other environmental factors such as inter-annual changes in river flow and the sealevel changes caused by the presence/absence of El Nino Southern Oscillation (ENSO) events.

7. Estuarine fauna

The shallow waters of the PHES support extensive stands of macroalgae and some seagrass, and these plants, in combination with a high phytoplankton productivity, support large populations of small invertebrate animals. These include zooplankton (microscopic to small animals that live suspended in the water column, e.g. fish larvae, tiny crustaceans) and benthic invertebrates (small animals such as worms and molluscs that live on or in estuarine sediments), which are favoured food items for many fish and bird species (Day 1981). The large numbers of invertebrate fauna and the sheltered conditions in the PHES help to support valuable fisheries and important breeding and feeding grounds for waterbirds. The fringing vegetation and the shallow intertidal flats of the PHES are also important feeding and shelter areas for waterbirds.

Monitoring of estuarine fauna in the DCMP was largely confined to the most conspicuous components (to humans): fish and birds. Zooplankton numbers were not studied, and only limited monitoring of benthic invertebrate communities was carried out. A brief discussion of benthic invertebrates is presented in this chapter, but attention is focused largely on fish and birds.

7.1 Benthic invertebrates

7.1.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the benthic invertebrate fauna of the PHES was dominated by high numbers of a few species of small, fast-growing and extremely fecund organisms such as the worm *Capitella capitata* (Rose 1994). This domination by a small number of species is a classic symptom of eutrophication (Pearson & Rosenburg 1978). The benthic invertebrate community was severely stressed during *Nodularia* blooms (November to March) and the subsequent periods of anoxia, sometimes to the extent of mass mortalities occurring. As a result the density and biomass of benthic fauna peaked in autumn and winter rather than spring and summer, as is more typical. The species of benthic invertebrates that dominated the PHES had reproductive strategies and larval dispersal mechanisms that enabled them to rapidly colonise areas denuded by periods of anoxia. The success of the dominant invertebrates was also related to their ability to exploit the extra habitat and food afforded by large accumulations of macroalgae.

7.1.2 Predicted effects of the Dawesville Channel

The overall species richness of the benthic invertebrate community was expected to increase following the opening of the Dawesville Channel, due to the more stable salinity regime, the absence of *Nodularia* and the decreased frequency and duration of anoxic periods. Although the species of benthic invertebrates dominant before the Channel opened were considered likely to remain important (particularly in the short-term, if macroalgal accumulations remained large), the return was predicted of the larger, longer-lived species of polychaete worms and bivalve molluscs that are typical of adjacent, less eutrophic estuaries such as Leschenault Inlet and the lower reaches of the Swan/Canning Estuary.

The opening of the Channel was expected to allow increased recruitment of marine organisms into the PHES throughout the year, while the more marine salinity regime would enable these species to compete more effectively against euryhaline species. Brackish and freshwater species were expected to retreat further upstream in the rivers.

The increased tidal range was expected to inundate areas previously exposed and expose areas previously inundated, while inundation of the intertidal zone would be more frequent, thereby creating a less extreme environment, particularly in summer. Thus, the opening of the Channel was expected to result in the loss of a small proportion of subtidal habitat and the creation of a larger area of intertidal habitat, while a greater proportion of the intertidal habitat would have less extreme conditions and therefore greater invertebrate abundance and species richness (PIMA 1994).

7.1.3 Observed effects of the Dawesville Channel

Post-Dawesville sampling of shallow-water benthic fauna was carried out by the WRC once a year (in summer) at three sites along the western side of the

PHES — Dawesville, Island Point and Cox Bay. Although data have not been fully processed, initial impressions are that the dominance of *Capitella capitata* has decreased and the abundance of larger longer-lived worms such as *Ceratonereis* species and *Leitoscoloplos normalis* have increased. Large numbers of the mollusc *Arthritica semen* were also observed in northern Peel Inlet (Rose, *pers. comm.*).

7.2 Fisheries

The PHES is the most important commercial estuarine fishery (by weight of catch) in Western Australia, and it is also heavily utilised for recreational fishing. The fish and crustaceans found in the PHES constitute three main groups:

- euryhaline species that spend their entire life cycle in estuaries (e.g. black bream, yellow tail trumpeter and school prawns);
- marine species that enter the estuary as juveniles and mature there during periods of high salinity (e.g. crabs, king prawns, yellow-eye mullet, cobbler, whiting, mulloway and tailor);
- marine species that enter the estuary occasionally and usually in low numbers and when salinities are essentially marine (e.g. the western school whiting).

In the following discussion the term 'fish' includes the important crustaceans such as large prawns and crabs as well as fin fish.

7.2.1 Prior to the opening of the Dawesville Channel

Approximately 60 species of fish were documented as occurring in the PHES before the opening of the Channel, the majority of these being marine species that entered the system as juveniles. Species richness was generally highest during the summer months when marine salinities prevailed and juveniles were recruited into the estuary (Kinhill Engineers 1988).

The bulk of the commercial catch was made up of five species (Steckis 1991): yellow-eye mullet (*Aldrichetta forsteri*), sea mullet (*Mugil cephalus*), western king prawn (*Penaeus latisulcatus*), blue manna crab (*Portunus pelagicus*) and cobbler (*Cnidoglanis macrocephalus*). Recreationally important species included blue manna crab, king prawn, cobbler, whiting (*Sillaginodes punctata*) and tailor (*Pomatomus saltator*).

The two algal symptoms of eutrophication in the PHES appeared to affect the fisheries differently. The macroalgal accumulations were strongly associated with an increase in fish catches, particularly in the 1970s, and Steckis (1991) attributed the high abundance of sea mullet, cobbler and yellow-eye mullet to the abundance of macroalgae, which provided both shelter from predators and an abundant supply of food (i.e. benthic invertebrates). The western king prawn, however, appeared to be adversely affected by accumulations of the macroalgae *Cladophora* and *Ulva*, possibly because these covered the substrate into which juvenile prawns burrowed (Potter *et al.* 1991).

Benthic fish and crabs were believed to be adversely affected by *Nodularia* blooms, and many fish species avoided bloom-affected areas (Lenanton *et al.* 1985). There was also evidence to suggest that species richness was lower during those summers that had intense *Nodularia* blooms. On occasion, the anoxic conditions associated with *Nodularia* blooms caused fish kills (Hesp *et al.*, in preparation). *Nodularia* also had a major effect on fishing activities in the PHES: haul netting was the preferred fishing technique of commercial fishers, but was precluded during intense *Nodularia* blooms because it relies on visual detection of fish schools. Commercial fishermen also concentrated their activity in Peel Inlet rather than Harvey Estuary because they were convinced that there were fewer fish in bloom-affected areas. Nonetheless, these effects were highly localised, and the presence of *Nodularia* did not appear to affect fish abundance in the PHES as a whole (Steckis 1991).

7.2.2 Predicted effects of the Dawesville Channel

The Dawesville Channel would provide another route for recruitment of fish from the ocean. This factor, along with a more marine salinity regime, was expected to result in an increase in recruitment of those species which mature or only occur at marine salinities. Estuarine species were not expected to be greatly affected, because they tolerate a broad range of salinities. However, the more stable salinity regime was expected to impact negatively on the juveniles of sea mullet, which prefer low salinity conditions. It was therefore predicted that there would also be less adult sea mullet in the system.

The improved water quality and the absence of *Nodularia* blooms were expected to be beneficial to fish communities, particularly to benthic fish and crabs, and the reduced frequency and duration of anoxic conditions were expected to result in fewer fish kills. Higher salinities were also expected to be beneficial to crabs, which prefer marine salinities.

However, the distribution pattern of the western king prawn indicated that it was correlated with slightly hypersaline conditions. It was predicted that improved flushing following the opening of the Channel would reduce the occurrence of hypersaline conditions and therefore make the PHES less suitable to this species. It is now known that the occurrence of western king prawns in slightly hypersaline areas was coincidental rather than a deliberate choice. School prawns (*Metapenaeus dalli*), which moved into the Murray River to breed in the summer months, were not expected to be adversely affected by estuarine salinity changes.

The effect of changes in macrophyte abundance on fish communities was also uncertain. The distribution pattern and densities of macroalgae and seagrass were expected to change, possibly from a macroalgal-dominated system to a seagrass-dominated system in the long term, but the PHES was still expected to be characterised by extensive macrophyte stands (see Section 6.1.2).

The more regular tidal exposure of shallow feeding areas was not expected to favour certain fish, crabs and prawns, and, if the predicted increase in macroalgal levels in the short term occurred, it was anticipated that there would be increased mortality of benthic species such as crabs and cobbler due to increased levels of macroalgal harvesting particularly of juveniles caught up in harvested macroalgae. It was also predicted that fishing pressure would increase in the PHES as it became more recreationally attractive due to improved water quality.

7.2.3 Observed effects of the Dawesville Channel

Post-Channel data indicated that compared with predictions, the Dawesville Channel resulted in a far earlier recruitment of juvenile western king prawns and juvenile crabs into Harvey Estuary, and their retention in Harvey Estuary for a far longer period, presumably due to the maintenance of marine salinities for longer periods (unpublished Fisheries Research Development Council grant milestone report). The maximum densities of prawns and crabs in Harvey Estuary were far higher compared to data from pre-Channel years. Completely unexpected was the fact that prawns and crabs left Peel Inlet at a smaller size than before the opening of the Channel. This outcome may simply be an effect of the Dawesville Channel allowing a much more rapid return to the ocean.

Comparison of post-Channel (1996-97) data from the fish-sampling program with available pre-Channel (1979-81) data was complicated by average freshwater discharge in the winter of 1996, which resulted in a protracted period of low salinities from May to September in 1996 compared to conditions of low freshwater discharge in 1979-81. Although it was not possible to fully gauge the impact of the Dawesville Channel, it appeared that marine species of fish such as blowfish (*Torquigener pleurogramma*) were far more abundant and penetrated further south into the Harvey Estuary. There was also evidence that the proportion of marine fish species in the PHES was higher. Six-lined trumpeter (*Pelates sexlineatus*) and gobbleguts (*Apogon rueppellii*) were, however, far less abundant. The latter two species are typically most abundant in dense macroalgal accumulations (Loneragan *et al.* 1986), and may have been adversely affected by the disappearance of dense *Cladophora* stands from Peel Inlet by the early 1980s rather than by the opening of the Dawesville Channel.

In 1996-97 mean numbers of fish species per sample in Peel Inlet and northern Harvey Estuary were lower compared to 1979-81, but higher in its southern half (Figure 7.1a). Mean density of fish per sample in Peel Inlet was lower in 1996-97 compared to 1979-81, similar in northern Harvey Estuary and higher in southern Harvey Estuary (Figure 7.1b). The lower numbers of species and fish densities in Peel Inlet were probably due to the reduction of macroalgal levels there.

Catch per unit effort (CPUE) data from the commercial fishery provided further evidence that crabs continued to be abundant. However, commercial catches of western king prawn, based on beamtide trawling in the Mandurah Channel, declined dramatically even though prawns were still abundant in the PHES. Large numbers of prawns were observed emigrating out through the Dawesville Channel, where strong currents make it very difficult for commercial fishers to use their beamtide trawls.

CPUE data for the period from May 1989 to April 1996 also indicated:

- a higher abundance of cobbler, sea garfish, Australian herring and western sand whiting since the opening of the Dawesville Channel;
- little change in the abundance of sea mullet, yellow-eye mullet, tailor, King George whiting and blue manna crabs.

7.3 Birds

The PHES is an internationally significant habitat for waterbirds, as recognised by its listing as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia 1990). Tens of thousands of waterbirds gather on the PHES each year, and over 80 species have been recorded, 27 of which are listed on the Japan-Australia Migratory Birds Agreement (JAMBA) and China-Australia Migratory Birds Agreement (CAMBA).

Estuarine waterbird communities vary considerably throughout the year. Resident species are present all year round, whereas migratory species are present for only part of the year — mainly spring and summer in southwestern Australian estuaries (Wykes 1990). The majority of waterbirds found in the PHES can be broadly grouped into the following categories (EPA 1988):

- migratory waders (sandpipers, plovers, stilts and stints), which feed on benthic invertebrates in intertidal areas at low tide;
- resident waders (banded stilts, black-winged stilts, red-capped plovers), which are usually found in shallow inland non-tidal wetlands and rarely in estuaries with marked tidal influence;
- long-legged waders (herons, egrets, oystercatchers, ibises and spoonbills), which feed on fish and benthic invertebrates in shallow waters;
- fish-eating birds (e.g. pelicans, cormorants, terns and grebes), which occur year round and fish in deeper waters than waders;
- waterfowl (ducks, swans, coots and swamp hens), which feed mainly on large aquatic plants (especially the seagrass *Ruppia* and some species of macroalgae) and are found year round providing there is access to low-salinity water for drinking;
- gulls, which are omnivorous scavengers.

The majority of these groups roost on sandy spits and cays, or in the fringing vegetation (salt marsh and trees) of estuaries. Few species breed in estuaries, and those that do (pelicans, swans, Pacific black ducks, grey teal, Australian shelducks) tend to build their nests on low-lying islands or in undisturbed areas of fringing vegetation.

7.3.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the PHES was considered somewhat unusual in that it had large populations of resident waders (e.g. the banded stilt), presumably due to the lack of tidal variation in the system. The system was also particularly favourable to small species of waders due to the extensive areas of extremely shallow waters that persisted for many days. The shallow areas were believed to be very important for pre-migratory fat deposition in late summer/early autumn, as feeding opportunities between the PHES and Shark Bay are limited at this time of year (Waterways Commission 1994). The PHES also regularly supported larger numbers of pelicans than any other waterbody in the southern half of the State: it was one of only two pelican breeding sites south of Shark Bay and one of the most significant habitats for black swans in Western Australia (Lane *et al.* 1997).

7.3.2 Predicted effects of the Dawesville Channel

The main factors likely to affect waterbird numbers in the PHES due to the opening of the Dawesville Channel were identified as follows:

- alterations in tidal amplitude causing the inundation of sandy cays and spits and changes to fringing vegetation, which would affect the roosting, breeding and feeding patterns of those species of waterbirds that use these areas;
- changes in food sources for waterbirds (seagrasses, macroalgae, benthic invertebrates and fish);

- the expected increase in recreational boating (see Chapter 9) and boat access into shallow areas during high tides, which would disturb those species of birds that favour quiet sections of the PHES.

The exact impacts of these changes — positive or negative — were not easy to predict, largely because predictions about changes in habitat availability (for roosting, breeding and feeding) and food sources were also uncertain. However, pelican nesting success on low-lying islands in the PHES was identified as a potential concern, and the altered tidal regime caused by the Dawesville Channel was not expected to be favourable to resident waders (banded stilts) if their feeding opportunities were limited or interrupted. Migratory waders were not expected to be adversely affected by the altered tidal regime: these feed during receding, low or advancing tides and utilise estuaries in other parts of the world that have greater tidal ranges than the PHES.

Another area in the PHES of particular concern was the southern end of the Harvey Estuary, including the Harvey River delta and lower Harvey River. This area was a near-ideal dry-season refuge for waterfowl, as it was relatively secluded, sheltered by stands of swamp sheoak, swamp paperbark and flooded gum, had a year round supply of fresh water for drinking, and was in close pro(imity to extensive shallows for feeding and loafing (Lane *et al.* 1997). Changes in salinity regime and tidal heights due to the opening of the Dawesville Channel had the potential to alter both the fringing vegetation and freshwater drinking supplies.

Changes in food sources were considered a lesser concern, as most species of waterbirds are opportunistic feeders of invertebrates and fish: the availability of these food sources was not expected to decline, even though the species composition might well change. However, changes in the species composition, distribution or productivity of the submerged macrophyte beds (particularly *Ruppia*) had the potential of reducing available black swan food sources. Increased tide heights also had the potential to affect swan numbers by allowing increased boating access to feeding, loafing and moulting areas that in the past have been little disturbed: swans are particularly vulnerable to human interference during their annual moulting period as they are then unable to fly.

7.3.3 Observed effects of the Dawesville Channel

Assessment of waterbird use of the PHES after the opening of the Dawesville Channel included surveys of all species plus specific monitoring exercises addressed to the following area of concern:

- pelican nesting activity and success;
- numbers of pelicans;
- numbers of black swans;
- salinity changes and waterbird use in the upper Harvey Estuary, Harvey River delta and lower Harvey River;
- numbers of banded stilts;
- waterbird roost sites: elevation measurements of three major roost sites at Herron Point Ford, Point Birch and Nirimba Cay were carried out to decide the need for 'topping up' of old roosting sites or the creation of new ones.

As for fringing vegetation surveys (see Chapter 6), one of the major problems hindering interpretation of the effect of the Channel on waterbird use in the PHES was the lack of baseline data (Lane *et al.* 1997). Comparisons had to be made with data collected in the mid-1970s, when environmental conditions were quite different to the early 1990s. Another potential problem in interpreting changes due to the opening of the Channel was compounding effects of wetland degradation by other human activities (such as use of trail bikes and four-wheel-drive vehicles), increased boating activity in the PHES and increased urban development around the shores of the estuary.

Data on the surveys of all waterbird species are still being processed, but strong impressions were gained that:

- little egrets (*Egretta garzetta*) were more numerous and widespread (reflecting a general trend in southwestern Australia);
- there was no decline in numbers of eastern curlew (*Numenius madagascariensis*), a species rarely observed elsewhere in southwestern Australia;
- curlew sandpipers (*Calidris ferruginea*) were far less abundant in 1996-97 than in 1976-77, although it was uncertain whether this was due to Channel effects or variations in numbers migrating to Australia.

The findings of the more specific monitoring exercises were as follows:

- a previously successful summer breeding site for pelicans (*Pelecanus conspicillatus*) on Nirimba Cay was lost due to inundation, and there was no pelican breeding on Creery and Boodalan Islands, in this case due to excessive disturbance (boating activity, people, dogs, foxes); however, pelican breeding on Boundary Island in the last three years appeared sufficient to maintain total pelican numbers at roughly the levels determined by surveys conducted between February 1975 and November 1976 (Lane *et al.* 1997);
- black swan (*Cygnus atratus*) counts in October, December and February 1975-77 varied considerably (2162-8057), but were generally far greater than in 1996-97 (472-1052): the reasons for the decline are unknown, but may include variations in macroalgae abundance and distribution, a matter that is being investigated;
- results are still being processed from the studies on salinity measurements and waterbird use in the upper Harvey Estuary, Harvey River delta and lower Harvey River, on banded stilt (*Cladorhynchus leucocephalus*) numbers and on waterbird roosting sites.

8. Human health issues

Apart from the presence of *Nodularia* blooms, the main human health concerns in the PHES prior to the opening of the Dawesville Channel were:

- infection with Ross River virus (RRV) or Barmah-Forest virus (BFV) via bites from mosquitoes carrying the viruses;
- odours from rotting algae (phytoplankton and macroalgae).

By far the more serious of these two concerns was risk of infection with RRV or BFV, which have the potential to cause severe debilitating and persistent disease in humans. Ross River Virus causes the disease epidemic polyarthritis in humans, the symptoms of which include joint pain and swelling and lethargy that can last for many months or years after the initial infection. Barmah-Forest Virus causes a similar disease, although there is some evidence that the symptoms are milder.

8.1 Mosquitoes

8.1.1 Prior to the opening of the Dawesville Channel

Salt marshes are breeding-grounds for a number of species of mosquitoes, and, prior to the opening of the Channel fringing salt marsh occupied about 10% of the total area of the PHES. The surrounding region was identified as having a severe saltmarsh mosquito problem as early as 1985 (Wright 1988). In addition, the Peel Region was known to be a major focus of two mosquito-borne viruses that cause human disease: RRV and BFV (Lindsay *et al.* 1992, 1995; Jasinska *et al.* 1997). The mosquito Aedes camptorhynchus was the major vector of RRV and BFV in the Peel Region. It breeds in salt marsh and brackish wetlands, predominantly from winter through to spring.

Aedes vigilax also carried RRV in the Peel Region, although to a lesser extent. It is known as the summer saltmarsh mosquito because it breeds in salt marshes in the warmer months. Numbers of this species were generally low, apart from two occasions — Peel Inlet in February 1989 and Harvey Estuary in March 1990 — which both followed severe cyclonic activity off the Western Australian coast (Jasinska *et al.* 1997). *Aedes vigilax* is considered a nuisance species even aside from potential RRV infection, because it is a vicious biter and can travel long distances — regularly up to 10 km and occasionally up to 100 km — from its breeding sites (Jasinska *et al.* 1997).

Mosquito control throughout the Peel Region was undertaken jointly by the Health Department of Western Australia (HDWA) and the Peel Region Contiguous Local Authority Group (CLAG), and consisted of the following components:

- Aerial application of larvicide-coated sand granules dropped from a helicopter one to four times between September and April (HDWA). The warmer months of the year are the period of most prolific growth of mosquitoes as well as the major activity period for RRV and BFV. Human exposure to biting mosquitoes is also greatest during the warmer months, thus increasing the adverse health and nuisance impacts of mosquitoes at this time of year.
- Monitoring of mosquito larvae in salt marshes every two to three days to determine appropriate times to apply larvicides (CLAG).
- Monitoring of adult mosquito populations and their infection rates with RRV and BFV (HDWA via the Department of Microbiology at the University of Western Australia).
- Public education (HDWA).

Aedes camptorhynchus comprised about 70% of the total adult mosquito population in the Peel Region prior to the opening of the Dawesville Channel, and was the main species targeted by larvicide application. Aerial application of larvicide as a mosquito control measure commenced in 1988/89, but was not required on a frequent and widespread basis until the spring/summer of 1994/95 (after the Dawesville Channel was opened). In the summer of 1988/89 populations of this species persisted into summer, and there was an associated outbreak of RRV. This outbreak was attributed to frequent inundation of breeding sites caused by a short-term rise in sea level off the coast of Western Australia as a result of strengthening of the Leeuwin Current after an El Nino/Southern Oscillation (ENSO) event (Lindsay *et al.* 1992).

8.1.2 Predicted effects of the Dawesville Channel

It was recognised that more frequent and widespread tidal inundation of salt marsh would occur when the Dawesville Channel was opened, which would result in increased frequency of inundation of breeding areas for salt marsh mosquitoes (Kinhill Engineers 1988) as well as an extended breeding season for *Aedes camptorhynchus* into summer. It was expected that an increased level of effort in the mosquito control program would be required to achieve effective management.

8.1.3 Observed effects of the Dawesville Channel

After the opening of the Dawesville Channel aerial application of larvicide increased to 15 to 18 times per season. Compared to pre-Channel conditions, overall adult mosquito numbers decreased, but larger numbers of adult *Aedes camptorhynchus* were detected in the summer of 1995/96, and there was a marked increase in the numbers of adult *Aedes vigilax* in the summers of 1994/95, 1995/96 and 1996/97 (Figure 9.1). These increases occurred despite the massive increase in larvicide application and their relative success (72.5%-82.5% average larval kill rates for the three seasons). *Aedes vigilax* may now be the major vector of RRV in the Peel Region.

As the use of larvicides adversely affects non-target organisms as well as mosquito larvae, the HDWA (via the Department of Environmental Science at Murdoch University) investigated the effectiveness and environmental impact of runnels in the salt marsh as a mosquito control measure. Significant reductions in larval mosquito populations were achieved using runnels (via increased water exchange and access for predators), especially in spring and summer (Latchford 1997). Furthermore, the runnels had low maintenance requirements (removal of minor siltation at runnel entrances and the cutback of vegetation after summer), and minimal impacts on the surrounding vegetation, although the latter was only monitored for one year. The feasibility of runnelling at a larger scale, and longer term impacts on adjacent fringing vegetation, remain to be determined.

The nuisance and health impacts of mosquitoes were considered greater than in pre-Channel years for two reasons. Firstly, the increased numbers of adult *Aedes camptorhynchus* and *Aedes vigilax* occurred in summer, the time of greatest human exposure to mosquito bites — and therefore RRV infection — due to increased outdoor recreational activities. Secondly, adult *Aedes vigilax* bite viciously at any time of day and travel long distances from breeding sites, and therefore their 'nuisance value' for a given number of mosquitoes is much greater than for nearly all other species.

The number of confirmed cases of RRV in the Peel Region from 1987/88 to 1996/97 is shown in Figure 9.2. Data indicated a strong link between ENSO events, adult mosquito populations and outbreaks of RRV, and this relationship appeared to apply both before and after the opening of the Dawesville Channel. During ENSO years (e.g. 1986/87 and late 1990 to late 1994) sea levels at the coast were lower due to a weak Leeuwin Current and mosquito problems were less, but the rise in sea level due to strengthening of the Leeuwin Current after ENSO events resulted in increased mosquito populations (due to increased inundation of salt marsh) and RRV outbreaks. A very strong ENSO event also occurred in 1997, and mosquito counts and confirmed cases of RRV were low (Lindsay, *pers. comm.*). However, notwithstanding the considerable influence of ENSO events, the number of RRV cases was consistently higher in post-Channel than in pre-Channel years.

8.2 Odours

8.2.1 Prior to the opening of the Dawesville Channel

Rotting algae give off offensive odours, and the hydrogen sulphide ('rotten egg' gas) and ammonia released during the decomposition process can be harmful to human health at high concentrations. While the amounts of these gases are seldom high enough to be a major health risk to humans, the smell of some species of decomposing algae (e.g. *Nodularia*, *Ulva*) is particularly nauseating and can cause headaches.

Complaints about smells from decomposing macroalgae along the shores of Peel Inlet were made to local government authorities as early as the 1960s. Anecdotal evidence indicates that the level of complaints was particularly high during the years of massive accumulations of *Cladophora* (until 1979, when *Cladophora* disappeared from the system), in years when *Ulva* was a significant part of macroalgal biomass (i.e. after years of heavy winter runoff) and in years when thick scums of *Nodularia* washed up on the shores of the estuary. Odours from decomposing *Nodularia* are considered a cause of illness by some local residents.

Complaints about weed accumulations and the associated odours were the main driving force behind the macroalgal harvesting program. Initially, harvesting was carried out manually with rakes and pitchforks (in the early 1970s), but the level of equipment used became increasingly sophisticated. Tractors and front-end loaders were used for shore harvesting from the 1970s onwards, but can only operate in water up to 10 cm deep. Offshore harvesters, which can operate in deeper waters (greater than 45 cm deep), have been in use since 1983. Annual harvesting totals varied from 15,000 to 20,000 m^3 in the middle to late 1980s, and from 5000 to 10,000 m^3 between 1990/91 and 1993/94. Harvesting was, and still is, carried out mainly along the Coodanup and Novara/Falcon foreshores, areas of the most intensive human habitation adjacent to extensive shallows.

8.2.2 Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in the cessation of *Nodularia* blooms. Macroalgal accumulations were not expected to diminish in the short term, and it was anticipated that the level of macroalgal harvesting would initially remain unchanged or even increase in response to complaints from the public.

8.2.3 Observed effects of the Dawesville Channel

After the Channel opened there was a marked decrease in the level of formal complaints about macroalgae made to the Peel Inlet Management Authority (PIMA), indicating that the public perceived a lessening of the 'weed problem'. The level of macroalgal harvesting was also less: 1300 cubic metres in 1995/96 and 1500 cubic metres in 1994/95. As noted in previous chapters, these represent data obtained during years of below average rainfall; the performance of the Dawesville Channel during wet years has yet to be gauged.

9. Social and economic uses

As noted in Chapter 1, the PHES is an important area for recreation, tourism and commercial fishing.

9.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the macroalgal problem in the PHES appeared to benefit the commercial fishery, but the excessive weed growth was perceived by locals and tourists alike as aesthetically unpleasant, malodorous and a nuisance to recreational pursuits (O'Brien *et al.* 1994). Macroalgal harvesting along beaches in the Peel Inlet was undertaken with some success, but met with a degree of criticism because it caused shoreline erosion, which in turn led to loss of fringing vegetation and also caused the death of juveniles of certain commercially important fish caught in the harvested weed, notably juvenile crabs and cobbler.

The *Nodularia* blooms were viewed as highly undesirable by commercial fishermen because they fouled nets, hindered fishing practices and were believed to deleteriously affect fish (see Chapter 7). *Nodularia* can also be toxic to mammals, and there were public health concerns (see Chapter 8). The green surface scum and peculiarly nauseating odour of *Nodularia* blooms were viewed as particularly unattractive and likely to discourage tourism, particularly boating. The business community relying on real estate was also concerned about reduced property values (O'Brien *et al.* 1994), while some property developments, e.g. at Point Grey, were disallowed by the Environmental Protection Authority due to poor water quality.

9.2 Predicted effects of the Dawesville Channel

The improvements in water quality, particularly water clarity, and loss of *Nodularia* blooms anticipated with the opening of the Dawesville Channel were predicted to benefit local residents and recreational users (EPA 1988). The Channel would also provide an extra and unimpeded access route to coastal waters, and the combination of these features was expected to result in increased recreational and tourism opportunities and improved property development possibilities. Further benefits were expected in the longer term, provided the predicted reductions in macroalgal accumulations occurred and particularly if they were replaced by seagrass meadows. There were, however, some concerns about the effects of increased urban development and population pressure on the environment (O'Brien *et al.* 1994).

While there was generally little dissent that the expected improvements in water quality would be beneficial, the public expressed concern over a number of potential impacts that were largely centred around the expected increase in tidal range, such as flooding of low-lying land at high tide, reduced boating access during periods of low tide and an increase in salt marsh areas suitable for mosquito breeding. The salt marsh mosquitoes *Aedes vigilax* and *A. camptorhynchus* are known vectors of Ross River virus, which causes epidemic polyarthritis, and predicted increases in the mosquito population were identified as a considerable health risk.

9.3 Observed effects of the Dawesville Channel

After the opening of the Channel the improvement in water quality and absence of *Nodularia* blooms in the estuary were noted by members of the public, and there were fewer complaints about weed accumulations (see Chapter 8). These changes were also perceived as favourable to tourism and property development opportunities, and property developments previously disallowed by the Environmental Protection Authority due to poor water quality (see Section 9.1) were able to proceed.

Recreational fishers reported an early crab season and that crabs were more numerous but smaller in size; however, they were moving out of the system earlier particularly via the Dawesville Channel. The situation was the same for king prawns, while school prawns were reported to have moved into the rivers in big numbers (Waterways Commission 1994). Fishing, crabbing, prawning and boating remained popular recreational activities, and the PHES was still used heavily by local residents, day visitors (particularly from the Perth metropolitan area) and holiday-makers, especially during the summer months.

Although an improvement in estuarine water quality was noted by the public, concerned residents along the Serpentine River reported extremely thick blooms of dinoflagellates that turned the water reddish brown in autumn 1995, as well as *Nodularia* blooms in the summers of 1994/95 and 1995/96. The Serpentine was closed to fishing and swimming for an extended period in the spring/summer of 1996/97. In the lower reaches of the Murray River a phytoplankton bloom turned the waters green for several months in the summer and early autumn of 1995 (Waterways Commission 1995). Associated with these blooms were occasional fish and crab deaths due to low oxygen levels in the evening and when the blooms collapsed and decomposed (Waterways Commission 1995).

There was a major outbreak of Ross River virus in the Peel Region in the summer of 1995/96 and elevated levels of RRV activity in the summer of 1994/95 (see Chapter 8). However, two major outbreaks of RRV also occurred prior to the opening of the Dawesville Channel, in the summers of 1988/89 and 1991/92. The concern was expressed that the Peel Region might now be an endemic focus (or reservoir) of RRV in the Southwest, with potential for activity of the virus, and subsequent cases of infection, in humans every spring/summer (Lindsay, *pers. comm.*). As discussed in Chapter 8, a mosquito management program coordinated by HDWA and CLAG, coupled with an intensive public education program on how to minimise exposure to mosquito bites was set up to prevent any increased incidence of RRV.

Despite the mosquito problems and poor water quality in the Serpentine and Murray Rivers, there was little apparent impact on the social and economic uses of the PHES after the opening of the Dawesville Channel. To a large extent this can be attributed to an effective public information program. The Dawesville Channel Social Impact and Public Information Program was initiated in early 1995, and was based on providing the public with up-to-date and accurate information about the Channel and changes to the estuary. A Community Reference Group was established as a link to the community, and a telephone hotline was established to answer people's queries and concerns. A series of 12 'Dawesville Topics' sheets detailing changes to the estuary were prepared; a secondary school education pack and a variety of posters, displays and media communications (radio and newspaper) were devised; and 15-20 talks were given to schools and community interest groups each year.

The pro-active approach described above meant that most community concerns were effectively dealt with in the first 12 months after the opening of the Channel. The program is due to continue until the end of 1998, and, although it is now mainly concerned with addressing public information needs, appropriate management procedures remain in place to quickly and deal effectively with any major social impact that might arise.

10. Estuarine management

Prior to the opening of the Dawesville Channel the control of macroalgal accumulations in Peel Inlet and blooms of *Nodularia* in Harvey Estuary were the principal issues confronting managers of the PHES (Hodgkin *et al.* 1980). There was concern that the environmental health of the system was declining too rapidly, and, if left unchecked, would lead to the collapse of the biological systems (DCE 1984).

With the objective of ensuring that the PHES remained 'clean, healthy and resilient' (EPA 1988) the Peel Inlet and Harvey Estuary Management Strategy was developed to address the algal problem as well as the impacts of future human uses of the estuary and its catchment. Legally binding environmental conditions were promulgated, ministerial commitments were made by the three proponents (the Ministers for Transport, Agriculture and Waterways) and targets for phosphorus input to the PHES and for estuarine water quality were set (EPA 1988; see also Chapter 5). To further strengthen these arrangements, a Statement of Planning Policy was prepared by the Department of Planning and Urban Development and an Environmental Protection (Peel-Harvey Estuary) Policy was gazetted in 1992 in terms of the Environment Protection Act of 1986 (Government of WA, 1992a and b).

The objectives of the Statement of Planning Policy were:

- to improve the social, economic, ecological, aesthetic and recreational potential of the Peel-Harvey Coastal Plain Catchment;
- to ensure that changes to land use within the PHES catchment were controlled so as to avoid and minimise environmental damage;
- to increase high-water-using vegetation cover within the Peel-Harvey Coastal Plain Catchment;
- to prevent land uses likely to result in excessive nutrient export into the drainage system.

The objectives of the Environmental Protection Policy were:

- to set out environmental quality objectives for the PHES which if achieved would rehabilitate it and protect it from further degradation;
- to outline the means by which the environmental quality objectives for the PHES were to be achieved and maintained.

This set the scene for land-use management to reduce phosphorus runoff from urban, rural and industrial areas. In spite of this situation, construction of the Dawesville Channel was still seen to be necessary to 'jolt the estuary away from the existing regime of excessive algal production towards a more balanced and healthier system' (Kinhill Engineers 1988).

After the opening of the Dawesville Channel the 'Peel Region Strategy' (DPUD 1994) was published by the Ministry for Planning. Although subservient to the Statement of Planning Policy and the Environment Protection Policy, its significance lies in the emphasis placed on the whole catchment rather than just the coastal plain catchment. Although it reinforces the strategies adopted in 1992, the Peel Region Strategy ultimately depends on a high degree of cooperation between state and local government agencies, local community groups and private enterprise.

Thirteen different agencies, some of which underwent name changes in 1996, were involved in implementing the Peel Inlet and Harvey Estuary Management Strategy (Figure 10.1). The Ministries of Transport, Water Resources (previously Waterways) and Primary Industries (previously Agriculture) remain the proponents of the strategy, and they are legally bound to carry out the management commitments that were set in 1994.

Since the opening of the Dawesville Channel the issues confronting managers of the Peel-Harvey Estuarine System have altered. *Nodularia* blooms did not occur in the main body of the PHES after the opening of the Channel, but they still adversely affected the lower reaches of the Serpentine River, as did a number of other toxic species in both the Serpentine and Murray Rivers. Toxic phytoplankton blooms in the Serpentine made it necessary to erect warning signs declaring it unsafe for swimming and fishing on a number of occasions. The mosquito population and the incidence of Ross River virus increased, but the level of macroalgal accumulations near built-up areas in Peel Inlet decreased, as evidenced by the reduced number of complaints from the public. However, it is still too early to ascertain the full impact of the Dawesville Channel on management of the PHES.

11. Conclusions

The data reviewed strongly suggested that the environmental health of the PHES started to improve in the early 1990s, before the Dawesville Channel was opened. The following evidence is presented in support of this opinion:

- the downward trend in phosphorus concentrations in the Harvey River in the 1980s (see Chapter 5);
- the shorter than expected duration of *Nodularia* blooms in 1991 and 1992 (see Chapter 6);
- the lower than expected macroalgal accumulations in the Peel Inlet in 1993 (see Chapter 6).

There seems little doubt that the response of the Harvey River was partly due to the success of catchment management measures designed to reduce the phosphorus run-off from farms through reduced fertiliser application rates from 13 to 9 kg/ha by 1984 (Hodgkin *et al.* 1985; Waterways Commission 1994). Market forces — high fertiliser prices and low beef prices — also had a major influence on reducing fertiliser inputs throughout the catchment and, by 1994, all known major point sources in the catchment (e.g. the Wandalup Farms piggery and the wastewater treatment plant at Pinjarra) had either put effluent management systems in place or were in the process of installing them. In addition, the dredging of the Mandurah Channel, Sticks Channel and Fairbridge Bank, completed in 1987, produced greater hydraulic improvements than expected, and this would have influenced the environmental health of the PHES.

Despite the improvements in estuarine health noted above, it is doubtful whether the objective of the three-part management strategy (to restore the estuary to health and resilience) could have been accomplished using only catchment management measures plus improved exchange through dredging of the Mandurah Channel, due to the following facts:

- The improvement in the environmental health of the PHES in the early 1990s might have been partly due to a slow decline in nutrient status due to the below-average river flows (as defined by Hodgkin *et al.* 1985) that characterised the years from 1976 to 1996. That is, the 'nutrient legacy' from the years of high river inflow in the late 1960s and early 1970s and high levels of fertiliser use until the early 1980s was slowly being reduced.
- The decrease in nutrient inputs achieved through management of the Harvey catchment have been offset by a recent increase in inputs from the Serpentine River.
- Urban development around the PHES is proceeding rapidly.

The effects of the Dawesville Channel on the PHES are summarised below by means of a comparison between pre- and post-Channel conditions, but two points should be borne in mind. Firstly, the present-day condition of the PHES is partly attributable to the success of the catchment management strategy, to the efforts of the AgWA Extension Services and to the cooperation of the farmers on the coastal plain. Secondly, the real benefit of the Dawesville Channel will only become evident when the rainfall pattern returns to 'normal' and run-off from the coastal plain catchment increases.

11.1 Conditions prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the PHES had only limited tidal exchange with marine waters via the narrow 5 km-long Mandurah Channel. Seasonal changes in salinity were extreme:

- almost freshwater conditions occurred during periods of winter river run-off;
- salinities gradually increased via tidal exchange during spring and early summer;
- hypersaline conditions (greater than marine salinity) developed in late summer and autumn due to the effects of evaporation.

Poor exchange with marine waters resulted in a high level of retention of nutrients from catchment run-off, and this nutrient enrichment resulted in large accumulations of macroalgae in Peel Inlet in summer and autumn, and massive *Nodularia* blooms in Harvey Estuary in late spring/early summer.

The salinity regime in Peel Inlet was less variable than in Harvey Estuary. The Inlet had higher salinities than the Estuary during winter and spring; marine salinities re-established one or two months earlier (by the end of December instead of the end of January); and the degree of hypersalinity was less in late summer and autumn. Deoxygenation of bottom waters in Peel Inlet mostly occurred during periods of stratification, although *Nodularia* blooms spreading out from Harvey Estuary affected both oxygen levels and turbidity in the western part of the Inlet. Unlike the Estuary, water clarity in the Inlet was sufficient to allow the growth of extensive stands of macroalgae in summer and autumn, and macroalgal uptake of nutrients helped to maintain low levels of organic nutrients and chlorophyll a in the water column during these seasons.

Water quality was particularly poor in Harvey Estuary due to its physical and chemical features, particularly its greater distance from the Mandurah Channel and phosphorus-rich inflow from the Harvey River. The Harvey Estuary was generally less saline (except in autumn), more prone to salinity stratification, more turbid (due to both *Nodularia* blooms and continued resuspension of fine sediments by wind-driven waves) and more nutrient enriched, and it had higher levels of chlorophyll a than Peel Inlet (due to *Nodularia* blooms). Deoxygenation of bottom waters in the Estuary also occurred during periods of stratification, during and after *Nodularia* blooms. Periods of severe deoxygenation in turn caused the death of benthic invertebrates and fish.

The variable salinity regime and periods of poor water quality in the PHES were tolerated by few species of aquatic plants and invertebrates, but these species were nonetheless highly productive due to the nutrient-enriched conditions. The high productivity of aquatic plants and invertebrates in turn helped maintain large populations of fish and waterbirds.

The region around the PHES was identified as having a severe salt marsh mosquito problem almost ten years before the Dawesville Channel was opened. Inundation of salt marshes and wetlands fringing the PHES in winter and spring (during periods of catchment run-off) provided favourable conditions for breeding of the mosquito *Aedes camptorhynchus*, the main vector of RRV and BFV in the Peel Region.

11.2 Observed effects of the Dawesville Channel

The observed effects of the Dawesville Channel were largely as predicted, although it should be noted that the first two years after the opening of the Channel had below average rainfall. Tidal fluctuations in the PHES increased to about half of oceanic levels, resulting in increased tidal flushing and rapid re-establishment of marine salinities after the cessation of river run-off. Water quality improved, particularly in the Harvey Estuary, where periods of stratification and deoxygenation were shorter and less frequent, *Nodularia* blooms were absent and turbidity during spring was less. In contrast to pre-Channel years, water quality in Harvey Estuary was very similar to that in Peel Inlet.

The more stable salinity regime and improved water quality resulted in an increased number of species of aquatic plants and animals, particularly those requiring marine salinities. These were also able to stay in the system for a larger part of the year. Compared to the salinity regime and resident biota of pre-Channel years, the PHES was more like a sheltered marine embayment for much of the year.

Macroalgal populations appeared to decline, seagrass distribution and production increased, and little effect on fringing vegetation was observed. Biological productivity remained high, as evidenced by the numbers of fish, crabs, prawns and waterbirds present. Numbers of black swans appeared to decline, possibly as a result of loss of preferred food sources (*Ruppia* and certain species of macroalgae).

Effects of winter outflow from the Dawesville Channel on the adjacent marine environment were minimal due to rapid dispersion and dilution of estuarine waters in the high-energy conditions characteristic of the nearshore area in winter. However, there was a deterioration in the water quality of the lower reaches of the Murray and Serpentine Rivers, particularly the latter. Whether the changes in river water quality were due more to the influence of the Dawesville Channel or to changes in catchment inputs remains unclear.

The increased tidal amplitude exacerbated the mosquito problem due to increased frequency of inundation of tidal salt marshes, particularly in summer. Numbers of adult salt marsh mosquitoes — especially the species

Aedes vigilax — (increased significantly in summer despite a three-fold increase in the number of aerial larvicide applications.

From the human perspective the Dawesville Channel resulted in:

- enhanced amenity due to improved water quality;
- fewer complaints about odours from macroalgal accumulations;
- improved business development opportunities (this may also be viewed as detrimental, depending on personal viewpoints);
- an earlier crab season, with increased numbers of crabs;
- adverse effects on the commercial prawn fishery due to the inability of commercial fishers to catch prawns moving out to sea via the Dawesville Channel — actual prawn numbers did not appear to decline;
- more frequent discolouration of the lower reaches of the Serpentine and Murray Rivers due to blooms of phytoplankton in summer and autumn, including some toxic species — problems were more severe in the Serpentine River, and on occasions it was necessary to close it to swimming and fishing;
- increased summer mosquito populations and mosquito-borne viral diseases of humans, with the associated effects of increased nuisance from biting mosquitoes, especially the vicious biter *Aedes vigilax*, increased risk of transmission of RRV and BFV, and a far greater level of aerial applications of mosquito larvicide.

The physical, chemical and biological features of the PHES before the Dawesville Channel, the predicted effects of the Channel and preliminary findings from post-Channel monitoring are summarised in Table 0.1.

Overall, the Channel can be viewed as largely beneficial to the ecology of the PHES, but detrimental to that of the lower reaches of the Serpentine and Murray Rivers. From the human perspective the Channel can be viewed as either beneficial or detrimental, depending on the relative importance attached to the mosquito problem and to the decreased amenity of the lower reaches of these two rivers.

It is again emphasised that the above assessment was based on two (and in some cases three) years of data. A full assessment of the impacts of the Dawesville Channel must include the long-term responses of the biological community, including natural population variations, and incorporate years of average and above-average rainfall.

Table 1.1 Summary of physical, chemical and biological characteristics of the PHES prior to opening the Dawesville Channel, and the predicted changes after the opening (Adapted from Table 6 of EPA 1988)

Factor	Prior to opening the Dawesville Channel	Predicted effects of the Dawesville Channel	Condition observed after the opening of the Dawesville Channel
Tides			
Daily Tidal Range	Peel Inlet 17% of ocean tide. Harvey Estuary 15% of ocean tide.	Peel Inlet 45-50% of ocean tide. Harvey Estuary 60-70% of ocean tide.	Peel Inlet 48% of ocean tide; Harvey Estuary 55% of ocean tide.
Duration of Tidal Inundation/ Exposure		Decreased	As predicted.
Frequency of Tidal Inundation/ Exposure		Increased	As predicted.
Flooding			
Flood Levels	Predominantly driven by river inflow.	Small increase in area flooded by daily or storm surge tides on the east side of the estuary. Other estuarine shorelines too steep.	As predicted.
Decrease In Flood Levels	Average water level decrease of 0.4 m in 10 days.	Average water level decrease of 0.4 in 3 days.	As predicted.
Hydraulic Characteristics			
Average Residence Time	Peel Inlet: 30 days. Harvey Estuary: 50 days.	Peel Inlet: 10 days. Harvey Estuary: 17 days.	As predicted.
Water Exchange Per Tidal Cycle	Mandurah Channel: 5.5×10^6 m^3. Grey Channel: 3.5×10^6 m^3.	Mandurah Channel: 6.3×10^6 m^3. Grey Channel: 6.4×10^6 m^3. Dawesville Channel: 16.5×10^6 m^3.	As predicted.
Stratification	Stratified conditions prevailed in most of winter and early spring.	Period of stratified conditions reduced by about 2 months. However, stratification expected to be more intense.	As predicted.
Sediment Characteristics			
Estuarine Sediments	Total phosphorus in surface sediments more than doubled in the last 100 years. A high proportion of total phosphorus was non-apatite phosphorus, and readily released for plant growth under anoxic conditions.	Gradual depletion of non-apatite phosphorus stores in sediment. Reduced periods of anoxia and therefore less release of phosphorus from sediments to the water column.	Preliminary data indicates nutrients similar to pre-Channel data.
Riverine Sediment	Phosphorus concentrations quite variable.	No predictions made.	Draft report completed.
Nearshore Marine Areas			
Nearshore Sediment Transport	Longshore sediment transport from south to north of about 60,000 cubic metres per year.	Disruption of sediment transport processes by Channel breakwaters. Sand bypassing needed.	Significant realignment of shoreline south of Channel. Sand bypassing undertaken as required.

Factor	Prior to opening the Dawesville Channel	Predicted effects of the Dawesville Channel	Condition observed after the opening of the Dawesville Channel
Channel Stability	Not applicable.	Channel configuration unstable. Formation of flood tide shoal in Harvey Estuary expected.	Minor sediment level changes within the Channel. Flood tide shoal formed in Harvey Estuary.
Nearshore Water Quality	Low nutrient levels, and high turbidity.	Jet plume from Channel up to 1 km offshore during ebb tides in winter (when rivers are flowing): estuary waters should be rapidly dispersed and diluted.	Plume moved north in winter, was confined to less than 2 km offshore and 3 km north of Channel. Rapid dispersion of plume occurred.
Nearshore Benthic Habitats	Patches of reef, intersperse with bare sand. Diverse macroalgal communities on reef in spring, summer and autumn, but communities 'scoured' off reef surfaces during winter storms.	Little change expected due to rapid dispersion of plume during winter, and fact that macroalgal communities are 'scoured' off reef surfaces during winter storms.	As predicted. Freshwater discharge had almost ceased by time of algal recruitment to reefs in spring.
Water Quality			
Salinity	Extreme salinity regime, especially in Harvey Estuary, from essentially fresh water in winter to hypersaline by late summer.	Marine salinities to prevail for most of the year, but strong stratification expected during months of river run off. Hypersalinity to end. Stratification in lower reaches of Murray and Serpentine Rivers.	As predicted, except that hypersaline conditions (although less extreme) still occurred.
Dissolved Oxygen	Frequent periods of deoxygenation in spring and sometimes summer, especially in Harvey Estuary.	Reduced frequency and duration of periods of deoxygenation in estuary. Deoxygenation still likely in lower reaches of Murray and Serpentine Rivers.	As predicted.
Turbidity	Turbidity high in winter due to run-off, and high in spring/ early summer due to *Nodularia* blooms, particularly in Harvey Estuary. Higher levels of wind-stirring of fine sediments in Harvey Estuary.	Reduction in turbidity due to absence of *Nodularia* blooms and more rapid loss of river run off. Progressive improvement in Harvey Estuary due to loss of suspended fine sediments to ocean.	Reduced turbidity in spring due to absence of *Nodularia* blooms and more rapid rapid loss of river runoff. Turbidity in Harvey Inlet still high in summer due to resuspension of sediments.
Nutrients	High nutrient levels associated with winter runoff, and with nutrient release from sediments during periods of anoxia. Overall nutrient levels in Harvey Estuary higher than in Peel Inlet.	Little impact on high nutrient levels associated with winter runoff, but a more rapid return to ow nutrient levels due to increased oceanic exchange and and less sediment nutrient release.	As predicted. Little difference in nutrient levels between Harvey Estuary and Peel Inlet.
Groundwater In Vicinity of Channel	Thin lenses of fresh water overlying brackish groundwater.	Decrease in groundwater levels and increase in groundwater salinity accompanying dewatering during Channel construction.	Groundwater levels recovered rapidly following dewatering; however, groundwater salinities remained elevated. Groundwater monitoring ceased in May 1995.

Factor	Prior to opening the Dawesville Channel	Predicted effects of the Dawesville Channel	Condition observed after the opening of the Dawesville Channel
Chlorophyll a	Minor peaks associated with winter diatom blooms, and extremely high levels associated with *Nodularia* blooms in late spring/early summer, especially in Harvey Estuary.	Decrease in size of winter diatom blooms and absence of *Nodularia* blooms. *Nodularia* blooms to continue in lower reaches of rivers.	As predicted. Harvey Estuary and Peel Inlet virtually indistinguishable. High chlorophyll a levels in lower reaches of Murray and Serpentine Rivers due to both *Nodularia* and dinoflagellate blooms.
Estuarine Flora			
Phytoplankton	Community dominated by a few euryhaline species and *Nodularia*. See also chlorophyll a levels above.	Increased species diversity, and more marine species prevalent. See also chlorophyll a levels above.	As predicted.
Macroalgae	Large accumulations of macroalgae in Peel Inlet, dominated by a few species of opportunistic green algae.	Increased growth of macroalgae in the short term, and the occurrence of macroalgae in waters and in southern Harvey Estuary, due to better water clarity. Declining levels of macroalgae in the long term, with red and brown algae more dominant.	Macroalgal levels in Peel Inlet appeared appeared to decline, but some accumulation occurred in southern Harvey Estuary (although of far lesser magnitude than in Peel Inlet). The dominance of green algae over red and brown algae was less.
Seagrasses	Ephemeral patches of seagrass in Peel Inlet. The main species (*Halophila ovalis*) has a relatively high tolerance to low salinities and high turbidity.	The more marine salinities and improved water clarity should result in the growth and expansion of areas of *Halophila*, and less tolerant species may establish near the Channel entrance.	*Halophila* extended into deeper waters in Peel Inlet and further into Harvey Estuary. Small patches of less tolerant species established near the Channel entrance.
Fringing Vegetation	Large expanses of fringing salt marsh, dominated by Sarcocornia species in the lower marsh and *Halosarcia* species or Juncus in the higher marsh.	Altered tidal regime will result in the expanse of areas of Sarcocornia marsh to higher ground, the retreat of *Halosarcia* species and an increase in extent of Juncus. Less extreme salinity regime will cause changes in community composition.	Too early to discern changes: fringing communities will take several years to respond.
Estuarine Fauna			
Zooplankton	Community dominated by a few euryhaline species.	Increased species diversity, and more marine species prevalent.	No data available.
Benthic Invertebrates	Classic symptoms of eutrophication. Community dominated by high numbers of a few euryhaline species that are short-lived, fast-growing and extremely fecund.	Increased species diversity, and more marine species present. Greater numbers of larger, longer-lived species (due to less eutrophic conditions).	Data still being processed, but numbers of some short-lived species appeared to decline and a few larger, longer-lived species were found.
Fish Communities	Most important commercial estuarine fishery in Western Australia. High numbers of fish, prawns and crabs, linked to high levels of macroalgae and food (benthic invertebrates).	More species present which mature or only occur at marine salinities. Fish populations not expected to decline if macrophyte cover (whether macroalgae or seagrass) remain extensive.	Numbers of the main commercial species were either little affected or increased in abundance. More marine species were present. Prawns and crabs were recruited to Harvey Estuary far earlier and stayed longer.

Factor	Prior to opening the Dawesville Channel	Predicted effects of the Dawesville Channel	Condition observed after the opening of the Dawesville Channel
Fish Communities cont.	Most species utilised PHES when marine salinities prevailed, and were recruited to the system as juveniles.	Species preferring low salinities may be adversely affected.	
Waterbirds	The most important waterbird habitat in southwestern Australia. Over 80 species recorded, attracted to sheltered conditions, large expanses of shallow waters and abundant food supply (benthic invertebrates). Large numbers of migratory waders; also large numbers of resident waders (usually found in inland waters) due to lack of tidal variation.	Main food sources likely to remain abundant. However, altered tidal regime may affect the feeding habits of resident waders and the availability of roosting sites in the intertidal zone. Some low-lying breeding sites may be lost due to tidal inundation.	Loss of one summer breeding site for pelicans, but pelican numbers maintained. A possible decline in numbers of black swans. Other data not fully processed.
Social and Economic Uses			
Residents	Considerable use of estuary for passive recreation, fishing, crabbing and boating.	Improved recreational amenity.	Little change in recreational use of estuary.
Fishing	Highly productive commercial fishery. Presence of *Nodularia* affected fishing methods, and was believed to adversely affect fish populations.	Concerns that some commercial species might be affected, but absence of *Nodularia* blooms considered beneficial.	Abundances of commercial species increased or unchanged. Lower commercial catches of western king prawns as prawns leaving via the Dawesville Channel can't be caught with current fishing methods.
Tourism	Considerable use of estuary for passive recreation, fishing, crabbing and boating.	Improved recreational amenity.	Little change in recreational use of estuary.
Property Development	Concern by business community that *Nodularia* blooms and macroalgal accumulations adversely affected property values.	Improved development opportunities.	Not fully realised as yet.
Public Health			
Mosquitoes	Major saltmarsh mosquito problem in Peel Region, and known area for Ross River virus (RRV).	Increased breeding areas for salt marsh mosquitoes, particularly in summer, due to increased frequency of tidal inundation of salt marsh.	Increased numbers of mosquitoes in summer despite massive increase in aerial larvicide use, particularly the vicious biter *Aedes vigila*(. High levels of RRV activity.
Odours From Decomposing Algae	Frequent complaints by residents to authorities, particularly during summer months.	Potential increase in level of complaints. Increased level of weed (macroalgae) harvesting required.	Fewer complaints, and less weed harvesting needed.

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14. Acronyms

ACRONYM	FULL TITLE
ABC	Abundance-Biomass Comparison
AgWA	Agriculture Western Australia
AHD	Australian Height Datum
BFV	Barmah-Forest Virus
CALM	Conservation and Land Management, Western Australia
CAMBA	China-Australia Migratory Birds Agreement
CDI	Community Degradation Index
CPUE	Commercial Catch per Unit Effort
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity-Temperature-Depth
DCE	Department of Conservation and Environment, Western Australia
DCMP	Dawesville Channel Monitoring Programme
DEP	Department of Environmental Protection, Western Australia
DMH	Department of Marine and Harbours, Western Australia
FWA	Fisheries Western Australia
DoT	Department of Transport, Western Australia
DPUD	Department of Planning and Urban Development, Western Australia
DMSV	Digital Multi-Spectral Video
EPA	Environmental Protection Authority, Western Australia
EPP	Environmental Protection Policy
ERMP	Environmental Review and Management Programme
GIS	Geographic Information System
HDWA	Health Department of Western Australia
JAMBA	Japan-Australia Migratory Birds Agreement
LGA	Local Government Authorities
MFP	Ministry for Planning, Western Australia
PHES	Peel-Harvey Estuary System

PHPMG	Peel-Harvey Project Managers Group
PIMA	Peel Inlet Management Authority
PMG	Project Managers Group
PPG	Peel Preservation Group
ppt	Parts Per Thousand
PWD	Public Works Department, Western Australia
RAOU	Royal Australasian Ornithological Union
REI	River and Estuaries Investigation Branch of the Water and Rivers Commission
RRV	Ross River Virus
SOG	Senior Officer Group
SPOT	Systeme Probatoire de Observation de la Terre
SPP	Statement of Planning Policy
TP	Total Phosphorus
UWA	University of Western Australia
WAWA	Water Authority of Western Australia
WC	Water Corporation, Western Australia
WRC	Water and Rivers Commission, Western Australia
WWC	Waterways Commission, Western Australia

15. Glossary

Accretion	Accumulation
Amphipod	Small crustaceans belonging to the order Amphipoda
Anaerobic	Absence of free oxygen
Anoxic	Deficiency of oxygen
Apatite phosphorus	Crystalline mineral of calcium phosphate and fluoride
Arbovirus	A group of viruses with an RNA nucleic acid core, that are borne (and therefore transmitted) by arthropods (i.e. by members of the phylum Arthropoda, which includes insects, spiders and crustaceans)
Benthic	Associated with the bottom
Benthic invertebrates	Small animals that live on or in estuarine sediments
Biomass	The weight of all organisms forming a given population or inhabiting a given region
Bivalve	Mollusc with a shell in two parts hinged together
Bloom	Sudden increase in microalgae concentration in the water column, defined here as chlorophyll a levels of greater than 20 µg/L
Brackish	Water salinity between that of fresh and marine waters
Calanoid copepod	Free-swimming, largely planktonic copepods of the order Calanoida
Chaetomorpha	A genus of free-floating, wire-like green macroalgae
Copepod	Small crustaceans belonging to the subclass Copepoda
Cyst	The resting stage or spore of some types of algae
Detritus	Organic debris from decomposing plants and animals
Dewatering	Removing water, i.e. lowering the watertable
Diatom	Microscopic algae with siliceous cell walls that belong to the algal division Bacillariophyta
Dinoflagellate	Motile microscopic algae with flagellae that belong to the algal division Dinophyta
Diurnal	Daily
Dredging	Artificial removal of submerged sediment
Ebb tide	Falling tide
Enteromorpha	A genus of free-floating, ribbon-like green macroalgae
Epiphyte	Algae that grow attached to seagrasses
Euryhaline	Able to tolerate wide variation in salinity

Eutrophic	Highly productive in terms of organic matter formed
Flood tide	Rising tide
Gastropod	Molluscs with a single shell (includes snails). c/f bivalves
Harmonic analysis	Analytic method used to determine tidal constituents
Harpacticoid copepod	Largely benthic (and some parasitic) copepods of the order Harpacticoida
Herbivore	Plant-eater
Hypersaline	Water salinity in excess of marine waters (>about 40 ppt)
Infauna	Animals living within the sediments
Intertidal	Region between the low and high tidal levels
Isopod	Small crustaceans belonging to the order Isopoda
Larvicide	Chemical designed to kill larvae
Macroalgae	Large algae
Macrobenthos	Large organisms living attached to the bottom
Macrophyte	Seagrasses and macroalgae
Microtidal	Small tidal range (< 1 m)
Mollusc	Large taxonomic of animals including bivalves and gastropods. The term is often used to refer to shellfish.
Nematode	Unsegmented worms of the phylum Nematoda
Nodularia	Genus of toxic blue-green microalgae
Non-vascular	Not possessing a vascular system: in referring to non-vascular plants, these include algae, mosses and liverworts
Oligochaete	Segmented worms with few bristles that belong to the class Oligochaeta
Omnivore	Plant and animal eater
Organic phosphorus	Phosphorus incorporated in organic tissues
Phytoplankton	Free-floating microscopic plants
Piscivorous	Fish-eating
Polychaete	Segmented worms with many bristles that belong to the class Polychaeta
Propagules	Any part of plant capable of growing into a new organism
Recruitment	The replenishment of a biological community by outside sources of juveniles or propagules
Redox reactions	Chemical reactions occurring due to reduction and oxygenation processes
Residence time	Time required for a waterbody to be flushed to the ocean

Secchi depth	Measure of water clarity determined from the depth at which a secchi disk can be seen from the surface
Senescent cells	Dying or decaying cells
Species richness	The number of different types of species present in a given area
Spring tide	Largest tide experienced during a lunar tidal cycle
Storm surge	Elevated water level occurring during storms
Stratified	Water column divided into at least two discrete water masses
Superphosphate	Form of artificial fertiliser high in phosphate
Taxa	The name given to scientific groupings or classifications of related organisms
Tidal constituents	Frequency components of the tidal signal related to different driving mechanisms
Tidal prism	Total volume of ocean water entering an estuary on a flood tide
Turbidity	Measure of water clarity
Tychoplankton	Organisms that spend part of the 24-hour day associated with the benthos
Ulva	A genus of lettuce-like green macroalgae
Vascular	Containing vessels for conveying sap or water (in the case of plants) or blood (in the case of animals)
Zooplankton	Microscopic to small animals that live suspended in the water column

Figure 2.1: Pre-Dawesville Channel and predicted post-Channel tidal ranges in the ocean, Peel Inlet and Harvey Estuary

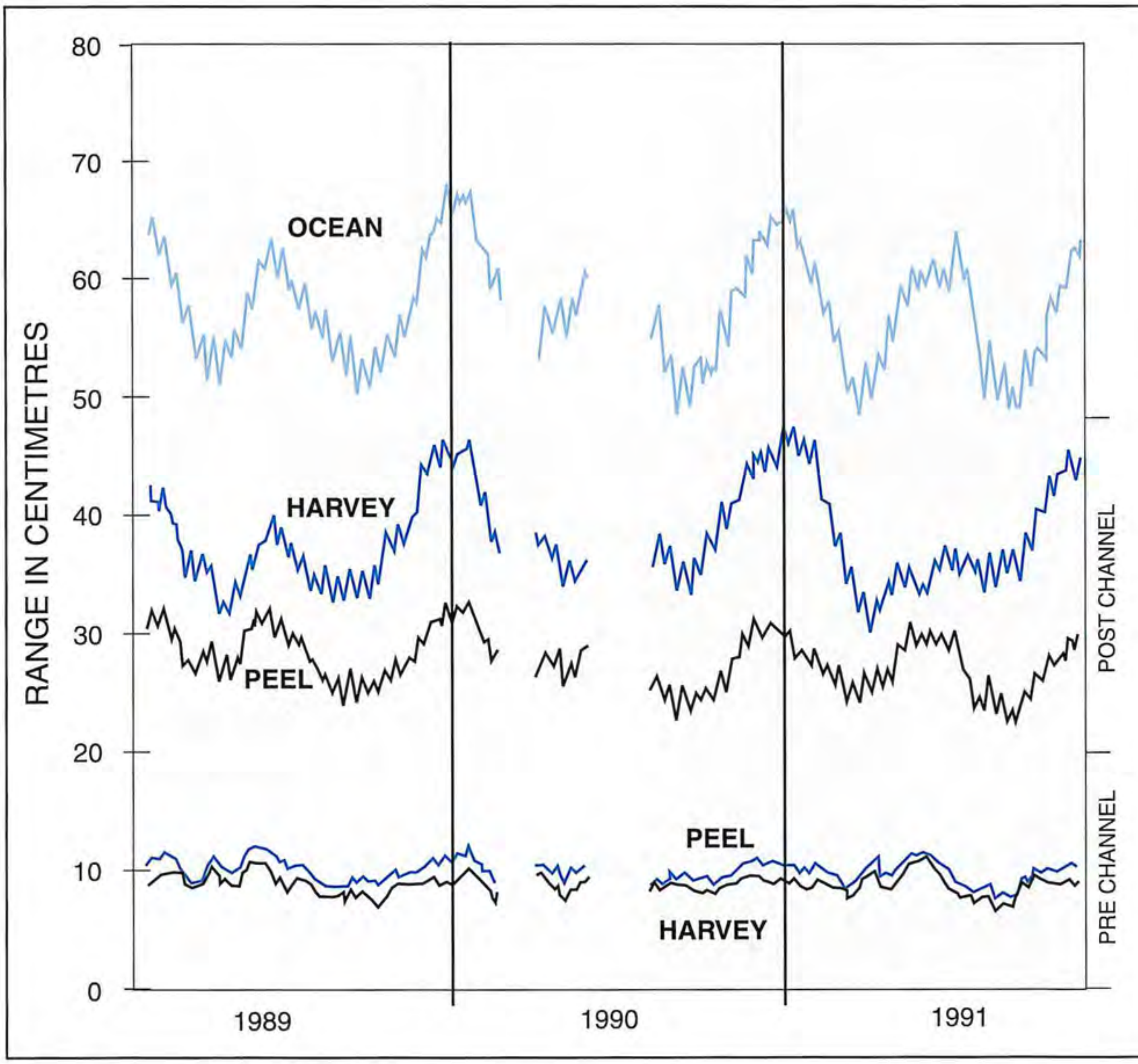
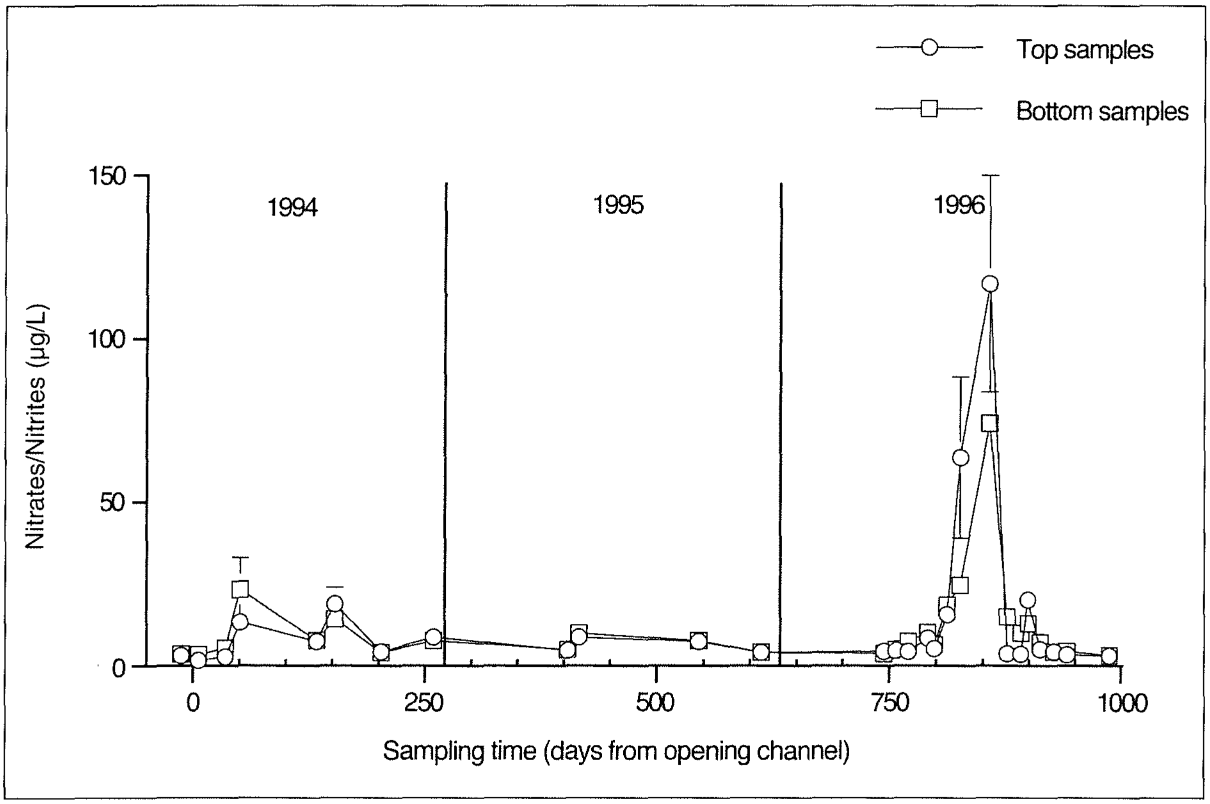
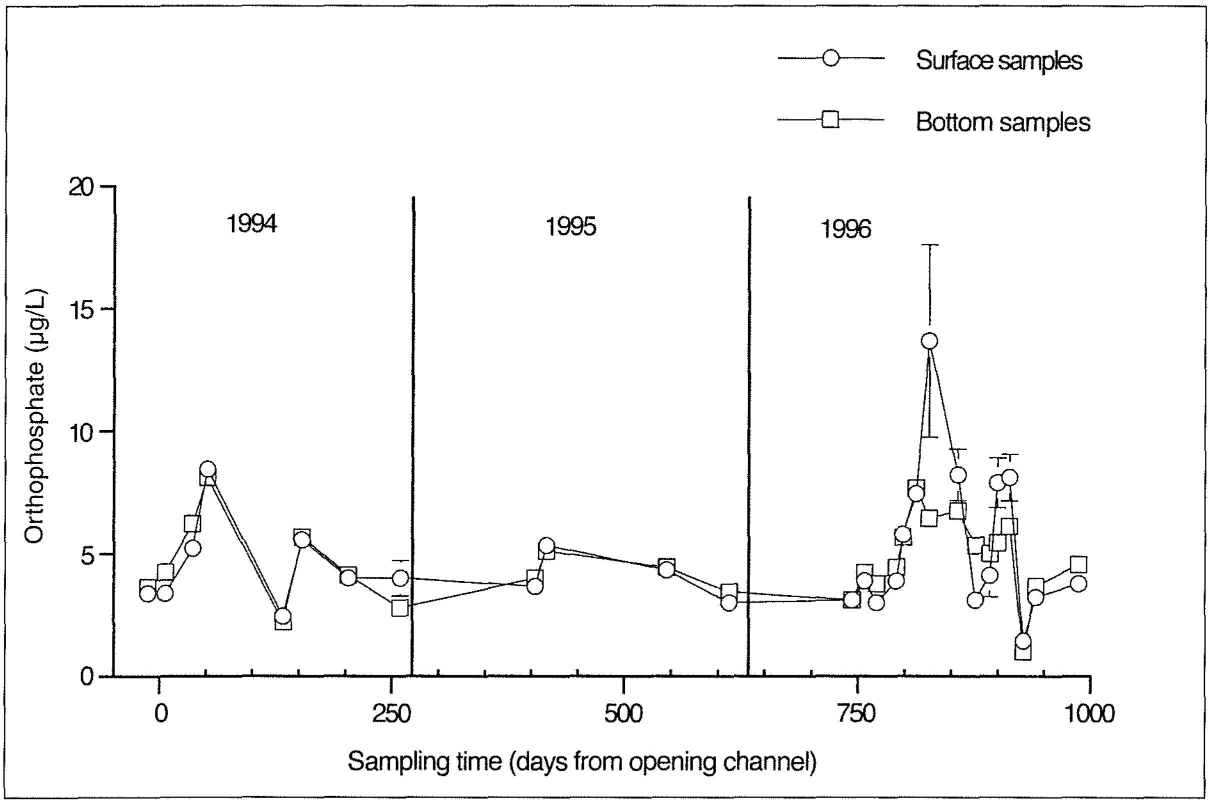


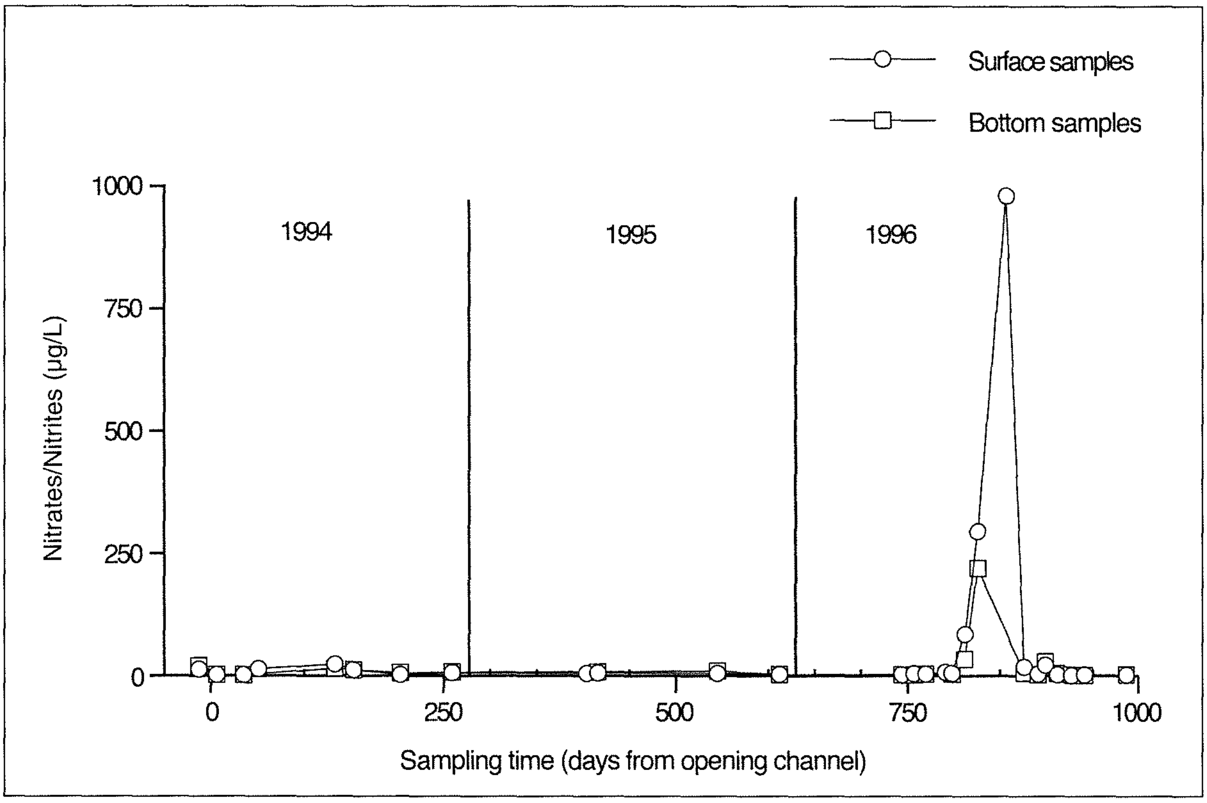
Figure 4.1: Inorganic nutrient concentrations at nearshore sites (mean ±1 standard error).

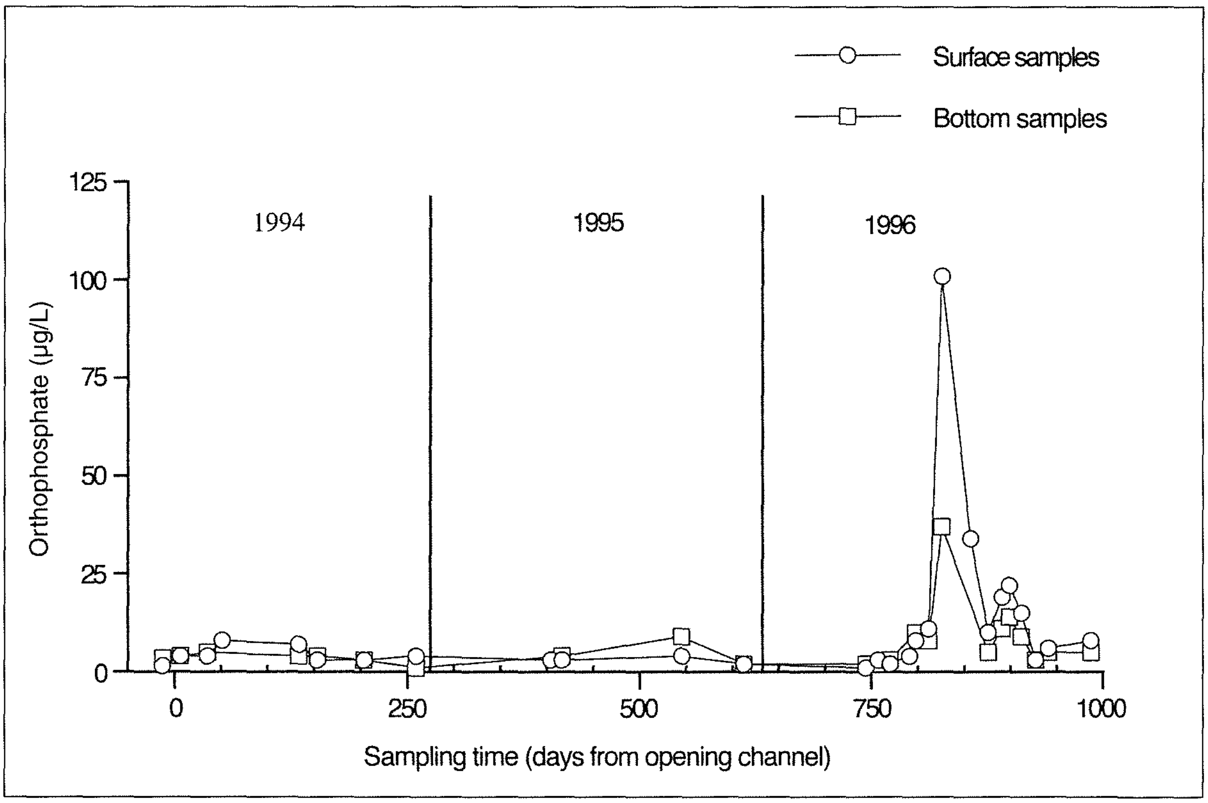




Note: Vertical lines denote end of calender year

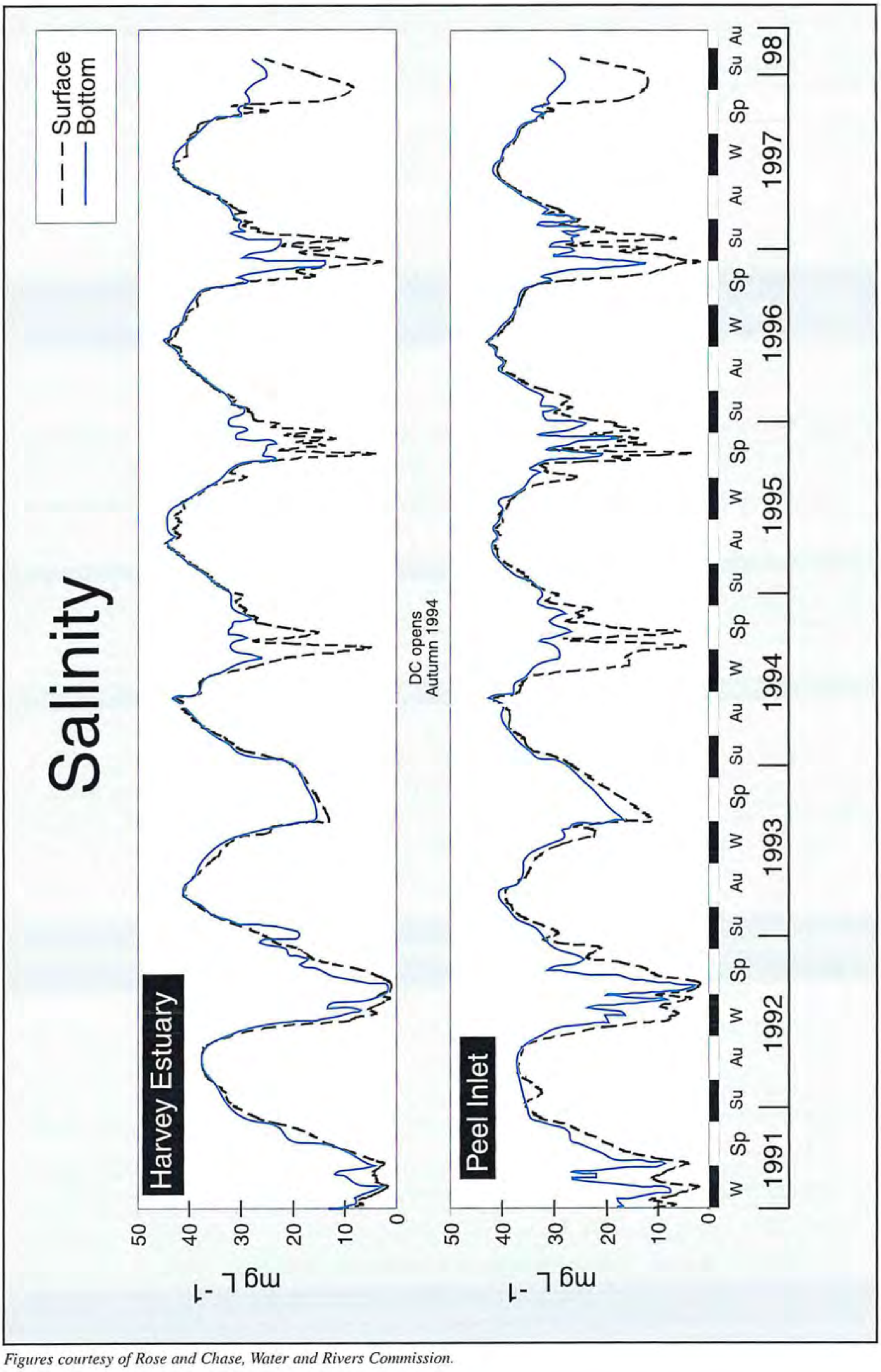
Figure 4.2: Inorganic nutrient concentrations at Dawesville Channel site.





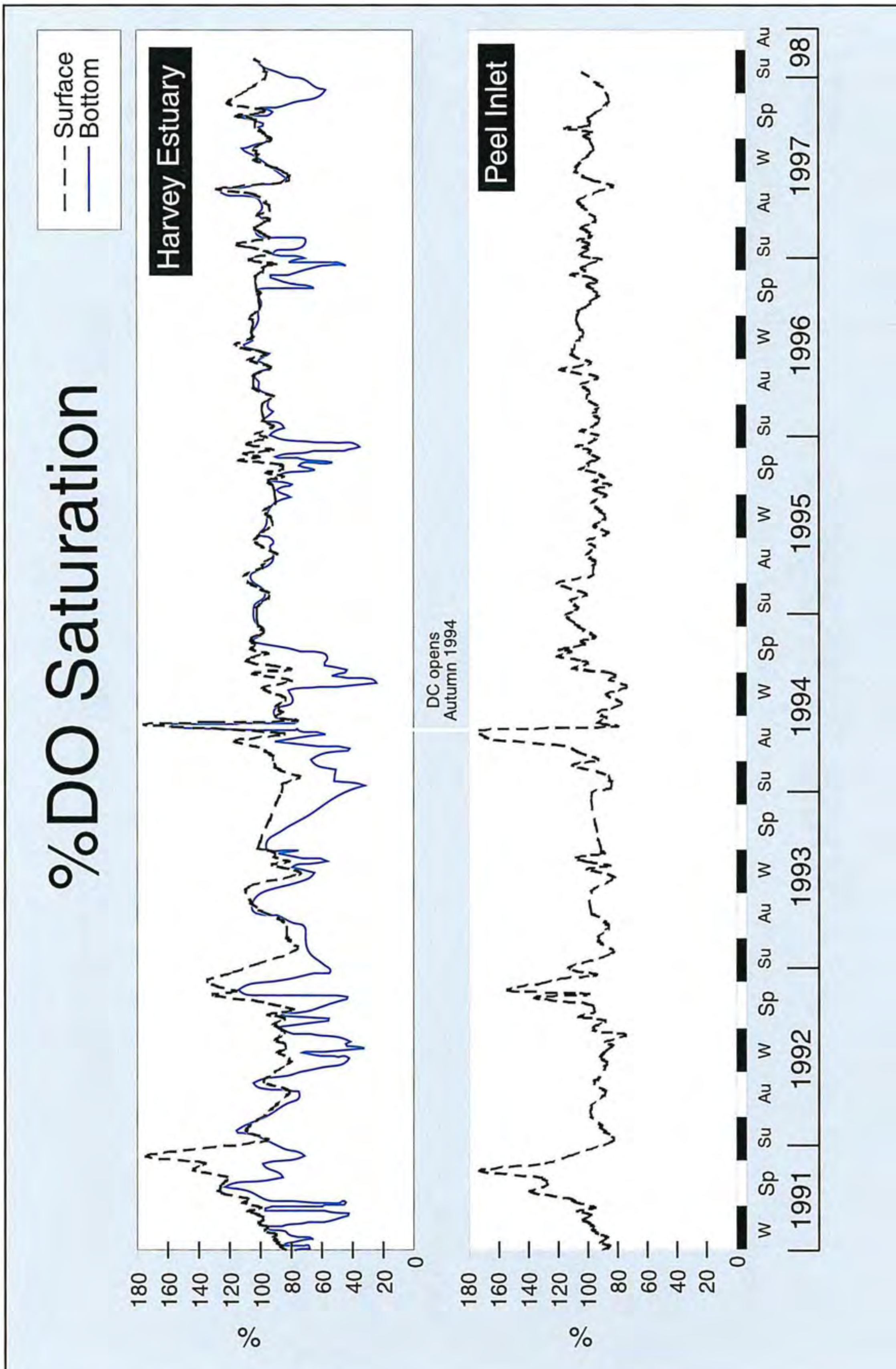
Note: Vertical lines denote end of calender year

Figure 5.1: Mean salinity levels in estuarine waters.



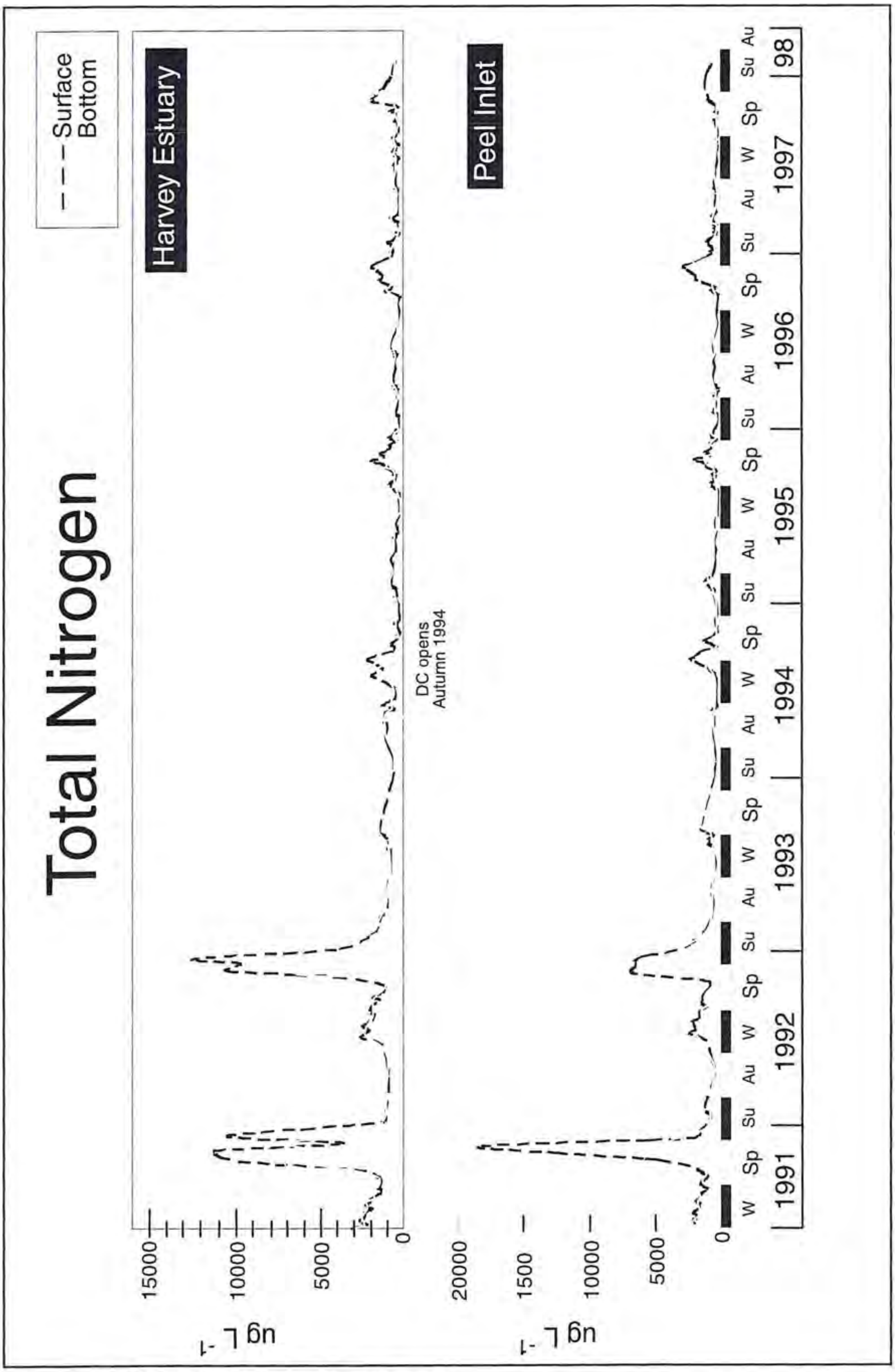
Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.2: Mean oxygen levels (% dissolved oxygen saturation) in estuarine waters.



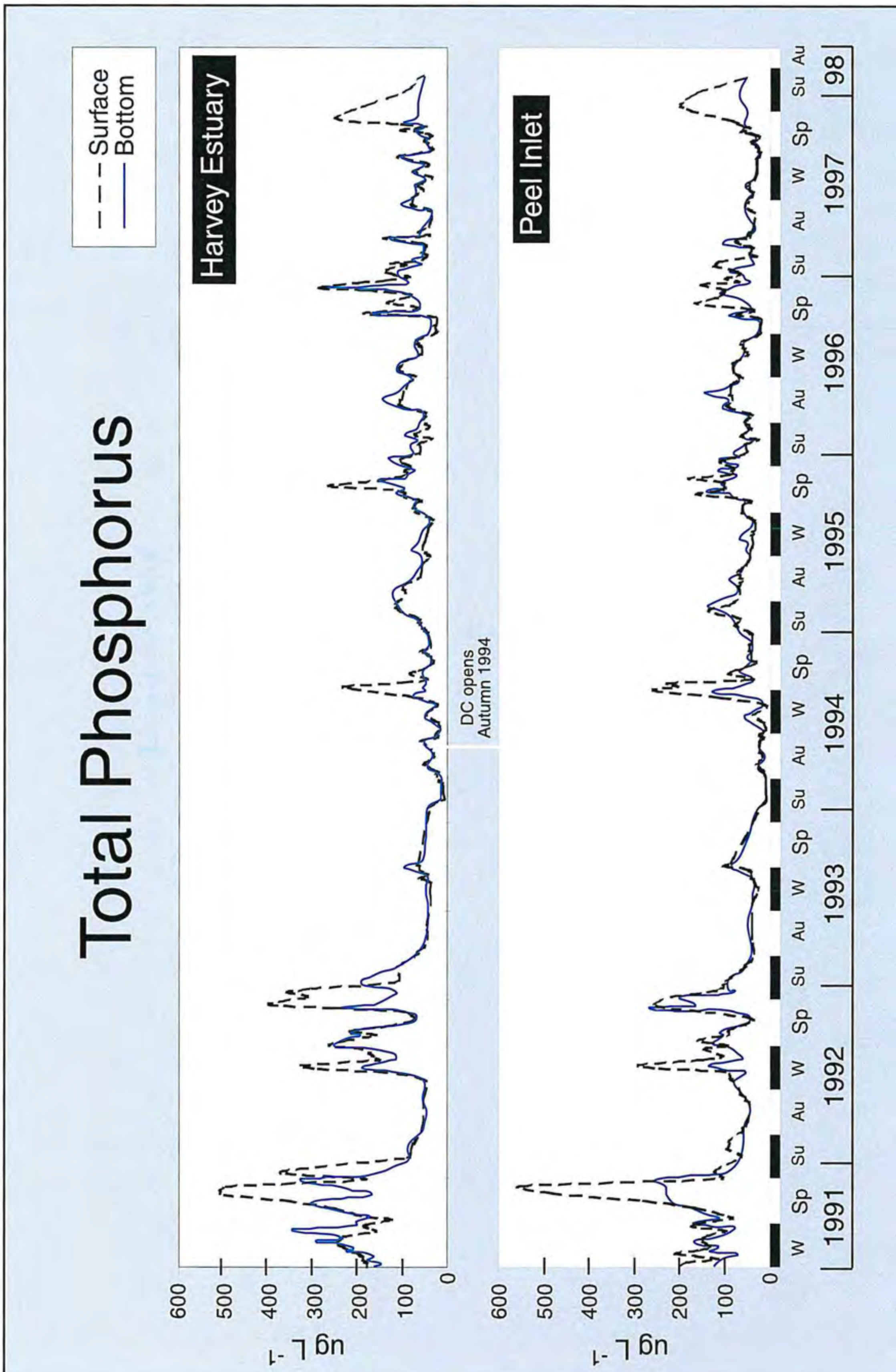
Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.3: Mean total nitrogen levels in estuarine waters.



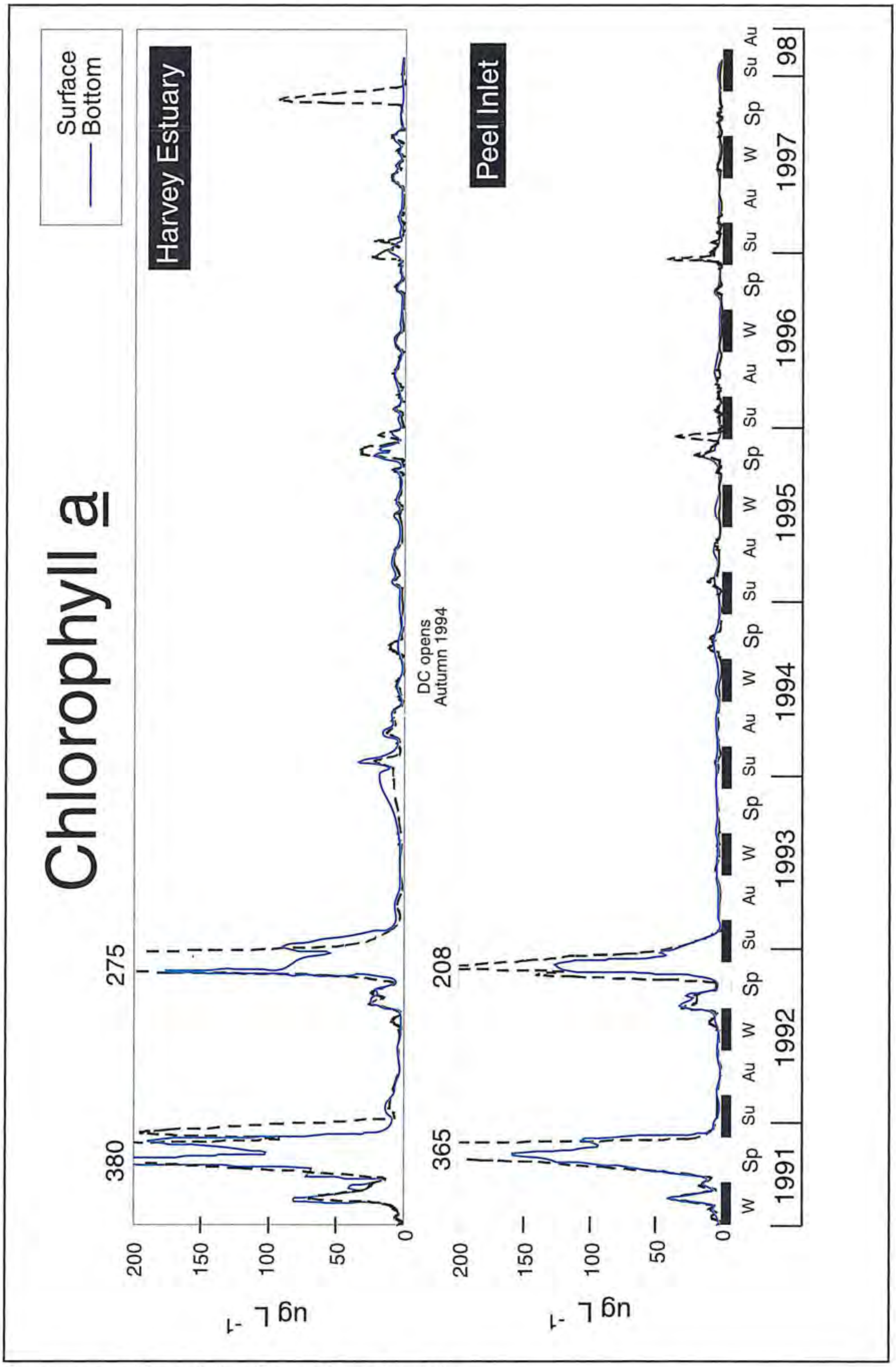
Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.4: Mean total phosphorus levels in estuarine waters.



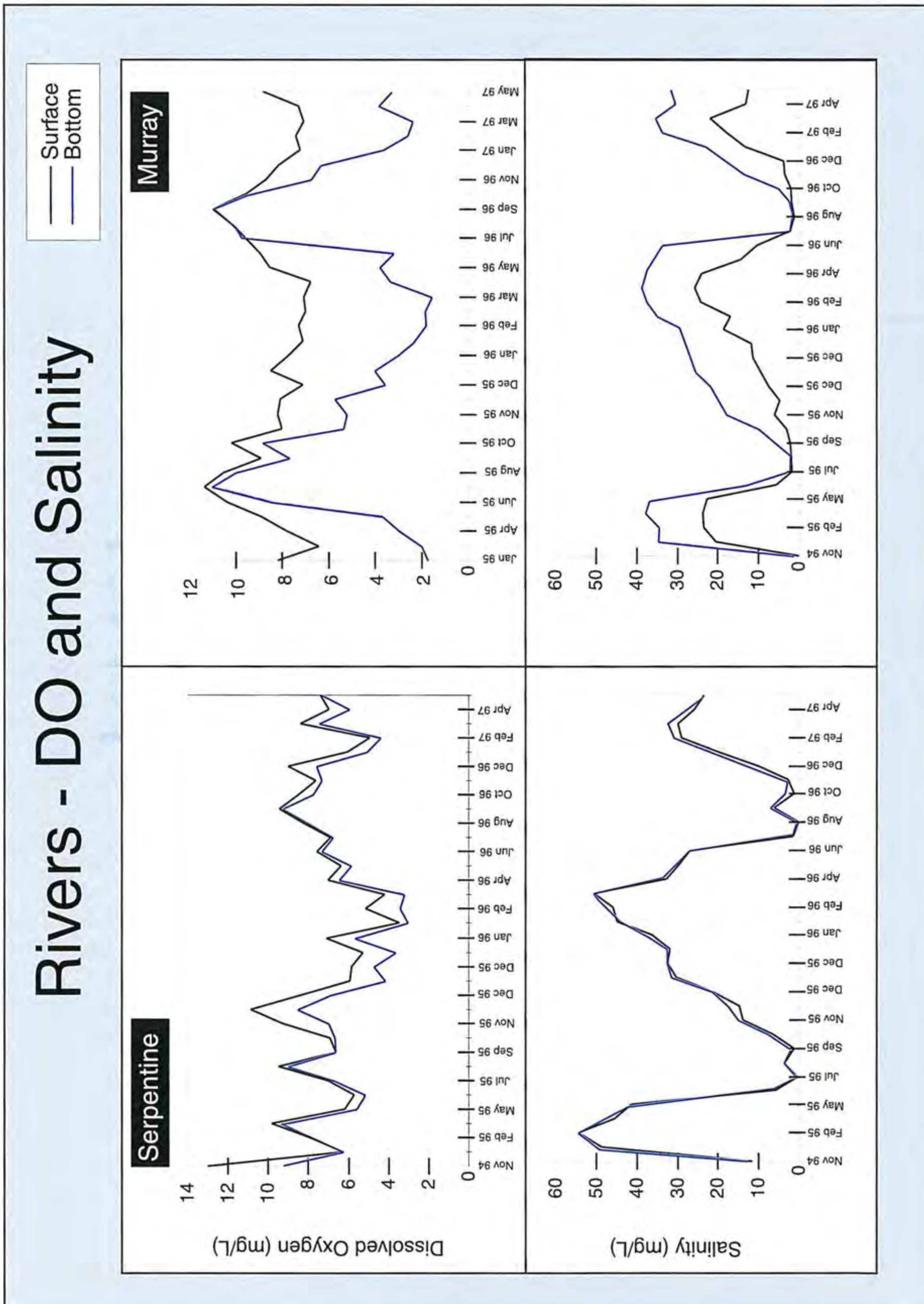
Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.5: Mean chlorophyll a levels in estuarine waters.

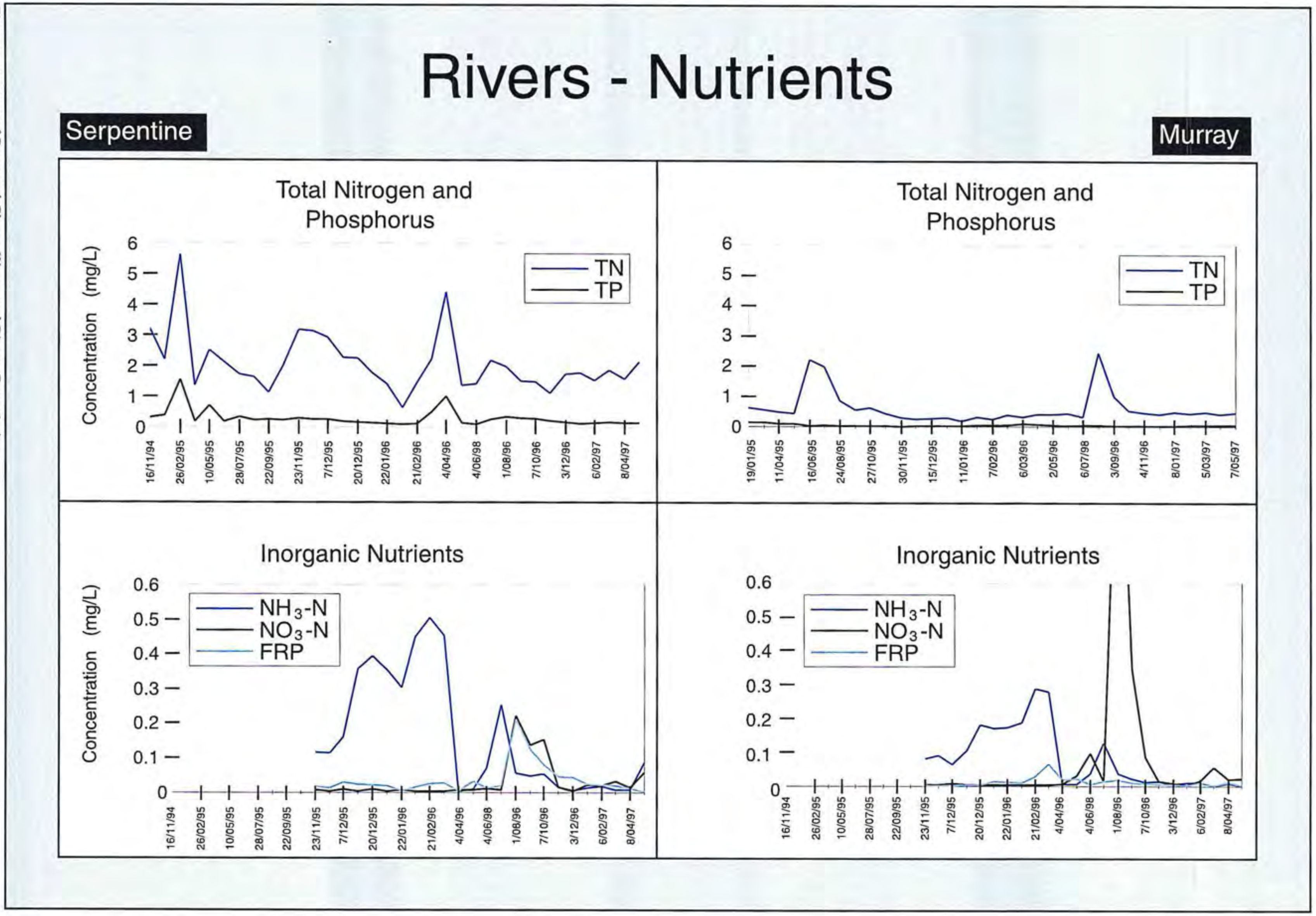


Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.6: Mean salinity and dissolved oxygen levels in the Serpentine and Murray Rivers.



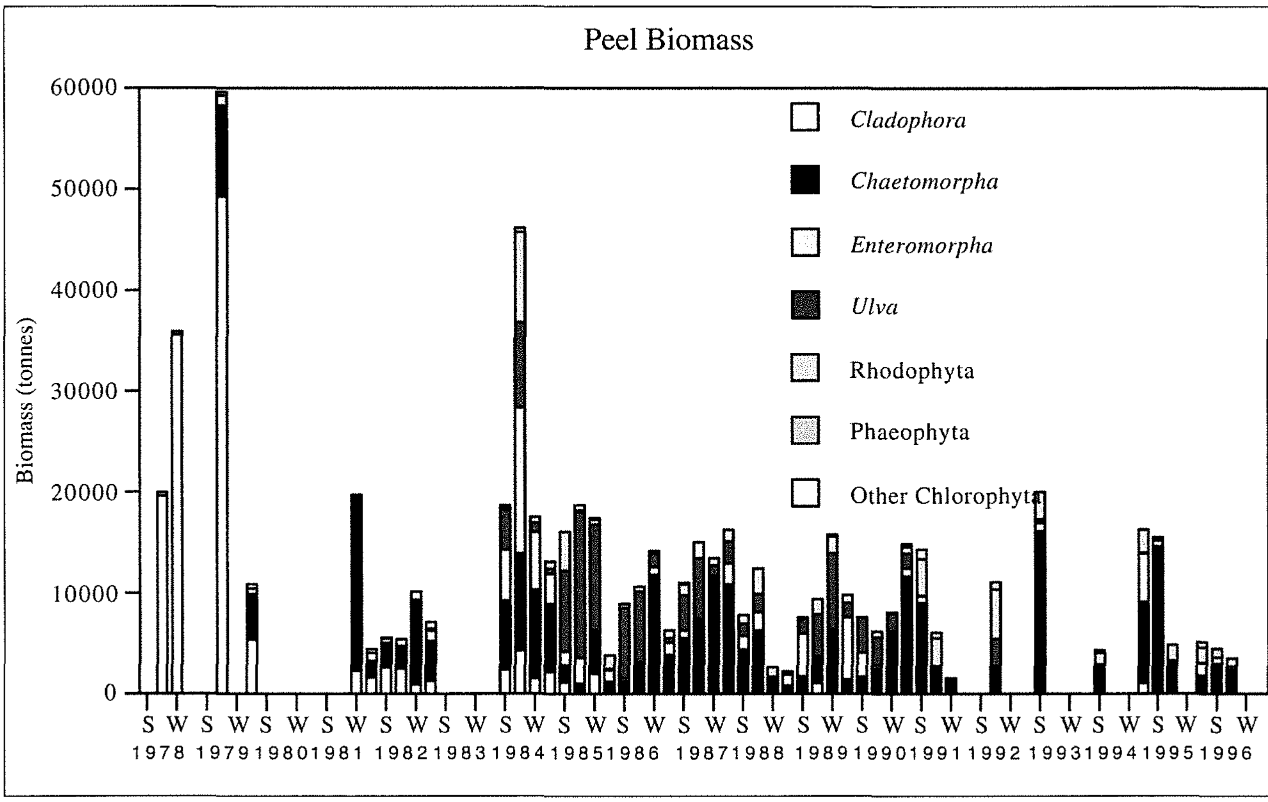
Figures courtesy of Rose and Chase, Water and Rivers Commission.



Figures courtesy of Rose and Chase, Water and Rivers Commission.

Figure 5.7: Mean total nitrogen and total phosphorus levels in the Serpentine and Murray Rivers.

Figure 6.1: Macroalgal biomass and compostion in Peel Inlet and Harvey Estuary from 1978 to 1996.



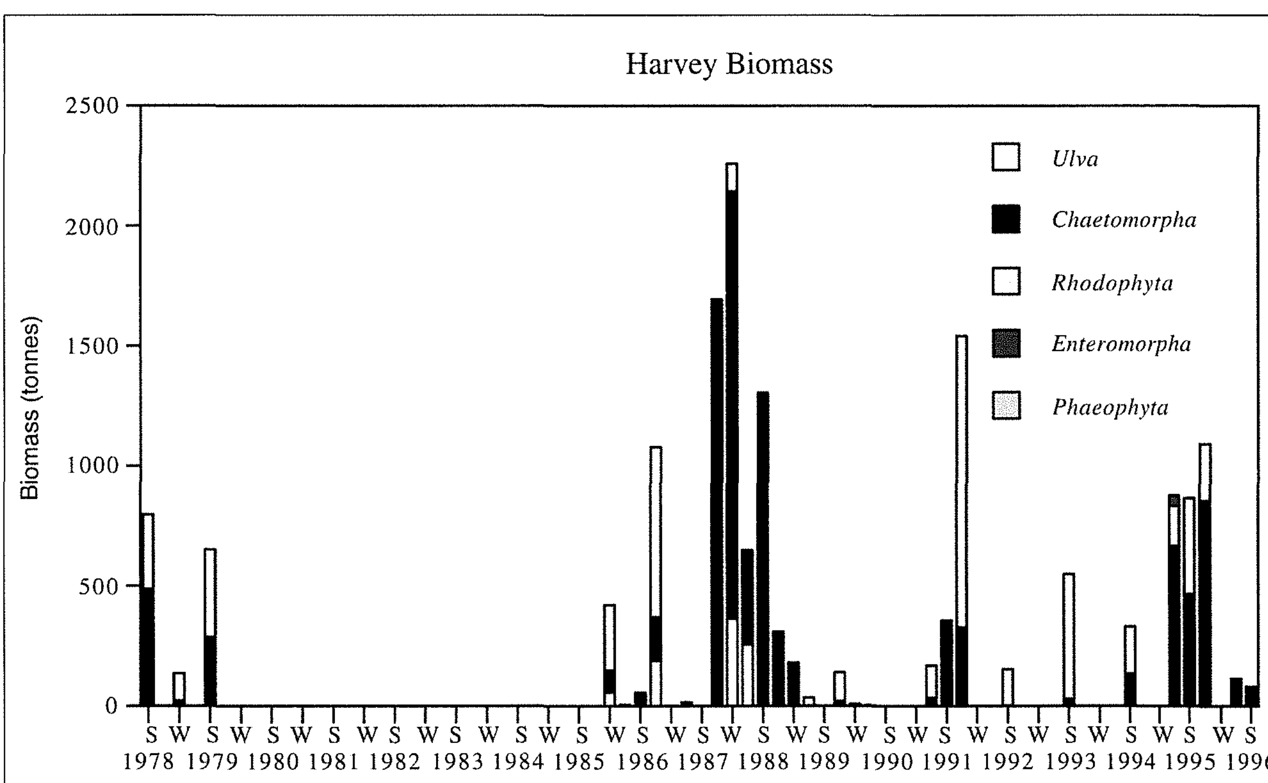


Figure 7.1: The mean number of species (A) and mean density of fish (B) caught in various regions of the PHES in 1979-81 and 1996-97.

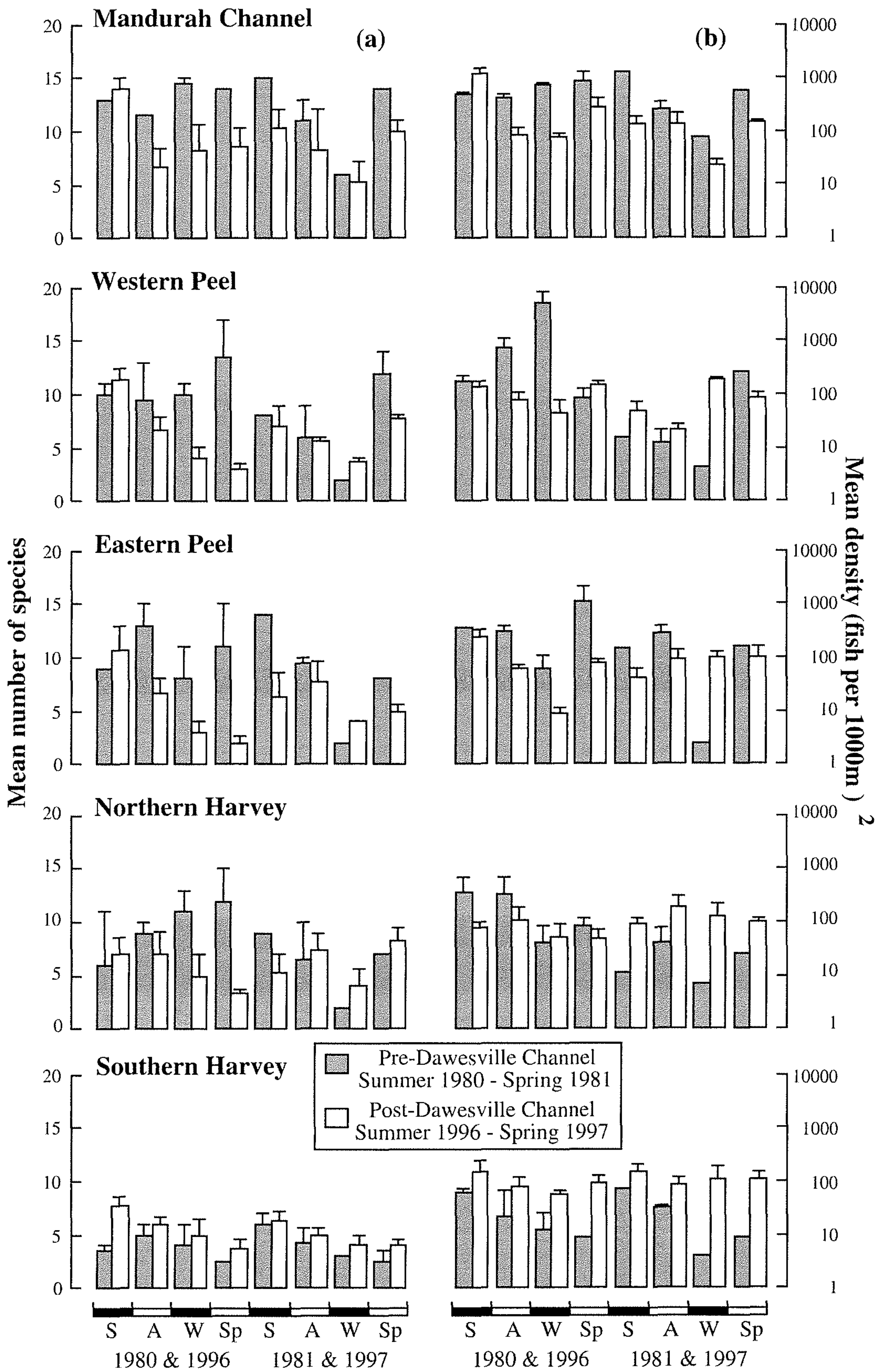
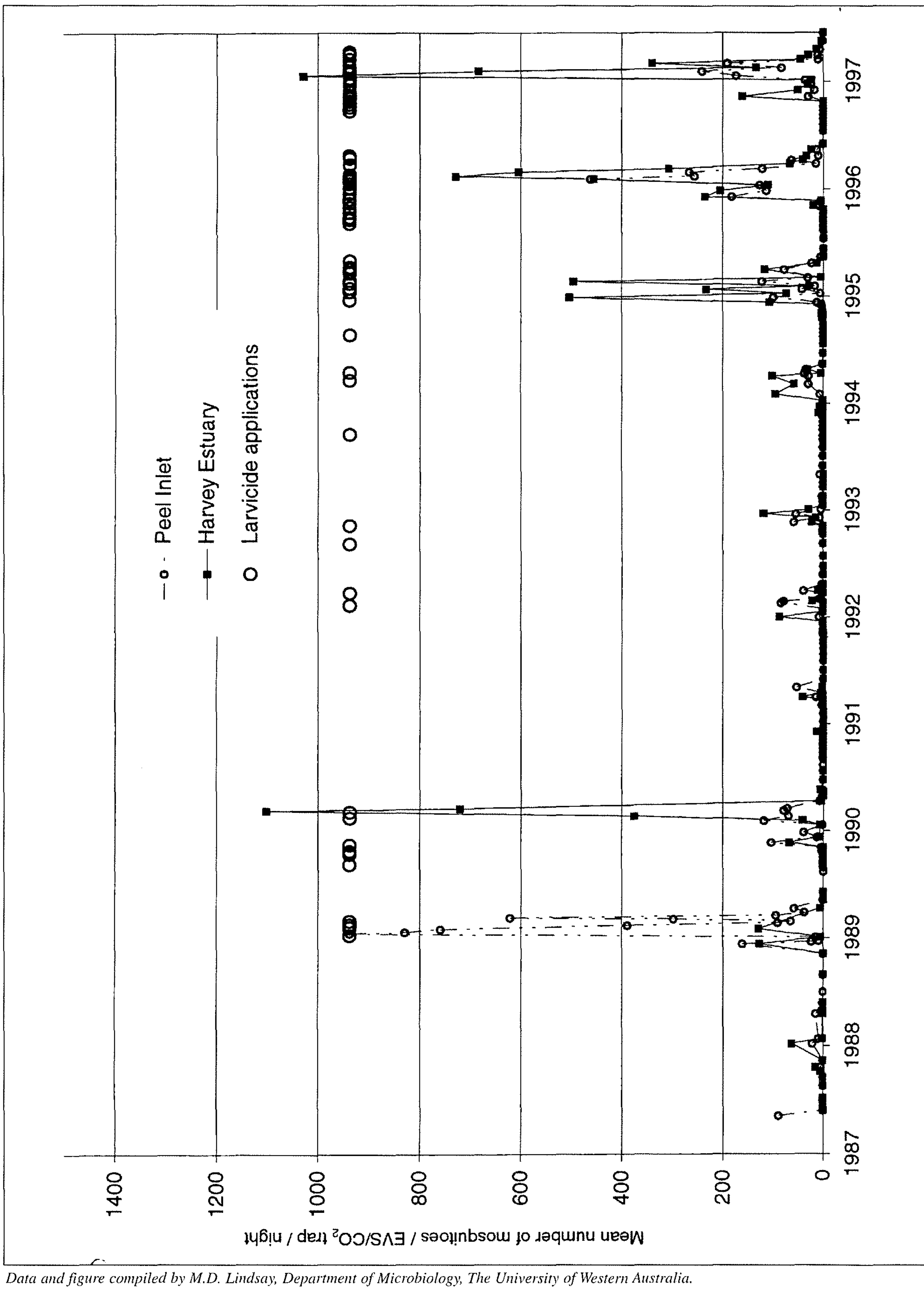
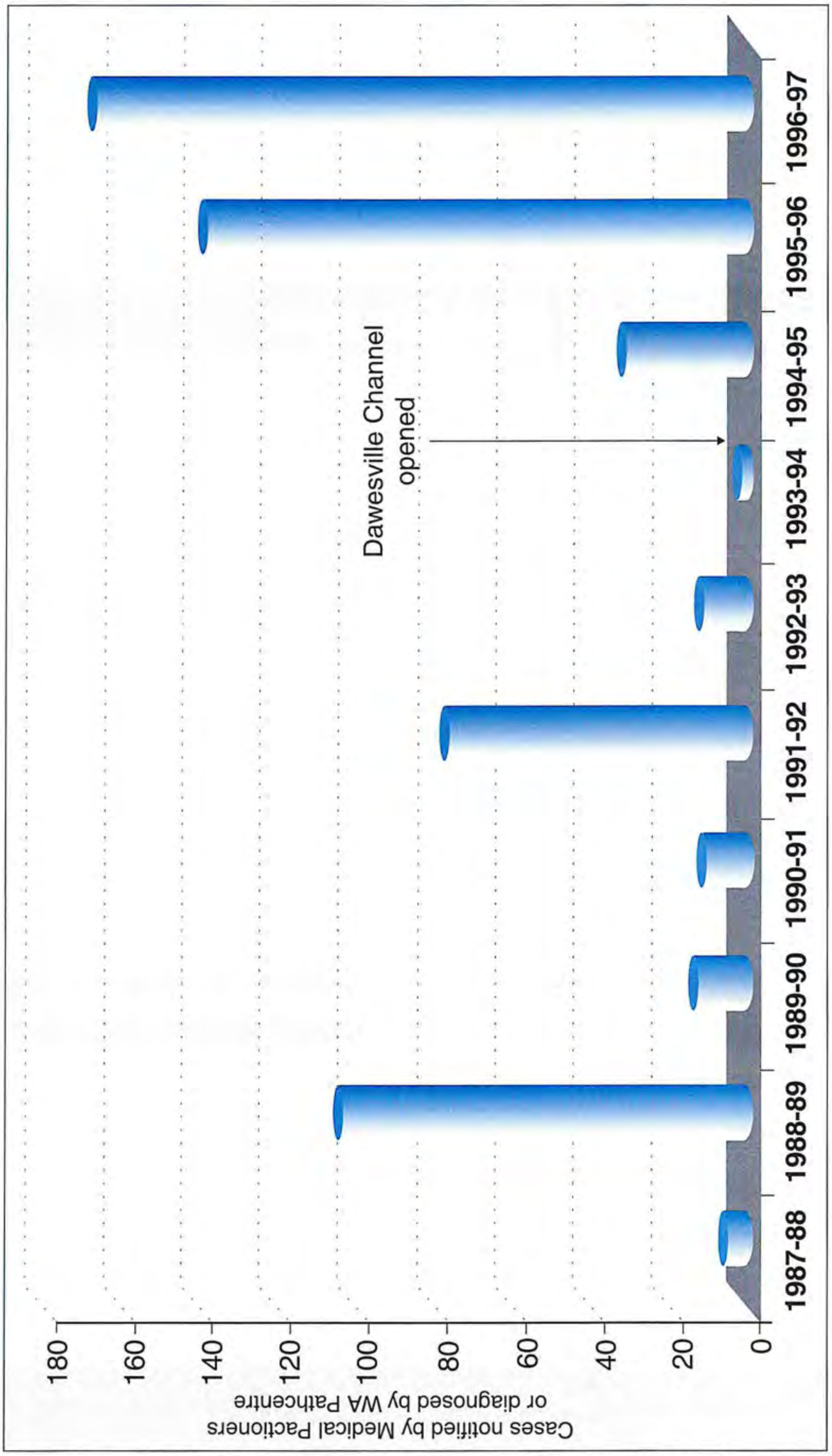


Figure 8.1: Mean number of adult Aedes vigilax *per EVS/CO_2 trap per night at Peel Inlet and Harvey Estuary trapping sites and timing of aerial applications of larvicide in the Peel region, 1987 - June 1997.*



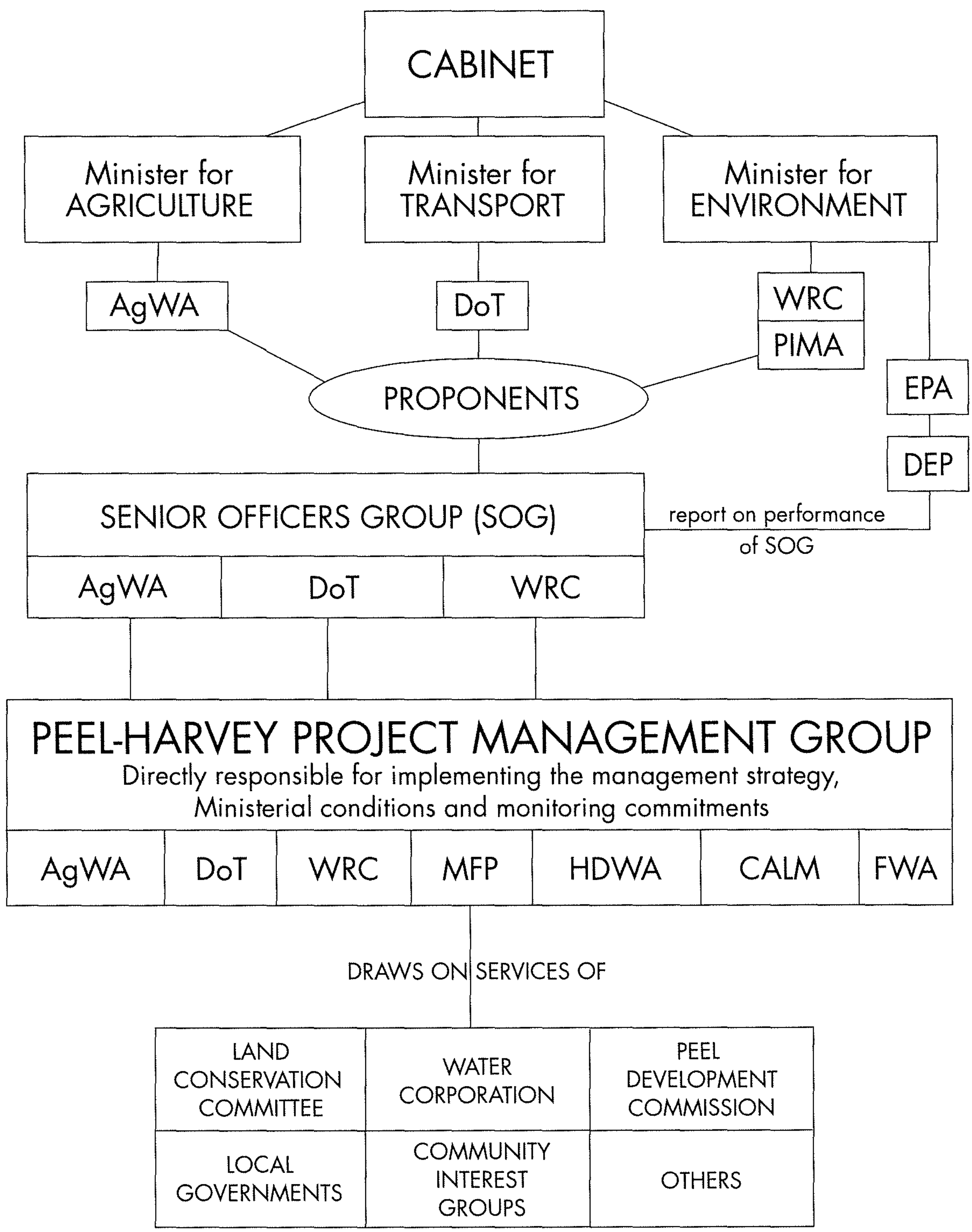
Data and figure compiled by M.D. Lindsay, Department of Microbiology, The University of Western Australia.

Figure 8.2: Number of serologically confirmed cases of Ross River virus disease each year in the Peel region (Cities of Mandurah and Rockingham, Shires of Murray and Waroona), Western Australia, July 1987 - June 1997.



Data and figure compiled by M.D. Lindsay, Department of Microbiology, The University of Western Australia.

Figure 10.1: Organisational structure of the agencies involved in management of the Peel-Harvey Estuarine System.



Dawesville Channel
Technical Review

APPENDIX 1

MINISTERIAL CONDITIONS AND PROPONENTS COMMITMENTS FOR THE PEEL INLET AND HARVEY ESTUARY MANAGEMENT STRATEGY

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

D.A. LORD & ASSOCIATES PTY LTD

WATER AND RIVERS
COMMISSION

MINISTER FOR ENVIRONMENT

STATEMENT THAT A PROPOSAL MAY BE IMPLEMENTED (PURSUANT TO THE PROVISIONS OF THE ENVIRONMENTAL PROTECTION ACT 1986)

PEEL INLET-HARVEY ESTUARY MANAGEMENT STRATEGY - STAGE 2

MINISTER FOR TRANSPORT
MINISTER FOR AGRICULTURE
MINISTER FOR WATERWAYS

This proposal may be implemented subject to the following conditions:

1. The proponents shall adhere to the proposal as assessed by the Environmental Protection Authority and shall fulfil the commitments made and listed in Appendix 2 of Environmental Protection Authority Bulletin 363, as amended (copy of commitments attached).

2. The proponents shall develop proposals for control of phosphorus through catchment management, to the satisfaction of the Environmental Protection Authority, and shall implement them as rapidly as possible so that, in conjunction with the Dawesville Channel, the following objective is met:

   . the Peel-Harvey System becomes clean, healthy and resilient.

   To achieve this objective, the following interim targets should be used:

   (1) annual phosphorus input to the system shall not exceed 85 tonnes in more than four years out of ten (on average) and shall not exceed 165 tonnes in more than one year out of ten (on average). [These are based on 60 and 90 percentile loads]; and

   (2) average phosphorus concentration in estuary water shall not exceed 0.2 milligrams per litre in nine years out of ten (on average).

These target figures shall be reviewed by the Environmental Protection Authority after 3 years or sooner if environmental conditions dictate, in the light of measured performance of the System and may subsequently be varied by the Environmental Protection Authority.

3. The proponents shall jointly prepare an Environmental Protection Policy for the Peel-Harvey catchment in consultation with such persons and agencies as Government may specify, to the satisfaction of the Environmental Protection Authority, in accordance with the objective and targets specified in Condition 2 above. The target date for the Draft Policy (under Section 26 of the Environmental Protection Act 1986) is 31 December 1989.

4. The proponents shall develop in consultation with such persons and agencies as Government may specify, an integrated catchment management plan designed to meet the objective and targets specified in Condition 2 above, to the satisfaction of the Environmental Protection Authority, and which shall be in accordance with the principles to be developed in the Environmental Protection Policy for the area pursuant to Condition 3. The target date for the implementation of the integrated catchment management plan shall be 31 December 1990.

5. The proponents shall ensure that the moratorium on clearing and drainage in the Peel-Harvey coastal plain catchment proposed in the Stage 2 Environmental Review and Management Programme (Commitment 3.6) continues until the Minister for Environment is satisfied that these activities would be environmentally acceptable.

6. Relevant decision-making authorities shall ensure that all developments within 2 kilometres of the Peel-Harvey Estuary System (as defined in the Estuarine and Marine Advisory Committee Report to the Environmental Protection Authority, Department of Conservation and Environment Bulletin 88, March 1981.) include appropriate nutrient-attenuating waste disposal systems and management practices, to the satisfaction of the Environmental Protection Authority.

7. Prior to construction, a dredging and spoil disposal management plan for the Dawesville Channel shall be prepared by the proponents, to the satisfaction of the Environmental Protection Authority. Dredging not already forming part of the proposals in the Stage 2 Environmental Review and Management Programme shall be the subject of separate assessment by the Environmental Protection Authority.

8. The proponents shall ensure that weed harvesting and control is continued and increased as necessary to manage the expected initial increase in the occurrence of nuisance macroalgae.

9. Decisions on developments which may release phosphorus or nitrogen to the environment in the Peel-Harvey Estuary area and coastal plain catchment area should be conservative until the new assimilative capacity of the Peel-Harvey Estuary System is determined and the effects of the management elements have been measured or are being managed. To this end, such proposals for development in these areas shall be referred to the Environmental Protection Authority for assessment. These developments include new and expansion of existing intensive horticultural and intensive animal industries.

10. The Peel-Harvey regional park concept, as originally proposed in the System 6 Redbook report (Conservation Reserves for Western Australia: The Darling System - System 6, Department of Conservation and Environment Report 13, Parts I and II, October 1983.) shall be implemented within such time as to be determined by the Minister for Environment.

11. If the Dawesville Channel is constructed, the proponents shall be responsible for ensuring that mosquito management is effective and is carried out in an environmentally acceptable manner, to the satisfaction of the Minister for Environment and the Minister for Health.

12. The proponents shall be jointly responsible for the environmental aspects of:

    (1) the construction, operation, monitoring and maintenance of the Dawesville Channel and its impacts within the estuaries and within the immediate marine environment;

    (2) the management and required monitoring of the catchment, and collection of data necessary for the development of the integrated catchment management plan for the Peel-Harvey catchment; and

    (3) all in-estuary monitoring and management, including weed harvesting.

    All of the above shall be carried out to the satisfaction of the Environmental Protection Authority.

13. Prior to the construction of the Dawesville Channel, the proponents shall prepare in stages, a monitoring and management programme, to the satisfaction of the Environmental Protection Authority. This programme shall include:

    (1) essential additional baseline monitoring required to be in place as soon as possible and prior to construction commencing;

    (2) construction stage impacts and monitoring, prior to construction; and

    (3) operational and long-term monitoring, in stages, to be determined by the Environmental Protection Authority.

Barry Hodge, MLA
MINISTER FOR ENVIRONMENT

MANAGEMENT COMMITMENTS MADE BY THE PROPONENTS

The following list has been amended by the EPA and accepted by the proponents to reflect the 'whole of Government approach' which is essential for management of this proposal.

1. DAWESVILLE CHANNEL

1.1 The proponents will conduct a detailed survey to locate, assess and offer protection to Aboriginal sites and heritage.

1.2 During construction of the Dawesville Channel, the proponents will ensure the continuity of road access, power supply, communications, and water and sewerage services that require relocation, and will minimize dust and noise impacts upon nearby residential areas.

1.3 Spoil from the excavated channel will be used in redeveloping the fill areas as a stable and varied landscape, reflecting naturally occurring topography elsewhere on the coastal strip.

1.4 The proponents will manage spoil disposal to minimize disturbance to important land elements, including coastal dunes, tree belts along Old Coast Road and near the estuary foreshore. Spoil disposed of adjacent to the undisturbed coastal dunes will be contoured to co-ordinate with natural dune topography in order to minimize the potential for erosion.

1.5 The land area used to dispose of excavated material will be contoured to facilitate possible future development into a prime residential and holiday area. Views from existing residences near the estuary will be retained, taking into consideration that these views may have been ultimately reduced by foreshore development and landscaping, irrespective of the proposed channel development.

1.6 Littoral sand drift northwards along the ocean coast will be mechanically bypassed beyond the channel entrance, to minimize siltation within the channel and to avoid adverse effects on beaches to the north and south.

1.7 The Dawesville Channel will be maintained as a navigable waterway, although, as with the existing Mandurah Channel, sea conditions at the ocean entrance may frequently preclude its use by small boats.

1.8 The estuary will be closely monitored to evaluate the management strategy's success in reducing the algal nuisance and to enable the development of appropriate management strategies to mitigate any deleterious effects that may occur. Current and proposed future monitoring studies in the estuary are described in Section 13 of the ERMP and Section 11 of the EPA assessment report.

2. CONTROL OF WEED ACCUMULATIONS

2.1 Weed harvesting will be continued most likely at an increased rate, until the weed nuisance in the estuary is successfully reduced.

2.2 Possible methods of improving the efficiency of harvesting operations, and the possible use of algicides to control weed growth, will be evaluated by the proponents and implemented if shown to be practicable.

2.3 The Peel Inlet Management Authority will continue the existing programme of shoreline management and will rehabilitate areas where weed accumulations or harvesting operations cause excessive retreat of the shoreline.

3. CATCHMENT MANAGEMENT

3.1 The proponents will continue to provide advice to farmers on fertilizer requirements, based on accurate assessment by paddock-specific soil tests.

3.2 The proponents will encourage further development and use of individual-nutrient fertilizers, and will undertake detailed investigations of ways to overcome existing economic constraints to their production and use.

3.3 The proponents will ensure that large-scale field trials are carried out to ascertain the technical and economic feasibility of converting use of sandy soils from agriculture to forestry. Private enterprise involvement in these studies will be encouraged.

3.4 The EPA and the Department of Agriculture will continue to provide advice to producers to define and implement practicable and cost-effective waste management strategies for control of point sources of phosphorus.

3.5 The Department of Agriculture will coordinate the preparation and implementation of a detailed catchment management plan aimed at reducing phosphorus losses to the estuary to less than 85 t/a in a 60 percentile year with minimal economic or social disruption to the catchment community.

3.6 The proponents will implement a moratorium on further clearing and drainage in the catchment, pending determination of the success of the catchment management plan in reducing phosphorus losses from existing cleared land.

3.7 The success of catchment management measures in reducing phosphorus losses to the estuary will be monitored by the proponents and audited by the EPA. The social and economic effects of catchment management measures upon the catchment community will be closely monitored by the proponents. Current and proposed future monitoring studies are described in Section 13 of the ERMP and in Section 11 of the EPA assessment report. The catchment management plan will be regularly reviewed by the EPA.

WESTERN AUSTRALIA

MINISTER FOR THE ENVIRONMENT

STATEMENT TO AMEND CONDITIONS APPLYING TO A PROPOSAL (PURSUANT TO THE PROVISIONS OF SECTION 46 OF THE ENVIRONMENTAL PROTECTION ACT 1986)

PROPOSAL :	PEEL INLET - HARVEY ESTUARY MANAGEMENT STRATEGY, STAGE 2 (010/701)
CURRENT PROPONENT :	MINISTER FOR TRANSPORT MINISTER FOR AGRICULTURE MINISTER FOR WATERWAYS
CONDITIONS SET ON :	3 JANUARY 1989
CONDITIONS AMENDED ON :	2 OCTOBER 1991

Condition 1 is amended to read as follows:

1A Proponent Commitments

In implementing the proposal, including the amendments reported on in Environmental Protection Authority Bulletins 543 and 640, the proponent shall fulfil the commitments (which are not inconsistent with the conditions or procedures contained in this statement) made and listed in Appendix 2 of Environmental Protection Authority Bulletin 363, as amended, and subsequently, including the Department of Marine and Harbours letter of 24 February 1992 on reclamation associated with the Dawesville Channel. (A copy of the commitments is attached).

1B Implementation

Subject to the conditions in this amended statement, the manner of detailed implementation of the proposal shall conform in substance with that set out in any designs, specifications, plans or other technical material submitted by the proponent to the Environmental Protection Authority with the proposal. Where, in the course of that detailed implementation, the proponent seeks to change those designs, specifications, plans or other technical material in any way that the Minister for the Environment determines on the advice of the Environmental Protection Authority, is not substantial, those changes may be effected.

The following conditions and procedure are inserted following condition 14 (which resulted from the amendment of 2 October 1991):

15 Estuary Reclamation (Dawesville Channel)

15-1 The proponent shall ensure that the total area of estuary reclaimed in association with the construction of the Dawesville Channel does not exceed 25 hectares (ha). Five hectares of this land may be granted to Wannunup Development Nominees Pty Ltd as part of an existing Land Exchange Agreement with the State Government. The remaining 20 hectares shall be available for public use. Five hectares of this land can include part of the canal waterway, to be available for public use.

15-2 The proponent shall endeavour to reduce the area of reclamation associated with the construction of the Dawesville Channel specified in condition 15-1 by increasing the height of the spoil, consistent with the recreational use of the reclaimed land, to the requirements of the Environmental Protection Authority on advice of the Peel Inlet Management Authority.

16 Foreshore Vegetation (Dawesville Channel)
Foreshore vegetation in and near the area of construction of the Dawesville Channel should be retained wherever possible.

16-1 The proponent shall ensure that the foreshore vegetation in and near the area of construction of the Dawesville Channel is retained wherever possible. Those stands of Casuarina, Paperbark and Tuart which are located on/along the existing foreshore and outside the proposed alignment of the channel should be retained, to the requirements of the Environmental Protection Authority on advice of the Peel Inlet Management Authority.

17 Compliance Auditing
In order to ensure that environmental conditions and commitments are met, an audit system is required.

17-1 The proponent shall prepare periodic "Progress and Compliance Reports", to help verify the environmental performance of the Peel Inlet - Harvey Estuary Management Strategy, Stage 2, in consultation with the Environmental Protection Authority.

Procedure

The Environmental Protection Authority is responsible for verifying compliance with the conditions contained in this statement, with the exception of conditions stating that the proponent shall meet the requirements of either the Minister for the Environment or any other government agency.

If the Environmental Protection Authority, other government agency or proponent is in dispute concerning compliance with the conditions contained in this statement, that dispute will be determined by the Minister for the Environment.

Note
Conditions 15 and 16 relate to the construction of the Dawesville Channel and should be audited in association with condition 7.

K. J. Minson

Kevin Minson MLA
MINISTER FOR THE ENVIRONMENT

Dawesville Channel
Technical Review

APPENDIX 2

HYDRODYNAMICS

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

D.A. LORD & ASSOCIATES PTY LTD

WATER AND RIVERS
COMMISSION

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2. Hydrodynamics

Prior to the construction of the Dawesville Channel, occasional dredging was conducted in the Mandurah Channel principally to maintain navigable waters. After the mid-1980s, dredging of the Mandurah Channel was conducted with the secondary aim of increasing flushing rates in the Peel-Harvey Estuarine System to ameliorate the adverse effects of severe nutrient enrichment (Hodgkin *et al.* 1985). The Dawesville Channel was designed primarily to mitigate the adverse effects of nutrient enrichment by increasing the marine flushing of the system. The opening of the Dawesville Channel was expected to cause profound changes to the prevailing hydrodynamics within the PHES, including modifications to the tidal levels, water circulation and structure, exchange characteristics and extreme water levels. The influence of the Channel on these hydrodynamic processes is described below.

2.1 Tidal levels

Water levels in the PHES are influenced by several factors including astronomical tides, river inflows, atmospheric pressure changes, wind forces, storm surges and long-term fluctuations in mean sealevel. The water levels in the PHES are monitored at a series of tidal gauges maintained by the Department of Transport (DoT). These gauges are deployed at the following locations (Figure 1):

- Centre of the Peel Inlet
- Centre of the Harvey Estuary
- Mandurah Channel
- Ocean side of the Dawesville Channel
- Estuary side of the Dawesville Channel
- Murray Lakes Canal Development
- Fauntleroy Drain
- Robert Bay Drain
- Mealup Drain

2.1.1 Prior to the opening of the Dawesville Channel

Before the opening of the Dawesville Channel, tidal water movements in the Peel Inlet were solely due to exchanges through the Mandurah Channel. Tidal fluctuations in the Harvey Estuary were due to exchanges with the Peel Inlet via the Grey Channel, which resulted in a substantial attenuation and lag in water-level variations between the Peel Inlet and Harvey Estuary (DoT 1996).

Daily astronomical tides in the ocean adjacent to the PHES range from 20 cm to 90 cm; however, prior to the opening of the Dawesville Channel, the daily mean tidal range in the Peel Inlet and Harvey Estuary averaged 17% and 15% of the ocean tides respectively (DMH 1993). The daily tidal range in the PHES seldom exceeded 10 cm due to flow restriction by the Mandurah Channel (Kinhill Engineers 1988). However, the longer period (monthly and seasonal) tidal constituents were not attenuated by the Mandurah Channel, and so caused corresponding changes in the estuarine water level (DoT 1996).

In 1987 the Mandurah Estuary (Fairbridge Bank) and Sticks Channel were dredged to form a straighter and wider channel to aid navigation and to increase the flushing rate of the PHES. Hearn and Lukatelich (1990) performed a harmonic analysis of the tides in the ocean and at the centre of the Peel Inlet to examine the influence of this dredging on the amplitude and phase of the main astronomical tidal components in the Peel Inlet. The mean tidal range in the ocean was 49.3 cm, and this was attenuated in the Peel Inlet to 4.5 cm (c. 9% of the mean ocean tide) before dredging of the Mandurah Channel and 6.9 cm (c. 14% of the mean ocean tide) after dredging. The maximum tidal range in the ocean of 90.8 cm was attenuated in the Peel Inlet to 8 cm (c. 9% of the maximum ocean tide) before dredging and 11.8 cm (c. 13%) after dredging.

Prior to the opening of the Dawesville Channel, high-tide levels in the Harvey Estuary lagged behind those in the Peel Inlet by approximately 3 hours, due to strong attenuation of the low-amplitude tide through the narrow Grey Channel (Hart 1995).

2.1.2 Predicted effects of the Dawesville Channel

Several studies predicted the likely effects of the Dawesville Channel on tidal levels within the PHES, including those of Dufty (1983), Tong (1985a, 1985b), Hearn and Hunter (1986), Eliot (1993) and the Department of Marine and Harbours (1993). The results of several of these are summarised in Table 1.

The Department of Marine and Harbours (1993) conducted a comprehensive suite of simulations of the expected water level regimes in the PHES following the opening of the Dawesville Channel, which indicated a marked increase in the amplitude of tidal oscillations in both the Peel Inlet (45%-50% of the ocean tide range) and Harvey Estuary (60%-70%) (Figure 2.1). Following the opening of the Channel, the tidal range in the Harvey Estuary was expected to be greater than that of the Peel Inlet (Table 2).

Table 1: The mean tidal range of the PHES relative to the ocean tide following the opening of the Dawesville Channel, as predicted by several numerical modelling studies.

STUDY	PEEL INLET	HARVEY ESTUARY
Actual before opening the Dawesville Channel	14%	13%
Tong (1985b)	15-20%	45-50%
Eliot (1993)	30%	40%
DMH (1993)	45-50%	60-70%
Actual after opening the Dawesville Channel	60%	62%

Source: Hart (1995)

Table 2: Comparison of water levels modelled before and after the opening of the Dawesville Channel and observed water levels after the opening.

DESCRIPTION	MODELLED BEFORE CHANNEL OPENING(CM)	PREDICTED AFTER CHANNEL OPENING(CM)	OBSERVED AFTER CHANNEL OPENING(CM)
Maximum Level			
Peel Inlet	53.1	64.1	88.6
Harvey Estuary	53.1	65.1	90.4
Average Daily High Water			
Ocean	26.4		
Peel Inlet	5.0	13.5	15.8
Harvey Estuary	4.3	16.6	18.2
Mean Water Level			
Ocean	-4.0		
Peel Inlet	-0.3	-1.3	2.6
Harvey Estuary	-0.3	-2.4	3.2
Average Daily Low Water			
Ocean	-31.1		
Peel Inlet	-4.7	-14.1	-8.9
Harvey Estuary	-4.7	-21.3	-10.0
Minimum Level			
Peel Inlet	-39.9	-47.9	-46.4
Harvey Estuary	-39.9	-60.9	-49.6
Average Daily Range			
Ocean	57.5		
Peel Inlet	9.7	27.6	24.7
Harvey Estuary	8.6	37.9	28.2

Note: The simulations were based on the ambient conditions from 1989 to 1991 inclusive and incorporated the effects of rainfall and river and drain inflows. The observed water levels were determined between 1994 and 1997. Elevations are relative to Australian Height Datum (AHD) (adapted from DMH 1993 and Tremarfon 1997b).

The predicted increase in the tidal range in the PHES would result in a corresponding increase in the intertidal area and the inundation of low-lying land (Humphries & Ryan 1993). Hence, the upper level of the estuary shoreline would be submerged more often but the period of submergence would be reduced, whereas the lower levels of the estuary shoreline would be exposed more frequently but the period of exposure would be reduced (Humphries & Ryan 1993). The impact of these changes in water-level ranging were expected to be most apparent on the eastern shores of the Peel Inlet and at the southern end of the Harvey Estuary, as these shorelines are the flattest (Hodgkin *et al.* 1985). It was also predicted that saline water might move 300 m further up agricultural drains during high tide (Humphries & Ryan 1993; Waterways Commission 1994).

2.1.3 Observed effects of the Dawesville Channel

After the opening of the Dawesville Channel, tidal fluctuations in the Harvey Estuary were dominated by flow through the Channel and tidal fluctuations in the Peel Inlet were influenced by flows through both the Mandurah and Dawesville Channels (DoT 1996). A phase change in the diurnal tidal constituents within the PHES resulted in the Harvey Estuary experiencing high tide approximately 43 minutes before the Peel Inlet (DoT 1996).

The amplitude of both the diurnal and semi-diurnal tidal constituents increased in the PHES. The tidal range increased from an average of c. 10 cm for both the Peel Inlet and Harvey Estuary to 24.7 cm for the Inlet and 28.2 cm for the Estuary (Table 2). The maximum spring tide range in the Peel Inlet increased from 12.3% to 48% of the ocean tide; whereas in the Harvey Estuary the maximum spring tide range increased from 11.6% to 55% (Tremarfon, 1997a).

The observed tidal ranges were relatively close to those predicted by DMH (1993). However, Tremarfon (1997a) conducted a study to compare the predicted and observed water level fluctuations in the PHES and found that the ocean water levels were, on average, higher (5.8†cm) following the opening of the Dawesville Channel (between 1994 and 1997) than for the three-year period (1989 to 1991) which had been used as a datum to predict the changing water levels after the opening of the Channel. As a result the observed water levels in the PHES following the opening of the Channel were higher than predicted (Tremarfon 1997a). The influence of these elevated ocean water levels was more pronounced in the Harvey Estuary than in the Peel Inlet due to the location of the Dawesville Channel, and hence the recorded water levels in the Inlet were more closely related to those predicted by the numerical modelling (Tremarfon 1997a). The original hydrodynamic model was re-run using the observed 1994 to 1997 ocean water levels (Tremarfon 1997b) and, as expected, the simulated water levels in the PHES were closer to the observed levels than those originally predicted.

2.1.4 Status of the monitoring program

Tidal datum levels after the opening of the Dawesville Channel were established for the five tide gauges in the PHES. These gauges are still operational, whereas the three placed in the agricultural drains to ascertain the extent of tidal propagation were decommissioned in June 1997. Data from these gauges were to be employed to examine the change in the upstream extent of tidal penetration in the Harvey, Murray and Serpentine Rivers; however, this has not yet been reported.

2.2 Water circulation and structure

Water circulation in the PHES is principally controlled by flows from the river, tidal exchange with the ocean and wind forces acting across the water surface. The main factor controlling vertical density differences is the differences in salinity between oceanic, estuarine and riverine waters.

2.2.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the increased exchange of oceanic water in the Peel Inlet via the Mandurah Channel caused the Inlet to be more saline than the Harvey Estuary in winter and spring. However, in summer and autumn the Estuary was more saline than the Inlet due to the relatively high evaporation rates and limited exchange with oceanic waters in the Estuary.

The PHES was generally well mixed in summer and autumn, with a salinity difference of up to 10 ppt (Hodgkin *et al.* 1985). However, despite the shallow depth, the PHES could experience prolonged periods of stratification during calm periods in winter and spring when oceanic and/or estuarine waters would intrude below the fresh river waters (Lukatelich & McComb 1989). Persistent strong winds could mix the water to a uniform salinity, but with the return to calm weather the stratified condition was rapidly re-established (Hodgkin *et al.* 1985). The Peel Inlet generally showed stronger stratification than the Harvey Estuary during winter, as the incoming marine water from the Mandurah Channel often formed a thin bottom salt wedge that underlay the relatively fresh river waters (Hart 1995).

2.2.2 Predicted effects of the Dawesville Channel

The predicted, and intended, effect of the Dawesville Channel was to increase the exchange of estuarine and ocean waters and thereby produce a more consistent marine environment within the PHES. Hence, the episodes during which the estuarine waters remained either almost fresh or hypersaline were expected to reduce in intensity, frequency and duration (DoT 1996).

The opening of the Channel was predicted to cause an increase in the rate of water movement within the PHES. However, it was anticipated that this would only be appreciable in the vicinity of the Dawesville Channel and perhaps near the narrow Grey Channel (Hodgkin *et al.* 1985). The increased current flow in the vicinity of the Dawesville Channel was expected to result in the development of a flood-tide delta in the Harvey Estuary, and the design of the Channel was aimed at minimising this (Hodgkin *et al.* 1985).

Humphries and Ryan (1993) predicted that the increased flushing following the opening of the Dawesville Channel would reduce the duration of stratification during winter and early spring by approximately two months. It was anticipated, however, that the stratification would be of greater intensity, particularly in the northern Harvey Estuary where the salinity of the estuarine waters would become closer to that of the ocean (Hodgkin *et al.* 1985). During summer, with decreased river input, the anticipated increase in exchange characteristics was also predicted to improve the mixing of the estuarine waters, resulting in salinities close to marine conditions and less frequent stratification (Humphries & Ryan 1993). However, stratified conditions were expected to persist in the lower reaches of the Serpentine and Murray Rivers (Humphries & Ryan, 1993).

2.2.3 Observed effects of the Dawesville Channel

Observations of the water quality within the PHES following the opening of the Dawesville Channel have realised the prediction of more marine, less variable conditions. Sufficient wind-induced mixing occurred in summer to inhibit vertical stratification; hence, vertical stratification was predominantly limited to the winter months, with fresh river water overlying estuarine water. Vertically mixed conditions returned rapidly, however (DoT 1996). The Peel Inlet also remained more stratified than the Harvey Estuary (Hart 1995). On several occasions a three-layer stratification was observed, with ocean waters overlain by estuarine waters which were in turn overlain by fresh riverine waters. However, the stability and persistence of this water column structure is uncertain due to the relatively large time between monitoring exercises (DoT 1996; see Appendix 5).

A significant horizontal salinity gradient was observed along the length of the Harvey Estuary during summer. It appeared that this was maintained by a balance between tidal exchange and evaporation, such that relatively marine salinities prevailed close to the north end of the Harvey Estuary, near the Dawesville Channel, and hypersaline conditions (up to 48 ppt) towards its south end (Wilson & Latchford 1995). This balance indicated that the level of water exchange between the Harvey Estuary and the ocean is very near to the minimum required for adequate mixing. Monitoring in the Peel Inlet revealed relatively little variation in water structure across its width, which suggested that satisfactory water exchange occurs. These findings indicated that dredging of Grey Channel would not be justified, as doing so would likely increase the rate of flushing within the Peel Inlet and reduce the rate of flushing in the Harvey Estuary (DoT, 1996).

2.2.4 Status of the monitoring program

Water quality measurements in the estuary have not been obtained since 1996.

2.3 Exchange characteristics

The PHES has a large ratio of basin surface area to channel cross-section, which, despite being microtidal, could result in strong tidal currents through the Mandurah and Grey Channels, and it was anticipated that strong currents might also occur in the Dawesville Channel (Hearn 1995). There have been no studies of the actual water circulation patterns within the PHES and the DoT recognised the difficulty in adequately characterising these flows due to the large basin area, low water speeds, tidally varying flows, wind effects and seasonally stratified conditions (DoT 1996). Hence, to describe the flow regime in the PHES, the DoT examined the exchange characteristics of the three principal channels (DoT 1996).

2.3.1 Prior to the opening of the Dawesville Channel

The residence times (number of days required for the water volume to be flushed to the ocean) for the PHES prior to opening the Dawesville Channel were determined by Dufty and Bowden (1983) using numerical modelling. This study incorporated the effects of wind and tidal mixing, but excluded river flows, and an annual average residence time for the PHES of 75 days was determined (Table 3). Kinhill Engineers (1988) noted that, by taking account also of river flows, the estimated annual average residence time for the PHES would be approximately 44 days. Humphries and Ryan (1993) presented predictions of the mean residence times in the Peel Inlet and Harvey Estuary prior to the opening of the Dawesville Channel of 30 and 50 days respectively.

Table 3: Residence times in the Harvey Estuary and PHES due to wind and tidal mixing only.

PERIOD	HARVEY ESTUARY	PEEL-HARVEY SYSTEM
Summer	133 days	103 days
Winter	88 days	47 days
Annual average	110 days	75 days

Source: Dufty and Bowden (1983)

From approximately 1940 onwards, the sand bar at the mouth of the Mandurah Channel was regularly kept open by dredging and the placement of training walls to maintain navigable conditions (PWD 1983). After the mid-1980s, the dredging was conducted with the secondary aim of increasing the flushing of the PHES. Hearn (1995) calculated that dredging of the Sticks Channel would decrease the residence time from astronomic tidal exchange from 44 days to 18 days.

The Department of Transport deployed current meters in the Mandurah and Grey Channels on two occasions prior to the opening of the Dawesville Channel (October/November 1993 and March/April 1994). The analysis of these data has not been formally reported by the Department of Transport, but data summary sheets have been prepared and are summarised in Table 4.

Table 4: Measured currents (m/s) through the Mandurah and Grey Channels prior to the opening of the Dawesville Channel.

PERIOD	FLOOD MAXIMUM	EBB MAXIMUM	FLOOD AVERAGE	EBB AVERAGE
Mandurah Channel				
22/10/93-15/11/93	0.83	0.60	0.58	0.46
09/03/94-11/04/94	0.83	0.69	0.51	0.48
Grey Channel				
23/10/93-15/11/93	0.47	0.43	0.39	0.26
10/03/94-14/03/94	Current meter malfunction			

Source: Department of Transport memorandum

2.3.2 Predicted effects of the Dawesville Channel

Modelling of the water exchange between the PHES and the ocean was conducted by Dufty (1983), Tong (1985b), Hearn and Hunter (1986), Eliot (1993) and DMH (1993). However, DMH (1993) noted that numerical diffusion, inherent in the model used by Dufty (1983), may have adversely affected his results. Hearn and Hunter (1986) modelled the barotropic flushing of the Harvey Estuary, ignoring the Peel Inlet.

The Dawesville Channel was designed to increase the exchange of estuarine waters with the ocean and hence reduce residence times in the estuary. Humphries and Ryan (1993) presented predictions that showed a reduction in the mean residence times in the Peel Inlet from 30 days to approximately 10 days and in the Harvey Estuary from 50 to approximately 17 days.

Mathematical modelling indicated that the volume of water exchanged through the Dawesville Channel would be more than double the original flow through the Mandurah Channel (Hodgkin *et al.* 1985). The opening of the Dawesville Channel was also predicted to approximately double the exchange between the Peel Inlet and Harvey Estuary (Hodgkin *et al.* 1985), with the net effect of greatly increasing the flushing of estuary water to the sea.

The total volume of ocean water entering the estuary on a flood tide (tidal prism) via the Mandurah Channel was predicted to decrease by approximately 10% with the opening of the Dawesville Channel (Ryan 1993). However, the Department of Conservation and Environment (1985a) presented a table of the modelled water exchanges through the three channels in the PHES which indicated that the total water exchange per tidal cycle would increase in the Mandurah and Grey Channels after the opening of the Dawesville Channel (Table 5).

Table 5: Modelled water exchange per tidal cycle through the PHES channels before and after opening of the Dawesville Channel, during typical summer conditions.

CHANNEL	PRIOR TO OPENING THE DAWESVILLE CHANNEL (M3 X 106)	AFTER OPENING THE DAWESVILLE CHANNEL (M3 X 106)
Dawesville	-	15.6
Mandurah	5.5	6.3
Grey	3.5	6.4

Source: DCE (1985a)

A summary of predictions of the volume exchange and velocities through the Dawesville Channel was undertaken by the Department of Marine and Harbours (1993), which indicated that the predicted flow volumes and velocities were slightly greater in winter (Table 6).

Table 6: Predicted Dawesville Channel flow volumes and velocities.

DESCRIPTION	SUMMER	WINTER	SOURCE
Average volume exchange per tidal cycle*	16.5×10^6 m^3	17.1×10^6 m^3	Tong (1985b)
Peak volume exchange per tidal cycle*	22.03×10^6 m^3	33.01×10^6 m^3	Dufty (1983)
Peak volume exchange per tidal cycle*	23.4×10^6 m^3	28.6×10^6 m^3	Tong (1985b)
Peak ebb tide velocity*	0.8 m/s	1.2 m/s	Dufty (1983)
Peak velocity	0.85 m/s	1.1 m/s	Tong (1985b)
Mean maximum velocity	0.70 m/s	0.77 m/s	Tong (1985b)

Source: DMH (1993)

Note: calculated assuming the peak velocity is constant across the cross-sectional area of the channel and a sinusoidal tide of 24 hour period.*

The Department of Marine and Harbours (1993) modelled flows through the Dawesville Channel and predicted that the average peak tidal flows would be 1.03 m/s for the flood and 1.13 m/s for the ebb tides (Table 7). The maximum flood and ebb flows in the Dawesville Channel were predicted to be 1.90 m/s and 1.85 m/s, respectively (DMH 1993). The average flood and ebb flow velocities through the Grey Channel, after the opening of the Dawesville Channel were predicted to increase, which could cause erosion of the narrow central section of the Grey Channel (DMH 1993; Table 7). It was expected that this erosion would increase the channel cross-sectional area and allow greater transmission of flows between the Harvey Estuary and the Peel Inlet and thereby reduce the predicted differences in tidal ranges and elevations between these two basins (DMH 1993).

Table 7: Modelled average daily peak flow through three channels of the PHES.

CHANNEL	FLOOD MODELLED(M/S)	EBB MODELLED(M/S)
Dawesville	1.03	1.13
Mandurah	0.57	0.62
Grey	0.87	0.82

Adapted from DoT (1996)

2.3.3 Observed effects of the Dawesville Channel

Flow measurements through the three channels of the PHES were obtained during three periods following the opening of the Dawesville Channel: April to June 1994, October to December 1994 and April to May 1995. The analysis of these data has not been formally reported by the Department of Transport but data summary sheets have been prepared and are summarised in Table 8.

Table 8: Measured currents (m/s) through the Mandurah and Grey Channels following the opening of the Dawesville Channel.

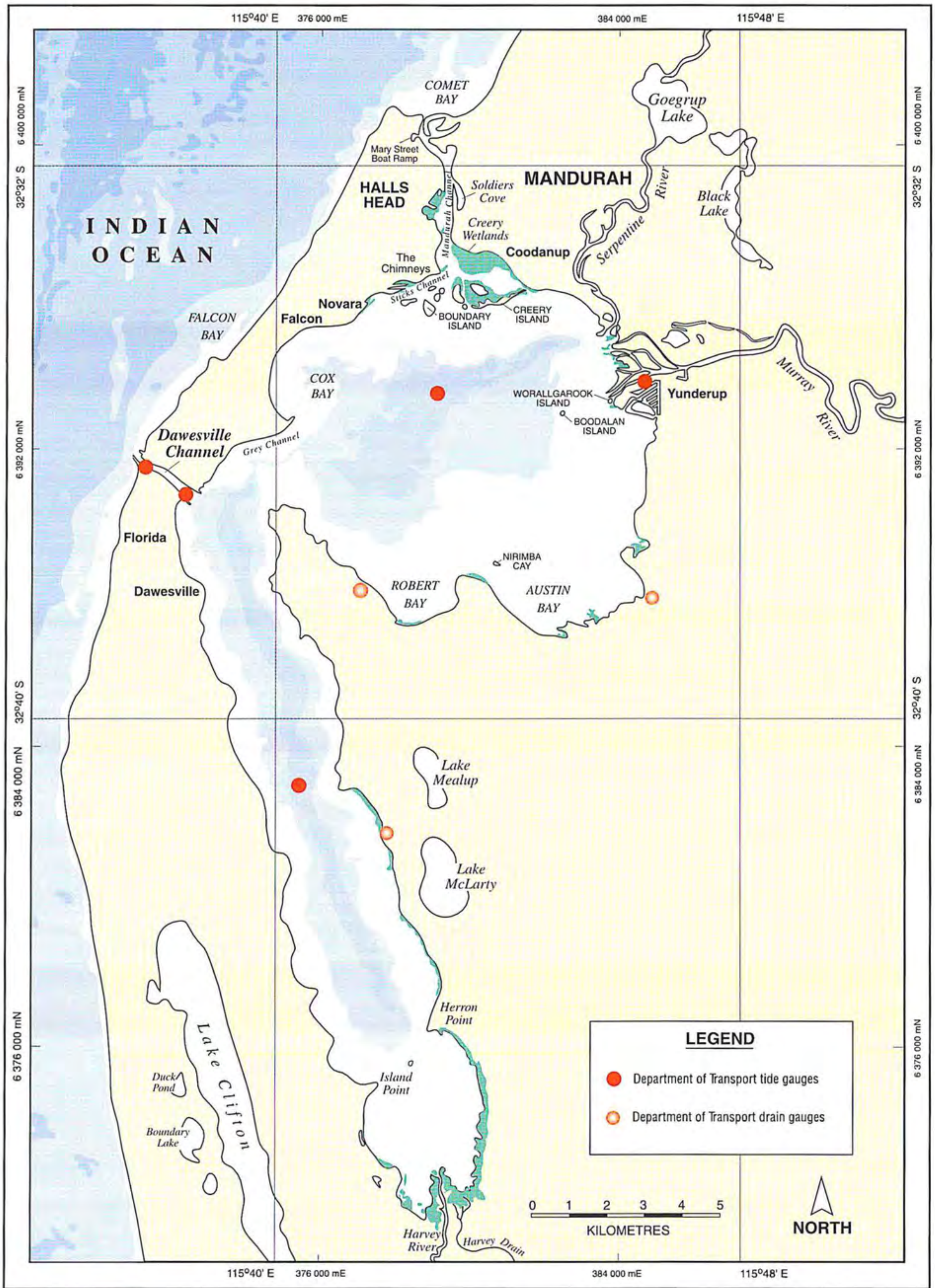
PERIOD	FLOOD MAXIMUM	EBB MAXIMUM	FLOOD AVERAGE	EBB AVERAGE
Dawesville Channel				
13/04/94-03/06/94	2.04	1.42	1.31	0.87
07/11/94-07/12/94	Current meter malfunction			
28/04/95-30/05/95	2.17	2.09	1.77	1.68
Mandurah Channel				
14/04/94-03/06/94	0.97	0.77	0.59	0.54
13/10/94-03/06/94	0.68	0.60	0.46	0.40
10/04/94-30/05/95	0.68	0.63	0.48	0.48
Grey Channel				
May to June 1994	Current meter malfunction			
27/10/94-09/12/94	1.02	1.15	0.41	0.58
11/04/95-11/05/95	0.49	0.39	0.36	0.30

Source: Department of Transport memorandum

The maximum flood and ebb flows through the Dawesville Channel observed during April/May 1995 were 2.17 and 2.09 m/s respectively. These observations were slightly above the predicted maximum flows of 1.90 and 1.85 m/s. The observed flood currents through the Mandurah Channel were close to predictions, whereas the ebb currents through it and the flood and ebb currents in the Grey Channel were in excess of those predicted (cf. Tables 7 and 8).

2.3.4 Status of the monitoring program

No further measurements or analysis of the exchange characteristics of the PHES are planned at this stage.



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Auth: KH/BH | Date: 2/98

Water and Rivers Commission

Dawesville Channel Monitoring Programme

Two Year Technical Review

LOCATION OF TIDE AND DRAIN GAUGES

Figure 1

2.4 Extreme water levels

Extreme water level conditions in the PHES are principally driven by river flood inputs and/or storm surge events. The regime of extreme water levels prior to and after the opening of the Dawesville Channel is described below.

2.4.1 Prior to the opening of the Dawesville Channel

Prior to the opening of the Dawesville Channel the narrow Mandurah Channel attenuated the effects of ocean surge events, and so the majority of the extreme water levels within the PHES were governed by river flows (DoT 1996). The 1-in-100-year river flood level was estimated to be 1.8 m AHD in the Peel Inlet and 1.3 m AHD in the Harvey Estuary (DoT 1996). Due to the restricted flows through the Mandurah Channel, the water could take up to nine to ten days to recede to tidal levels (DoT 1996).

2.4.2 Predicted effects of the Dawesville Channel

Humphries and Ryan (1993) noted that the Dawesville Channel would allow the flood waters to drain to the ocean more readily, and hence there would be a reduction in the level and duration of river floods after its opening. Modelling by the DMH (1993) indicated that the 1-in-100-year flood level in the Peel Inlet would be lowered by approximately 0.7 m to 1.1 m AHD and in the Harvey Estuary by approximately 0.3 to 1.0 m AHD. The 25-year flood levels were expected to be reduced to levels comparable to those induced by high astronomic tides (Ryan 1993).

It was predicted that the duration of elevated flood levels would decrease substantially, with the 1-in-100-year flood receding within approximately five days rather than nine to ten days (DMH 1993; Humphries & Ryan 1993). Statistics of the persistence of submergence and exposure were modelled for before and after the opening of the Dawesville Channel for both the Peel Inlet and Harvey Estuary (DMH 1993). As an example, water levels in excess of 0.45 m AHD in the Peel Inlet were predicted to occur approximately six times more frequently after the opening of the Channel than before; however, these levels would endure for less than 14 hours compared with 80 hours prior to the opening (DMH 1993).

According to predictions the opening of the Dawesville Channel would allow ocean surges to be more readily transmitted into the PHES. The DMH (1993) predicted that a storm with a similar magnitude to tropical cyclone Alby, with an ocean surge level of approximately 95 cm, would result in water levels approximately 20 cm higher after the opening of the Dawesville Channel than with the Mandurah Channel alone. The opening of the Channel would extend the period of peak water levels during a storm event such that the first component of the water level peak would be driven by oceanographic factors (tides and storm surge) and the second component would be due to river flows from the catchment areas (DMH 1987). Hence, the water levels were expected to rise and fall more rapidly and the overall duration of these elevated levels was expected to be less and to follow more closely the ocean surge levels (Humphries & Ryan 1993).

The predictions indicated that the overall effect of the construction of the Dawesville Channel would be to change the likely source of extreme water levels from flooding episodes to storm surge episodes (DoT 1996). However, given that storm events may occur at any time of the year, whereas floods are typically limited to winter, it was expected that extreme levels would occur over a wider portion of the year (DoT 1996). DoT (1996) also predicted that the maximum water level would decrease.

2.4.3 Observed effects of the Dawesville Channel

The observed statistics of the persistence of submergence and exposure for the Peel Inlet were similar to the modelled figures. However, for the Harvey Estuary the observed frequency and persistence of submergence was greater and the observed frequency and persistence of exposure less than predicted (Tremarfon 1997a). These differences were a result of the higher ocean levels experienced during the period after the opening of the Dawesville Channel (1994 to 1997) than during the period taken as the basis for modelling (1989 to1991). However, observations to date have indicated that they were not above historically recorded levels (DoT 1996).

A detailed analysis of extreme water level events using an ocean tide data set from 1897 to 1996 was conducted by Tremarfon (1997b). This indicated that the 10-, 50- and 100-year return period extreme high water levels in both the Peel Inlet and Harvey Estuary were 0.78, 0.84 and 0.87 m above AHD respectively.

2.4.4 Status of the monitoring program

The DoT has prepared a map (based on topographic maps, aerial photography and limited ground levelling) of the low-lying areas to establish the 1.6 m (AHD) flood level. The extreme high-water levels following the opening of the Dawesville Channel were less than those experienced prior to its opening. Hence, no further investigations of extreme water levels in the PHES are planned at this stage.

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Technical Review

APPENDIX 3

SEDIMENTS

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

D.A. LORD & ASSOCIATES PTY LTD

WATER AND RIVERS
COMMISSION

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3. Sediments

The geology and sedimentology of the PHES have been extensively described by the University of Western Australia (1976) and Brown *et al.* (1980). However, the principal importance of sediments in the ecology of the PHES is their role in phosphorus recycling, as they have the ability to both bind and release phosphate depending on the physical and chemical nature of the sediments and overlying waters (Hill *et al.* 1991). Lukatelich (1985) noted that the major source of phosphorus for both the *Nodularia* blooms and the macroalgal accumulations in the PHES was that released from the sediments. The factors that determine the importance of the sediments on water quality include the size and composition of the sediment phosphorus store and the potential for its release (Lukatelich 1987). The rate of phosphorus release from the sediments depends on the physical and chemical nature of the sediments, the bacterial activity in the sediments, the history of enrichment and the flushing rate of the system (Marsden 1989).

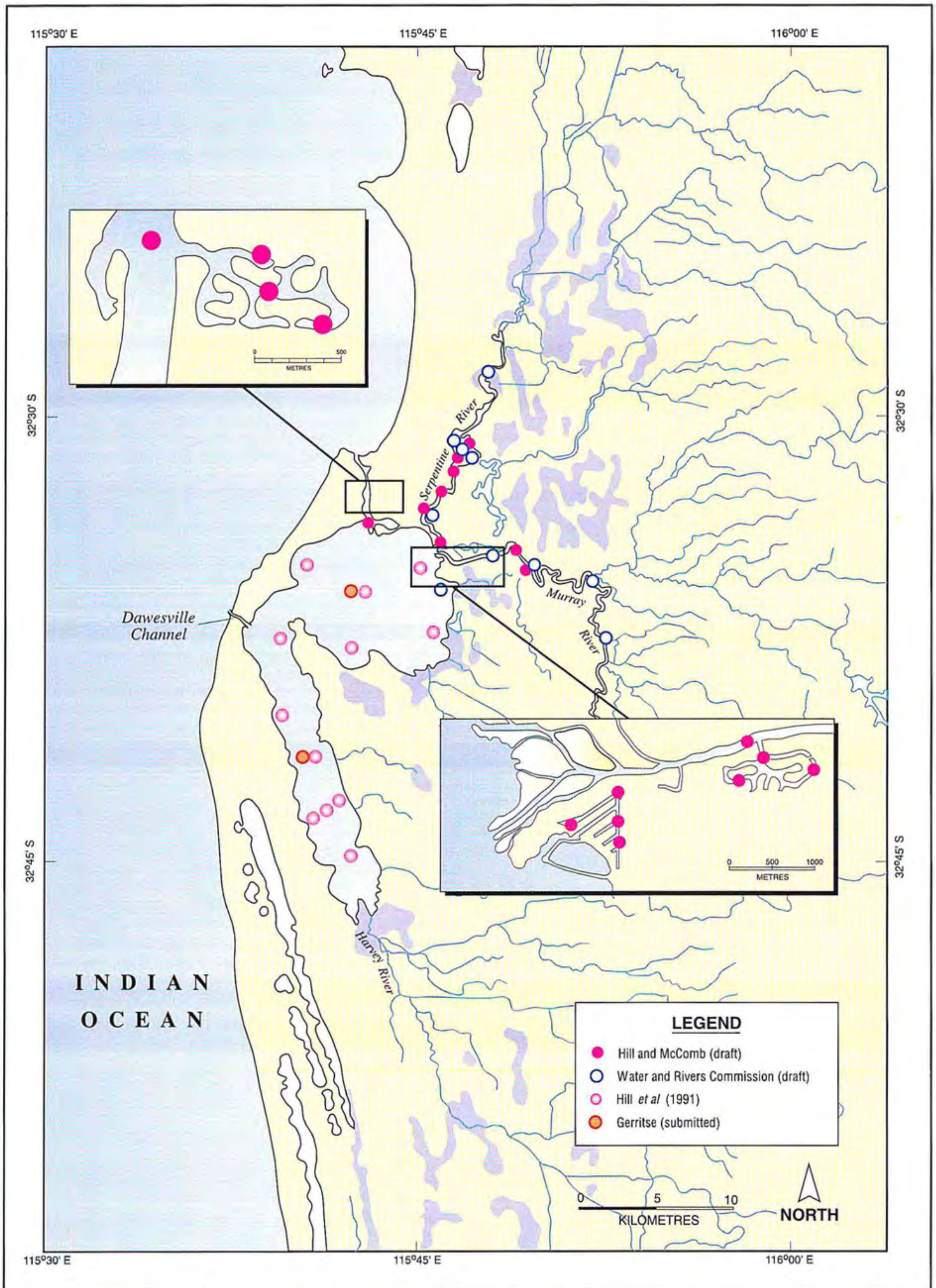
In the PHES, the principal route for the transfer of phosphorus from the water column to the sediments is via biological uptake by winter diatom blooms which absorb phosphorus from the nutrient rich-waters. The phosphorus then settles out of suspension in the form of senescent diatom cells, faecal pellets resulting from zooplankton grazing and phosphorus attachment to suspended particles (Lukatelich 1985). Hillman *et al.* (1990) estimated that approximately 50%-70% of the riverine phosphorus, predominantly as phosphate, was trapped in algal blooms prior to the opening of the Dawesville Channel. The collapse of the diatom bloom and subsequent decomposition resulted in anoxic conditions and caused high phosphorus release from the sediment, which helped support the development of *Nodularia* blooms.

The total phosphorus concentration in the sediments may be divided into organic and inorganic components, and the inorganic phosphorus may in turn be divided into apatite phosphorus and non-apatite phosphorus, apatite being a crystalline mineral of calcium phosphate and fluoride. It should be noted that there is generally no significant correlation between the *total phosphorus* content of sediments and the trophic state of the overlying waters (Williams & Mayer 1972). It is the amount of bioavailable *non-apatite phosphorus*, and the potential for its release and recycling, that determines the contribution of the sediment phosphorus store to the overlying waters.

Phosphate is sorbed to Fe(III) under oxic conditions whereas under anaerobic conditions Fe(III) is reduced to Fe(II) and phosphate is released (Mortimer 1949). Bacteria can also store phosphorus under oxic conditions, and bacterial phosphorus release occurs under anaerobic conditions. Hence, redox reactions of iron (Bates & Neafus 1980) and bacterial activity in the sediment (Bostrom *et al.* 1985) play major roles in controlling phosphate exchange between the sediments and the overlying waters. In particular, anaerobic conditions can control the rate of release of phosphate from the sediment into the overlying water column, sediment phosphorus release rates being an order of magnitude less under toxic conditions than under anaerobic conditions (Lukatelich 1985). Sediments from the Harvey Estuary have been used to examine the processes of phosphorus absorption by sediments by McAuliffe *et al.* (draft A) and the influence of nitrate applications on sediment phosphorus release (McAuliffe *et al.* draft B).

3.1 Estuarine sediments

Peel Inlet sediments are predominantly medium to coarse sands along the shallow margins and fine sands in the central basin (Brown *et al.* 1980). The sediments in Harvey Estuary are generally coarse sands along the eastern margin, silt in the central basin and silty sand along the western margin (Brown *et al.* 1980). As the Peel Inlet has a smaller fetch length than the Harvey Estuary, there is less mixing, resuspension and redistribution of sediment particles in the Inlet than in the Estuary (Hill *et al.* 1991). Consequently, the sediments in the Inlet are more uniform than those in the Estuary with respect to their physical characteristics. Sediment samples have been obtained from several sites within the PHES (Figure 1).



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LOCATION OF ESTUARINE AND RIVERINE SEDIMENT SAMPLING SITES

Figure 1

Auth: KH/BH | Date: 2/98

3.1.1 Prior to the opening of the Dawesville Channel

The sediments in the PHES accumulated phosphorus because the riverine phosphorus input historically exceeded the phosphorus losses from the system. Regular sediment sampling reported by Hill *et al.* (draft A) between 1982 and 1989 indicated that the mean annual total sediment phosphorus concentrations in the Peel Inlet and Harvey Estuary ranged from 167 to 258 µg/g and 595 to 714 µg/g respectively. Sediment samples obtained in May 1984 by Lukatelich (1985) support these results. The proportion of non-apatite phosphorus in the Peel Inlet and Harvey Estuary accounted for 20%-43% and 35%-52% of the total phosphorus concentration in each estuary respectively (Table 1). Observations of the sediment phosphorus concentration between 1982 and 1989 showed higher concentrations in the Harvey Estuary than in the Peel Inlet, and in the Estuary the highest concentrations were observed in water depths of *c.* 1.5 m through the centre of the Estuary and were higher on the western shore than the eastern shore (McComb, draft). The annual variation in sediment total phosphorus concentration did not display a consistent pattern at all sampling sites (McComb, draft). Examination of the annual variations in sediment total phosphorus indicated an unusually high concentration in 1983, corresponding to an unusually high algal biomass in that year; however, no other annual variations in sediment total phosphorus were observed, which suggested that the sediment had a high buffering capacity.

Table 1: Sediment phosphorus concentration in the Peel Inlet and Harvey Estuary with ± standard error.

YEAR	ORGANIC PHOSPHORUS (µg/g)	APATITE PHOSPHORUS (µg/g)	NON-APATITE PHOSPHORUS (µg/g)	TOTAL PHOSPHORUS (µg/g)
Peel Inlet				
1982	42±12	80±6	43±91	67±24
1983	59±4	81±7	78±10	243±19
1984	65±13	86±8	98±11	258±37
1985	55±6	75±6	79±8	212±18
1986	67±13	67±13	74±5	218±15
1987	66±7	77±6	52±5	222±18
1988	81±7	88±13	45±4	220±18
1989	60±6	63±8	103±22	237±7
Harvey Estuary				
1982	175±18	142±19	219±4	595±108
1983	203±25	177±23	280±38	704±89
1984	165±27	131±15	306±64	591±109
1985	169±21	163±12	354±35	692±58
1986	209±8	189±26	237±25	663±39
1987	235±16	155±17	300±26	714±41
1988	248±24	153±11	279±26	670±61
1989	163±33	135±12	308±35	627±66

Source: Hill et al. *draft A*

Sediment cores obtained from the Peel Inlet and Harvey Estuary by Gerritse *et al.* (submitted) indicated that the total and inorganic phosphorus concentration in surface sediments in the PHES had more than doubled over the past 100 years. Inventories of phosphorus in sediment cores suggested an accumulation of approximately 25 kg of phosphorus per hectare, which was consistent with observations that more than half of all the phosphorus entering the PHES was flushed to the ocean (Black & Hodgkin 1984; Gerritse *et al.* submitted). Examination of the cumulative input of phosphorus from the Murray and Serpentine Rivers between 1977 and 1991 indicated that the inventory of anthropogenic phosphorus in the cores accounted for 70% of the dissolved inorganic phosphorus and 20% of the total phosphorus in the Peel Inlet. In the Harvey Estuary the anthropogenic phosphorus store in the sediment accounted for approximately 25% of the dissolved inorganic phosphorus and 15% of the total phosphorus inputs (Gerritse *et al.*, submitted).

3.1.2 Predicted effects of the Dawesville Channel

The increased tidal range and flushing characteristics expected with the opening of the Dawesville Channel were predicted to increase the rate at which suspended sediments were removed from the Estuary (Hodgkin *et al.* 1985; Humphries & Ryan 1993). As a consequence, Humphries and Ryan (1993) predicted an increase in the particle size range of the estuarine sediments towards coarser, sandier fractions.

The opening of the Channel was expected to result in an increase in the flushing of the waters of the PHES and would result in the maintenance of oxic conditions throughout most of the year. As noted above, sediment phosphorus release rates were observed to be an order of magnitude less under oxic conditions than under anaerobic conditions (Lukatelich 1985); hence it was predicted that with the opening of the Channel there would be a significant decrease in sediment release of phosphorus within the PHES (Lukatelich 1985). In addition, Humphries and Ryan (1993) noted that the increased flushing characteristics associated with the Dawesville Channel would cause more rapid removal of high-nutrient river water from the Harvey Estuary and thereby reduce the proportion retained in the sediments.

Kidby *et al.* (1984) employed an indicative model to suggest that a relatively modest increase in the summer flushing rate would rapidly deplete the sediment phosphorus storage, whereas even a significant depletion in the riverine phosphorus loading would have relatively little impact on the rates of phosphorus buildup.

3.1.3 Observed effects of the Dawesville Channel

No data are available on the sediment characteristics of the PHES following the opening of the Dawesville Channel.Preliminary results suggest that nutrient concentrations in the sediment are similar to pre-channel conditions. A more comprehensive survey will be conducted in December 1998.

3.1.4 Status of the monitoring program

A monitoring program to examine the physical and chemical characteristics of the estuarine sediments following the opening of the Dawesville Channel has been proposed but not yet initiated. It is understood that sediment samples were obtained, on behalf of the Water and Rivers Commission, from one site in the Peel Inlet and one site in the Harvey Estuary during a single sampling occasion in early February 1998. A more comprehensive survey will be undertaken in December 1998 and results should be available by June 1999.

3.2 Riverine sediments

Riverine sediment data were available for sites in the Serpentine and Murray Rivers (Figure 1). A review of the literature indicated that no sediment sampling was conducted in the Harvey River.

3.2.1 Prior to the opening of the Dawesville Channel

Hill *et al.* (draft B) obtained surface sediment samples from the Murray (three sites) and Serpentine (four sites) and from Goegrup Lake (two sites) in July 1990. The median grain size of the surface sediments of the Murray and Serpentine Rivers ranged from 0.06 to 0.16 mm and from 0.20 to 0.87 mm respectively, whereas the range, in Goegrup Lake was 0.25 to 0.47 mm.

The sediment phosphorus concentration in the Murray River was observed at three sites: the two upstream sites had a total phosphorus concentration of 665 μg/g (Ravenswood Hotel) and 742 μg/g (Pinjarra Road bridge) and the downstream site (North Yunderup) 129 μg/g (Hill *et al.*, draft B). In the Serpentine River the total phosphorus concentrations of the sediments were determined from four sites: those of the three downstream sites ranged from 142 to 259 μg/g, whereas at the most upstream site (downstream of Goegrup Lake) it was 713 μg/g. The total phosphorus concentrations in sediments at two sites in Goegrup Lake were found to be 284 and 685 μg/g.

3.2.2 Predicted effects of the Dawesville Channel

No predictions about the effects of the Dawesville Channel on riverine sediment quality appear to have been made.

3.2.3 Observed effects of the Dawesville Channel

Sediment samples were obtained in January 1996 from the Murray and Serpentine Rivers and Goegrup Lake by the Water and Rivers Commission (draft). These observations indicated that the sediments from the Murray River were coarser than those of the Serpentine. This is in contrast to the finding of Hill *et al.* (draft B), in which the sediments of the Serpentine River were found to be coarser; however, it is considered that this change was due to the location of the sampling sites and not a response to the opening of the Dawesville Channel. The total phosphorus concentration of the sediments in the Murray and Serpentine Rivers ranged from 12.8 to 392.6 μg/g and 21.4 to 536.8 μg/g respectively. The total phosphorus concentrations in the Murray and Serpentine Rivers were generally less than those observed by Hill (draft B), both the maximum and minimum values being below those observed in July 1990 (Hill, Draft B).

The total nitrogen concentration of the sediments from the Murray and Serpentine Rivers ranged from 20 to 2699 μg/g and 191 to 6119 μg/g respectively (Water and Rivers Commission, draft). The median concentration of total nitrogen in the sediments of the Murray contained seven times less total nitrogen than those of the Serpentine. The sediments of the Serpentine River generally had a higher total phosphorous concentration and much higher total nitrogen concentration than those of other estuarine rivers in southwestern Australia (Water and River Commission draft). Heavy metal concentrations in the both the Murray and Serpentine Rivers were low.

Examination of faecal sterols by Lemming (1996) indicated that piggeries' effluent was entering the Serpentine River via the Gull Road drain. This type of effluent, when untreated, is rich in phosphorus.

Prior to the opening of the Dawesville Channel the Murray and Serpentine Rivers regularly experienced algal blooms, and it appears that these have been more pronounced since the opening (Water and Rivers Commission draft). In particular, the Serpentine River appears to have been experiencing a pattern of algal succession similar to that observed in the PHES prior to the opening of the Channel, with a *Nodularia* bloom in late spring through to early autumn (Water and Rivers Commission, draft). It was not clear whether the more pronounced algal blooms were due to an increase in catchment nutrient inputs to the rivers or to increased sediment nutrient release as a result of stratification brought about by the opening of the Channel.

3.2.4 Status of the monitoring program

Final reports on the riverine sediment sampling remain to be completed by Hill *et al.* (draft B) and the Water and Rivers Commission (draft). A sediment survey which includes the examination of the concentrations of apatite and non-apatite phosphorus will be conducted in December 1998. A report will be available in June 1999.

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APPENDIX 4

NEARSHORE MARINE AREAS

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

D.A. LORD & ASSOCIATES PTY LTD

WATER AND RIVERS
COMMISSION

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4. Nearshore marine areas

4.1 Shoreline and channel stability

The Dawesville Channel interrupts the longshore transport of sediment along the coast and therefore influences the stability of the nearshore shoreline. In addition, the stability of the Channel itself was an important design consideration; in particular, it was important to minimise any tendency for it to silt up. The coastal region to the north and south of the Channel was surveyed in May 1985, February 1992, February 1993, February 1994, April 1995, December 1995 and March 1997 (Figure 1). The Dawesville Channel and a region of the Harvey Estuary were surveyed in January 1995, December 1995 and April 1997 (Figure 1).

4.1.1 Prior to the opening of the Dawesville Channel

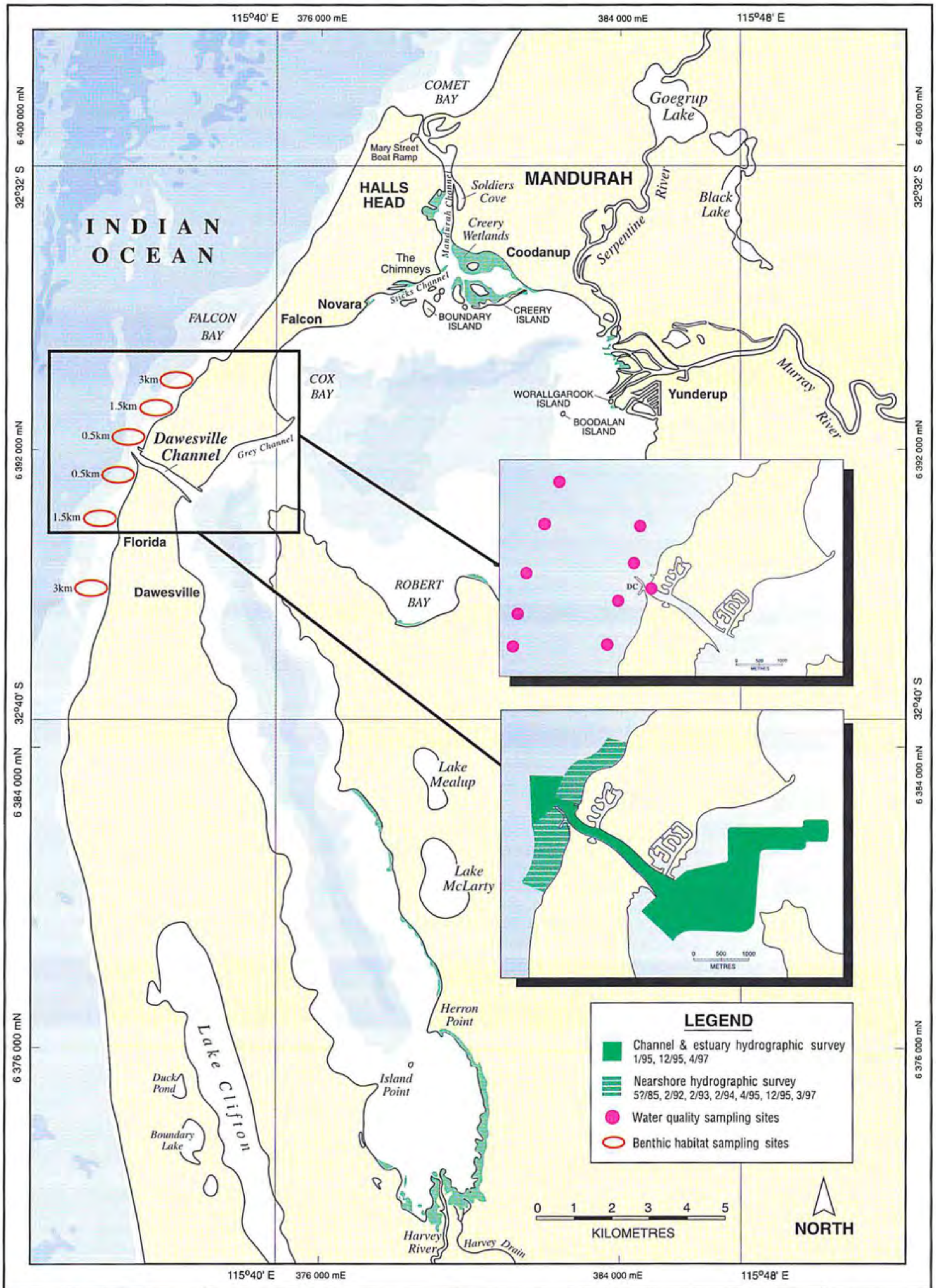
A significant effect of the construction of the Dawesville Channel and its associated breakwaters was the disruption of coastal longshore sediment transport. To assist in the design of the Channel, a range of coastal engineering, geomorphological and stratigraphic techniques were therefore employed to estimate the quantity of littoral drift (DMH 1987). The most consistent estimate from these studies was approximately 60,000 m^3 of sediment moving annually along the ocean shore from south to north. It was considered that the majority of this sediment was transported during occasional high wave-energy events that could transport slugs of sediment of approximately 10,000-30,000 m^3 (DMH 1987).

4.1.2 Predicted effects of the Dawesville Channel

It was anticipated that disruption of nearshore sediment transport due to the construction of the Dawesville Channel would result in deposition within the Channel, erosion of the adjacent beaches and possible formation of an ebb tide delta (Humphries & Ryan 1993). In addition, Humphries and Ryan (1993) noted that changes in the water circulation patterns within the PHES might cause localised changes to the position of the estuarine shoreline. It was suggested that such changes could include an expansion of the fringing rush and samphire wetlands into the surrounding flats (Humphries & Ryan 1993; see Appendix 6).

To accommodate the anticipated longshore sediment load arriving from the south, a spur groyne with a design capacity of 85,000 m^3 was designed for the southern breakwater of the Dawesville Channel to act as a sediment trap (DoT 1996, draft). To facilitate sediment bypassing to the north, two submarine pipes were installed across the Channel at the time of construction. In addition, physical modelling of the Channel prior to construction indicated that sediment might be deposited within it from the north during periods of northwesterly winds; hence a small northern breakwater was also designed (DMH 1987).

Investigations of the expected stability of the Dawesville Channel were conducted by Tong (1985a, 1985b), Dufty (1983), Foster and Nittam (1985), DMH (1987) and Eliot (1993). The analysis by Tong (1985a, 1985b) indicated that the Dawesville Channel would remain stable if it had a depth of 4.5 m. Dufty (1983) also considered the Channel to be stable, but his analysis was based on Harvey Estuary being separated from Peel Inlet at the Grey Channel. Foster and Nittam (1985) considered the Channel to be unstable at depths less than 6 m. Analysis of channel stability by DMH (1987) indicated that a channel depth of 6 m would be necessary for stable conditions and 6.5 m was desirable. DMH (1987) also considered the stability of a stepped channel that was 4.5 m from the Harvey Estuary to the Old Coast Road and then 6.5 m deep from the Old Coast Road to the ocean. This channel design was considered to be superior to a constant 4.5 m channel but was still not stable and required the step to be located closer to the Harvey Estuary. A constant 6.5 m-deep channel was considered undesirable due to the anticipated problems with sediment mobilisation within the PHES. On balance, a tapered channel with a stepped profile was considered to be satisfactory (DMH 1987). Modelling by Eliot (1993) also indicated that the designed Dawesville Channel was unstable.



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LOCATION OF HYDROGRAPHIC SURVEYS, NEARSHORE WATER QUALITY AND BENTHIC HABITAT SITES

Figure 1

Auth: KH/BH | Date: 2/98

4.1.3 Observed effects of the Dawesville Channel

To alleviate the expected reduction in sediment feed to the northern beaches caused by the construction of the Dawesville Channel, approximately 150,000 m^3 of sediment was placed on the beaches to the north of the Channel during its construction (DoT, draft). After the opening of the Channel, three periods of sand bypassing were undertaken: February 1996 to March 1996 — 22,000 m^3; December 1996 to February 1997 — 39,000 m^3; and August 1997 to September 1997 — 16,000 m^3.

Sediment accretion continued to prevail on the southern beaches following the construction of the Channel and caused a significant realignment of the shoreline to the south (DoT 1996). The rate of sediment accretion appeared to slow after 1995. The beaches to the north generally experienced erosion between the 1992 and 1994 surveys, accretion between 1994 and the December 1995 survey, and then another minor period of erosion till March 1997.

The sediment volume changes within the Dawesville Channel were relatively small, showing a slight increase between January 1995 and December 1995 and a decrease between January 1995 and April 1997. The sediment volume changes within the Channel exhibited a gradient from maximum accretion on its ocean (deeper) side to maximum erosion towards its estuary (shallower) side. The region of greatest sediment accretion was located at the ocean end of the Channel on its northern side. Sediment volume changes in the areas surveyed within the Harvey Estuary and Grey Channel were relatively minor.

4.1.4 Status of the monitoring program

A five-year contract was established in May 1995 for a land-based dredge to conduct sand bypassing at the Dawesville Channel of up to 80,000 m^3 per year. It is envisaged that considerable economic benefit will be gained by using this mobile bypassing plant at both the Dawesville Channel (typically between December and mid-February) and the Mandurah Channel (typically between June and October).

The considerable variation in the nearshore sediment volumes in the vicinity of the Dawesville Channel warrants the continuation of annual hydrographic surveys. These surveys may also be used to assist in the planning of the sediment bypassing operations. The region of the Channel near the ocean entrance where accretion is occurring should also be surveyed annually. It appears that the Channel is generally stable, with minor regions of accretion and erosion arising due to flow patterns through the variable-depth Channel. Due to the relative stability of the Dawesville Channel and estuary the Department of Transport (DoT draft) has recommended that the next hydrographic survey of the entire Dawesville Channel and the northern region of the Harvey Estuary be conducted in three years, at which time the future monitoring requirements could be re-evaluated.

4.2 Nearshore water quality

4.2.1 Prior to the opening of the Dawesville Channel

There is very little in the way of water quality data for coastal waters adjacent to the Dawesville Channel prior to the opening of the Channel. A single survey of ten fixed locations adjacent to the mouth of the Dawesville Channel (five 'outer' sites 3 km offshore, four 'inner' sites 1 km offshore and one site in the Channel: Figure 1) was carried out in March 1994 (Chase 1995), and typical nutrient concentrations of local coastal waters from Yanchep to Mandurah were known through research carried out during the Perth Coastal Waters Study (PCWS) (Buckee *et al.* 1994). During the PCWS two sites near Dawesville were sampled in September 1993, and two sites 2 km offshore from the mouth of the Mandurah Channel in February 1994. The available data on total phosphorus (TP), orthophosphate-phosphorus (PO_4), total kjeldahl nitrogen (TKN), nitrate-plus-nitrite ($NO_{2,3}$), ammonium (NH_4) and chlorophyll a (chl. a) are presented in Table 1.

The data in Table 1 are typical of the relatively low nutrient concentrations in local coastal waters. The nearshore waters of the Dawesville area were also relatively turbid (secchi depths typically less than 2 m) due to constant resuspension of sediments in the high wave energy-environment (Chase 1995; Montgomery 1995).

Table 1: Available water quality data on nearshore coastal waters off Dawesville before the Dawesville Channel was opened.

PARAMETER (ALL DATA IN µg/l)	SEPTEMBER 1993	FEBRUARY 1994	MARCH 'INNER' SITES	MARCH 'OUTER' SITES
TP	14	5-14	22	20
PO_4	2.5-3.5	2-3	3	2.5
TKN	250-290	100-230	120	110
$NO_{2,3}$	2-8	1-2	16.5	7.5
NH_4	no data	3-6	45	16
chl. a	0.2-0.4	0.2-0.7	1.4	0.8

4.2.2 Predicted effects of the Dawesville Channel

The construction of the Dawesville Channel was expected to cause an increase in the loads of fine particulate sediment, organic matter, nitrogen, phosphorus and humic substances discharged to the marine waters immediately offshore, particularly in winter and spring (Humphries & Ryan 1993).

The area offshore of the Dawesville Channel does not have transverse bars and therefore water movement is not restricted. The jet from the Dawesville Channel was predicted to discharge water up to 1 km offshore during ebb tides, and this, combined with longshore currents, was expected to ensure sufficient dispersion of estuarine waters to prevent excessive buildup of nutrients in nearshore waters (EPA 1988). Furthermore, it was anticipated that the phosphorus would be rapidly immobilised as it converted to apatite (Humphries & Ryan 1993).

The DoT predicted that the Dawesville Channel would flush approximately 120 tonnes of phosphorus and 1000 tonnes of nitrogen from the PHES per year. These nutrients were predicted to generally travel northwards from the Channel between the reefs, with occasional movements southwards alongshore depending on wind and sea conditions (DoT 1996).

4.2.3 Observed effects of the Dawesville Channel

The extent and location of the Dawesville Channel plume in adjacent coastal waters was determined from two conductivity-temperature-depth (CTD) surveys carried out during ebb tides. The number of surveys was limited by instrument difficulties and rough sea conditions. During the two successful exercises carried out so far, the plume was limited to less than 2 km offshore and approximately 3 km north of the Channel (DoT 1996).

The effect of the Dawesville Channel on water quality in nearshore waters during ebb tides was monitored on 28 occasions from March 1994 to December 1996; sampling depended on ebb tides and weather, and was therefore conducted at irregular intervals (Latchford *et al.* 1997). Surface and depth samples were obtained at ten fixed locations adjacent to the mouth of the Channel (Figure 1).

The plume was buoyant throughout the winter months, during which period the greatest quantities of nutrients were exported. During late summer and early autumn it was denser than seawater and contained limited quantities of nutrients. Nutrient levels in the offshore sampling sites were lower during the winters of 1994 and 1995 than in that of 1996 (Figure 4.1): this was attributed to the low rainfall and therefore limited nutrient export from the Peel-Harvey catchment in 1994 and 1995 compared to 1996, as clearly seen by nutrient concentrations in Channel waters (Figure 4.2). The DoT (1996) observed that, within the plume, total phosphorus concentrations varied from 12 to 70 µg/L, while background oceanic concentrations varied from 12 to 30 µg/L.

Elevation of inorganic nutrient levels at the offshore sampling sites was clearly confined to periods of river discharge. Although baseline data are sparse, there was no indication that there was any buildup of nutrients.

Available data did not enable plume dimensions to be calculated, but the rapid dilution and dispersion of the plume were readily seen by comparing the inorganic nutrient levels for the Channel site with those of the offshore sampling sites (Figures 4.1 and 4.2).

Comparisons of nutrient levels at the ocean entrance with background offshore levels from the 1994/95 data were used to estimate the nutrient flux during the sampling period. This resulted in an estimated total phosphorus export of 280 kg per tidal cycle, which represents 100 tonnes of phosphorus per year. Similar calculations determined that some 2400 kg of total nitrogen was exported from the estuary per tidal cycle, which represents 900 tonnes of nitrogen per year. These values agreed well with those predicted (DoT 1996).

4.2.4 Status of the monitoring programme

Since the Dawesville Channel opened, the frequency of sampling for collection of water quality data in the adjacent nearshore area has varied from fortnightly to greater than monthly intervals. However, since December 1996 no sampling has been carried out.

4.3 Nearshore benthic habitats

4.3.1 Prior to the opening of the Dawesville Channel

As for water quality, there was scant information on the Dawesville nearshore benthic environment prior to the opening of the Dawesville Channel. Pre-Channel monitoring was limited to a series of aerial survey videos and an intensive two-day ground truthing exercise carried out in March 1994 (Walker 1994). The modelled, and since observed, northwards movement of the estuarine plume resulted in the choice of six sites for monitoring. Sites 0.5, 1.5 and 3 km north of the Channel were chosen as areas where environmental changes might occur, while locations 0.5, 1.5 and 3 km south of the Channel represented 'control' sites.

Reef macroalgae were considered the best biota for monitoring the effects of the Channel on the nearshore environment. Macroalgae are fixed organisms (unlike plankton and fish populations) and respond to *in-situ* changes to the environment by showing conspicuous changes in community composition (Montgomery 1995). Benthic biota and macroalgal biomass were therefore sampled during the pre-Channel survey, but plankton, very small organisms, infauna (animals living within the sediments or reefs) and motile species (such as fish) were not sampled.

The pre-Channel survey (Walker 1994) found that the study area was characterised by an extensive complex of reefs of high relief (greater than 0.5 m elevation above the surrounding sediment) and areas of bare sand. On the upper surfaces of the reefs there was a diverse community dominated by red algae. These comprised about two-thirds of all algal species present, with the remainder predominantly brown algae: extensive gardens of the brown alga *Ecklonia radiata* were conspicuous at the 0.5 km north site. Some seagrass (mainly *Amphibolis antarctica*) was present throughout the study area, but green algae were scarce and few animals were visible, particularly on upper reef surfaces. The survey sites were revisited in May 1995, and no effects of the Dawesville Channel were apparent. The winter of 1994 had low run-off, so the 1995 sampling was regarded as a further 'baseline'for future monitoring (Walker *et al.* 1995).

A comprehensive survey of macroalgae from Falcon Bay to the Florida townsite, out to approximately 300 m from the shore, was carried out in 1995 by Montgomery (1995). His studies indicated that macroalgal community complexity was highest in March and May, prior to the onset of winter weather patterns. A huge decline in the biomass and species richness was observed in the winter months, with all but the most resilient species scoured from the reef surfaces. The Dawesville coastline has no outer barrier reef system and therefore receives the full impact of the high-energy conditions associated with winter storms (unlike the more sheltered lagoons of Perthís coastal waters). During early summer there was a high frequency of juvenile algae on the reefs, and by late summer/early autumn the floristic composition was similar to that of reef systems in metropolitan and northern Perth coastal waters. There was a large natural variation in species composition and biomass, and comprehensive statistical analyses of community structure and patterns found no obvious environmental gradients (Montgomery 1995). It appeared that many biotic and abiotic factors were interacting to control species distribution. The distributions of the algae were, in effect, chance occurrences that reflected stochastic recruitment and settlement events.

4.3.2 Predicted effects of the Dawesville Channel

Before the Dawesville Channel was opened it was recognised that the nearshore environment could be affected by outflowing estuarine waters that had low salinity, and high loads of nutrients, sediments and other run-off material (particularly after periods of heavy rainfall). Apart from the obvious impact of low salinity water and high nutrient levels on marine species, there were potential impacts due to changes in the nature of the substratum (deposition of organic material and a change in reef architecture due to accumulation of sediments in reef gullies and potholes) and increased turbidity due to suspended particulates in the water column. However it was considered that environmental impacts on the nearshore marine environment would be minimal and acceptable (EPA 1988) because the characteristically high-energy conditions of the nearshore area — particularly during winter — would ensure rapid dispersion and dilution of estuarine waters. Nearshore coastal waters were also characteristically turbid, due to the considerable wave energy that the area experiences, and thus the biota were already adapted to turbid conditions.

4.3.3 Observed effects of the Dawesville Channel

The work of Montgomery (1995) confirmed the predicted effects of the construction of the Dawesville Channel, and noted that impacts are also reduced because the greatest outflow of estuarine water occurs in winter, when macroalgal communities are effectively scoured off reef surfaces due to winter storms. Furthermore, the hydrodynamics of the area appeared to ensure that little sediment settlement occurred. Montgomery (1995) also noted that the macroalgal community of late summer/early autumn would be the best integrator of any long-term effects due to the Dawesville Channel, and recommended that studies be concentrated at the phyla level (comparing community changes in red, brown and green algae) rather than individual species composition. Kelp gardens at the 0.5 km north site were identified as particularly useful for monitoring because kelps are sensitive to low salinity and nutrient enrichment, and do not recruit to soft substrate (i.e. they would not recruit to the area if the reefs became overlain by estuarine sediments). The 0.5 km north site was also in the direct line of the estuarine plume.

The most recent survey of the nearshore benthic environment was undertaken in April 1996. No significant changes in community structure were found, with fluctuations in red, brown and green algal biomass consistent with the considerable natural variability of the area (Montgomery & Walker 1996). Based on data collected after two winters of relatively low river flow, no deleterious effects on the nearshore marine environment had resulted from the construction of the Dawesville Channel. Nonetheless, due to the underlying seasonal variation, any changes to species composition may take several years to identify. The cumulative effect of undetectable (at present) changes to physico-chemical conditions may also cause measurable impacts in the long-term.

4.3.4 Status of the monitoring program

The present monitoring program has been refined after three years of sample collection, and the sites and methodology used are appropriate for detecting future impacts. Data collected to date have been presented and interpreted in three annual reports (Walker 1994; Montgomery 1995; Montgomery & Walker 1996). However, as regards nearshore water quality monitoring, no sampling has been carried out since 1996.

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Dawesville Channel
Technical Review

APPENDIX 5

WATER QUALITY

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

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WATER AND RIVERS
COMMISSION

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5. Water quality

5.1 Inputs

The water quality of the PHES depends largely on the amount of exchange with oceanic waters and the amount and quality of river inflow: groundwater, urban run-off and direct rainfall are of lesser importance (Kinhill Engineers 1988). Although the main focus of this document is on the impact on the PHES of increased oceanic exchange following the opening of the Dawesville Channel, any discussion of the subsequent changes in water quality must also consider changes in nutrient inputs from river inflow.

This section summarises available data on catchment inputs to the PHES. The construction of the Dawesville Channel also had localised effects on groundwater quality, and a brief account of these is included.

5.1.1 Catchment runoff

From the late 1970s to 1989, nutrient inputs to the PHES from catchment run-off were monitored by the DCE/EPA (now the DEP). Since 1990 monitoring has been carried out by the WRC. Data sets are the most complete for the Harvey, Murray and Serpentine Rivers, particularly for total phosphorus. Water quality monitoring of catchment streams is the basis of an ongoing catchment nutrient audit required under ministerial conditions for the Peel Inlet and Harvey Estuary Management Strategy, and compliance is measured against interim targets set by the EPA for phosphorus input to the PHES (see also Appendix 10). The interim targets are:

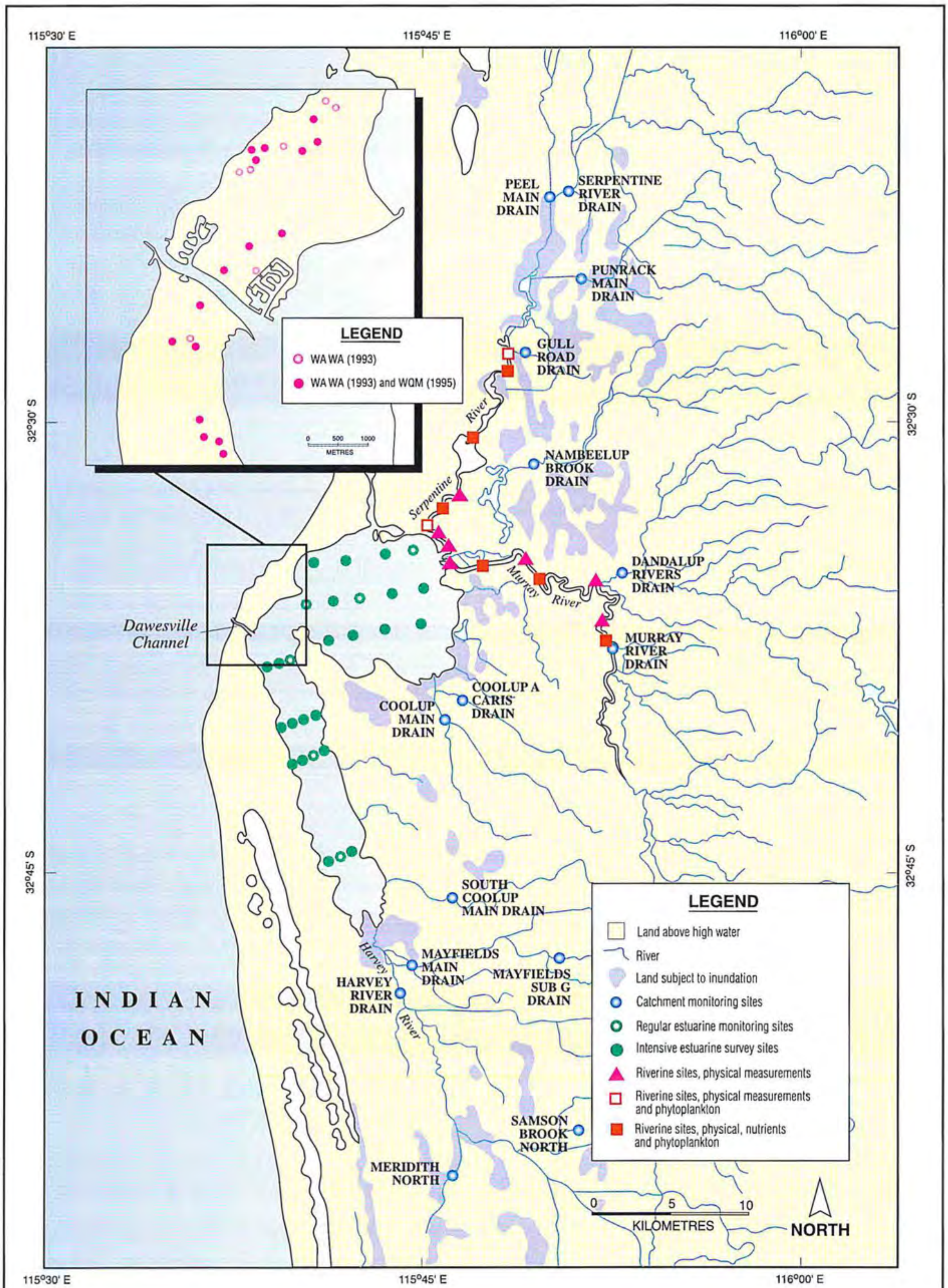
Annual phosphorus input to the system shall not exceed 85 tonnes in more than four years out of ten (on average) and shall not exceed 165 tonnes in more than one year out of ten (on average). (These figures are based on 60th and 90th percentile loads.)

Sample sites for the current catchment monitoring program are shown in Figure 1. Although monitoring has improved in recent years due to better measurements of flow throughout the catchments, a recent critique of the catchment monitoring program by the WRC has highlighted the limitations of the network coverage and sampling regimes (Wittenoom *et al.* 1998). Some catchments are not gauged, while the tidal lower sections of the catchment cannot be gauged by conventional methods. Nutrient loads for a substantial part of the catchment (24%) cannot be estimated by direct measurements, and must be modelled using observed data and extrapolation techniques. (Note: a large number of agricultural activities occur in these sections of the catchment, and there are sewage and waste disposal facilities as well as septic tanks.) A major limitation of using this modelled data is the failure to capture real trends because of environmental and/or land-use changes.

As loading estimates are currently made using a combination of collected and modelled data, they cannot accurately reflect what is happening in the catchment, and therefore cannot be used to evaluate the performance of the catchment management program. Furthermore, the data collected up to 1989 are not statistically comparable with those collected since 1990 because different methods were used to calculate nutrient loads. The extent of the monitoring network has also changed since 1990: flow gauges have been installed and decommissioned at different sites, and sampling sites have been reduced for operational reasons.

For environmental compliance of catchment loads to be tested over time the monitoring network and methods of calculation must be consistent, and for total catchment inputs to be calculated all major inflows must be monitored; neither of these conditions has ever been met in the Peel-Harvey catchment monitoring program. The weekly grab samples currently taken at most sites for load estimates also introduce a high degree of error, because nutrient concentrations in stream waters vary with the rate of stream discharge.

In summary, the network coverage and sampling regimes of the PHES catchment monitoring program cannot support load-based compliance testing (Wittenoom *et al.* 1998). Nor can the performance of the catchment management program be assessed from catchment nutrient loads or the validity of the original management targets tested (see ministerial conditions in Appendix 10). The constraints associated with catchment data must also be borne in mind when trying to interpret changes in the water quality and biota of the PHES. Wittenoom *et*



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Water and Rivers Commission
Dawesville Channel Monitoring Programme
Two Year Technical Review

LOCATION OF CATCHMENT, GROUNDWATER, ESTUARINE AND RIVERINE QUALITY MONITORING SITES

Figure **1**

Auth: KH/BH | Date: 2/98

al. (1998) conclude by stating that 'either the (catchment monitoring) programme must be redesigned to support calculation of accurate and precise loads, or the nature of the targets and compliance testing must change. In the interim it is important to generate information that fulfills the intent of compliance testing and makes use of the available data.'

Wittenoom *et al.* (1998) further note that detectable improvements in water quality produce environmentally significant results, and therefore trends in the nutrient concentrations of the waters of the catchment drainage network may be a more useful performance indicator for the integrated catchment management program.

Catchment nutrient data

In the period up to 1989 the DCE/EPA estimated that streamflow into the PHES catchment ranged from 370 to 1200 x 10^6 m^3, and total phosphorus input varied from 95 to 237 tonnes. Over this period the Harvey River contributed 30%-40% of annual stream inflow to the PHES, but between 50% and 75% of the annual phosphorus load. The Murray contributed large volumes of stream inflow, but had low nutrient concentrations and therefore contributed less total phosphorus. The Serpentine generally contributed less than 25% of stream inflow, but its nutrient concentrations were much higher than those of the Murray, and its contribution to total phosphorus loads was therefore higher. These data are summarised in Table 1.

Table 1: Available data on annual nutrient input data for the PHES from 1983 to 1989.

YEAR, AND PARAMETER	SERPENTINE	MURRAY	HARVEY
1983			
Volume of run-off	106 x 10^6 m^3	721 x 10^6 m^3	246 x 10^6 m^3
Nitrogen input	not available	not available	357 tonnes
Phosphorus input	40 tonnes	65 tonnes	80 tonnes
Flow-weighted total phosphorus concentration	0.38 mg/L	0.09 mg/L	0.32 mg/L
1984			
Volume of run-off	117 x 10^6 m^3	200 x 10^6 m^3	162 x 10^6 m^3
Nitrogen input	not available	not available	381 tonnes
Phosphorus input	36 tonnes	9 tonnes	45 tonnes
Flow-weighted total phosphorus concentration	0.31 mg/L	0.05 mg/L	0.28 mg/L
1985			
Volume of run-off	67 x 10^6 m^3	241 x 10^6 m^3	182 x 10^6 m^3
Nitrogen input	117 tonnes	391 tonnes	273 tonnes
Phosphorus input	21 tonnes	15 tonnes	52 tonnes
Flow-weighted total phosphorus concentration	0.31 mg/L	0.06 mg/L	0.28 mg/L
1986			
Volume of run-off	83 x 10^6 m^3	156 x 10^6 m^3	120 x 10^6 m^3
Nitrogen input	141 tonnes	160 tonnes	241 tonnes
Phosphorus input	22 tonnes	6 tonnes	44 tonnes
Flow-weighted total phosphorus concentration	0.26 mg/L	0.04 mg/L	0.37 mg/L

YEAR, AND PARAMETER	SERPENTINE	MURRAY	HARVEY
1987			
Volume of run-off	62 x 10^6 m^3	119 x 10^6 m^3	71 x 10^6 m^3
Nitrogen input	103 tonnes	198 tonnes	114 tonnes
Phosphorus input	13 tonnes	7 tonnes	19 tonnes
Flow-weighted total phosphorus concentration	0.21 mg/L	0.06 mg/L	0.27 mg/L
1988			
Volume of run-off	106 x 10^6 m^3	413 x 10^6 m^3	284 x 10^6 m^3
Nitrogen input	96 tonnes	946 tonnes	650 tonnes
Phosphorus input	33 tonnes	18 tonnes	91 tonnes
Flow-weighted total phosphorus concentration	0.31 mg/L	0.04 mg/L	0.32 mg/L
1989			
Volume of run-off	67 x 10^6 m^3	173 x 10^6 m^3	205 x 10^6 m^3
Nitrogen input	not available	not available	not available
Phosphorus input	13 tonnes	4 tonnes	46 tonnes
Flow-weighted total phosphorus concentration	0.20 mg/L	0.02 mg/L	0.22 mg/L

Note: Reliable estimates for total catchment input are not available

WRC nutrient input data for 1990-95 are more accurate than estimates for earlier years. Available data, summarised in Table 2, also illustrate some of the characteristics found by the DCE/EPA for the 1983-89 period (Table 1). The data in Table 2 also indicate that the relative importance of Harvey River nutrient inputs to the PHES has declined and that of the Serpentine has increased.

Table 2: Available data on annual nutrient input for the PHES from 1990 to 1995.

YEAR AND PARAMETER	SERPENTINE	MURRAY	HARVEY	TOTAL INPUT
1990				
Volume of run-off	55 x 10^6 m^3	219 x 10^6 m^3	153 x 10^6 m^3	594 x 10^6 m^3
Nitrogen input	60 tonnes	145 tonnes	202 tonnes	643 tonnes
Phosphorus input	8 tonnes	5 tonnes	30 tonnes	84 tonnes
Median total phosphorus concentration	0.11 mg/L	0.02 mg/L	0.14 mg/L	not applicable
1991				
Volume of run-off	152 x 10^6 m^3	334 x 10^6 m^3	240 x 10^6 m^3	1,045 x 10^6 m^3
Nitrogen input	262 tonnes	286 tonnes	339 tonnes	1,442 tonnes
Phosphorus input	41 tonnes	19 tonnes	65 tonnes	222 tonnes
Median total phosphorus concentration	0.19 mg/L	0.01 mg/L	0.30 mg/L	not applicable
1992				
Volume of run-off	157 x 10^6 m^3	389 x 10^6 m^3	179 x 10^6 m^3	1,019 x 10^6 m^3
Nitrogen input	176 tonnes	368 tonnes	205 tonnes	1,223 tonnes
Phosphorus input	42 tonnes	8 tonnes	34 tonnes	167 tonnes
Median total phosphorus concentration	0.25 mg/L	0.01 mg/L	0.19 mg/L	not applicable
1993				
Volume of run-off	54 x 10^6 m^3	279 x 10^6 m^3	132 x 10^6 m^3	518 x 10^6 m^3
Nitrogen input	not available	not available	not available	not available
Phosphorus input	10 tonnes	5 tonnes	20 tonnes	50 tonnes
Median total phosphorus concentration	0.12 mg/L	0.01 mg/L	0.14 mg/L	not applicable
1994				
Volume of run-off	67 x 10^6 m^3	not available	153 x 10^6 m^3	not available
Nitrogen input	not available	not available	not available	not available
Phosphorus input	17 tonnes	not available	39 tonnes	not available
Median total phosphorus concentration	0.16 mg/L	not available	0.19 mg/L	not applicable
1995				
Volume of run-off	74 x 10^6 m^3	not available	140 x 10^6 m^3	not available
Nitrogen input	not available	not available	not available	not available
Phosphorus input	22 tonnes	not available	38 tonnes	not available
Median total phosphorus concentration	0.19 mg/L	not available	0.15 mg/L	not applicable

Note: Total input includes contributions from ungauged areas

The fundamental problems of testing compliance with the nutrient loads set out in the ministerial conditions has already been discussed, nor can compliance be determined as yet because the conditions are expressed upon a basis of ten years of data. It is noted that in the period 1990-93 phosphorus loads exceeded both the 60th percentile (85 tonnes) and 90th percentile (165 tonnes) loads of the ministerial conditions twice.

The EPA (1988) also proposed interim target flow weighted mean total phosphorus concentrations of:

- Serpentine River: 0.135 mg/L (50th percentile), 0.137 mg/L (90th percentile);
- Murray River: 0.046 mg/L (50th percentile), 0.047 mg/L (90th percentile);
- Harvey River: 0.104 mg/L (50th percentile), 0.107 mg/L (90th percentile).

The median concentrations measured for the Harvey and Serpentine Rivers in 1990-95 do not meet the EPA targets, but, as with the nutrient input targets, the validity of the water quality targets is unknown.

The WRC has recently carried out a detailed statistical analysis of trends in total phosphorus (TP) and total nitrogen (TN) concentrations in PHES catchment waters monitored between 1983 and 1995 (Donohue *et al.* 1998). Some important findings of this work are as follows:

- TP concentrations in the Harvey River fell by about 0.03 mg/L each year between 1982 and 1985, by about 0.01 mg/L annually between 1986 and 1989, and changed little between 1990 and 1995.
- There was an emerging trend of increased nutrient concentrations in the Serpentine River from 1992 (0.01 mg/L each year). It was not known whether this increase was from catchment inputs or increased sediment/water column nutrient cycling due to increased stratification in the river.
- The Murray River has changed little since 1983, but may be improving very slowly.
- TP concentrations in the Gull Road Drain, which drains into the Serpentine River, fell dramatically (by 2.1 mg/L per year) between 1985 and 1987, and there was an unconfirmed trend (i.e. one not statistically proved) of a slower decline (0.26 mg/L per year) between 1988 and 1995. However, concentrations remained extremely high and were a significant source of nutrients to the Peel Inlet.
- TP concentrations in the Meredith Drain, which drains into the Harvey River, changed little between 1982 and 1988, but fell by 0.05 mg/L each year between 1990 and 1995. It is interesting to note that large-scale soil amendment programs were implemented to improve nutrient retention in the Meredith subcatchment in the early 1990s, and AgWA monitoring data also confirmed decreases in TP concentrations between 1990 and 1995, but found little further change after 1995 (Rivers, 1997).
- TP concentrations increased in Nambeelup Brook, which drains into the Serpentine River, by 0.04 mg/L each year between 1990 and 1995, and there was an emerging trend of increasing TP concentrations in the Mayfields Main Drain, which drains into Harvey Estuary.

It is logical to attribute the improvement in quality of waters draining into Harvey Inlet to catchment management actions that are discussed further in the following section. Unfortunately, there was also an apparent increase in nutrient inputs to Peel Inlet from the Serpentine River.

Catchment land use

From an estuary management/nutrient enrichment point of view, the most critical component of the 11,300 km^2 catchment of the Peel-Harvey Estuarine System is the 2190 km^2 area situated on the coastal plain (Figure 1).

Until 1985, when the EPA finally placed a moratorium on drain construction and the Department of Agriculture launched its fertiliser efficiency program, the coastal plain catchments of the Serpentine, Murray and Harvey Rivers served not only as the focus of a highly subsidised, organised drainage scheme but also as an area in which the overfertilisation of farmlands was commonplace (Bradby 1997).

The Agricultural Bank, the Drainage Boards, the Lands Department and the Public Works Department all became responsible for the installation and maintenance of an extensive network of drains in the area which, by design, radically altered the complex system of interconnected wetlands and streams that characterised the coastal plain. As much of the area was sandy, the relatively fertile soils of the swamps (large, flat seasonally waterlogged depressions in the area) were targeted for the growing of potatoes and vegetables and, with the proliferation of the beef industry, superphosphate fertilisers were applied to pastures at rates that commonly exceeded 600 kg/ha (Bradby 1997).

The history of drainage activity and fertiliser use in the coastal plain catchments that surround the Peel-Harvey is given in Table 3. It is noteworthy that the first large-scale mortality of fish populations in the PHES occurred in 1910, shortly after the systematic alteration of wetlands and rivers commenced. By 1940 most large wetlands in the catchment had been drained and most of the trees alongside rivers and streams had been cleared.

In the 1970s market forces, namely high fertiliser prices and low beef prices, had a major influence in reducing fertiliser inputs throughout the whole catchment. By 1975, for example, these forces had reduced the amount of fertiliser used in the catchment by approximately 37%. Subsequent improvements in fertiliser use efficiency had further reduced fertiliser application to a third of late 1960s levels by 1987. Attention then focused upon eliminating or controlling the run-off from other types of land uses in the catchment that were responsible for large nutrient inputs to the PHES.

Intensive farming operations such as piggeries, sheep-holding yards, dairies and poultry farms were important sources of pollution within the catchment in the 1980s (Bradby 1997). However, through the introduction of effluent storage ponds and effluent stripping practices, significant improvements had been achieved in this area by the early 1990s. The EPA's agreed-to 'faecal pollution strategy' to reduce phosphorus discharge from the Wandalup Farms Piggery's wastewater treatment system by at least 75% by 1994 and to reduce these to 360 kg/year after 1996, serves as an example.

Due to nutrient leaching and stormwater run-off, the ever-increasing amount of waterfront urban residential development, particularly where housing without deep sewerage is involved, has been an additional source of pollution for a long time. However, by 1994 a major source of nutrient-enriched water — the wastewater treatment plant at Pinjarra, which discharges a treated effluent directly into the Murray River — had been brought under control through the construction of a 5-ha basin amended with 3000 tonnes of bauxite residue and an artificial wetland (Bradby 1997).

In attempting to assess the effects of the Dawesville Channel on the present-day water quality of the PHES, it is essential to bear in mind that at the time the Channel was about to be opened:

- All major point sources in the catchment had put effluent management systems in place to the satisfaction of the EPA (Bradby 1997) and that these alone prevented 34 tonnes of phosphorus per year from entering the region's waterways.
- The amount of fertiliser applied in the catchment was reduced through market forces from 27,000 tonnes/annum in the late 1960s to 17,000 tonnes/annum by 1975, and further reduced to 9500 tonnes/annum by 1987 due to improvements in fertiliser use efficiency throughout the catchment.
- Considerable progress in land care (environmental repair) had been achieved.
- Wetland drainage had been severely curtailed.

In brief, all the major catchment management issues that had resulted in the original environmental deterioration of the PHES had largely been resolved.

Table 3: History of drainage activity and fertiliser use in the coastal plain catchments of the Peel-Harvey Estuarine System.

YEAR	DRAINAGE ACTIVITY	FERTILISER USE
1890s	Large-scale clearing and ringbarking of forested areas to increase summer flows.	No record.
1900	*Drainage Act of 1900* passed. Harvey and Coolup Main Drains dug in the Harvey catchment.	No record.
1907	PWD takes over maintenance of the drainage network.	No record.
1910	Drainage Boards become established.	No record.
1920	Peel Main Drain dug through Peel Estate and Serpentine Flats; rivers straightened and deepened to improve discharge characteristics; levees constructed to prevent flooding of surrounding farmland.	No record.
1925	*Land Drainage Act of 1925* removes power of drainage boards.	No record.
1930	The Great Depression. To help reduce unemployment, government allocates large amounts of money for extending drainage network, increasing capacity of drains and de-snagging rivers. Harvey River Diversion Project commences to prevent flooding of Harvey River and siltation of Harvey Main Drain.	No record.
1940s	Parts of the drainage network upgraded to act as irrigation canals.	No record.
1950s	Large areas of the catchment cleared and converted to pastures. Rock bars on Serpentine River removed and downcutting of the river commences. Drains on Peel Estate re-dug; South Coolup Main Drain (leading into the Harvey Estuary) constructed, together with drains leading into Austin Bay and SE of Point Grey. Wetland called "Duck Pool" drained. Birrega drain reconstructed for fourth time.	Fertiliser cheap and plentiful: superphosphate used on large scale with application rates of 600 kg/ha not uncommon on coastal plain. Rate of fertiliser application drops but, with clearance of more land, total amount applied in catchment increases to 27, 000 tonnes annum.
1970	Widening of Harvey River continues.	
1974	Meredith Drain, in middle reaches of Harvey River, completed.	Price of superphosphate more than doubles and is applied in autumn only, thereby greatly increasing likelihood of it being washed away by first winter rains.
1975		Beef prices crash. Within 5 years almost a third of beef farmers left industry; amount of fertiliser used drops to 17, 000 tonnes/annum.

YEAR	DRAINAGE ACTIVITY	FERTILISER USE
early 1980s	Meredith Drain targeted as a significant source of nutrient pollution. Clearing of crown land for agricultural development continues.	Four new approaches to improving fertiliser use emerge: (1) timing of fertiliser application split to include late spring; (2) use of slow-release fertilisers containing higher levels of sulphur; (3) soil testing programs; (4) use of bauxite residue to amend soil to reduce P loss.
1983	Effectiveness of remnant wetlands as nutrient sinks investigated and, in 1985, a moratorium on wetland drainage declared by EPA.	Research shows up to 30% of fertiliser lost to drainage and over 50% unaccounted for in surface soil or run-off water. Farmer education (fertiliser efficiency) program launched and Landcare movement, incorporating creation of Land Conservation District Committees (LCDs), emerges.
1987		Fertiliser use down to 9500 tonnes/annum (rate 9 kg/ha), representing major overall reduction in use. DOWNWARD TREND in total phosphorus concentration in Harvey River becomes evident.
1991	Review of environmental aspects of drainage management in catchment conducted by Water Authority.	Renewed interest in soil amendment using bauxite residue; concept of integrated catchment management introduced. Duration of *Nodularia* blooms declines and, in 1993, macroalgal accumulations in Peel Inlet follow suit.
1994		30,000 tonnes of bauxite residue applied to farms (totalling 1500 ha) in Meredith subcatchment.
1995	Streamlining (i.e. fencing off of watercourses and replanting with local trees and shrubs) extends along 150 km of creeklines.	

Modified from Bradby (1997)

5.1.2 Groundwater

The Dawesville Channel was not expected to substantially alter groundwater nutrient exchanges into the PHES. However, dewatering during its construction caused a localised effect on groundwater levels and salinity in its immediate vicinity.

Studies of the groundwater in the immediate vicinity of the Dawesville Channel prior to its construction indicated that most of the shallow groundwater was brackish, with a series of thin freshwater lenses overlying this saline water table (Owens 1992). These lenses were intersected by several private bores, the majority of which were installed *c.* 30 years ago. The bores were initially used for domestic water supply; following the introduction of the reticulated water system to the region, however, they were principally used for watering domestic gardens (Owens 1992). In a survey of domestic bores in the vicinity of the proposed Dawesville Channel, a total of 24 were recorded and 15 observed; of those observed only 8 were serviceable (Owens 1992).

The Dawesville Channel was constructed by dry excavating to a depth of -6.5 m AHD, and dewatering was conducted using two sumps at the ocean and estuary sites. The ocean sump was dewatered from January to July 1993 and the estuary sump from April to June 1993 (WAWA 1993). It was anticipated that this dewatering process would disturb the thin freshwater lens in the immediate vicinity of the Channel and result in saltwater intrusion (Groundwater Resource Consultants 1986).

Monitoring of groundwater levels and salinity in a series of private bores (Figure 1) was initiated prior to the construction of the Channel (May 1992) and was continued until May 1995; observations were obtained approximately monthly (Owens 1992; WAWA 1993; Water Quality Monitoring 1995). The location of the monitoring sites is shown in Figure 1. These observations indicated that, during the dewatering phase of construction, water levels within the monitoring bores dropped approximately 2.5 to 4 m (Water Quality Monitoring 1995). The levels recovered to the pre-dewatering levels within approximately a month of the cessation of dewatering. The groundwater salinity increased during dewatering in the majority of the monitored bores from 1800-3000 mg/L to approximately 6000 mg/L total dissolved solids. Following dewatering, the maximum salinities (*ca.* 15,000 mg/L total dissolved solids) were observed in the bores closest to the Channel.

These localised groundwater impacts arising from the construction of the Dawesville Channel were anticipated. The groundwater *levels* in most bores recovered to pre-dewatering levels soon after the completion of dewatering, but the groundwater *salinity* in most bores remained considerably above the pre-dewatering concentrations. Monitoring of several of the bores suggested that the salinity concentrations were slowly declining, but in the majority of bores they had not reached pre-dewatering levels by the cessation of monitoring (May 1995), prompting recommendations of continued monitoring (Water Quality Monitoring 1995). However, the Department of Transport (DoT) ceased groundwater monitoring in May 1995. The DoT currently subsidises the excess water bills of the affected residents, but it is intended that this subsidy will be discontinued soon.

5.2 Estuarine water quality

Water quality has been monitored on a weekly to monthly basis at all six sites in the PHES (Figure 1) from March 1979 until the present, whereas the three sites in Peel Inlet and the central Harvey Estuary site have been monitored since August 1977. Variables measured include:

- the physical parameters of salinity, temperature, dissolved oxygen, % oxygen saturation, pH, secchi depth, depth and light attenuation coefficient;
- the nutrient parameters of phosphate phosphorus (PO_4), total phosphorus (TP), organic phosphorus (OP), ammonium nitrogen (NH_4), nitrate+nitrite nitrogen ($NO_{2,3}$), Kjeldahl nitrogen (KN), organic nitrogen (ON), atomic nitrogen to phosphorus ratio (N:P) and dissolved silicate ion (SiO_4);
- the biological parameters of chlorophyll a (a measure of phytoplankton abundance) and phaeophytin (a degradation product of chlorophyll, and therefore a sign of recently collapsed blooms), phytoplankton counts and phytoplankton species present.

5.2.1 Prior to the opening of the Dawesville Channel

Water quality data for the period 1977 to 1993 were summarised and analysed in a report that included average monthly flow rates for the Murray, Serpentine and Harvey Rivers (James & Dunn 1996). The statistical analysis of the data set found that concentrations of PO_4, salinity and SiO_4 reflected changes in freshwater inflow during the year. Levels of chlorophyll a, organic nutrients and water turbidity reflected organic processes, and no systematic decrease or increase was found in these parameters over the 14-year period analysed. Furthermore, the maximum level of chlorophyll a in both the Peel Inlet and Harvey Estuary could be predicted with reasonable accuracy on the basis of the minimum level of salinity and the maximum level of water clarity during the preceding eight months of the year in the Harvey Estuary alone. This reinforced the hypothesis that *Nodularia* blooms were initiated in the Estuary, and that nutrient inputs and favourable conditions of salinity (both of which depended on river inflow) determined the size of the blooms. James and Dunn (1996) also provided 10th, median and 90th percentile values at each site for each month for the parameters of the 12-year data set. The main features of these data are summarised below.

Salinity and temperature

Prior to the opening of the Dawesville Channel the salinity of the PHES underwent considerable variation during the year due to a combination of the seasonality of the river flow, high evaporation rates in summer and poor exchange between the ocean and the estuary. Estuary water became nearly fresh in winter (less than 3 ppt), reflecting the seasonal influx of river run-off. Salinities returned to marine levels (35 ppt) during late spring and summer, when river flows effectively ceased. Peak salinities occurred in March and April, and were greater than sea water (up to 50 ppt) due to evaporative concentration of salt, particularly in the Harvey Estuary. Compared to the Peel Inlet, the Estuary was both more saline in late summer/early autumn and less saline in winter and spring. Differences between the two waterbodies were particularly noticeable from July to January, when the Estuary was up to 8 ppt less saline due to its greater distance from oceanic exchange.

During winter and spring the water column of the PHES often became strongly stratified in periods of calm weather, with a layer of fresh river water overlying the denser marine water that moved in with each tidal cycle.

Temperature in the waters of the PHES fluctuated from about 13°C in July to 23°C in January/February, although temperature extremes were several degrees greater in the shallow margins of the system.

Dissolved oxygen

The shallow waters of the PHES were generally well oxygenated throughout the water column for most of the year, and the annual cycle of levels of oxygen saturation largely reflected biological activity. Peak values occurred during spring (over 100%), coinciding with the highest phytoplankton levels (phytoplankton release oxygen during photosynthesis), and mostly remained between 80% and95% for the remainder of the year

Levels of oxygen saturation in summer and autumn were generally higher in Peel Inlet (above 90%) than Harvey Estuary (80%(85%), consistent with the higher levels of sediment organic matter and bacterial action in the latter. Also, bottom waters in the Estuary in particular often became oxygen-depleted under the stratified conditions that developed during calm periods in winter and spring, as oxygen was consumed during the decomposition of organic matter from collapsed winter diatom blooms. The strong salinity stratification effectively prevented the transfer of oxygen from the fresher surface waters to the saltier bottom waters.

Turbidity

There were marked seasonal changes in water turbidity, reflecting inputs of turbid river runoff, resuspension of sediments by wind-induced waves (particularly during winter storms) and spring phytoplankton blooms. Turbidity was greatest during winter and spring, and least in the calm months of autumn. Throughout the year Peel Inlet was less turbid (secchi depths of 0.6-2.0 m) than Harvey Estuary (0.3-1.7 m). The greater turbidity of the Estuary waters was due to a combination of higher phytoplankton levels, a greater proportion of fine sediments that were more easily resuspended by wave action, and a far greater fetch relative to prevailing wind directions.

Nutrients

Concentrations of inorganic nutrients (PO_4, NH_4 and $NO_{2,3}$) in the PHES were dominated by river inputs from July to September. The median values for this period were not quoted by James and Dunn (1996); however, they were expected to be close to the median values averaged across all sites, which were PO_4 concentrations of 20-40 µg/L and 20-55 µg/L for the Peel Inlet and Harvey Estuary respectively, with concentrations at or below 10 µg/L for the rest of the year (again, values for the Estuary were slightly higher overall). Averaged (median values averaged across all sites) NH_4 concentrations peaked at 300 µg/L for the Estuary in July and remained between 25 and 85 µg/L from spring to autumn. Averaged NH_4 concentrations in Peel Inlet peaked at 180 µg/L in July and were less than 40 µg/L from spring to autumn. The pattern for $NO_{2,3}$ was similar to that of PO_4 and NH_4, although differences between Peel Inlet and Harvey Estuary were less pronounced: peak values of 180 µg/L occurred in July, and values from spring to autumn generally remained below 20 µg/L in the Estuary and below 10 µg/L in the Inlet.

Concentrations of organic nutrients largely reflected phytoplankton levels (due to the nutrients bound in phytoplankton: see below), and therefore higher levels were observed in Harvey Estuary. Averaged levels of organic phosphorus in the Estuary remained at about 60 µg/L from late summer to autumn, increased slightly from August to October, then increased considerably (up to 260 µg/L) from November to January. Averaged levels of organic nitrogen remained at around 1200 µg/L for most of the year, and peaked at over 4000 µg/L in November and December. Averaged levels in Peel Inlet for both parameters followed similar seasonal trends, but were 50%-75% of Estuary values.

Chlorophyll a

Averaged (median values averaged across all sites) chlorophyll a levels in the PHES were generally low from late summer through to early winter (5-10 µg/L in Harvey Estuary and 2-5 µg/L in Peel Inlet). In most years there was a small increase in chlorophyll a levels (usually up to 20 µg/L in the Estuary and 10 µg/L in the Inlet) in late winter associated with a diatom bloom, and then from November to January there was a dramatic increase (usually to over 100 µg/L) in the Estuary associated with blooms of *Nodularia*. Increases in chlorophyll a in Peel Inlet due to *Nodularia* blooms also occurred, but seldom exceeded 50 µg/L except in waters close to Harvey Estuary.

5.2.2 Predicted effects of the Dawesville Channel

Before the opening of the Dawesville Channel the PHES was poorly flushed with oceanic waters as there was only one single shallow channel to the ocean at the northern end of Peel Inlet. Furthermore, the physical and chemical features of the Harvey Estuary (particularly its greater distance from the Mandurah Channel and the nature of nutrient inflow from the Harvey River) resulted in it being less saline, more prone to stratification and deoxygenation, more turbid, more nutrient enriched and having higher levels of chlorophyll a than the Inlet.

The Dawesville Channel was predicted to allow more than three times greater exchange between the PHES and the ocean: in effect 10% of the estuary's volume would be flushed each day. The increased oceanic exchange was expected to increase water salinity to marine levels for most of the year and increase the rate at which suspended sediments, nutrients and phytoplankton were removed from the estuary. The predicted impacts on estuarine water quality are discussed below; these are drawn from EPA (1988), Humphries and Ryan (1993) and Hart (1995).

Salinity and temperature

The opening of the Dawesville Channel was not expected to significantly affect the temperature regime of the PHES, but was expected to result in a more stable salinity regime, closer to that of oceanic water for much of the year.

Before the Channel was constructed salinity in the PHES usually reached 20 ppt in late November/December, and marine salinities by January. It was predicted that with the opening of the Channel salinity would reach at least 20 ppt by the end of September and marine salinities (approximately 35 ppt) by November and that conditions of hypersalinity in autumn would cease. The inflow of marine water from the Channel rather than from Peel Inlet was expected to cause stronger salinity stratification in Harvey Estuary during periods of river inflow, but a decrease of about two months in the overall period of stratification.

Dissolved oxygen

Although stronger salinity stratification was expected to occur in the Harvey Estuary in winter and early spring, the degree of oxygen depletion in bottom waters of the PHES was expected to be less severe (particularly in the Estuary) because of the regular inflow of well-oxygenated oceanic water. The period during which stratified conditions developed in the PHES was also expected to decrease, and therefore deoxygenated conditions to occur less frequently. The expected reduction in winter diatom blooms and *Nodularia* blooms during late spring and early summer (see below) would also reduce organic matter loading to the sediments and therefore reduce the level of oxygen depletion of bottom waters caused by subsequent bacterial decomposition of organic matter.

Turbidity

Increased oceanic exchange was expected to elevate the rate at which suspended sediments and phytoplankton were removed from the estuary, and this was expected to improve water clarity. The anticipated decline in *Nodularia* blooms (see below) would also result in improved water clarity. The improvement in water clarity was expected to be particularly noticeable in Harvey Estuary. The differences in water clarity between the Estuary and Peel Inlet were also expected to lessen with time, due to both the decline in *Nodularia* blooms and the gradual depletion (through tidal exchange) of the fine sediments easily resuspended by wave action in the Estuary.

Nutrients

Peak concentrations of inorganic nutrients in the PHES depend on nutrient concentrations in winter river run-off, and so the Dawesville Channel was not expected to alter these. However, the increased oceanic exchange was expected to lead to lower overall concentrations of nutrients in the water column during the period of winter run-off, particularly as the expected stratification of the water column would enhance flushing of the surface layer of nutrient-rich river water from the estuary. Due to the expected decrease in phytoplankton levels, improved conditions of oxygenation and enhanced loss of nutrient-rich fine sediments and organic matter from the PHES, it was also predicted there would be less release of PO_4 from the sediments. The effect of these changes on inorganic nutrient concentrations in the water column would depend on how quickly sediment phosphorus stores were depleted and/or converted to forms unavailable to plant growth (apatite, aluminium and iron oxides).

Organic nutrient concentrations in the PHES were expected to decrease due to the predicted decrease in phytoplankton levels.

Chlorophyll a

Prior to the opening of the Dawesville Channel, salinity levels and nutrient concentrations were particularly favourable for the germination of *Nodularia* in spring and the subsequent development of blooms in early summer (see Appendix 6).

It was predicted that, with the opening of the Channel, the winter diatom bloom would be of lesser magnitude, because increased oceanic exchange would reduce the amount of nutrients available to the phytoplankton. Furthermore, a significant proportion of the phytoplankton population would be lost to sea. As a result, there would be less loading of the sediments with organic matter when the diatom blooms collapsed, and less release of phosphorus for the growth of *Nodularia* in spring and summer. Sediment phosphorus release to the water column would also be lessened due to the less frequent occurrence of low oxygen conditions. Added to this, the predicted changes in the salinity regime in spring and summer would be much less favourable for the germination and growth of *Nodularia*. It was postulated that the more marine conditions and absence of *Nodularia* might allow blooms of marine species of phytoplankton to occur, but large blooms were not expected, particularly in the long term, due to the reduced nutrient status of the estuary.

5.2.3 Observed effects of the Dawesville Channel

Since the opening of the Dawesville Channel, water quality monitoring of the PHES has continued on a weekly to monthly basis at the six sites shown in Figure 1. The monitoring programme involves the parameters listed in Section 5.2, and reports on water quality data are available for the periods July 1994 to April 1995 (Wilson & Latchford, 1995), and May 1995 to April 1996 (Wilson *et al.* 1996). Chase (1995) analysed the data collected from April 1994 to August 1995, and a comparison of water quality data before and after the opening of the Channel (based on data from July 1991 to April 1997) was prepared (Wilson & Paling 1998). The results of these reports are presented below, but they represent only conditions during two years of low rainfall (and therefore low river flow) and one year of average rainfall, 1996, so firm conclusions about the impact of the Dawesville Channel cannot be drawn.

The data below are discussed in terms of mean values rather than medians, as non-parametric analysis of post-Channel data has not been carried out as yet. Direct comparison with the results of James and Dunn (1996) was not possible, and therefore data interpretation concentrates on general trends. In some cases post-Channel means are compared with pre-Channel medians to give an approximation of changes in water quality.

Salinity and temperature

During both 1994 and 1995 the salinity regimes of Peel Inlet and Harvey Estuary were very similar, while surface salinities in the winter of 1996 were lower (Figure 5.1). As predicted, mean salinities reached 20 ppt by the end of September and 35 ppt (marine salinities) by November. In 1994 — which had less river inflow than 1995 — 20 ppt was attained in surface waters by the end of August and bottom salinities never fell below 25 ppt. Surface salinities seldom fell below 10 ppt in either year, but the water column was strongly stratified during July and August in 1994 and from July to the end of September in 1995.

The predicted cessation of hypersaline conditions in autumn did not occur, although given that both 1994 and 1995 were dry years the degree of hypersalinity was less extreme than in pre-Channel times. For example, the two sites closest to the Channel (sites 2 and 58) never exceeded 40 ppt. The remaining four sites did exceed 40 ppt, with site 31 (the Harvey Estuary site furthest from the Channel) reaching over 46 ppt from late summer to early autumn in both years.

During both years, surface salinities were lower than bottom salinities during ebb tides, but the salinity during flood tides approached that of bottom waters. The nutrient-rich lower salinity water was clearly not mixing with oceanic waters, which facilitated nutrient loss and reduced the periods of low salinities. According to hydrodynamic studies by Hart (1995), it also appeared that during summer and autumn the incoming flood tide forced water in the Harvey Estuary towards the south, with little mixing between the ocean and estuary waters. Evaporation therefore still resulted in hypersaline conditions. Hart (1995) concluded that a shift from vertical stratification to horizontal stratification occurred in the PHES as a result of the construction of the Dawesville Channel.

Dissolved oxygen

Inspection of raw data (Wilson *et al.* 1997) indicated that the bottom waters of the two sites closest to the Dawesville Channel remained well oxygenated throughout the monitoring period. In central Peel Inlet and central Harvey Estuary the degree of oxygen saturation fell below 70% in late July and August in all three years. At the southernmost site in the Estuary, the degree of oxygen saturation in bottom waters fell below 50% from mid-July to mid-August in 1994, from mid-August to early September in 1995 (with both periods including one week of almost complete anoxia) and for one-week periods in July, August and late September in 1996. In bottom waters at the easternmost site in Peel Inlet, the degree of oxygen saturation fell below 40% in July 1994 (with one week of almost complete anoxia), for one week in both July and August 1995, and for one week in August 1996. Periods of deoxygenation at the central Peel Inlet and central Harvey Estuary sites appeared to be shorter and less frequent compared to conditions before the opening of the Dawesville Channel, and were confined to winter and early spring. Effects on periods of deoxygenation were less obvious at the southernmost Estuary and easternmost Inlet sites. Overall, the level of oxygenation of waters in the PHES improved (Figure 5.2).

Turbidity

Levels of turbidity measured during spring and to a lesser extent during summer were less than those in pre-Dawesville Channel years, particularly in Harvey Estuary. For example, the median (i.e. 50th percentile) values for 1977-93 data for secchi depths at site 1 (central Harvey Estuary) in September, October, November and December were 0.5, 0.7, 0.3 and 0.3 m respectively, and mean values for the corresponding months in 1994 were 1.4, 1.9, 1.0 and 0.6 m. The corresponding pre-Dawesville median values for site 7 (central Peel Inlet) were 0.9, 1.2, 0.7 and 0.9 m, and the 1994 mean values 2.0, 2.0, 1.2 and 0.8 m. The improvement in water clarity in early to midspring was attributed to the more rapid loss of turbid river water, and to the absence of *Nodularia* blooms in late spring and summer (see below).

Nutrients

The peak nutrient concentrations in the PHES depend on concentrations in river inflow, and the Dawesville Channel did not affect these. Therefore little difference was found between pre-Channel and post-Channel nutrient concentrations in winter months (Wilson *et al.* 1996). There were, however, noticeable changes during the remaining months of the year, the main ones being:

- inorganic and organic nutrient concentrations measured from late spring to late autumn in Harvey Estuary were very similar to those in Peel Inlet;
- NH_4 concentrations from spring to autumn were considerably less than in pre-Dawesville Channel years, particularly in Harvey Estuary, and largely remained below 20 µg/L;
- organic nitrogen concentrations from spring to autumn were considerably less than in pre-Dawesville Channel years, particularly in Harvey Estuary, and largely remained below 600 µg/L;
- organic phosphorus concentrations in November, December and January were considerably less than in pre-Dawesville Channel years, particularly in Harvey Estuary.

During pre-Dawesville Channel years, the overall nutrient status of Harvey Estuary was significantly higher than that of Peel Inlet, but with the opening of the Channel the nutrient status of the former appeared to decrease, and the two water bodies were very similar in terms of water quality (Figures 5.3 and 5.4). If anything, the data reported by Wilson and Latchford (1995) and Wilson *et al.* (1996) suggested that the nutrient status of Peel Inlet was slightly higher than that of Harvey Estuary, at least with respect to nitrogen.

The decline in organic nitrogen and organic phosphorus concentrations in both waterbodies was attributed to lower levels of phytoplankton, particularly *Nodularia* blooms in late spring and early summer. The decline in NH4 concentrations was attributed to lesser loading of the sediments with organic material derived from phytoplankton, and therefore a lower level of inorganic nutrient release from the sediments.

Chlorophyll a

The opening of the Dawesville Channel had a dramatic impact on chlorophyll a concentrations in the PHES (Figure 5.5). As for nutrient concentrations, a major feature of chlorophyll a data collected since the Dawesville Channel opened was that values for Harvey Estuary were considerably lower, and there was little difference between it and Peel Inlet. From July 1994 to April 1995 mean chlorophyll a levels for both Peel Inlet and Harvey Estuary remained below 10 µg/L, and were also generally below this level from May 1995 to April 1996 except in August and September 1995. *Nodularia* blooms did not occur in either the Inlet or the Estuary. Both 1994 and 1995 were dry years, and *Nodularia* blooms have also failed to occur during dry years before the Channel was opened, but apparently no *Nodularia* bloom occurred in late 1996 after a winter of heavy freshwater inflow (Latchford, *pers. comm.*). However, *Nodularia* blooms occurred in the Serpentine River in 1994, 1995 and 1996, affecting chlorophyll a levels in the eastern side of Peel Inlet when river water moved downstream during ebb tides.

5.2.4 Environmental compliance

Water quality monitoring of the PHES is the basis of an ongoing audit required under ministerial conditions for the Peel Inlet and Harvey Estuary Management Strategy, and compliance is measured against the following interim target set by the EPA:

Average phosphorus concentration in estuary water shall not exceed 0.02 milligrams per litre in nine years out of ten (on average).

The interim target does not specify the site number and locations, sampling frequency, sampling methodology or statistical procedures to be used in assessing compliance. Furthermore, it is unclear whether levels of orthophosphate phosphorus, organic phosphorus or total phosphorus are to be assessed. If the assumption is made that total phosphorus is intended, neither the median values for 1992 (82 µg/L in Peel Inlet, 136 µg/L in Harvey Estuary) — a year of low phosphorus input —

nor those for 1995 (59.5 µg/L in Peel Inlet, 74 µg/L in Harvey Estuary) and 1996 (60 µg/L in Peel Inlet, 72 µg/L in Harvey Estuary) have ever fallen below the compliance target.

The compliance target of 0.02 mg/L needs review: it is more suitable for nearshore coastal waters than for a southwestern Australian estuary. It is noted that national water quality guidelines (ANZECC 1992) specify indicative ranges for inorganic nutrient levels in healthy estuaries (5-15 µg/L PO_4, 10-100 µg/L NO_3 and <5 µg/L NH_4), but strongly recommend that site-specific guidelines be developed for each estuary.

5.2.5 Status of the monitoring program

The current sampling program was initiated in the late 1970s, and, although the six sites monitored provided an adequate representation of the PHES then, the Dawesville Channel produced effects that previously did not have to be considered. Hart (1995), Wilson and Latchford (1995) and Wilson *et al.* (1996) found that there were sometimes considerable differences in nutrient levels of surface waters during ebb and flood tides, and that tidal action appeared to result in oceanic waters pushing back estuarine waters, with little mixing between the two. It was recognised that with changes in water circulation patterns due to the opening of the Dawesville Channel, the original six sample sites might not adequately represent the PHES any more. Two comprehensive sampling exercises, one in winter 1996 and one in summer 1997, involving 28 sites (13 in Peel inlet and 15 in Harvey Estuary; Figure 1) were therefore carried out, with measurements taken during both flood and ebb tides (Wilson *et al.* 1997).

The results of these intensive surveys demonstrated that the original six sites represented the waters of the PHES remarkably well on most occasions, given the complexity of the system (Wilson *et al.* 1997). For this reason alone Wilson *et al.* (1997) recommended the original six sites be retained, quite apart from the value of their historical data. The intensive survey data also found that measurements during ebb and flood tides differed little in summer, but differed greatly in winter: during ebb tides in winter, river water appeared to move down the western side of Harvey Inlet and (to a lesser extent) the southern side of Peel Inlet. Wilson *et al.* (1997) concluded that representation of the PHES — particularly for salinity and inorganic nutrient levels — could be improved by the addition of one site 2 km north-northwest of the central Harvey Estuary site, and one site in the southeastern corner of Peel Inlet.

Although environmental monitoring by AgWA personnel is not part of the DCMP, it is also noted that data reported by Rivers (1997) indicated that heavy metal levels in PHES waters frequently exceeded ANZECC guidelines — far more so than in the Murray and Serpentine Rivers.

5.3 Riverine water quality

5.3.1 Prior to the opening of the Dawesville Channel

Algal blooms were a feature of the Murray and Serpentine Rivers before the opening of the Dawesville Channel, with a massive bloom of *Nodularia* in the Serpentine River in 1970 considered the first sign that serious eutrophication problems were occurring in the PHES. Other than in 1992/93, no consistent river water quality sampling program was undertaken, and some subsequent blooms may have occurred and gone unrecorded. *Nodularia* blooms were observed in the Serpentine River in the late spring/summer of 1989/90, late spring 1992 and early autumn 1994. ANZECC national water quality guidelines for inorganic and total nutrient concentrations in rivers (ANZECC 1992) were exceeded in the Serpentine River between November 1992 and January 1993. It was also known that stratification occurred in the lower reaches of the Harvey, Serpentine and Murray Rivers in spring, as tidal movements carried saline waters upstream.

5.3.2 Predicted effects of the Dawesville Channel

It was recognised that the opening of the Dawesville Channel might not prove beneficial to the lower reaches of the rivers. It was anticipated that saline water would be carried further upstream, particularly in bottom waters, with stratification possibly stronger and earlier to develop; oxygen depletion would therefore occur for increased periods of time. Conditions of oxygen depletion were also predicted for the lower reaches of the rivers after any sudden inputs of fresh water from a storm during summer or autumn. As riverine sediments were believed to be nutrient-rich, the predicted conditions of oxygen depletion were expected to cause sediment nutrient release in the lower reaches of the rivers (PIMA 1994), which would stimulate phytoplankton blooms. The expected phytoplankton blooms would in turn cause an increase in organic nutrient concentrations, leading to further enrichment of riverine sediments.

It was also predicted that *Nodularia* blooms would continue to occur in suitable regions — i.e. nutrient-rich, lower salinity waters of the lower reaches of the rivers — and that conditions of strong salinity stratification and high nutrient levels might favour toxic species of dinoflagellates (see also Appendix 6).

5.3.3 Observed effects of the Dawesville Channel

In recognition of potential problems in riverine water quality, in November 1994 the WRC initiated a monitoring program involving seven sites in each of the Serpentine and Murray Rivers (Figure 1). Monthly measurements of salinity, temperature, dissolved oxygen, secchi depth, turbidity, inorganic and total nutrients, and phytoplankton cell counts were carried out at each site between November 1994 and June 1996. After July 1996 weekly to monthly monitoring was carried out, depending on the presence of blooms, but some sites were only monitored for physical parameters, or physical parameters and phytoplankton cell counts (see Figure 1).

Available data indicated that strong salinity stratification and depletion of oxygen in bottom waters occurred in the Murray River except during periods of winter river flow, whereas this was less decidedly the case in the Serpentine River (Figure 5.6). However, nutrient concentrations in the Serpentine were generally much higher than in Murray (Figure 5.7), and often exceeded ANZECC's (1992) indicative ranges for total nitrogen (100-750 μg/L) and total phosphorus (10-100 μg/L), at which eutrophication problems may occur.

Nodularia blooms occurred in the Serpentine River from late spring to the end of summer in 1994/95, 1995/96 and 1996/97, and it was necessary to erect warning signs declaring the it unsafe for swimming and fishing on foura number of occasions. The bloom in 1996/97 — which followed a year of average rainfall — was particularly intense and extensive. In contrast, the late spring/summer of 1997/98 coincided with an El Nino Southern Oscillation (ENSO) event (which meant that coastal water levels were particularly low) and a low winter river flow, and data indicated that conditions in the Serpentine River were the best since the opening of the Channel.

Overall, algal blooms appeared more pronounced after the opening of the Dawesville Channel (see Appendix 6). In particular, the Serpentine experienced a similar pattern of algal succession to that of the PHES prior to the opening of the Dawesville Channel, with a *Nodularia* bloom in late spring through to early autumn (Water and Rivers Commission, draft).

There were no water quality data for the Harvey River other than nutrient concentrations for the catchment monitoring sites and monitoring of salinity profiles undertaken by the Department of Conservation and Land Management (CALM) to check on effects of increased salinities on fringing vegetation and waterbirds (see Appendix 7). A full analysis of the results of the CALM surveys was not available, but there were preliminary indications of increased saltwater penetration upstream (Lane *et al.* 1997).

5.3.4 Status of the monitoring program

Water quality monitoring of the tidal reaches of the Serpentine and Murray Rivers has been inconsistent, and no monitoring of the Harvey River has been carried out except that involving catchment monitoring sites and the salinity profiles measured by CALM. This is a matter of concern, as deterioration of riverine water quality was predicted as a potential effect of the opening of the Dawesville Channel. This prediction has been realised, particularly in the Serpentine River during summer and autumn.

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Dawesville Channel
Technical Review

APPENDIX 6

ESTUARINE FLORA

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

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WATER AND RIVERS
COMMISSION

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6. Estuarine flora

6.1 Non-vascular plants

Non-vascular plants monitored in the DCMP include phytoplankton and macroalgae.

In phytoplankton communities the changing estuarine environment results in a succession of different species becoming dominant at different times of the year, according to which species is most competitive under the prevailing conditions of light, temperature, salinity and nutrient supply (Day 1981). Different species of diatoms usually predominate, but dinoflagellates become more competitive in warm, calm conditions. Certain species of blue-green algae such as *Nodularia* are independent of inorganic nitrogen concentrations in the water column, because they can fix atmospheric nitrogen, and are therefore favoured by high concentrations of inorganic phosphorus (Kinhill Engineers 1988).

Macroalgae do not grow as fast as phytoplankton, which can double their populations in less than a day: therefore rapid successional changes in species composition do not occur. Estuarine conditions tend to favour euryhaline species of macroalgae (i.e. species that tolerate a broad range of salinities), the majority of which belong to two phyla: red algae (*Rhodophyta*) and green algae (*Chlorophyta*) (Day 1981). Brown algae (*Phaeophyta*) generally do not tolerate salinities less than marine levels. Successional changes in macroalgal communities can occur throughout the year, but over periods of months. As with phytoplankton, the prevailing conditions of light, temperature, salinity and nutrient supply determine which species predominate. For example: red algae are generally more competitive under conditions of low light supply (i.e. turbid water); some species of green algae are capable of extremely fast growth rates under conditions of high nutrient supply; and brown algae are favoured by conditions of low nutrient supply and marine salinities (Lavery *et al.* 1995).

6.1.1 Phytoplankton

Successional changes in phytoplankton species composition are a normal feature of estuarine waters, and phytoplankton 'blooms', defined here as chlorophyll a levels of greater than 20 µg/L, can be a natural feature in estuaries little affected by human activities (Day 1981). Changes in phytoplankton communities are only indicative of deteriorating environmental health when massive blooms occur regularly and for long periods, and/or the blooms are of toxic species of dinoflagellates or toxic blue-green algae such as *Nodularia* (McComb 1995). Both of these scenarios are associated with excessive nutrient enrichment.

Nodularia is known to be toxic to humans if ingested via contaminated shellfish (e.g. mussels, cockles and oysters), and some species of dinoflagellates (e.g. of the genus *Alexandrium*) produce paralytic shellfish poison, a neurotoxic group of protein-like compounds which can cause anything from skin rashes, dizziness and mucosal tissue inflammation up to death by respiratory failure in persons consuming contaminated filter-feeding shellfish (Hosja & Deeley 1994). During intense dinoflagellate blooms the tissue of some planktivorous fish may also become contaminated, and persons eating large amounts of small whole fish may be at risk. The deaths of piscivorous birds due to eating contaminated fish is also possible, and has been recorded in the USA (W. Hosja, WRC, *pers. comm.*).

The work of Cannon (1993a, 1993b) in the shallow upper reaches of the Port Adelaide River has indicated that the most favourable conditions for toxic dinoflagellate blooms vary between species, but appear to include:

- extended periods of calm sunny weather;
- conditions of low salinity (around half seawater salinity);
- vertical stratification of the water column;
- warm water temperatures (above 15°C);
- a nutrient supply to sustain the bloom.

These conditions are very similar to those that favour *Nodularia*, except that *Nodularia* only requires high levels of inorganic phosphorus in the water column (Hodgkin *et al.* 1985).

Prior to the opening of the Dawesville Channel

Phytoplankton biomass, as measured by chlorophyll a levels, was discussed in Appendix 5. The first recorded indication that excessive nutrient enrichment was affecting the phytoplankton communities of the PHES was in 1970, when a massive bloom of *Nodularia* appeared in the Serpentine River. *Nodularia* blooms appeared in Harvey Estuary in 1973 and 1974 (which were years of very high rainfall), but aroused little comment; the next three years (1975-77) had relatively low rainfall and no blooms were reported (Hodgkin *et al.* 1985). The first large-scale bloom of *Nodularia* appeared in Harvey Estuary in 1978, and also drifted out into Peel Inlet (Hodgkin *et al.* 1985). Aside from the periods of *Nodularia* blooms, diatoms were the dominant phytoplankton group in the PHES. A list of the phytoplankton species characteristic of the PHES is given by Chase (1995).

Prior to the opening of the Dawesville Channel, blooms of diatoms (usually species of the genera *Cerataulina, Skeletonema, Cyclotella* and *Chaetoceros*) occurred in winter, although chlorophyll a values seldom exceeded 50 μg/L. Dinoflagellate blooms also occurred — e.g. species of the genera *Ceratium, Prorocentrum, Gymnodium* and *Peridium* — particularly in Harvey Estuary. Blue-green algae (*Nostoc, Oscillatoria, Spirulina* and *Microcystis*) were also present, but usually in relatively low numbers. The winter blooms collapsed by spring, which was attributed to grazing by zooplankton, and the phytoplankton community was subsequently dominated by massive blooms of *Nodularia* (chlorophyll a values commonly greater than 100 μg/L and sometimes greater than 1000 μg/L), which appeared in late spring almost every year after 1978.

Nodularia akinetes (i.e. spores or seeds) lie dormant in sediments and germinate after several days of near-fresh salinities in warm water (Huber 1985). After germination, the organism is capable of growing well at salinities from 3 to 30 ppt, water temperatures from 16°C to 30°C and relatively low light levels, but it does not grow well at marine salinities (35 ppt) (Huber 1985). *Nodularia* is capable of nitrogen fixation and therefore not reliant on inorganic nitrogen supplies in the water column; the conditions of high phosphorus levels in the Harvey Estuary, along with low salinities (around half to three-quarters of marine levels) and warm temperatures (around 20°C), were particularly favourable to this species in spring and early summer. The blooms collapsed in summer, which was attributed to high salinities (around 30 ppt), although nutrient depletion may also have played a role (Lukatelich & McComb 1986). Following the collapse of the *Nodularia* bloom, there was often a much smaller bloom of diatoms (usually species of the genera *Asterionella* and *Chaetoceros*) or dinoflagellates (usually *Ceratium, Prorocentrum, Gymnodium* and *Dinophysis*), presumably due to the nutrients released by decaying *Nodularia*.

The only years in which *Nodularia* did not bloom were 1987 and 1990, which were years of low river flow and therefore had lower phosphorus inputs and reduced periods of favourable salinities for *Nodularia*. However, in 1991 and 1992, *Nodularia* blooms were large but of short duration. It was postulated that improved flushing of the PHES due to dredging of the Sticks Channel in 1987 resulted in nutrient concentrations declining more quickly after winter run-off ceased; hence the decrease in duration of *Nodularia* blooms (Lavery *et al.* 1995).

Blooms of blue-green algae (mainly *Nodularia*) and dinoflagellates were also common in the Serpentine River in summer and autumn, while in the Murray River blooms of diatoms and dinoflagellates were common in summer and autumn (WRC, unpublished data).

Predicted effects of the Dawesville Channel

As discussed in Appendix 5, with the opening of the Dawesville Channel the 'window' of favourable conditions for the germination of *Nodularia* akinetes — salinities less than 15 ppt combined with temperatures around 20°C — was expected to virtually disappear except in years of very heavy run-off (e.g. as in 1973 and 1974, when the Harvey River annual flow was around 400 million cubic metres). Furthermore, even if *Nodularia* blooms were initiated, their growth would be retarded due to the rapid return to marine salinities with the cessation of river run-off. It was also predicted that the winter diatom bloom would be of lesser magnitude, because increased oceanic exchange would reduce the amount of nutrients available to the phytoplankton, and a significant proportion of the population would furthermore be lost to sea. As a result, there would be less loading of the sediments with organic matter when the diatoms blooms collapsed, and less release of phosphorus for the growth of *Nodularia* and other species of phytoplankton in spring and summer. Sediment phosphorus release to the water column would also be lessened due to reductions in periods of low oxygen levels.

It was predicted that the more marine conditions and absence of *Nodularia* might allow blooms of marine species of phytoplankton to occur, but large blooms were not expected due to the rapid loss of nutrients from the estuary. Large blooms were considered even less likely in the long term, with the expected progressive decline in the nutrient status of the estuary. However it was predicted that *Nodularia* blooms would continue to occur in suitable regions (i.e. nutrient-rich, lower salinity waters) of the lower reaches of the rivers.

Observed effects of the Dawesville Channel

No *Nodularia* blooms occurred in Peel Inlet or Harvey Estuary in 1994, 1995 or 1996, and phytoplankton biomass in the PHES — as measured by chlorophyll a levels — decreased overall (see Appendix 5). This suggested that the high nutrient levels associated with river inflow were rapidly lowered due to oceanic exchange. Diatoms dominated the phytoplankton communities in the PHES throughout the year, although the species previously typical of the winter diatoms were confined to a much shorter period and those more commonly found in marine salinities were prevalent (Chase 1995).

Diatoms dominated the phytoplankton communities in the PHES, apart from a dinoflagellate bloom in the Harvey Estuary during mid-August 1995. The diatom community composition previously typical of the winter diatoms (of the genera *Cerataulina, Skeletonema, Cyclotella* and *Chaetoceros*) was confined to a much shorter period, and species more commonly found in marine salinities were prevalent (*Nityschia, Asterionella, Thalassiosira* and *Chaetoceros*). Species richness had also increased (Chase 1995).

Although there were no *Nodularia* blooms in Peel Inlet or Harvey Estuary, they occurred in the Serpentine River from late spring to the end of summer in 1994/95, 1995/ 96 and 1996/97. Blooms of blue-green algae (mainly *Nodularia*, but also *Anabaenopsis, Merismopedia, Oscillatoria, Anabaena* and *Microcystis*) and dinoflagellates (during summer and autumn) dominated in the Serpentine River, and blooms of the Haptophyte *Prymnesium*, which can be lethal to fish, also occurred in April/May 1997. In the Murray River diatom blooms predominated in summer and autumn, but the potentially toxic dinoflagellate species *Alexandrium minutim* was detected in moderate densities in February 1996.

The occurrence of dinoflagellate blooms in the lower reaches of the Serpentine River and — to a far lesser extent — the Murray River (including a potentially toxic species), and the continued occurrence of *Nodularia* blooms in the Serpentine indicated that conditions favourable to toxic phytoplankton blooms occurred regularly in the lower reaches of these rivers. These changes may not all be due to the opening of the Channel, as catchment monitoring studies indicate that nutrient inputs to some parts of the Serpentine may have increased (see Appendix 5).

Status of the monitoring program

Phytoplankton levels and species composition are measured in water samples taken in the water quality monitoring program, which was discussed in Appendix 5. On the basis of available data, the occurrence of large blooms in Peel Inlet and Harvey Estuary appears unlikely, but this cannot be confirmed until more years of higher rainfall are experienced. Chase (1995) analysed the composition of the phytoplankton community before and after the opening of the Dawesville Channel based on data collected between January 1993 and August 1995, and it would be useful to repeat this exercise using a more comprehensive data base.

The occurrence of dinoflagellate blooms — including a potentially toxic genus — in the lower reaches of the Murray and Serpentine Rivers and the continued occurrence of *Nodularia* blooms in the Serpentine are cause for concern. Conditions favourable to toxic phytoplankton blooms may now occur regularly in the lower reaches of the these rivers.

6.1.2 Macroalgae

Although nutrient enrichment resulted in large amounts of macroalgae in the PHES, its macroalgal species richness (the number of different species of macroalgae) has always been low even by estuarine standards. This is because most species of macroalgae require a hard surface to grow on, and the predominantly sandy or muddy floor of PHES offers few attachment sites. Furthermore, few species of macroalgae could tolerate the extremes of salinity that occurred in the PHES.

Prior to the opening of the Dawesville Channel

Nutrient enrichment of the PHES has affected both the species composition and biomass of macroalgal communities. Since the 1960s the macroalgal community has been dominated by species of opportunistic green algae, mainly *Cladophora, Chaetomorpha, Ulva* and *Enteromorpha* (Lavery *et al.* 1995).

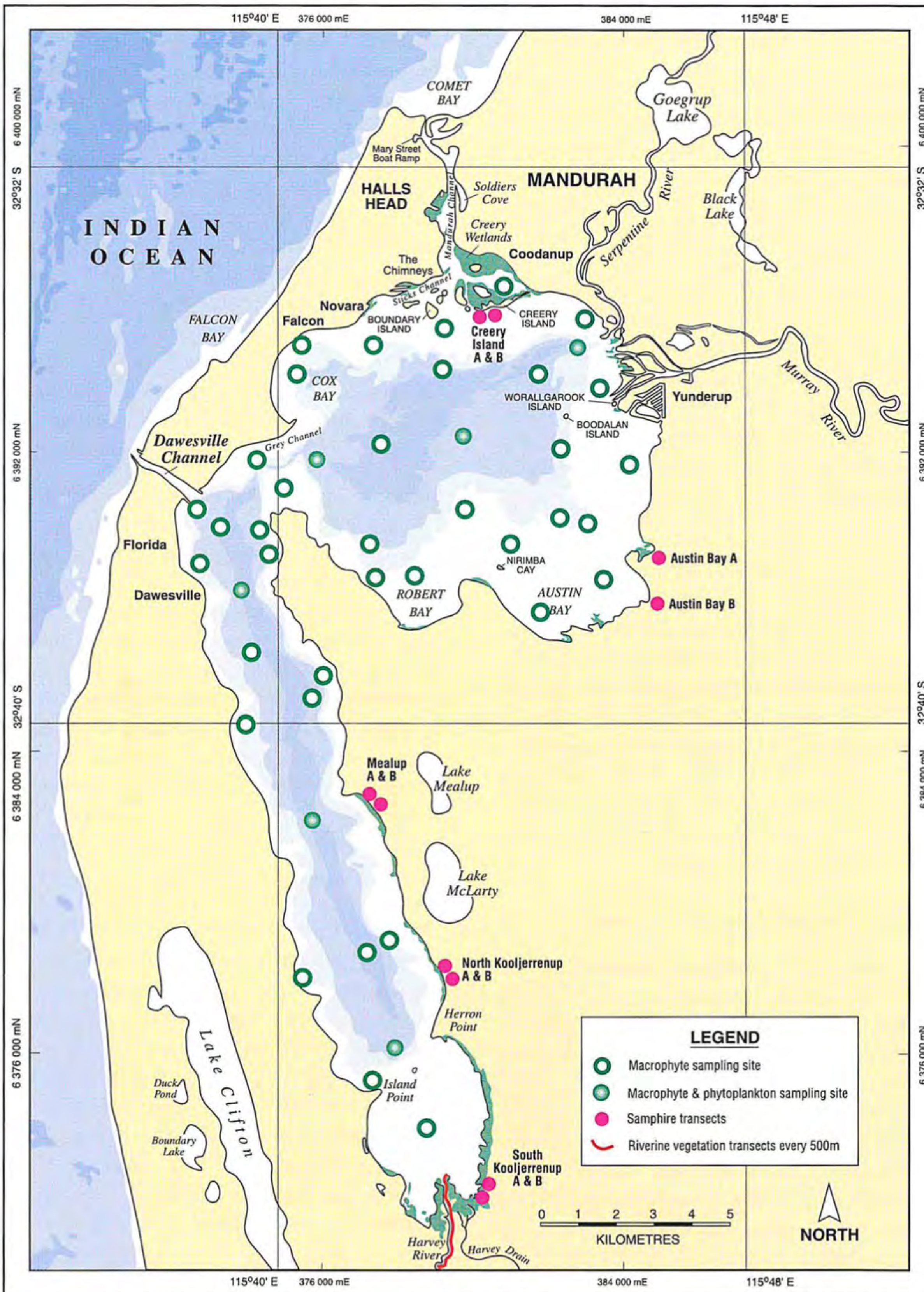
Macroalgal accumulations have been harvested from the shores and shallows of Peel Inlet since the 1970s, and drifting wracks of algae have been harvested using conveyor harvesters in deeper water (greater than half a metre) since 1984. This was originally carried out as a cosmetic exercise, but in recent years has been used as a management tool to minimise the development of large accumulations of macroalgae that might get washed ashore or block navigation channels (Rose, *pers. comm.*).

Prior to the opening of the Dawesville Channel nuisance proportions (to people) of macroalgae in the PHES occurred mainly in Peel Inlet and the northern end of Harvey Estuary. Research on the main species of macroalgae in the PHES established that nutrients and light were the main factors affecting their growth (Lavery *et al.* 1995, and references cited therein). The eastern populations of macroalgae in Peel Inlet were believed to depend largely on nutrients from the Murray and Serpentine Rivers, whilst the Harvey River was an important nutrient source for the populations of macroalgae in western Peel Inlet (Lavery *et al.* 1995). The Harvey Estuary had far less macroalgal accumulation, which was attributed to the turbidity of the water and therefore lower light availability for macroalgal growth.

Large macroalgal accumulations were first noticed in the Peel Inlet in the 1960s and reached their highest levels in the 1970s. Measurements of macroalgal biomass and species composition in the PHES took place at 30-42 sites (Figure 1) at least once a year between 1978 and 1994, with the exception of 1980 and 1983 (Lavery *et al.* 1995). From these data, maps of macroalgal distribution and biomass were produced. Estimated total macroalgal biomass was generally in the range 5000-20,000 tonnes, although it reached 60,000 tonnes in 1979.

Cladophora montagneana dominated the system until 1979, then underwent a dramatic decline in biomass (Lukatelich & McComb 1985). The initial appearance of accumulations of this organism was linked to above-average river flows coupled with high fertiliser applications in the catchment, and therefore high nutrient inputs, between 1963 and 1968. *Cladophora montagneana* was very successful in colonising the deeper areas of Peel Inlet, where it formed a bed of algal balls overlying a dark ooze of decomposing algae and anoxic sediment (McComb *et al.* 1981), which served as a nutrient source for the alga during subsequent periods of lower nutrient inputs. A severe winter storm in July 1978 was believed to have dislodged the beds in the deeper waters, transporting much of the alga to the shore. Thus the nutrient cycling mechanism that helped maintain *Cladophora montagneana* populations was disrupted. A following summer of low-light conditions due to a *Nodularia* bloom, and further loss of the alga during the winter of 1979 as material was exported to the shores without subsequent replenishment from the deep growth sites, were believed to be responsible for the effective disappearance of this species from the estuary (Lavery *et al.* 1995).

From 1979 until the opening of the Dawesville Channel there were considerable fluctuations in macroalgal biomass, and one of *Chaetomorpha linum, Ulva rigida* or *Enteromorpha* species (principally *E. intestinalis*) was dominant, with occasional periods of co-dominance (Lavery *et al.* 1995). The relative abundance of these species was strongly linked to changes in light and nutrient conditions. Maximum macroalgal biomass was generally attained in late summer/early autumn: although nutrient concentrations were more favourable for growth in spring, water clarity and salinity were seldom favourable. Until the 1990s it appeared that the level of nutrient inputs influenced species composition, with *Chaetomorpha* more competitive during periods of lower nutrient conditions (i.e. during summer and autumn), and *Ulva* and *Enteromorpha* during periods of higher nutrient availability (i.e. during spring). Total macroalgal biomass was, however, strongly linked to light availability (i.e. water clarity) over the summer period. In addition, the pattern of river nutrient inputs of preceding years also influenced macroalgal responses, because — unlike most other documented systems with a macroalgal problem — the PHES has a pulsed nutrient supply (i.e. associated with river inflow in winter and early spring) rather than a constant one (e.g. from sewage). Therefore a sequence of low-rainfall years could result in general depletion of estuarine nutrients



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Water and Rivers Commission
Dawesville Channel Monitoring Programme
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LOCATION OF PHYTOPLANKTON, MACROPHYTE AND FRINGING VEGETATION MONITORING SITES

Figure **1**

and 'seed' populations of macroalgae, while a sequence of high-rainfall years could have the opposite effect.

The influence of nutrient and light conditions in determining relative macroalgal abundance became less clear in the 1990s. River flows and phosphorus inputs in 1991 and 1992 were average or above average, yet *Chaetomorpha* was dominant, and furthermore *Nodularia* blooms were large, but of short duration. The inference was that nutrient concentrations were declining more quickly after the cessation of winter run-off, and one potential explanation offered for this was improved flushing of Peel Inlet due to the dredging of the Sticks Channel in late 1987. Hearn (1995) calculated that the dredging would increase astronomic tidal exchange from 11.8 to 18.1 estuarine volumes per year and barometric tidal exchange from 8.3 to 20.2 estuarine volumes per year.

After a low river flow in the winter of 1993, the macroalgal biomass in the summer/autumn of 1994 was the lowest recorded, and, although the expected dominance of *Chaetomorpha* occurred, total macroalgal biomass was far lower than predicted according to the light conditions. The conclusion drawn was that the overall nutrient status of Peel Inlet had declined as a result of improved flushing and/or reduced phosphorus loss from the catchment due to the catchment management program, and that the low macroalgal biomass was due more to low nutrient supply than to light availability (Lavery *et al.* 1995).

Predicted effects of the Dawesville Channel

With the opening of the Dawesville Channel, the species richness of the macroalgal community in the PHES was expected to increase due to increased recruitment of algal propagules from the ocean, improved water clarity and a less extreme salinity regime (Lavery *et al.* 1995). The importance of red and brown algae in the macroalgal community was predicted to increase in the long term, due to decreased competition from green algae (Lavery *et al.* 1995). If significant increases in seagrass cover occurred (see Section 1.2), drift macroalgae were also expected to be retained in the seagrass meadows to some extent, and this, combined with an overall decrease in macroalgal levels, was predicted to result in less accumulation of macroalgae on the shores of the PHES (Lavery *et al.* 1995).

The decrease in nutrient levels was expected to produce conditions more favourable to the growth of *Chaetomorpha* than of *Ulva* and *Enteromorpha*. The dominance of *Chaetomorpha* is uncommon in eutrophic estuaries elsewhere, and this may be in part due to the pulsed nature of the nutrient supply to the PHES. *Chaetomorpha* is able to maintain small populations over winter, permitting it to take advantage of the high nutrient levels in the water column — unlike *Ulva* and *Enteromorpha*, which must 'start from scratch' each spring without the benefit of nutrient stores accrued in winter. *Chaetomorpha* may also have a reduced dependence on water column nutrients, since it can form relatively thick floating banks, and may be more effective than *Ulva* and *Enteromorpha* in creating conditions suitable for sediment nutrient release.

Predictions of the effect of the opening of the Dawesville Channel on actual macroalgal biomass were less certain. Originally it was anticipated that the expected improvement in water clarity — while the nutrient status of the Peel Inlet was still relatively high — would cause a continuation and even an increase in macroalgal biomass in the short-term, but that the ongoing reduction in phosphorus availability would see biomass decline in the longterm (EPA 1988). Substantial accumulations of macroalgae were expected, particularly along the southeastern shoreline of Peel Inlet. The possibility was also raised of improved light conditions causing increased macroalgal growth in the Harvey Estuary, in the deeper waters of the estuarine system and in the lower reaches of the Murray and Serpentine Rivers (Waterways Commission 1994). However, the improved flushing of Peel Inlet due to dredging the Sticks Channel did not cause an increase in macroalgal growth (see above); thus there was uncertainty about whether macroalgal levels in the short term would be as high as originally expected (Lavery *et al.* 1995). Clearly the response of the PHES would still be strongly influenced by catchment nutrient inputs and by the pattern of catchment nutrient inputs over successive years. Of particular importance would be the degree to which early phytoplankton blooms and/or the development of thick layers of macroalgae were fuelled: both of these processes would influence rates of sediment nutrient release.

Observed effects of the Dawesville Channel

After the opening of the Dawesville Channel seasonal (spring, summer and autumn) sampling of macroalgal biomass and species composition took place at 42 sites in the PHES (Figure 1), maintaining continuity with the pre-Channel monitoring programme (Wilson *et al.* 1995, 1996). A comparison of pre-Channel and post-Channel macroalgal biomass was also carried out by Wilson *et al.* (1997).

As predicted, *Chaetomorpha* dominated macroalgal biomass. During 1994 and 1995 *Enteromorpha* and *Ulva* comprised over 30% of total macroalgal biomass in spring, and red algae accounted for over 25% in autumn. The spring biomass of *Enteromorpha* and *Ulva* was far less in 1996. In the summer and autumn of 1997 red and brown algae comprised over 50% of total macroalgal biomass. The predicted increase in species richness of the macroalgal community occurred, and 1997 data indicated that the relative contribution of red and brown algae to total macroalgal biomass may be increasing.

The majority of macroalgal biomass was in the shallows of Peel Inlet, particularly around the southeastern shoreline. Large accumulations of *Chaetomorpha* and red algae also occurred near Island Point in Harvey Estuary up to autumn 1996, but these were not present from spring 1996 to autumn 1997: instead, accumulations of *Cladophora montagneana* occurred at a site 2 km further north of Island Point. Macroalgal biomass was low in the deeper waters of Peel Inlet and Harvey Estuary, and largely consisted of red algae, which are known to have lower light requirements than green algae.

Prior to the opening of the Dawesville Channel, macroalgal biomass generally peaked in late summer/early autumn. After the opening, peak biomass occurred in spring. This change was attributed to an improvement in water clarity during that season — due to the absence of *Nodularia* blooms and increased exchange of stained river water with the ocean — coupled with conditions of high nutrient availability, favourable temperatures and favourable salinities. The altered conditions also enabled *Enteromorpha* and *Ulva* to compete more successfully with *Chaetomorpha* in spring 1994 and 1995, but by summer, when nutrient concentrations were lower, *Chaetomorpha* became dominant.

Chaetomorpha biomass declined from summer to autumn even though conditions of salinity, temperature and light were favourable. The tissue concentrations of nutrients in *Chaetomorpha* suggested that ambient (water column) nutrient concentrations were insufficient to sustain the summer populations, even though decomposing algae, and conditions suitable for sediment nutrient release, occurred under accumulations of *Chaetomorpha* at sites on the southeastern shores of Peel Inlet (Wilson *et al.* 1996).

Prior to the opening of the Dawesville Channel, the tissue concentrations of nutrients in macroalgae in western populations of Peel Inlet were generally higher than the eastern populations. The reverse scenario occurred after the opening of the Channel, with western populations even showing some signs of nutrient limitation. It was inferred that the increase in oceanic exchange had decreased the contribution of Harvey catchment nutrients (and *Nodularia* bloom nutrient inputs) to macroalgal populations along the western shores of the Inlet. Macroalgal populations along its eastern shores showed no sign of nutrient limitation, presumably because their main nutrient sources were the Murray and Serpentine Rivers — and possibly also *in-situ* nutrient recycling.

Total macroalgal biomass in Peel Inlet was around 15,000 tonnes in spring 1994 and summer 1994/95, remained around 5000 tonnes until autumn 1996, but declined to about 3000 tonnes in spring 1996 and 2000 tonnes in summer 1996/97 (Wilson *et al.* 1997b) (Figure 6.1). Both 1994 and 1995 were years of low rainfall and low nutrient input, and the levels of macroalgal biomass were not significantly different to those measured in years of low rainfall before the opening of the Channel. However, 1996 was a year of average rainfall, and macroalgal biomass was the lowest on record. Although a year of high rainfall was not experienced, the prediction that macroalgal biomass might increase with the improved water clarity following the opening of the Dawesville Channel was not realised. This may be due to one or more of the following causes:

- the *in-situ* nutrient status of the PHES was no longer sufficiently high to maintain high levels of macroalgal growth (particularly since the loss of nutrient inputs from *Nodularia* blooms), and therefore macroalgal biomass depended almost entirely on nutrient inputs from catchment run-off;

- the sediment nutrient pools were not accessed because less deoxygenation of the water column occurred and/or insufficient macroalgal biomass developed to cause broadscale nutrient recycling from the sediments;
- nutrients were released by recycling processes, but were more rapidly lost due to the increased oceanic exchange.

In summary, available data indicated that the opening of the Dawesville Channel had decreased nutrient availability for macroalgal growth in Peel Inlet. Macroalgal biomass in Harvey Estuary remained low compared to that in the Inlet, but conditions appeared more favourable for macroalgal growth along the western shores north of Island Point.

Status of the monitoring program

The current macroalgal monitoring program is being carried out efficiently, and data reports are produced promptly. The data on macroalgal biomass and species composition for the 42 sites provide a means to assess changes from year to year, but there are large errors associated with estimations of total macroalgal biomass because substantial areas are represented by single sites. Continuation of the present sampling program will provide data that can be compared with pre-Channel years, but comparisons should only be done at the broadest level, i.e. years of large, medium or low accumulations of macroalgae. As with the water quality sampling program, the macroalgal monitoring program was derived on the basis of the best information available at the time, and needs to be modified in the light of new data and the change in conditions due to the opening of the Dawesville Channel, e.g. the possibility of macroalgal accumulations in deeper waters due to improved water clarity.

6.2 Vascular plants

Vascular plants in the PHES include seagrasses, which grow under water, and fringing vegetation, which occupies the upper part of the tidal zone.

Seagrasses are essentially marine plants, and they are quick to die back if salinities fall below about three-quarters of marine levels and/or turbidity is too high. A few species of seagrass are found in the more marine parts of southwestern Australian estuaries, while quick-growing species such as *Halophila ovalis* often penetrate further into estuaries but are present intermittently, only becoming prolific in those months when marine salinities prevail and water clarity is suitable (Kirkman & Walker 1989).

Fringing vegetation is a more permanent feature of most southwestern Australian estuaries, with different species occupying different parts of the tidal zone according to their tolerance to salinity levels and degree of inundation. The response of fringing vegetation to changes in salinity levels and/or inundation patterns is one of gradual change (i.e. over periods of years) in species composition and in the extent of the zone occupied.

6.2.1 Seagrasses

The most common seagrass in southwestern Australian estuaries is the small species Halophila ovalis, which appears be more tolerant of low salinities (down to about half marine salinity) and low light supply (and therefore turbid waters) than other species of seagrass (Hillman *et al.* 1995). Other small species such as *Zostera mucronata* and *Heterozostera tasmanica* are often found near the mouths of southwestern Australian estuaries, where essentially marine conditions prevail (Kirkman & Walker 1989).

The aquatic angiosperm *Ruppia megacarpa* is also common in southwestern estuaries. *Ruppia* is not a seagrass in the strictest sense, since it flowers on top of the water rather than under water, but is usually included as one: it has an extremely broad range of salinity tolerance, from essentially freshwater to hypersaline conditions.

As a group, seagrasses are also intolerant to eutrophication (Shepherd *et al.* 1989). The principle cause of their intolerance appears to be light-related: they are effectively shaded out by the proliferations of macroalgae, epiphytes (algae that grow attached to seagrasses) and phytoplankton that develop in nutrient-enriched conditions.

Prior to the opening of the Dawesville Channel

Anecdotal evidence suggests that before the 1960s *Ruppia megacarpa* was prolific on the shallow fringes of both Peel Inlet and Harvey Estuary, and *Halophila ovalis* was common in the slightly deeper waters of the central basin of Peel Inlet (Kinhill Engineers 1988). The extent of these two species apparently declined considerably with the appearance of large macroalgal accumulations and *Nodularia* blooms.

Seagrass beds usually have a higher abundance and diversity of estuarine fauna, particularly benthic invertebrates and juvenile fish, than bare sand, and this is attributed to a combination of greater habitat complexity (and therefore more ecological niches to exploit), greater protection from predators, calmer conditions (due to the wave-baffling effect of dense macrophytes stands) and a more abundant food supply. However, although there was widespread loss of seagrasses in the 1970s and 1980s due to proliferation of algae in the PHES, effects on fauna appeared to be mitigated because the ecological functions of the macroalgal accumulations were similar to those of seagrasses (Steckis 1991).

Between 1978 and 1994, seagrass biomass and species composition was measured (if present) at the 30-42 sites monitored for macroalgae (Lavery *et al.* 1995). The most widespread seagrasses were Halophila ovalis and *Ruppia megacarpa*. Small beds of *Zostera mucrmnata* occurred near the entrance of the Mandurah Channel and *Heterozostera tasmanica* near the Sticks Channel, but measurements were not taken in these areas.

Although macroalgal (*Cladophora*) accumulations had disappeared from the deeper central basin of Peel Inlet by 1980, this area remained bare of seagrass until 1986, when *Halophila* reappeared. *Halophila* biomass increased substantially in 1987, and high biomass subsequently developed at three sites in the shallows of Peel Inlet in 1988, 1990 and 1994; this was attributed to conditions of high water clarity in these years (Lavery *et al.* 1995). However, stands of *Ruppia*, which occurred mainly in Austin Bay and Robert Bay, remained sparse. There were no seagrasses in the southern half of Harvey Estuary, and patches of *Halophila* in the northern half were extremely sparse and ephemeral.

Maps of seagrass distribution and estimates of total seagrass biomass were produced from the data collected between 1978 and 1994, but large errors are associated with them because of the extremely patchy nature of the seagrass stands. Seagrass biomass was not a major component of macrophyte (i.e. seagrass plus macroalgae) biomass in the PHES, although its importance was greater after winters of low run-off, and in the 1990s. The increased importance of seagrass in the 1990s may have been due to improved flushing of Peel Inlet following the dredging of the Sticks Channel (see also Section 1.1.2)

Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in a number of changes to the water column that would affect seagrasses. These were

- a less extreme salinity regime;
- maintenance of marine salinities for longer periods;
- improved water clarity, especially in spring and summer;
- increased tidal amplitude and frequency.

These changes to the water column were expected to result in the following effects on seagrasses:

- *Halophila ovalis* would expand its distribution throughout the PHES, including moving into deeper waters, providing macroalgal accumulations did not adversely affect its light supply;
- existing patches of *Zostera* and *Heterozostera* in and near the Mandurah Channel would expand;
- *Heterozostera* beds would establish near the entrance of the Dawesville Channel;
- stands of *Ruppia* would disappear from the shallow margins of the PHES that became regularly exposed due to increased tidal fluctuations (this would be most noticeable in Austin Bay and Robert Bay);
- *Ruppia* would move into deeper waters, particularly given the expected improvement in water clarity;
- in the long term, and if predicted changes in water quality occurred, the distribution and importance of seagrasses in the PHES would increase considerably (Lavery *et al.* 1995).

Observed effects of the Dawesville Channel

The pre-Dawesville Channel monitoring program for macroalgae and seagrasses continued after its opening (Wilson *et al.* 1995, 1996, 1997).

The present monitoring programme did not allow determination of the extent to which seagrass distribution changed in the PHES. However, appreciable seagrass biomass was consistently recorded at ten sites in Peel Inlet and northern Harvey Estuary, mostly in shallow waters. Stands of *Ruppia megacarpa* were still present in Austin Bay, but *Halophila ovalis* remained the dominant seagrass and generally attained higher biomass in summer and autumn than in pre-Dawesville Channel years of low to average rainfall, particularly in shallow-water sites in the northern half of Harvey Estuary. The presence of *Halophila ovalis* in deeper waters of the Estuary was also recorded for the first time, and *Heterozostera tasmanica* established near the entrance of the Dawesville Channel.

Status of the monitoring program

The present seagrass monitoring program is incorporated in the macroalgal sampling program, and as such it is carried out efficiently and reports are produced promptly. It provides useful data on seasonal changes in seagrass biomass at key sites, but was not intended for the purpose of providing accurate seagrass maps.

6.2.2 Fringing vegetation

Fringing vegetation plays an important role in the ecology of estuaries by supporting extensive food webs, acting as biological filters for waters discharging into the estuaries and providing habitats for waterbirds. In the PHES the fringing vegetation (often called salt marsh) occupies the upper part of the tidal zone from about mean water level to just above extreme high-water mark. The PHES has only three areas of extensive fringing vegetation: on either side of the Mandurah Channel (which includes the Creery wetlands), along the eastern side of Peel Inlet and around the Harvey delta. Only a narrow fringe of wetland exists elsewhere. Narrow fringing marshes also border the Serpentine River, including Goegrup Lake (McComb *et al.* 1995).

Salt marshes are usually typified by well-defined zones, each with its characteristic species composition. The two main factors influencing the distribution of salt marsh plants are usually the salinity of foreshore waters and the level of inundation by tidal and flood water. Groundwater expressions along the shores of an estuary can also affect zonation, particularly if it is of low salinity.

The most influential factor affecting salt marsh zonation is tide, which usually sets the upper and lower limits of the fringing vegetation. As the elevation of the marsh surface increases, the frequency of flooding tides decreases, and salt marsh is often divided into two zones: the lower (or intertidal) marsh, which is flooded almost daily, and the upper (or high) marsh, which is flooded irregularly (McComb *et al.* 1995).

In the lower marsh, frequent tidal immersion ensures a relatively constant soil salinity that rarely exceeds that of the flooding water. In the upper marsh there is greater variability in soil salinity, depending on climatic factors. In the PHES, winter rainfall can reduce soil salinities in the upper marsh, but in summer the evaporation of saline water left in elevated depressions when the tide recedes can result in extremely high soil salinities. The salinities of the overlying water and the soil water are dominant factors in determining the plant species present and their rate of growth (McComb *et al.* 1995).

Prior to the opening of the Dawesville Channel

A comprehensive study on the salt marshes of the PHES and the Serpentine River was carried out before the opening of the Dawesville Channel (McComb *et al.* 1995). It focused on the use of aerial photographs combined with ground truthing to document the changes in salt marsh area and continuity of cover from 1957 to 1994, and ten sites around the estuary were also selected for detailed studies on zonation of salt marsh communities.

The comprehensive analysis of aerial photography revealed that the salt marshes of the PHES were extremely dynamic and variable between 1957 and 1994. The general trends for the whole study area were:

- a significant loss of salt marsh area between 1965 and 1986, with a rapid decline between 1965 and 1977 (due to permanent breaching of the Mandurah Channel)followed by a slower rate of loss between 1977 and 1986 (due to human disturbance);
- an arrest in the loss of salt marsh area between 1986 and 1996.

Exceptions to the general trends were the Harvey delta and Austin Bay areas, which showed steady increases in salt marsh cover between 1977 and 1994, and the Lakes area (including Goegrup Lake) which showed a marked decline in area between 1986 and 1994. The rate of loss in the Lakes area also appeared to be increasing, but its cause was not clear.

The main *qualitative* change was a continuing decline in the cover continuity of the Creery wetlands since 1957. The Creery wetlands is the largest single area of salt marsh in the PHES, and clearly showed increasing damage from human contact, particularly in the form of vehicle tracks.

The saltmarsh zonation sites studied varied from steep narrow fringes to long flat expanses. Three plant complexes, subdivided into twenty communities, were identified: *Sarcocornia* complex (nine communities), *Juncus* complex (six) and *Halosarcia* complex (five) . The *Sarcocornia* complex dominated the lower marsh while the *Juncus* and *Halosarcia* complexes were found in the upper marsh. There were two major sequences in which the complexes were arranged. These were, in order from the water's edge to higher ground:

- bare ground > *Sarcocornia* complex > *Juncus* complex;
- bare ground > *Sarcocornia* complex > *Halosarcia* complex.

The communities of the *Sarcocornia* complex were widely distributed in the PHES, and were dominated by the samphire *Sarcocornia quinqueflora*. Other common species in the *Sarcocornia* complex included the sedge *Bolboshoenus caldwellii* (which sometimes occurred as almost small, almost pure stands at the water's edge), *Suaeda australis, Halosarcia* species, *Atriplex* species and *Frankenia pauciflora*. The *Juncus* complex was dominated by the rush *Juncus kraussii*, and was found in the upper marsh or close to the water's edge in brackish areas such as in the Serpentine River. Other species common in the *Juncus* complex included *Sarcocornia quinqueflora, Bolboshoenus caldwellii, Suaeda australis* and *Atriplex hypoleuca*. The *Halosarcia* complex was dominated by *Halosarcia halocnemoides*, and was found in the upper marsh where hypersaline conditions were experienced in summer but nearly freshwater conditions in winter. Other species in the *Halosarcia* complex included *Halosarcia indica* subspecies *bidens, Halosarcia indica subspecies leiostachya* and *Sarcocornia quinqueflora. Halosarcia indica* subspecies *leiostachya* was only found in the Creery wetlands, and does not appear to have been mentioned in other studies on Western Australian salt marshes.

The distribution of the saltmarsh vegetation appeared to be related to the percentage of tidal inundation in the year. The *Halosarcia* complex generally dominated in areas that were tidally inundated for less than 5% of the year, and the *Sarcocornia* complex in areas inundated for at least 10% of the year. The *Juncus* complex occurred in areas inundated for more than 10(50% of the year in riverine areas (where water salinities were lower), but was also found in less inundated areas in Harvey Estuary. These zonation patterns were not, however, consistent between sites, suggesting that other factors were involved, such as gradient, groundwater expressions, soil composition and nutrient availability.

Predicted effects of the Dawesville Channel

The percentage distributions of tidal inundations were predicted to change slightly with the opening of the Dawesville Channel. Modelling results indicated that elevations previously inundated for 5%, 10%, 30% and 50% of the year would change to 8%, 14%, 31% and 51% respectively (Ryan 1993). In those areas where the salt marsh experienced tidal inundation for 5% of the year, the frequency of one-hour inundations was expected to increase from 3 to 21 times a year in Peel Inlet, and from 2 to 22 times a year in Harvey Estuary. The frequency of ten-hour inundations, which occurred on an average of 2.5 times a year in Peel Inlet and once a year in Harvey Estuary, was expected to increase to four times a year in both water bodies.

The slight increase in inundation was expected to have little effect on the lower salt marsh, the majority of which was already inundated regularly for most of the year. The *Sarcocornia* species that dominate the lower marsh are furthermore very resilient, and were unlikely to be adversely affected by increased tidal energy. With regular inundation predicted to occur at slightly higher elevations, it was also predicted that the *Sarcocornia* complex would extend its distribution landwards, and this would be noticeable over a wider area in the flatter marshes. There was also the possibility that these species would be adversely affected by increased macroalgal smothering, due to increased tidal range and frequency, until macroalgal populations declined (McComb *et al.* 1995).

The higher water levels were expected to result in a landwards extension of the salt marsh. Seed dispersion would be aided, and the *Juncus* complex was expected to increase in extent on the landward edge of the marsh in Harvey Estuary. The higher winter salinities were not expected to affect Juncus in the Serpentine River, but there was the possibility that the increased water level, and increased erosion, would reduce its extent at the water's edge (McComb *et al.* 1995).

Although the *Sarcocornia* complex was expected to extend further landwards, the nearshore edge of the *Halosarcia* complex in the upper marsh was expected to recede. The less harsh conditions in the upper marsh due to more frequent inundation were also expected to result in other saltmarsh plants invading areas of *Halosarcia* complex, and/or for the less salt tolerant *Halosarcia indica* subspecies *bidens* to become more prominent in areas previously dominated by *Halosarcia halocnemoides* and *Halosarcia indica* subspecies *leiostachya*. If, however, the rise in water level and inundation frequency only produced a small change in the high summer salinities in areas occupied by *Halosarcia* complex, other species with lower salt tolerance might still be excluded, and the only change might be an increase in the size and vigour of Halosarcia bushes. Due to the extreme salinities they experience, *Halosarcia* bushes fringing the PHES are stunted compared to those in other salt marshes (McComb *et al.* 1995).

In addition to the changes in the extent of the three major saltmarsh complexes, the different species — and therefore communities — were expected to undergo different changes. For example, germination of *Bolboshoenus caldwellii* might be inhibited by higher winter salinities, germination of *Atriplex* seeds is reduced by saline conditions and inundation, while *Suaeda australis* tends to occur in areas of higher organic debris (mainly macroalgae) — which might lessen if macroalgal populations declined. The community distribution in the salt marshes of the PHES was therefore also expected to change. These changes were expected to occur gradually (over 5-20 years), although the invasion of quick-growing species, including introduced species such as *Watsonia bulbifera* and *Carpobrotus edulis*, was likely to be evident in 1-3 years (McComb *et al.* 1995).

Observed effects of the Dawesville Channel

There was no follow-up monitoring of seven of the ten samphire transects established just before the Dawesville Channel opened; afterwards, the Department of Conservation and Land Management (CALM) undertook fringing vegetation surveys, which had three components:

- Monitoring of samphires at 12 transects around the PHES on CALM land (Figure 1). These transects were established between October and December 1994, and were revisited at the same time each year. Three of them resampled transects established just before the Channel opened (Austin Bay B, North Kooljerrenup A and South Kooljerrenup A).
- Monitoring of seasonal freshwater wetlands in the Austin Bay Nature Reserve in late spring. Two transects were established to monitor rare freshwater aquatic plants in areas that were thought might be susceptible to ingress of salt water during storm surges.
- Monitoring of riverine vegetation, tree health and *Typha* patch dynamics along the lower 4 km of the Harvey River. Riverine vegetation was monitored along the eastern side of the River at transects established every 500m, to detect any changes due to the expected increased penetration of the saltwater wedge. Tree species also appear to segregate along the lower Harvey River in response to salinity, the three main species being, in order of decreasing salinity tolerance, *Melaleuca rhaphiophylla, Casuarina obesa* and *Eucalyptus rudis*. The 'health' of each tree species was gauged by tagging 30 individuals at the upper and lower end of their range along the river, and measuring various parameters such as tree girth (once a year), % live canopy and canopy colour (twice a year, usually spring and late autumn/early winter). The effect of anticipated salinity increases on the number, size and condition of *Typha* patches was also monitored in November 1994, November 1995 and May and November 1996.

The findings of the monitoring program are reported by Gibson (1997), and are briefly outlined below.

The data from monitoring of the samphire transects may be summarised as follows:

- transects at Creery Island changed little apart from an increase in mud cover at transect A from 0% to 11.5% and a decrease in *Triglochin mucronata* from 27% to 11%;
- transects at Carraburmup changed little;
- at Austin Bay, transect A had a decrease in algal mat cover (from 31% to 23%) and increase in mud cover (from 0 to 10%), while transect B had an increase in algal cover (from 13.6% to 23.6%) and a slight increase in *H. halocnemoides*;

- both transects at Mealup showed marked changes in profile, with erosion of the seaward edge; there were also decreases in the cover of mud (from 27-30% in 1994 to 0% in 1995) with corresponding increases in sand cover, slight decreases in *J. kraussii* cover and, in the case of transect A, a slight increase in *S. quinqueflora* cover;
- the North Kooljerrenup profiles changed little, but at transect A there were decreases in cover of *S. quinqueflora* (41% to 30%) and *J. kraussii* (21% to 7%) and increased cover of algal mat (7% to 20%) and sand (0.6% to 19.5%), while at transect B there were decreases in *J. kraussii* (22% to 7%) and *S. australis* (20% to 6%) and increased mud cover (0% to 15%);
- at South Kooljerrenup transect A there was an increase in mud cover (from 0 to 16.5%) but a decrease in algal cover (from 14% to 0.7%) and a slight increase in *Bolboschoenus caldwellii* cover, whereas transect B had an increase in *S. quinqueflora* cover (61% to 70%) and a decrease in *Atriplex prostata* cover (9.4% to 0.8%).

The above data did not indicate any consistent pattern in changes in species cover from 1994 to 1995, and although there were large decreases in algal mats at some sites and large increases at others, the response of samphires to the algal cover was variable.

The historical review of aerial photography described by McComb *et al.* (1995) indicated that there have been steady increases in saltmarsh cover at Austin Bay and the Harvey delta since 1977, and the data obtained in post-Channel monitoring were consistent with this finding. No detailed comparison was made with data from the three transects collected immediately before the opening of the Channel, but preliminary analysis showed no significant difference between these and the more detailed data collected six months later.

Monitoring of seasonal freshwater wetlands in the Austin Bay Nature Reserve found little change other than that consistent with year-to-year variations in environmental conditions. There was no evidence of saltwater intrusion.

Monitoring of the riverine transects showed moderate increases in cover of *Melaleuca rhaphiophylla* (0 km transect), *Casuarina obesa* (1 km transect) and *Eucalyptus rudis* (2 km transect). The tree health study also showed some unexpected results, with maximum growth occurring at the downstream population (contrary to the expected influence of any increase in salinity). The *Melaleuca rhaphiophylla* canopies at the downstream site showed obvious signs of stress (i.e. a yellowing canopy) after the summer of 1994/95, but these recovered to a healthy green by November 1995. It was not possible to determine if this seasonal fluctuation in canopy condition had resulted from the opening of the Dawesville Channel, as no pre-Channel data were available, but overall canopy condition of the marked *Melaleuca rhaphiophylla* trees did not change significantly. The data on *Typha* patch dynamics also did not indicate declines due to increased salinity: a general decline in number and size of patches from November 1994 to May 1995 was followed by an increase in the number and condition of patches to November 1996.

Gibson (1997) concluded that the results did little other than emphasise the dynamic and variable nature of fringing vegetation: the data did not indicate any clear effect attributable to the Dawesville Channel, but clear trends may take several more years to emerge. Gibson (1997) also strongly emphasised the difficulty in differentiating the influence of the Dawesville Channel on fringing vegetation from other environmental factors due to the lack of baseline (pre-Channel) data. Inter-annual changes in river flow are of obvious importance, and the sea-level changes brought about by the presence/absence of El Nino Southern Oscillation (ENSO) events also cause changes in saltmarsh inundation patterns, which in turn have a marked effect on saltmarsh mosquito populations in the PHES (see Appendix 8).

In addition to the CALM monitoring programme, a study was undertaken using airborne Digital Multi-Spectral Video (DMSV) to map the peripheral vegetation of the PHES and Serpentine and Murray Rivers (Glasson *et al.* 1996).

Remote sensing techniques provide a means to cover large areas using a vegetation classification that can be applied consistently, and therefore were potentially useful for the documentation and analysis of changes to fringing vegetation since the opening of the Dawesville Channel. The study of Glasson *et al.* (1996) provided useful data, but considerable technical problems were experienced. The DMSV produced massive data sets that were difficult to store and manipulate, and mosaicing of images to complete a composite scene was extremely time-consuming. Glasson *et al.* (1996) concluded that DMSV was unsuitable for rapid data classification and quantitative analysis where large areas of land cover are involved, and that satellite data (e.g. from SPOT: Systeme Probatoire de Observation de la Terre) may prove a better option. It was also concluded that DMSV methodology would require considerable further refinement before it was suitable for routine monitoring, and that it was best suited for a 'sampling' role for broad land-cover assessment, rather than detailed large-scale mapping.

Status of the monitoring program

Monitoring of the CALM transects is ongoing. It is carried out once a year, in late spring/early summer.

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Dawesville Channel
Technical Review

APPENDIX 7

ESTUARINE FAUNA

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

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WATER AND RIVERS
COMMISSION

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7. Estuarine Fauna

7.1 Invertebrates

The invertebrate community of estuaries includes zooplankton (microscopic to small animals that live suspended in the water column) and benthic invertebrates (small animals that live on or in estuarine sediments).

Zooplankton feed on phytoplankton, detritus and other zooplankton, and zooplankton communities in Australian estuaries tend to be dominated by a few species of calanoid copepods that tolerate a broad range of salinities (Rose 1994 and references cited therein). Estuarine zooplankton are capable of extremely rapid rates of growth and reproduction. Although most species have broad salinity tolerances, different species have different optimal conditions for growth and reproduction, and as with phytoplankton, this results in different species dominating zooplankton communities in different parts of the estuary at different times of the year (Day 1981). The distribution patterns of zooplankton are often linked to phytoplankton distribution patterns, as many species of zooplankton feed on phytoplankton.

The distribution and abundance of benthic invertebrates are also influenced by salinity fluctuations and therefore undergo pronounced seasonal and annual changes, but other factors such as sediment type and the presence of macrophytes (seagrasses and macroalgae) also have a strong influence. Like zooplankton, benthic invertebrate communities in Australian estuaries tend to be dominated by a few species of organisms that tolerate a broad range of salinities, but the dominant organisms cover a broader range of taxa, the main ones being polychaete worms, crustaceans (mainly amphipods) and molluscs.

7.1.1 Zooplankton

Zooplankton communities in Australian estuaries are often dominated by copepods of the genera *Sulcanus* and *Gladioferens* (Bayley 1975). In southwestern Australian estuaries *Gladioferens imparipes* is a euryhaline herbivore that commonly develops dense populations after the cessation of winter run-off, in response to the high phytoplankton levels fuelled by run-off nutrient inputs. The omnivorous species *Sulcanus conflictus* is also common, but is restricted to waters where salinities are between 4 and 25 ppt, whereas *Gladioferens imparipes* can tolerate marine salinities (Rose 1994).

Prior to the opening of the Dawesville Channel

Quantitative studies of the zooplankton of the PHES prior to the opening of the Dawesville Channel were carried out by Rippingdale (1977), Lukatelich (1987) and Rose (1994). Rippingdale (1977) and Lukatelich (1987) found that calanoid copepods, particularly *Gladioferens imparipes, Arcartia* species and *Sulcanus conflictus*, comprised over 80% of zooplankton abundance in the 1970s and early 1980s. In contrast, a survey in the late 1980s by Rose (1994) found that copepods contributed less than 7% of zooplankton abundance and that amphipods and nematodes contributed substantially. Rose (1994) also noted a high proportion of benthic organisms and tychoplankton (organisms that spend part of the 24-hour day associated with the benthos) in the zooplankton community. Rose (1994) suggested that distinctions between planktonic and benthic organisms might be blurred in shallow estuarine waters due to the suspension of benthic organisms by wind-generated turbulence and the reproductive and vertical migratory behaviour of some juvenile and adult benthic organisms.

Rose (1994) found that zooplankton abundance peaked in autumn and winter (rather than spring and summer, as in most other southwestern Australian estuaries), and attributed this to the deleterious effects of *Nodularia* between spring and summer. Large increases in amphipods and harpacticoids in autumn were also related to increased growth of macroalgae, and therefore increased habitat for these organisms. Rose (1994) concluded that the decline in the abundance of copepods during the 1980s was due to the harmful effects on the benthic resting stages of these organisms caused by low dissolved oxygen levels and gases and exudates produced by *Nodularia*. Rose (1994) also attributed an apparent increase in the abundance of amphipods and nematodes to the ability of these small, mobile, short-lived and highly fecund organisms to opportunistically recolonise areas affected by *Nodularia* blooms or macroalgal accumulations.

Predicted effects of the Dawesville Channel

The predicted absence of *Nodularia* and decreased periods of deoxygenation of the water column were expected to result in conditions more favourable to copepods, particularly the more marine species such as *Arcartia*. Increased recruitment of marine species through the Dawesville Channel was also expected. Amphipods and nematodes were considered likely to remain important components of the zooplankton, particularly in the short term if macroalgal accumulations remained large. Overall species diversity was expected to increase due to the more stable salinity regime, the absence of *Nodularia* and the decreased frequency and duration of anoxic periods. The opening of the Channel was also expected to result in a greater variety of food sources for zooplankton, which did not appear to graze *Nodularia*.

Observed effects of the Dawesville Channel

As far as the authors of this report are aware, no data on zooplankton communities have been collected since the opening of the Dawesville Channel.

Status of the monitoring program

Zooplankton communities were not monitored in the Dawesville Channel Monitoring Program.

7.1.2 Benthic invertebrates

The abundance and diversity of benthic fauna in estuaries typically undergo pronounced temporal and spatial changes. Seasonal and annual changes in benthic fauna communities are largely due to the changing influence of marine waters and river flow, while spatial patterns reflect gradients in dissolved oxygen, sediment type, depth (and therefore wave energy) and salinity (Day 1981). The abundance and diversity of these fauna are also usually far greater in seagrass beds and macroalgal accumulations than in adjacent unvegetated areas, and this is attributed to a combination of greater habitat complexity (and therefore more ecological niches to exploit), greater protection from predators, calmer conditions (due to the wave- baffling effect of dense macrophyte stands) and a more abundant food supply (Day 1981).

Prior to the opening of the Dawesville Channel

Most research on the benthic communities of the PHES prior to the opening of the Dawesville Channel were qualitative, taxonomic or physiological studies that were reported in unpublished theses or technical reports. The only quantitative seasonal data were obtained by Rose (1994), who studied the diversity, abundance and biomass of shallow water benthic invertebrate communities at Boodalan Island, Falcon Sticks, Dawesville and Point Grey. He noted that the benthic invertebrate communities of the PHES were affected by three main factors:

- the extreme salinity regime;
- wind-mixing and turbulence in the shallows, which could 'reset' the benthic community if sediments were scoured and also affected larval settlement of benthic organisms;
- excessive nutrient enrichment, which had led to a cycle of diatom blooms, *Nodularia* blooms and macroalgal growth, and the production of large amounts of detritus and associated conditions of anoxia and hydrogen sulphide production when these plants senesced.

Rose (1994) found that, compared to the nearby Swan/Canning Estuary (which has a slightly less extreme salinity regime, and is also subject to wind-mixing in the shallows), the benthic community of the PHES had higher densities of a few species of small, short-lived, fast-maturing organisms that produced large numbers of offspring. The dominant organisms were small polychaete worms (particularly *Capitella capitata*), amphipods (e.g. *Corophium minor, Tanais dulongi, Tethygenia elanora, Melita zeylanica*) and the small bivalve mollusc *Arthritica semen*. Some of these species were capable of continuously supplying propagules to the water column throughout the year, or of selectively releasing their young during favourable environmental conditions.

Although the PHES had higher *densities* of benthic invertebrates than in the Swan/Canning Estuary, its total benthic invertebrate *biomass*, and the biomass of molluscs in particular, were much lower, because the dominant species were small. The Swan/Canning Estuary had greater species diversity, and greater numbers of larger, longer living bivalve molluscs (e.g. *Xenostrobus securis* and *Sanguinolaria biradiata*) and polychaete worms (e.g. *Marphysa sanguinea* and *Leitoscoloplos normalis*). Rose (1994) also noted that the small gastropod mollusc *Hydrococcus brazieri*, which used to be the greatest contributor to benthic invertebrate density and biomass in the middle regions of the PHES in the 1970s, was no longer present.

Rose (1994) found that peaks in density and biomass of benthic fauna in the PHES occurred in autumn and winter, compared to spring and summer in the Swan/Canning Estuary. The fauna were severely stressed during *Nodularia* blooms and the subsequent periods of anoxia (sometimes to the extent of mass mortalities occurring), indicating that eutrophication had modified or suppressed increases in the density and biomass of benthic fauna during spring and summer despite otherwise favourable conditions of increasing salinity, temperature and particulate organic matter.

The dominance of benthic fauna by high numbers of a few species of small, fast-growing and extremely fecund organisms (particularly the polychaete *Capitella capitata*) was a classic symptom of eutrophication (Pearson & Rosenburg 1978). The organisms that dominated the PHES also had reproductive strategies and larval dispersal mechanisms that enabled them to rapidly colonise areas denuded by periods of anoxia. The success of the dominant amphipods was also related to their ability to exploit the extra habitat complexity and food afforded by large accumulations of macroalgae.

There were less data on the intertidal benthic fauna of the PHES. McComb *et al.* (1995) found that invertebrate abundance and species richness were generally greater in the lower intertidal areas due to the more regular inundation, whereas the irregular flooding of the higher intertidal areas, coupled with drying out and hypersaline conditions in summer, created a severe environment with low abundance and species richness. The lower intertidal areas were dominated by isopods, amphipods, copepods, oligochaete worms and *Arthritica semen*, abundance and species richness peaking in winter.

Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to allow increased recruitment of marine organisms into the PHES throughout the year, while the more marine salinity regime would enable these species to compete more effectively against euryhaline species. Brackish and freshwater species were expected to retreat further upstream in the rivers.

As for the zooplankton communities, the overall species diversity of the benthic invertebrate community was expected to increase due to the more stable salinity regime, the absence of *Nodularia* and the decreased frequency and duration of anoxic periods. There was also the possibility that total invertebrate biomass would be higher. Although the dominant organisms were considered likely to remain important (particularly in the short term if macroalgal accumulations remained large), the return was predicted of the larger, longer lived species of polychaete worms and bivalve molluscs that were typical of adjacent, less eutrophic estuaries such as Leschenault Inlet and the lower reaches of the Swan/Canning Estuary.

The increased tidal range was expected to inundate areas previously exposed and expose areas previously inundated, while inundation of the intertidal zone would be more frequent, thereby creating a less extreme environment, particularly in summer. Thus, the opening of the Dawesville Channel would result in the loss of a small proportion of subtidal habitat, a larger area of intertidal habitat would be created and a greater proportion of the intertidal habitat would have less extreme conditions and therefore greater invertebrate abundance and species richness (PIMA 1994).

Observed effects of the Dawesville Channel

Post-Channel sampling of shallow water benthic fauna was carried out by the WRC once a year (in summer) at three sites along the western side of the PHES (Dawesville, Island Point and Cox Bay). Although data have not been fully processed, initial impressions were that the dominance of *Capitella capitata* had decreased, and the abundance of larger, longer lived worms such as *Ceratonereis* species and *Leitoscoloplos normalis* had increased. Large numbers of Arthritica semen were also observed in northern Peel Inlet (Rose, *pers. comm.*).

Status of the monitoring program

Sampling of benthic invertebrate fauna is not a formal component of the Dawesville Channel Monitoring Program. Current sampling is carried out only once a year (in summer) as part of a program with high school students, and the data produced — although useful — are not scientifically rigorous.

Invertebrate community composition is a widely accepted indicator of environmental health (Warwick 1993), and the current level of invertebrate community sampling in the PHES is low compared to that of many interstate and overseas studies on the environmental health of estuaries and coastal waters (Warwick 1993; CSIRO 1996). Indices such as the Abundance Biomass Comparison (ABC) index proposed by Warwick (1986) are particularly useful for gauging the degree of environmental disturbance in an ecosystem. The use of the ABC index is based on the assumption that, in the undisturbed state, biomass is dominated by species large in biomass but few in number, and abundance is dominated by small species, whereas, in the severely disturbed state, communities become numerically dominated by a limited number of species which are characterised by very small individuals. Individual species of benthic invertebrates can also be useful indicators of environmental health, thereby providing a simple and effective management tool.

The role of benthic invertebrate sampling in the Dawesville Channel monitoring program needs reappraisal. Benthic invertebrates can provide an integrated measure of environmental health, and their potential use as a management tool should be investigated.

7.2 Vertebrates

Fish and birds are the most conspicuous components (to humans) of the vertebrate fauna of estuaries. Estuaries typically have sheltered conditions and large numbers of invertebrate fauna, which are favoured food items for many fish and bird species (Day 1981). Estuaries therefore often support valuable fisheries, and they are important breeding and feeding grounds for waterbirds.

Estuarine fish communities constitute three main groups, as follows:

- euryhaline species that spend their entire life cycle in estuaries (e.g. black bream, yellowtail trumpeter and school prawns);
- marine species that enter estuaries as juveniles and mature there during periods of high salinity (e.g. crabs, king prawns, yellow-eye mullet, cobbler, whiting, mulloway and tailor);
- marine species that enter estuaries occasionally and usually in low numbers and when salinities are essentially marine (e.g. the western school whiting).

The fish community in an estuary is therefore considerably influenced by spatial and temporal variations in salinity.

Estuarine waterbird communities also vary considerably throughout the year. Resident species are present all year round, whereas migratory species are present for only part of the year — mainly spring and summer in southwestern Australian estuaries (Wykes 1990).

7.2.1 Fisheries

The PHES is the most important commercial estuarine fishery (by weight of catch) in Western Australia, and is also heavily utilised for recreational fishing. It is noted that although commercially important crustaceans such as large prawns and crabs are not vertebrates, they are always included in fisheries data on commercial and recreational 'fish' catches. In the following discussion, the term 'fish' is used in the fisheries sense.

Prior to the opening of the Dawesville Channel

Approximately 60 fish species were documented as occurring in the PHES before the opening of the Channel, the majority of which were marine species that entered the system as juveniles. Prior to the opening of the Dawesville Channel species richness was generally highest during the summer months, when marine salinities prevailed and juveniles were recruited into the estuary (Kinhill Engineers 1988).

The bulk of the commercial catch was made up of five species (Steckis 1991): yellow-eye mullet (*Aldrichetta forsteri*), sea mullet (*Mugil cephalus*), western king prawn (*Penaeus latisulcatus*), blue manna crab (Portunus pelagicus) and cobbler (*Cnidoglanis macrocephalus*). Recreationally important species included blue manna crab, king prawns, cobbler, whiting (*Sillaginodes punctata*) and tailor (*Pomatomus saltator*).

The two algal symptoms of eutrophication in the PHES appeared to affect the fisheries differently. The macroalgal accumulations were strongly associated with an increase in fish catches, particularly in the 1970s. Steckis (1991) attributed the high abundance of sea mullet, cobbler and yellow-eye mullet to the abundance of macroalgae, which provided both shelter from predators and an abundant supply of food (i.e. benthic invertebrates). However, the blooms of *Nodularia* that became regular in the 1980s appeared to be less beneficial.

Benthic fish and crabs were believed to be adversely affected by *Nodularia* blooms, and many fish species avoided bloom-affected areas (Lenanton *et al.* 1985). There was also evidence to suggest that species richness was lower during those summers that had intense *Nodularia* blooms, while the anoxic conditions associated with them caused fish kills (Hesp *et al.*, in preparation). *Nodularia* also had a major effect on fishing activities in the PHES: haul netting was the preferred fishing technique of commercial fishermen, but was precluded during intense *Nodularia* blooms because it relies on visual detection of fish schools. Commercial fishermen also concentrated their activity in Peel Inlet rather than Harvey Estuary because they were convinced that there were less fish in bloom-affected areas.

Analysis of commercial catch per unit effort (CPUE) for the period 1984 to 1989 carried out by Steckis (1991) indicated that the abundance of the three most important fin fish was relatively stable despite the occurrence of *Nodularia* blooms. Although the presence of *Nodularia* was correlated with reduced abundance of sea mullet and cobbler (but not yellow-eye mullet), Steckis (1991) concluded that the outbreaks of *Nodularia* were both localised (i.e. the most dense accumulations were usually confined to parts of Harvey Estuary) and highly seasonal, and did not appear to affect fish abundance in the PHES as a whole.

The populations of prawns and crabs were more cyclical in nature, which was possibly at least partly due to changes in local coastal waters affecting spawning and recruitment to the PHES. Crabs were more abundant in years without *Nodularia* blooms, but interpretation of causes was confounded by the fact that years without *Nodularia* blooms were characterised by lower river input and therefore higher salinities, and crabs prefer salinities above 30 ppt. The western king prawn, however, appeared to be adversely affected by accumulations of the macroalgae *Cladophora* and *Ulva*, possibly because these covered the substrate into which juvenile prawns burrowed (Potter *et al.* 1991).

Predicted effects of the Dawesville Channel

The Dawesville Channel would provide another route for recruitment of fish from the ocean. This factor, along with a more marine salinity regime, was expected to result in an increase in recruitment and therefore greater contribution to the fish communities of those species which mature or only occur at marine salinities. Estuarine species were not expected to be greatly affected, because they tolerate a broad range of salinities. However, the more stable salinity regime was expected to impact negatively on the juveniles of sea mullet, which prefer low salinity conditions. It was thereforepredicted that there would also be fewer adult sea mullet in the system.

The improved water quality and the absence of *Nodularia* blooms were expected to be beneficial to fish communities, particularly to benthic fish and crabs, and the reduced frequency and duration of anoxic conditions were expected to result in fewer fish kills. Higher salinities were also expected to benefit crabs. However, the distribution pattern of the western king prawn indicated that it was correlated with slightly hypersaline conditions, and there was the possibility that improved flushing following the opening of the Channel would reduce the occurrence of hypersaline conditions and therefore make the PHES less attractive to this species. It is now known that the occurrence of western king prawns in slightly hypersaline areas was coincidental rather than a deliberate choice. School prawns (*Metapenaeus dalli*), which moved into the Murray River to breed in the summer months, were not expected to be adversely affected by estuarine salinity changes. The effect of anticipated changes in water movement was unknown.

The effect of changes in macrophyte abundance on fish communities was also uncertain. The distribution pattern and densities of macroalgae and seagrass were expected to change, possibly from a macroalgal-dominated system to a seagrass-dominated system in the long term, but the PHES was still expected to be characterised by extensive macrophyte stands (see Appendix 6). The amount of detritus available to the food webs was therefore expected to remain considerable. The research of Steckis (1991) on southwestern Australian estuaries indicated that fish abundance was correlated with macrophyte abundance, regardless of whether the macrophytes were predominantly seagrass or predominantly macroalgae. An exception to this rule was the western king prawn, which appeared to be adversely affected by overlying benthic macroalgal accumulations (Potter *et al.* 1991).

Potentially adverse effects on the fish community that were identified included the more regular tidal exposure of shallow feeding areas (which might not favour certain fish, crabs and prawns), increased fishing pressure as the PHES became more recreationally attractive due to improved water quality and increased mortality of benthic species such as crabs and cobbler due to increased levels of macroalgal harvesting (particularly juvenile fish and crabs caught up in harvested macroalgae).

Observed effects of the Dawesville Channel

Post-Channel monitoring of fisheries in the PHES was carried out as a collaborative effort between Murdoch University and the Fisheries Department of Western Australia (DoF), and the sampling sites for fish, prawns and crabs are shown in Figure 1. The post-Channel (1995-98) sampling program was based on the sites, sampling frequency and sampling methodology used in a pre-Channel sampling program carried out from 1979 to 1981. The following information is based on an unpublished summary report provided by Murdoch University and the DoF, an unpublished Fisheries Research Development Council (FRDC) grant milestone report and the Fisheries Department's Creel Survey of recreational fishing of Western Australian salmon and Australian herring in coastal waters (Ayvazian *et al.* 1997) and recreational catch and effort data for the PHES (unpublished data).

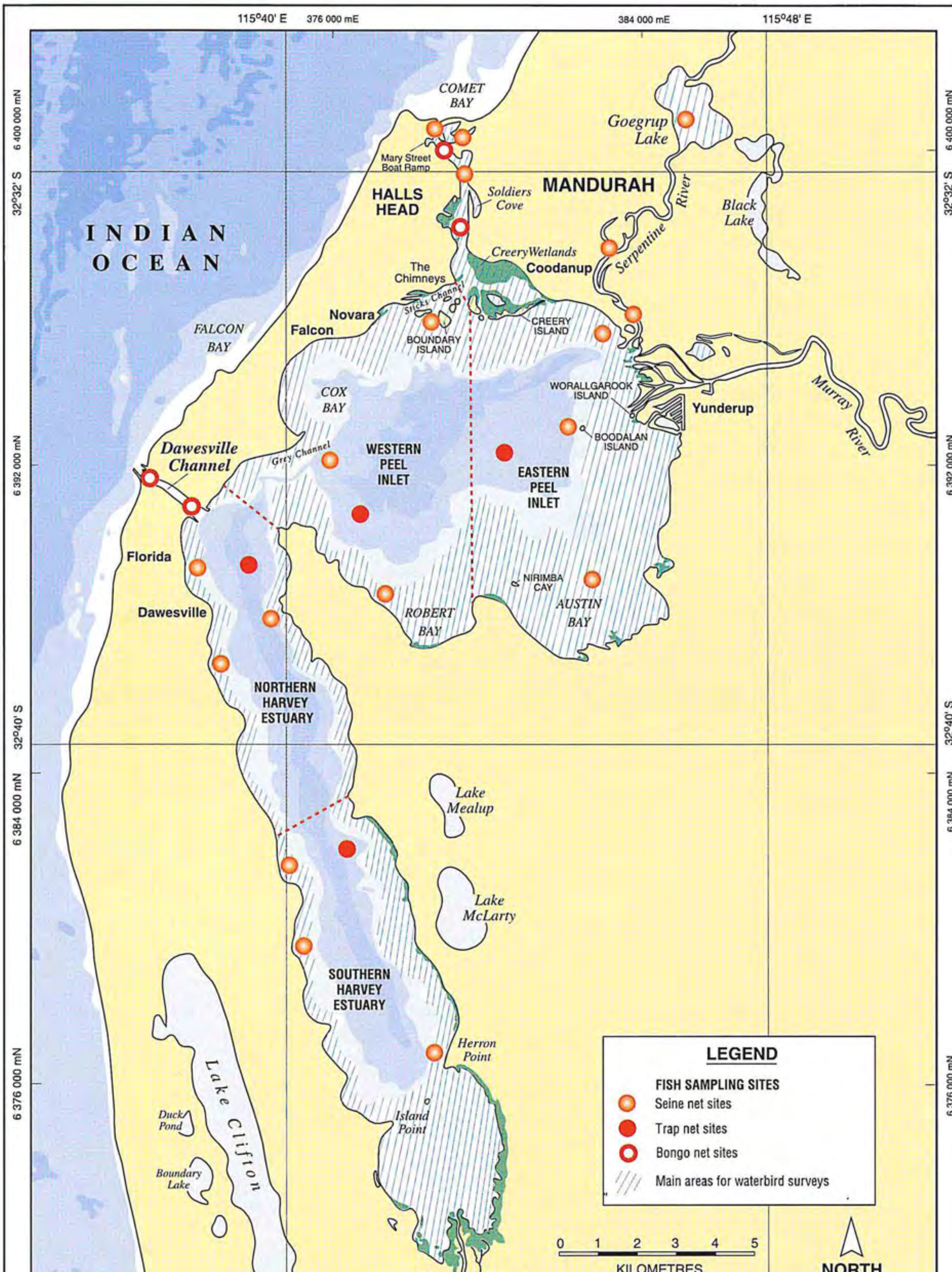
Data indicated that the opening of the Dawesville Channel resulted in a far earlier recruitment of juvenile western king prawns and juvenile crabs into Harvey Estuary, and their retention for a far longer period, presumably due to the maintenance of marine salinities for longer periods. In contrast to the pre-Channel situation, western king prawns were found in all months in the northern Harvey Estuary and in many months in southern Harvey Estuary.

The maximum densities of prawns and crabs in Harvey Estuary were far higher compared to data from pre-Channel years. Prawns and crabs also left Peel Inlet at a smaller size than before the opening of the Channel, which was a completely unpredicted event. This latter effect may simply be because the Dawesville Channel allowed a much more rapid return to the ocean. For the same reason, smaller crabs and prawns entered the Estuary earlier than in pre-Dawesville years, as prior to the opening of the Channel they had a far longer journey (taking up to several months) to reach the Estuary, by which time they had grown considerably. Analysis of prawn carapace width also showed that after the opening of the Channel the recruitment of prawns from different spawning periods occurred in 'bursts' at different times of the year.

Comparison of post-Channel (1996-97) fish data with available pre-Channel (1979-81) data was complicated by average freshwater discharge in the winter of 1996, which resulted in a protracted period of low salinities from May to September in 1996 compared to conditions of low freshwater discharge in 1979-81. Although it was not possible to fully gauge the impact of the Dawesville Channel, it appeared that marine species such as whitebait (*Hyperlophus vittata*) and blowfish (*Torquigener pleurogramma*) were far more abundant (8.3% of the catch in 1979-81 and 54.4% in 1996-97), whereas the six-lined trumpeter (*Pelates sexlineatus*) and gobbleguts (*Apogon rueppellii*) were far less abundant (57.1% of the catch in 1979-81 and 5.2% in 1996-97). *Pelates sexlineatus* feeds on macroalgae, and *Apogon rueppellii* is an estuarine spawning species that is typically most abundant in dense macrophyte stands (Loneragan *et al.* 1986). The decline in abundance of *Pelates sexlineatus* and *Apogon rueppellii* may have been caused by the disappearance of dense *Cladophora* stands from Peel Inlet by the early 1980s rather than effects brought about by the construction of the Dawesville Channel.

The mean numbers of fish species and mean density of fish per sample for 1996-97 are compared with data for 1979-81 in Figure 7.1. The figures for 1996-97 in Peel Inlet and northern Harvey Estuary were lower compared to 1979-81, but higher in the southern half of the Estuary (Figure 7.1a). Mean density of fish per sample in the Inlet was lower in 1996-97 compared to 1979-81, similar in the northern part of the Estuary and higher in the southern part (Figure 7.1b). The lower numbers of species and fish densities in Peel Inlet were probably due to the reduction of macroalgal levels in that part of the PHES, but it was clear that marine species of fish were penetrating far more into the southern Harvey Estuary. Fish species richness and density were highest in the Mandurah Channel in both pre- and post-Dawesville sampling periods, but spatial differences in fish densities within the Peel Inlet and Harvey Estuary were far less in 1996-97. The proportion of marine fish species in the PHES was also greater in 1996-97 than in 1979-81.

It is also noted that the level of harvesting of macroalgal accumulations was far lower in the summers of 1994/95 and 1995/96 than in pre-Channel years (see Appendix 8),



FROGGRAPHICS DAL-DAW 16/2/98

	Water and Rivers Commission **Dawesville Channel Monitoring Programme** **Two Year Technical Review** **LOCATION OF FISH AND WATERBIRD SAMPLING SITES**	Figure **1**
Auth: KH/BH · Date: 2/98		

and therefore the attendant mortality of benthic fish and crabs should also have decreased.

Catch per unit effort (CPUE) data from the commercial fishery provided further evidence that crabs continued to be abundant in the PHES, but the western king prawn catch, based on beamtide trawling in the Mandurah Channel, declined dramatically. Murdoch University research established that juvenile western king prawns were still using the PHES extensively, and CPUE data from the Comet Bay fishery show little change in the abundance of adult prawn stock in coastal waters adjacent to the Table 1). It was therefore hypothesised that a considerable proportion of the prawn population migrated out through the Dawesville Channel (rather than the Mandurah Channel), where strong currents make it very difficult for commercial fishers to use their beamtide trawls.

Interpretation of CPUE data was also complicated by the average freshwater discharge in the winter of 1996, when salinities declined to unusually low levels compared to the previous years of low rainfall. The conditions experienced in 1996 meant that further commercial catch data were required to establish whether there were any consistent trends in the abundance of the main commercial species. Bearing these constraints in mind, CPUE data for the period from May 1989 to April 1996 (Table 1) indicated:

- a higher abundance of cobbler, sea garfish, Australian herring and western sand whiting since the opening of the Dawesville Channel;
- little change in the abundance of sea mullet, yellow-eye mullet, tailor, King George whiting and blue manna crabs.

Table 1: Mean monthly fish catch per day per boat for each method and species for Peel-Harvey Estuarine System (selected species and methods), except for king prawn trawling (catches from block 3215 outside estuary).

		MEAN CATCH PER DAY PER VESSEL (kg)						
		SEASON						
SPECIES		May 89-Apr 90	May 90-Apr 91	May 91-Apr 92	May 92-Apr 93	May 93-Apr 94	May 94-Apr 95	May 95-Apr 96
Cobbler	Beach seine, haul net	36	3	2	12	18	43	48
	Gill (set) net	32	10	13	10	21	29	32
Crab, Sand (blue manna)	Drop net	20	33	37	18	50	36	47
	Gill (set) net	31	40	27	19	54	38	28
Garfish, Sea	Beach seine, haul net	-	1	-	-	-	-	3
	Gill (set) net	-	2	-	1	-	-	3
Herring, Australian	Beach seine, haul net	17	5	-	-	-	9	5
	Gill (set) net	-	-	1	-	-	1	11
Mullet, Sea	Beach seine, haul net	160	97	68	106	113	128	80
	Gill (set) net	102	27	68	82	52	62	40
Mullet, Yellow-eye	Beach seine, haul net	79	115	118	77	88	97	106
	Gill (set) net	89	56	88	45	184	30	54
Prawn, Western King	Beam tide trawl	40	14	17	45	17	3	7
	Trawling	55	28	64	46	41	66	55
Tailor	Gill (set) net	25	18	22	27	29	24	21
Whiting, King George	Beach seine, haul net	-	-	10	7	3	6	15
	Gill (set) net	5	-	18	15	9	3	9
Whiting, Western Sand	Beach seine, haul net	1	2	6	1	4	9	10
	Gill (set) net	3	2	3	6	1	5	2

The CPUE data provided evidence that species also targeted in recreational fishing before the opening of the Channel (blue manna crabs, king prawns, cobbler, whiting and tailor) did not become less abundant, and may even have increased in abundance.

Data on recreational fishing in the PHES were confined to boat-based crabbing and line fishing: there were none on shore-based crabbing or line fishing. Data from surveys carried out at PHES boat ramps between September 1996 and February 1997 are still being processed, but they indicated that blue manna crabs, Australian herring, tailor and whiting were the main recreational species caught during boat-based fishing in spring and summer, but silver bream, Western Australian salmon, blue mackerel and King George whiting were also caught in summer (DoF, unpublished data). The DoF creel survey of shore-based and boat-based recreational fishing in coastal waters in 1994 and 1995 established that the Australian herring was a targeted species, particularly by boat-based anglers, with recreational catches accounting for more fish than commercial catches (Ayvazian *et al.* 1997).

Status of the monitoring program

The collaborative research programs between the DoF and Murdoch University on the recruitment, distribution and emigration of fish, crabs and prawns in the PHES are due for completion in 1998. Commercial fish catch data are always available, as compilation and analysis of commercial fisheries data is an ongoing task carried out by the DoF. Data from the boat angler survey of the PHES that commenced in September 1996 are still being processed.

A report that summarises and interprets data on the shallow water fish and crustacean fauna of the PHES before the opening of the Dawesville Channel is being prepared by Dr T. Rose of the Swan River Trust in collaboration with Murdoch University personnel.

7.2.2 Birds

The PHES is an internationally significant habitat for waterbirds, as recognised by its listing, together with the Yalgorup Lakes, as a Wetland of International Importance under the Ramsar Convention (Government of Western Australia 1990). Tens of thousands of waterbirds gather on the PHES each year, and over 80 species have been recorded, 27 of which are listed on the Japan-Australia Migratory Birds Agreement (JAMBA) and China-Australia Migratory Birds Agreement (CAMBA). Some regularly observed species are found in few other southwestern Australian reserves, including the whimbrel, grey-tailed tattler and white-winged tern (Wykes 1990). The PHES is also of great significance for species resident in Australia such as pelicans, ducks, swans, grebes, stilts and avocets (ANCA 1996).

The majority of waterbirds found in the PHES can be broadly grouped into the following categories (EPA 1988):

- migratory waders (sandpipers, plovers, stilts and stints), which feed on benthic invertebrates in intertidal areas at low tide;
- resident waders (banded stilts, black-winged stilts, red-capped plovers), which are usually found in shallow inland non-tidal wetlands and rarely in estuaries with marked tidal influence;
- long-legged waders (herons, egrets, oystercatchers, ibises and spoonbills), which feed on fish and benthic invertebrates in shallow waters;
- fish-eating birds (e.g. pelicans, cormorants, terns and grebes), which occur all year round and fish in deeper waters than waders;
- waterfowl (ducks, swans, coots and swamp hens), which feed mainly on large aquatic plants (especially the seagrass *Ruppia* and some species of macroalgae) and are found all year round providing there is access to low-salinity water for drinking;
- gulls, which are omnivorous scavengers.

The majority of these groups roost on sandy spits and cays, or in the fringing vegetation (salt marsh and trees) of estuaries. Few species breed in estuaries, and those that do (pelicans, swans, Pacific black ducks, grey teal, Australian shelducks) tend to build their nests on low-lying islands or in undisturbed areas of fringing vegetation.

Prior to the opening of the Dawesville Channel

A comprehensive survey of waterbirds in the PHES was carried out in the mid-1970s (J.A.K. Lane, CALM, unpublished data), and a considerable number of waterbird surveys have been carried out by CALM in cooperation with the Royal Australasian Ornithological

Union (RAOU), particularly since 1982. As a result there is a large historical data base on waterbird populations.

The extensive areas of shallow waters and fringing marshes, abundant food supply and relatively undisturbed conditions in the PHES have resulted in extremely high counts of waterbirds (up to 100,000 individuals) during the spring/summer period. Austin Bay Nature Reserve is extremely rich in waterbird species, and is the major remaining reserve in southwestern Australia for samphire flats inhabited by little grassbirds and roosting sandpipers (Wykes 1990).

Prior to the opening of the Dawesville Channel the PHES was considered somewhat unusual in that it had large populations of resident waders (particularly the banded stilt), presumably due to the lack of tidal variation in the system. The system was also particularly favourable to small species of waders due to the extensive areas of extremely shallow waters that persisted for many days. The shallow areas were believed to be particularly important for pre-migratory fat deposition in late summer/early autumn, as feeding opportunities between the PHES and Shark Bay are limited at this time of year (Waterways Commission 1994). The PHES is also one of the most significant habitats for black swans in Western Australia, regularly supports larger numbers of pelicans than any other waterbody in the southern half of the State, and is one of only two pelican breeding sites south of Shark Bay (Lane *et al.* 1997).

Predicted effects of the Dawesville Channel

The main factors likely to affect waterbird numbers in the PHES following the opening of the Dawesville Channel were identified as follows:

- alterations in tidal amplitude causing the inundation of sandy cays and spits and changes to fringing vegetation (see Section 6.2.2), affecting the roosting, breeding and feeding patterns of those species of waterbirds that use these areas;
- changes in food sources for waterbirds (seagrasses, macroalgae, benthic invertebrates and fish);
- the expected increase in recreational boating (see Appendix 8) and boat access into shallow areas during high tides, which would disturb those species of birds that favour quiet sections of the PHES.

The exact impacts of these changes (positive or negative) were not easy to forecast, largely because predictions about changes in habitat availability (for roosting, breeding and feeding) and food sources were also uncertain. However, pelican nesting success on low-lying islands in the PHES was identified as a potential concern, and the altered tidal regime caused by the Dawesville Channel was not expected to be favourable to resident waders (banded stilts) if their feeding opportunities were limited or interrupted. Migratory waders were not expected to be adversely affected by the altered tidal regime: these feed during receding, low or advancing tides and they utilise estuaries in other parts of the world that have greater tidal ranges than the PHES.

Another area in the PHES of particular concern was the southern end of the Harvey Estuary, including the Harvey River delta and lower Harvey River. This area constitutes a near-ideal dry-season refuge for waterfowl, as it is relatively secluded, sheltered (due to stands of swamp sheoak, swamp paperbark and flooded gum), has a year-round supply of fresh water for drinking, and is in close proximity to extensive shallows for feeding and loafing (Lane *et al.* 1997). Changes in salinity regime and tidal heights due to the opening of the Dawesville Channel had the potential to alter both the fringing vegetation and freshwater drinking supplies.

Changes in food sources were considered a lesser concern, as most species of waterbirds are opportunistic feeders of invertebrates and fish: the availability of these food sources was not expected to decline, even though the species composition might well change. However, a potentially deleterious effect of changing food sources was identified for black swans due to changes in the species composition, distribution and/or productivity of the submerged aquatic plants (particularly Ruppia) on which swans feed. Increases in tide heights also had the potential to affect swan numbers by allowing increased access to feeding, loafing and moulting areas that in the past have been little disturbed: swans are particularly vulnerable during their annual moulting period as they then are unable to fly.

Observed effects of the Dawesville Channel

Assessment of waterbird use of the PHES since the opening of the Dawesville Channel has been carried out by CALM. Surveys of all species throughout the PHES were conducted in October 1996, December 1996 and

February 1997: these months cover periods when total waterbird numbers and the number of species (particularly transequatorial migrants) are highest. The survey methodologies, routes and times used are the same as those adapted in comprehensive surveys carried out at two-monthly intervals in 1976 and 1977. A similar exercise is planned for 1998-99, as it is expected that some effects of the Channel will take several years to appear.

In addition to the surveys of all waterbird species described above, CALM also carried out studies that target the areas of concern identified in the previous section. These studies were as follows:

- Pelican nesting activity and success, carried out at fortnightly to two-monthly intervals, depending on the site, since July 1994;
- Pelican counts, carried out at two-monthly intervals since October 1995;
- Black swan counts, carried out in October 1996, December 1996 and February 1997, to be repeated in 1997-98 and possibly 1998-99;
- Salinity measurements and waterbird use in the upper Harvey Estuary, Harvey River delta and lower Harvey River, measured at regular intervals from several hundred metres north of Herron Point Ford to the limit of salt water intrusion up the Harvey River (measurements taken every fortnight from mid-1994 to mid-1996, and monthly thereafter);
- Banded stilt counts, carried out as part of the surveys of all waterbirds in October 1996, December 1996 and February 1997, to be repeated in 1998-99;
- Measurements of the elevation of three major waterbird roost sites (Herron Point Ford, Point Birch and Nirimba Cay) were made prior to the opening of the Channel and are planned for 1999, to determine changes caused by increased tide heights; this will decide the need for 'topping up' of old roosting sites or the creation of new ones.

Preliminary findings of the CALM waterbird monitoring have been summarised in a draft report (Lane *et al.* 1997).

One of the major problems hindering interpretation of the effect of the Channel on waterbird use in the PHES has been the lack of baseline data. Ideally, waterbird numbers should have been monitored on a seasonal basis for at least two years prior to the opening of the Channel, but this was not done. To a large extent, comparisons had to be made with data collected in the mid-1970s, when environmental conditions were quite different from those of the early 1990s. Another potential problem in interpreting changes due to the opening of the Channel was confounding effects due to wetland degradation by other human activities (such as use of trail bikes and four-wheel drive vehicles), increased boating activity, and increased urban development around the shores of the PHES.

Lane *et al.* (1997) report that a previously successful summer breeding site for pelicans (*Pelecanus conspicillatus*) on Nirimba Cay has been lost due to inundation. There has also been no pelican breeding on Creery and Boodalan Islands, in this case due to excessive disturbance (boating activity, people, dogs, foxes). Breeding on Boundary Island in the last three years appears, however, to have been sufficient to maintain total pelican numbers, which are roughly comparable to numbers counted from February 1975 to November 1976.

Data on the surveys of all waterbirds are still being processed, but strong impressions have been gained that little egrets (*Egretta garzetta*) are more numerous and widespread (reflecting a general trend in southwestern Australia); there has been no decline in numbers of eastern curlew (*Numenius madagascariensis*), a species rarely observed elsewhere in southwestern Australia; and curlew sandpipers (*Calidris ferruginea*) were far less abundant in 1996-97 than in 1976-77, although it was uncertain whether this was due to Channel effects or variations in numbers migrating to Australia. Black swan (*Cygnus atratus*) counts in October, December and February 1975-77 varied considerably (2162-8057), but were generally far greater than in 1996-97 (472-1052). The reasons for the decline are unknown, but may include variations in macroalgae abundance and distribution, and this is being investigated.

Results are still being processed from the studies on banded stilt (*Cladorhynchus leucocephalus*) numbers; on salinity measurements and waterbird use in the upper Harvey Estuary, Harvey River Delta and lower Harvey River; and on waterbird roosting sites. These will be reported at a later date.

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Dawesville Channel
Technical Review

APPENDIX 8

HUMAN HEALTH

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

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WATER AND RIVERS
COMMISSION

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8. Human health

The three main human health concerns in the PHES are:

- the presence of *Nodularia* blooms;
- infection with Ross River virus (RRV) or Barmah-Forest virus (BFV) via bites from mosquitoes carrying the viruses;
- odours from rotting algae (phytoplankton and macroalgae).

The impact of the Dawesville Channel on *Nodularia* blooms was discussed in Appendices 5 and 6, and the other two matters are considered below. Of these concerns, by far the more important is the increased risk of infection with RRV or BFV due to greater numbers of mosquitoes carrying the viruses. RRV and BFV have the potential to cause severe debilitating and persistent disease in humans. RRV causes the disease epidemic polyarthritis in humans, the symptoms of which include joint pain and swelling and lethargy that can last for many months or years after the initial infection. BFV causes a similar disease, although there is some evidence that the symptoms are milder.

8.1 Mosquitoes

8.1.1 Prior to the opening of the Dawesville Channel

Salt marshes are breeding-grounds for a number of species of mosquitoes, and prior to the opening of the Channel fringing salt marsh occupied about 10% of the total area of the PHES.

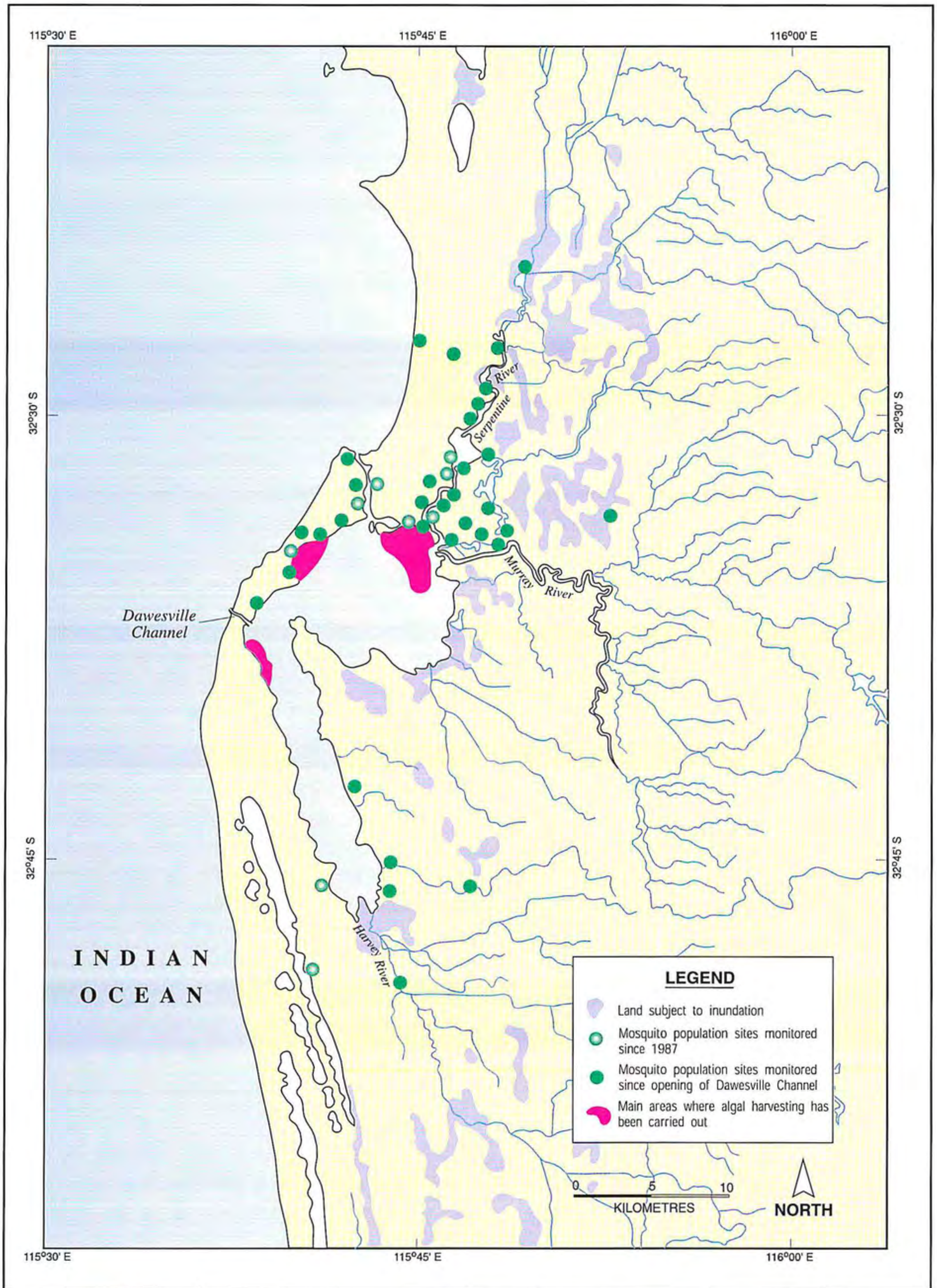
The surrounding region was identified as having a severe salt marsh mosquito problem as early as 1985 (Wright 1988). In addition, the Peel Region was known to be a major focus of two mosquito-borne viruses that cause human disease: RRV and BFV (Lindsay *et al.* 1992, 1995; Jasinska *et al.* 1997). Routine monitoring of mosquito populations and mosquito virus isolations commenced in 1987, and sampling was carried out approximately every two weeks at 6-12 sites around the PHES (Jasinska *et al.* 1997); the sites included salt marsh, brackish wetland and freshwater areas. Blood samples were also taken from local populations of western grey kangaroos and tested for RRV antibodies.

The mosquito *Aedes camptorhynchus* was the major vector of RRV and BFV in the Peel Region. It breeds in salt marsh and brackish wetlands, predominantly from winter through to spring. *Aedes vigilax* also carried RRV in the Peel Region, although to a lesser extent. It is known as the summer salt marsh mosquito because it breeds in saltmarshes in the warmer months. Numbers of this species were generally low, apart from two occasions — Peel Inlet in February 1989 and Harvey Estuary in March 1990 — which both followed severe cyclonic activity off the Western Australian coast (Jasinska *et al.* 1997). Aedes vigilax is considered a nuisance species even aside from potential RRV infection, because it is a vicious biter and can travel long distances — regularly up to 10 km and occasionally up to 100 km — from its breeding sites (Jasinska *et al.* 1997).

Mosquito control throughout the Peel Region was undertaken jointly by the Health Department of Western Australia (HDWA) and the Peel Region Contiguous Local Authority Group (CLAG), and consisted of the following components:

- Application of aerial larvicides granular Abate™ 50SG, dropped from a helicopter between September and April (HDWA). The warmer months of the year are the period of most prolific growth of mosquitoes as well as the major activity period for RRV and BFV. Human exposure to biting mosquitoes is also greatest during the warmer months, thus increasing the adverse health and nuisance impacts of mosquitoes at this time of year.
- Monitoring of mosquito larvae in salt marshes every two to three days to determine appropriate times to apply larvicides (CLAG).
- Monitoring of adult mosquito populations and their infection rates with RRV and BFV (HDWA via the Department of Microbiology at the University of Western Australia).
- Public education (HDWA).

Aedes camptorhynchus comprised about 70% of the total adult mosquito population in the Peel Region prior to the opening of the Dawesville Channel, and was the main species targeted by larvicide application. Aerial



Water and Rivers Commission
Dawesville Channel Monitoring Programme
Two Year Technical Review

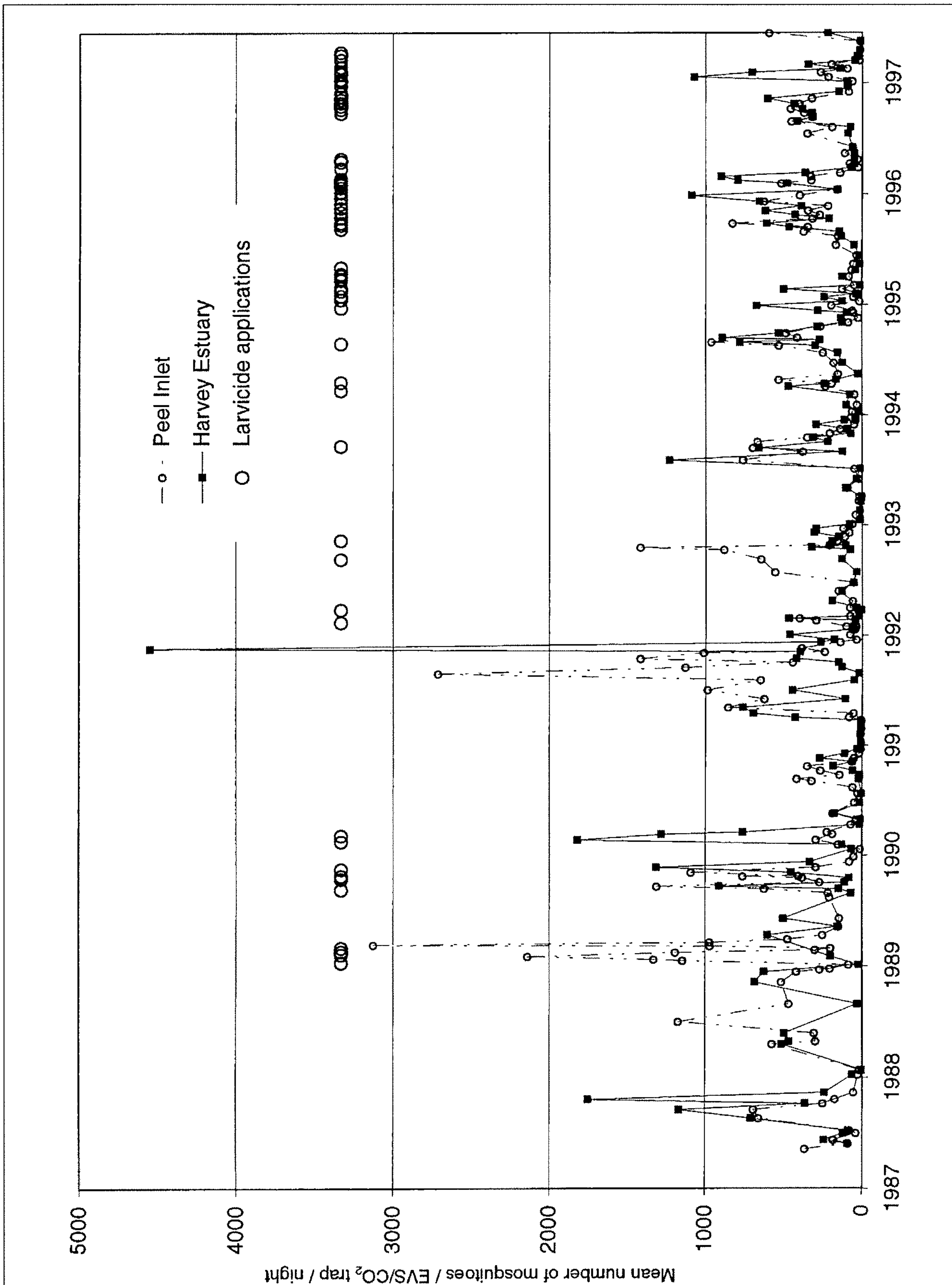
LOCATION OF SITES MONITORED FOR MOSQUITO POPULATION AND REGIONS WHERE ALGAL HARVESTING IS CARRIED OUT

Figure 1

Auth: KH/BH | Date: 2/98

FROGGRAPHICS DAL-DAW 16/2/98

Figure 2: Mean number of adult mosquitoes (all species) per EVS/CO_2 trap per night at Peel Inlet and Harvey Estuary trapping sites and timing of aerial applications of larvicide in the Peel region, 1987 - June 1997.



Data and figure compiled by M.D. Lindsay, Department of Microbiology, The University of Western Australia.

application of larvicide as a mosquito control measure commenced in 1988/89, but was not required on a frequent and widespread basis until the spring/summer of 1994/95 (after the Dawesville Channel was opened), except during 1988/89. In the summer of 1988/89 populations of this species persisted into summer, and there was an associated outbreak of RRV. This outbreak was attributed to frequent inundation of breeding sites caused by a short-term rise in sea level off the coast of Western Australia as a result of strengthening of the Leeuwin Current after an El Nino/Southern Oscillation (ENSO) event (Lindsay *et al.* 1992).

8.1.2 Predicted effects of the Dawesville Channel

It was recognised that more frequent and widespread tidal inundation of salt marsh would occur when the Dawesville Channel was opened, which would increase the frequency of inundation of breeding areas for saltmarsh mosquitoes (Kinhill Engineers 1988). A major concern was that the opening of the Channel would mimic the high-water-level scenario of 1988/89 on a regular basis, resulting in the persistence of populations of *Aedes camptorhynchus* into summer, and therefore lead to increased human infection rates from the RRV. It was also expected that increased saltmarsh inundation during summer would lead to increased numbers of *Aedes vigilax* and, given the ability of this species to travel long distances and its habit of biting during daylight hours as well as at night, many more residents of the Peel Region were likely to be exposed to this vicious biter. It was expected that an increased level of effort in the mosquito control program would be required to achieve effective mosquito management.

8.1.3 Observed effects of the Dawesville Channel

After the opening of the Dawesville Channel the number of sites routinely monitored for mosquito populations increased from 6-12 to 18-22 (Figure 1). The mean numbers of mosquitoes decreased after the opening of the Channel (Figure 2), but this trend must be interpreted with caution due to the massive increase in aerial larvicide applications since 1992. Larvicide application increased from 1-4 times per year prior to the construction of the Dawesville Channel, to 12 times in 1994/95 and 18 times in 1995/96 (Figure 2). Sampling bias may also have contributed to the perceived decrease: sampling effort increased considerably after April 1994, and the mean numbers of mosquitoes may have been affected by several of the new sites, which were considerably less productive than the 'core' sites which have been monitored since 1987. Future analyses will examine core sites individually to remove this bias (Jasinska *et al.* 1997).

Despite the decrease in mean numbers of mosquitoes, there were a number of other significant changes to mosquito and arbovirus activity that were cause for considerable concern:

- the presence of larger numbers of *Aedes camptorhynchus* in the summer months (in 1995/96) when the risk of transmission of RRV is greatest;
- a marked increase in the numbers of *Aedes vigilax* each summer (Figure 8.1) despite the massive increase in larvicide application (this species also appeared to have assumed a greater role in the transmission of RRV in the Peel Region);
- a considerable increase in the number of isolations of arboviruses (RRV and flaviviruses — the latter cause only mild human disease) from mosquitoes collected in the Peel Region;
- an increase in the percentage of western grey kangaroos with RRV antibodies.

The number of confirmed cases of RRV (in humans) in the Peel Region from 1987/88 to 1996/97 is shown in Figure 8.2; the data indicate a strong link between ENSO events, mosquito populations and outbreaks of RRV. During ENSO years (e.g. 1986/87, late 1990 to late 1994) sea levels at the coast were lower due to a weak Leeuwin Current and mosquito problems were less, but the rise in sea level due to strengthening of the Leeuwin Current *after* ENSO events resulted in increased mosquito populations and RRV outbreaks. This relationship appeared to apply both before and after the opening of the Dawesville Channel: an ENSO event occurred in 1997/98 and mosquito counts and confirmed cases of RRV were down (Lindsay, *pers. comm.).* However, notwithstanding the considerable influence of ENSO events, the number of RRV cases was consistently significantly higher after the Channel opened.

8.1.4 Status of the monitoring program

The monitoring and control of mosquitoes in the PHES is being conducted as a joint project between the HDWA, CLAG and the University of Western Australia's Department of Microbiology. The Department of Microbiology has a sampling programm for adult mosquitoes and disease counts; the mosquitoes are trapped, identified and then homogenised for processing to identify the presence of RRV and other arboviruses.

The area of inundation and hence mosquito-breeding is in the range of 100 to 600 ha, depending on recent fluctuations in the estuarine water levels. The period of inundation is approximately every 14 days, coincident with spring tides, and larvicide programs are required soon after this. The growth of larvae into mosquitoes takes approximately 2 weeks during the cooler months (e.g. September) and approximately 3 to 4 days in the warmer months (e.g February). The larvicides Abate™ 50SG and, more recently, Altosid™ are used. Results to date indicate that the larvicide program is approximately two-thirds effective (i.e. on average two-thirds of the larvae are killed on each application).

Another management solution investigated by HDWA (via the Department of Environmental Science at Murdoch University) was the physical alteration of the larval habitats (i.e. construction of runnels in the salt marsh) to increase water exchange and access for predators (Latchford 1997). Marked reductions in larval mosquito populations were achieved using runnels at a number of sites (to below problem levels in most instances), especially in spring and summer (Latchford 1997). The runnels furthermore had low maintenance requirements (removal of minor siltation at runnel entrances and the cutback of vegetation after summer) and minimal impacts on the surrounding vegetation, although the latter was only monitored for one year. This management option offers considerable promise, but the feasibility of runnelling at a larger scale and the longer term impacts on adjacent fringing vegetation remain to be determined.

8.2 Odours

Rotting algae give off offensive odours, and hydrogen sulphide ('rotten egg' gas) and ammonia released during the decomposition process can be harmful to human health at high concentrations. While the amounts of these gases are seldom high enough to be a major health risk to humans, the smell of some species of decomposing algae is particularly nauseating and can cause headaches. *Nodularia* also produces odours that have occupational health and safety concerns with prolonged exposure.

8.2.1 Prior to the opening of the Dawesville Channel

Complaints about smells from decomposing macroalgae along the shores of Peel Inlet were made to local governments as early as the 1960s. Anecdotal evidence indicated that the level of complaints was particularly high during the years of massive accumulations of *Cladophora* (until 1979, when *Cladophora* disappeared from the system), in years when *Ulva* was a significant part of macroalgal biomass (i.e. after years of heavy winter runoff) and in years when thick scums of *Nodularia* washed up on the shores of the estuary. Odours from decomposing *Nodularia* were considered a cause of illness by some local residents.

Complaints about weed accumulations and the associated odours were the main driving force behind the macroalgal harvesting program. Initially, in the early 1970s, harvesting was carried out manually with rakes and pitchforks, but the level of equipment used became increasingly sophisticated. Tractors and front-end loaders were used for shore harvesting in the 1970s and 1980s, and are still used today, but can only operate in water up to 10 cm deep. Offshore harvesters, which can operate in deeper waters (greater than 45 cm deep), have been in use since 1983. Annual harvesting totals varied from 15,000 to 20,000 m^3 in the middle to late 1980s and from 5,000 to 10,000 m^3 between 1990/91 and 1993/94 (Water and Rivers Commission, unpublished data). Harvesting was, and still is, carried out mainly along the Coodanup and Novara/Falcon foreshores (Figure 1), areas of the most intensive human habitation adjacent to extensive shallows.

A formal record of complaints about algae odours (and other pollution incidents) was not kept until 1992. From July 1992 to June 1993 there were 48 complaints about offensive odours and nine about weed on beaches. From July 1993 to June 1994 there were 12 complaints about offensive odours and 33 complaints about weed on beaches.

8.2.2 Predicted effects of the Dawesville Channel

The opening of the Dawesville Channel was expected to result in the cessation of *Nodularia* blooms, but macroalgal accumulations were not expected to diminish in the short term. As a result, it was anticipated that the level of macroalgal harvesting would be maintained or even increase in response to complaints from the public

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8.2.3 Observed effects of the Dawesville Channel

From July 1994 to June 1995 there were only six complaints about offensive odours, and eight complaints about weed on beaches. From July 1995 until the end of May 1996 there was one complaint about offensive odours and six about weed accumulations (mainly in the canal developments). The level of macroalgal harvesting over the same period ranged from 1300 cubic metres (1995/96) to 1500 cubic metres (1994/95) (WRC, unpublished data). Harvesting totals were not entirely reliable, as harvesting strategies varied over the years: in some years harvesting was carried out whenever personnel had time to do it, and in other years it was done exclusively in response to public complaints. Nonetheless, the marked decreases in the level of formal complaints and macroalgal harvesting indicated that the public perceived a lessening of the 'weed problem'. As noted in previous appendices, these represent data obtained during years of below average rainfall; the performance of the Dawesville Channel during wet years has yet to be gauged.

8.2.4 Status of the monitoring program

The formal complaints register is maintained by the Peel Inlet Management Authority, macroalgal harvesting is carried out in response to public complaints and a record is kept of the amount of macroalgae harvested.

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APPENDIX 9

SOCIAL AND ECONOMIC USES

Prepared for:

WATER AND RIVERS COMMISSION

Prepared by:

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9. Social and economic uses

As noted in Appendix 1, the PHES is an important recreational and tourism resource due to a combination of its biological features, sheltered waters, scenic surrounds and close proximity to the Perth metropolitan area. The two single most important commercial uses of the estuary are fishing and tourism. The former is discussed in some detail in Appendix 7.

9.1 Prior to the opening of the Dawesville Channel

Surveys carried out prior to the opening of he Dawesville Channel indicated that the single largest tourist attraction of the Peel Region was fishing and crabbing on the estuary, followed closely by the use of beaches and boating (Kinhill Engineers, 1988). Sightseeing and scenic tours were also favoured activities.

There was, and still is, considerable and frequent recreational use of the PHES, with passive recreation, e.g. picnicking, walking), prawning, crabbing, fishing and boating, the most popular recreational activities. Although the estuary was used heavily by local residents, the greater proportion of recreational users comprised day visitors and holiday-makers, especially during the summer months (Kinhill Engineers 1988). Local and visiting naturalist clubs also used the estuary extensively, particularly for birdwatching. Skiing and swimming were not major activities, although the beaches of the PHES were favoured by young families because the shallow waters are suitable for toddlers and small children.

While the macroalgal problem in the PHES appeared to benefit the commercial fishery, the excessive weed growth was perceived by locals and tourists alike as aesthetically unpleasant, malodorous and a nuisance to recreational pursuits (O'Brien *et al.* 1994). Macroalgal harvesting along beaches in the Peel Inlet was undertaken with some success, but met with a degree of criticism because of its destruction of fringing vegetation and subsequent shoreline erosion and the death of juveniles of certain commercially important fish caught in the harvested weed, notably crabs and cobbler.

The *Nodularia* blooms were viewed as highly undesirable by commercial fishermen because they fouled nets, hindered fishing practices and were believed to deleteriously affect fish (see Appendix 7). *Nodularia* can be toxic to mammals and there were public health concerns (see also Appendix 8). The green surface scum and peculiarly nauseating odour of *Nodularia* blooms were viewed as particularly unattractive and likely to discourage tourism, particularly boating. The business community relying on real estate was also concerned about reduced property values (O'Brien *et al.* 1994), while some property developments, e.g. at Point Grey, were disallowed by the Environmental Protection Authority due to poor water quality.

9.2 Predicted effects of the Dawesville Channel

The improvements in water quality, particularly water clarity, and loss of *Nodularia* blooms anticipated with the opening of the Dawesville Channel were expected to benefit local residents and recreational users (EPA 1988). The Channel would also provide an extra and unimpeded access route to coastal waters, and the combination of these features was expected to result in increased recreational and tourism opportunities and improved property development possibilities. Further benefits were expected in the longer term, provided the expected reductions in macroalgal accumulations occurred, and particularily if they were replaced by seagrass meadows. However, the improved opportunities for property development were also seen as a deleterious impact by some members of the public, since they would promote land speculation in the area, increase the pressure for waterside residences and canal estates, and result in the loss of fringing vegetation habitats and increased 'people pressure' on the environment (O'Brien *et al.* 1994).

Prior to the opening of the Dawesville Channel a public information program was set in place to:

- inform the community about the changes expected in the estuary;
- inform the community about the results of environmental monitoring;
- provide a focus for community inquiries;

- promote community involvement in environmental monitoring.

At the same time, a social impact assessment program was initiated to identify community concerns before the Channel was opened and recommend ways of managing potential impacts. A report on the latter exercise was published by the Waterways Commission in 1994 (O'Brien *et al.* 1994).

While there was generally little dissent that the expected improvements in water quality would be beneficial, the public expressed concern over a number of potential impacts that were largely centred around the expected increase in tidal range. These included (O'Brien *et al.* 1994):

- flooding of low lying-land at high tide and flooding associated with winter rains and high tides (with consequent damage to homes, tourist facilities and agricultural land);
- changes to the watertable (which would affect bores and septic systems);
- saline water intrusion into agricultural drains;
- the perception that water levels at low tide would cause temporary reductions in the navigability of boating channels and navigable areas overall, with safety implications for boating, skiing and swimming.

Department of Transport modelling studies indicated that most of these fears were unfounded and/or manageable. For instance a water-level assessment was carried out to investigate possible impacts on low-lying farmland and agricultural drains on the eastern shores of Peel Inlet, tidal gauges were installed on three agricultural drains, and options such as control gates (on drains) and protective earthworks were to be built if required.

The Peel Region was also recognised as having a salt marsh mosquito problem as early as 1985, and a major deleterious effect predicted with the opening of the Dawesville Channel was that more frequent and widespread tidal inundation of salt marsh would increase the frequency of inundation of breeding areas for salt marsh mosquitoes. The mosquitos *Aedes vigilax* and *Aedes camptorhynchus* were known vectors of Ross River virus, which causes the disease epidemic polyarthritis. The expected increases in the mosquito population were therefore identified as a considerable health risk. It was anticipated that an increased level of effort would be needed in the mosquito management program carried out jointly by the Health Department of Western Australia (HDWA) and the Peel Region Contiguous Local Authority Group (CLAG). The mosquito issue is discussed in more detail in Appendix 8.

9.3 Observed effects of the Dawesville Channel

In early 1995 a long-term Communication Strategy was developed that combined elements of the pre-Dawesville public information program and social impact assessment program. This amalgamation became the Dawesville Channel Social Impact and Public Information Program.

Addressing the social impacts associated with the Dawesville Channel became an iterative process, and was highly dependent on providing the public with up-to-date and accurate information about the Channel and changes to the estuary. A Community Reference Group was established as a link to the community, and a telephone hotline was established to answer people's queries and concerns. A series of 12 'Dawesville Topics' sheets detailing changes to the estuary were prepared; a secondary school education pack and a variety of posters, displays and media communications (radio and newspaper) were devised; and 15-20 talks per year were given to schools and community interest groups. Major reports published were the 'Dawesville Channel Social Impact Monitoring Study' (O'Brien *et al.* 1994), the 'Dawesville Channel — Environmental Impacts and their Management: Working Paper 1994' (Peel Inlet Management Authority 1994), and 'Securing the Future' (Waterways Commission, Department of Transport and Department of Agriculture 1994).

There appeared to be very little impact on the social and economic uses of the PHES after the opening of the Dawesville Channel. To a large extent this can be attributed to an effective public information program that identified the potential impacts of the Channel before it was opened and explained how these were going to be managed. This pro-active approach meant that most community concerns were effectively dealt with in the first 12 months after the opening of the Channel.

Furthermore, the development (housing and recreational facilities) of land around the Dawesville Channel itself was still far from complete, and its associated social and recreational impacts were not fully realised.

Members of the public noted the improvement in water quality and absence of *Nodularia* blooms in the estuary, and there were fewer complaints about weed accumulations in the summers of 1994/95 and 1995/96 (see Appendix 8). These changes were also perceived as favourable to tourism and property development opportunities, and property developments previously disallowed by the Environmental Protection Authority due to poor water quality (see Section 1.1) were able to proceed.

Recreational fishers reported an early crab season, that crabs were more numerous but smaller in size and that they were seen moving out of the system earlier (via the Dawesville Channel). The situation was the same for king prawns, while school prawns were reported to have moved into the rivers in big numbers (Waterways Commission 1995).

Although an improvement in estuarine water quality was noted by the public, there were reports of extremely poor water quality and fish and crab kills in the Serpentine and Murray Rivers. Concerned residents along the Serpentine reported extremely thick blooms of dinoflagellates that turned the water reddish-brown in autumn 1995, as well as *Nodularia* blooms in the summers of 1994/95 and 1995/96. The Serpentine was closed to fishing and swimming for an extended period in the spring/summer of 1996/97. In the lower reaches of the Murray River a phytoplankton bloom turned the waters green for several months in summer and early autumn of 1995 (Waterways Commission 1995). Associated with these blooms were occasional fish and crab deaths due to low oxygen levels in the evening and when the blooms collapsed and decomposed (Waterways Commission, 1995).

There was a major outbreak of Ross River virus in the Peel Region in the summer of 1995/96, and there have been elevated levels of RRV activity in the Peel region every year since the Channel opened (see Appendix 8). Concern was expressed that the Peel region may now be an endemic focus, or reservoir, of RRV in the Southwest, with potential for activity of the virus and subsequent cases of infection in humans every spring/summer (Lindsay, *pers. comm.*). The level of aerial spraying of mosquito larvicide carried out in the HDWA/CLAG mosquito management program increased three-fold to minimise incidence of Ross River virus, and an intensive public education program on how to minimise human exposure to mosquito bites was also carried out (see Appendix 8).

9.4 Status of the monitoring program

The Dawesville Channel Social Impact and Public Information Program is due to continue until the end of 1998, and, although it is now mainly concerned with addressing public information needs, appropriate management procedures remain in place to deal quickly and effectively with any major social impact that might arise.

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APPENDIX 10

ESTUARINE MANAGEMENT

Prepared for:

WATER AND RIVERS COMMISSION

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10. Estuarine management

10.1 Management Issues

10.1.1 Pre-Dawesville Channel

The 'algal problem' in the Peel-Harvey Estuarine System first became apparent in the mid-1960s (Hodgkin *et al* 1980). The problem that materialised revolved primarily around concerns associated with blooms of the macroalgae *Cladophora* and *Chaetomorpha* in the Peel Inlet (Hodgkin *et al.* 1980). These concerns, which were essentially of a socio-economic nature and adversely affected surprisingly few people (Skitmore & Bunbury 1985), amounted to:

- the fouling of the shallows and beaches adjacent to populated areas by decomposing algae;
- the offensive odour of the decomposing algae;
- the adverse effect of decomposing algae on tourism, recreation and property values;
- the fouling of fishermen's nets and the tangling of boat propellers;
- the periodic mortality of fish and crabs.

From an ecological point of view, there were two schools of thought about the algal problem. One was that, despite its unpleasant features for some members of the public, the macroalgal accumulations did not necessarily indicate 'a particularly unhealthy biological condition' (Hodgkin *et al.* 1985). In other words, regardless of the presence of macroalgae, plant and animal life continued to flourish in the Peel Inlet simply because of the ecological benefits to be derived from its sheltered nature, shallow waters, fluctuating salinity regime, long residence time of water in the system and high capacity for food production.

The other, more widely held, school of thought centred around the known toxicity of the blue-green alga *Nodularia spumigena*. The death of fish and benthic fauna in the Harvey Estuary due to severe oxygen depletion during the massive *Nodularia* bloom in the summer of 1980/81 also did much to fuel concerns, as did the prospect of the system becoming steadily more vulnerable because of the demands of the rapidly increasing human population (DCE 1985a). The worry was that the environmental health of the system was declining too rapidly and, if left unchecked, the 'rotting algae might lead to a total collapse of the biological systems in the estuary' (EPA, 1988). Thus, managers of the PHES were faced with a dilemma as to whether the priority was to improve the ecology or please the people (Hodgkin, *pers. comm.)*, and this was complicated by political pressure due to community concerns.

Other management issues included the damage being done to the shoreline by the tractors used to remove macroalgae beached near residential areas, with subsequent loss of fringing vegetation due to shoreline erosion, and the loss of juvenile fish caught in the harvested material (see Appendix 8).

10.1.2 Predicted management issues

When the EPA released the Stage 2 Environmental Review and Management Program (ERMP) in May 1988 for public comment, opposition to the proposed Dawesville Channel was fully expected. From the submissions received, concerns seemed to hinge mainly around the uncertainties surrounding its possible effects and the EPA's prediction that, because of the amount of phosphorus stored in the sediment on the floor of the PHES, the algal problem would not improve for a further 10 years (EPA 1988).

Without wishing to repeat the long list of management issues that were raised during the course of the public scoping exercise, many of which were examined by workers such as Humphries and Ryan (1993), the following overview provides an insight into the type of concerns raised about the Channel:

- The Dawesville Channel would treat only the symptom and not the cause.
- The algal problem in the PHES was overrated. Greater emphasis was simply needed on controlling macroalgae adjacent to the main population centres.
- The Dawesville Channel option was the only one to be extensively addressed. Hence, arguments in its favour were biased and the alternatives available were not fully explored.
- The Dawesville Channel would merely shift the eutrophication problem to one of ocean pollution. The influence of the Channel on the marine environment (and the usage thereof) needed further investigation.

- The Dawesville Channel would radically change the physical features of the PHES. Moreover, its effect would be sudden and irreversible. The increased tidal range would impact on non-target organisms such as the benthic flora and fauna, affect waterbird feeding grounds, alter the composition of the fish species present and affect the location of macroalgae growth areas. The increased tidal range would also cause the flooding of low-lying land, impact on existing buildings, infrastructures and drainage systems on the foreshore, reduce the navigability of boating channels at low tide, affect agricultural drains through the intrusion of saline water, impact on the fringing vegetation along 30 kms of shoreline and increase health risks in the area by exacerbating the existing mosquito problem.
- The Dawesville Channel would stimulate land speculation and increase 'people pressure' and the appeal of waterside residences and canal estates.

10.1.3 Post-Dawesville Channel

When the data reviewed in Appendices 3-9 were taken into account, it was clear that several of the above-mentioned management issues materialised after the opening of the Dawesville Channel. Others did not, either because it was too early to expect such changes to have occurred — for example the effects on fringing vegetation, and increased 'people pressure' — or because the data suggested otherwise, e.g. there was no increase in macroalgal population.

The management issues that materialised included:

- the increased flushing regimes of both the Peel Inlet and Harvey Estuary and the consequent reduced water residence time in the PHES;
- the increased tidal range;
- the reduced salinity range in the PHES (although high evaporation during summer still caused hypersalinity in late summer and autumn);
- the improved water quality, water clarity and benthic light availability in the Harvey Estuary;
- the decline in water quality in the Serpentine and Murray Rivers (this may be due to catchment inputs as well as the influence of the Dawesville Channel);
- the continued growth of macroalgae in the Peel Inlet and the occurrence of macroalgae in areas where they had previously never occurred, that is, in the southern shallows of the Harvey Estuary;
- the loads of fine particulate sediment and organic matter being exported from the estuary into the nearshore marine environment (although reef macroalgal communities were apparently not adversely affected);
- the continued tendency (although of lesser duration) for deoxygenation of the water and sediments on the floor of the estuary to occur due to salinity stratification;
- the much increased breeding of mosquitoes and increased presence of Ross River virus in mosquitoes in the Peel Region, and the costs associated with mosquito control;
- the decline in catches of western king prawns (due to reduced 'catchability' of the prawns rather than reduced numbers in the PHES);
- the intensification of development of marinas (canal estates) in areas adjacent to the Dawesville Channel.

10.2 Management Objectives

10.2.1 Pre-Dawesville Channel

Despite many of the warning signs of eutrophication having been evident prior to 1970, while management of the PHES was the task of local government authorities, the need to formulate a management plan was not really foreseen. However, in 1971 the Peel Inlet Conservation Advisory Committee was formed to establish guidelines and rules which will ensure that the whole area retains its main attractions (Waterways Commission 1992). Six years later, in 1977, the Peel Inlet Management Authority (PIMA) was formed to:

- preserve or enhance the quality of the environment and amenity of the waters of the Peel Inlet and associated land areas;
- control and, wherever practicable, prevent any act or omission which causes or is capable of causing pollution of these waters or that land;
- provide advice and disseminate knowledge on the conservation and good management of the Peel-Harvey system;

- work in cooperation with all the other authorities and bodies affected by the operation of the Waterways Conservation Act of 1976.

Unfortunately, establishing these management objectives appeared to be of no avail because the algal problem continued to worsen. It was only when it appeared that both the amenity value and the biota of the PHES were severely threatened that a proper management strategy (the Peel Inlet and Harvey Estuary Management Strategy) was formulated (DCE 1984).

The initial objective of the management strategy was:

'to reduce the algal nuisance to acceptable levels without further damage to the estuarine environment' (DCE 1984).

This was to be achieved *without causing loss of production of the estuarine fishery or of agriculture in the catchment* by combining the following management measures:

- continue, and if necessary modify and expand, the present weed harvesting measures to control the weed nuisance near populated areas;
- reduce the input of phosphorus to the estuary by continuing the program to modify agricultural practices on the coastal plain;
- increase the loss of nutrients to the sea by construction of the Dawesville Channel.

Acceptable levels were defined thus: *Nodularia* blooms should not occur more frequently than once in five years on the average, and weed should not foul beaches near populated areas (DCE 1984, 1985a).

While not part of the preferred strategy, enlargement (dredging) of the Mandurah channel was also proposed as a means of increasing marine flushing of the Peel Inlet (Hodgkin *et al.* 1985; Humphries & Croft 1983).

In 1986, after the EPA's assessment of the Stage 1 ERMP, the overall management objective originally set in 1984 was revised as follows:

'to produce and maintain an estuary system that is visibly clean and healthy and is ecologically healthy and resilient' (DCE 1985b).

Moderate enrichment of the system (that is, a mesotrophic condition) was considered environmentally acceptable: numerical water quality targets involving a 60% reduction of phosphorus inputs to the system were set; and, to ensure that severe oxygen depletion would not occur, the introduction of freshly oxygenated marine water via the Dawesville Channel was planned. The latter was regarded by the EPA as ìthe only action which can quickly bring the problem to manageable proportionsî for the resilience of the system (that is, its ability to recover after a major disturbance) to be achieved (EPA 1988).

However, once it was realised that the target for management was to strike a balance between the requirements of both the ecological components of the estuarine ecosystem and human users of the waterbody, the aim of the management program was revised again in 1992. This time, the management aim of the strategy was:

'to balance competing demands for use and development with the need to restore the nutrient balance of the waterway and conserve a healthy, functional, estuarine environment for present and future generations' (WWC 1992).

10.2.2 Legal framework for the Peel Inlet and Harvey Estuary Management Strategy

The Peel Inlet and Harvey Estuary Management Strategy was essentially developed to address the algal problem, although there were also concerns about the potential impacts of future human uses of the PHES and its catchment, particularly increased urban development. Legally binding Environmental Conditions for the strategy were first issued by the Minister for the Environment in January 1989. Management commitments by the proponents — the Minister for Transport, the Minister for Agriculture and the Minister for Waterways — were also agreed upon at this time (EPA 1988). Originally, 13 ministerial conditions and 18 commitments were set, and a copy of these is given in Appendix 1. Of particular note is Ministerial Condition 2, which sets interim targets for phosphorus input to the PHES and estuarine water quality so that the following objective is met: 'the Peel-Harvey System is clean, healthy and resilient'. The interim targets are:

- annual phosphorus input to the system shall not exceed 85 tonnes in more than four years out of ten (on average) and shall not exceed 165 tonnes in more than one year out of ten (on average) (these are based on 60th and 90th percentile loads);

- average phosphorus concentration in estuary water shall not exceed 0.2 milligrams per litre in nine years out of ten (on average).

In fact, the second of the two interim targets contained a typographical error, and according to the proponents was meant to be 0.02 milligrams per litre (EPA 1994): the latter figure has been used in the Environmental Protection (Peel-Harvey Estuary) Policy (see below).

Ministerial Condition 3 called for the preparation of an Environmental Protection Policy (EPP) for the Peel-Harvey catchment by the proponents. In December 1992, the Environmental Protection (Peel-Harvey Estuary) Policy was gazetted (Government of Western Australia 1992a) and has the full force of the law, as if it were part of the Environmental Protection Act (1986). The EPP sets environmental quality *objectives* of:

- a median load of total phosphorus from Serpentine River of less than 21 tonnes per annum;
- a median load of total phosphorus from Murray River of less than 16 tonnes per annum;
- a median load of total phosphorus from Harvey River of less than 38 tonnes per annum;
- a median total load of total phosphorus to the PHES of less than 75 tonnes per annum.

These long-term environmental quality *objectives* differ from the *interim* targets set in the ministerial conditions.

In October 1991, a fourteenth ministerial condition was included to recognise the draft Statement of Planning Policy for the Peel Harvey Coastal Catchment. In April 1993 an amendment of Condition 1 was made, Conditions 15 (estuary reclamation associated with construction of Dawesville Channel), 16 (protection of foreshore vegetation during construction of Dawesville Channel) and 17 (requirement for audit system to ensure environmental conditions and proponents' commitments are met) were added, and three further commitments were made by the Department of Marine and Harbours concerning estuary foreshore reclamation associated with the construction of the Dawesville Channel. A copy of the amended conditions and commitments is also given in Appendix 1.

In December 1993 the three proponents of the Peel Inlet and Harvey Estuary Management Strategy formally sent a review of ministerial conditions and management commitments to the EPA, requesting changes to a number of the conditions and commitments. The request was made because it was felt that some of the conditions could be cleared and that several other conditions were either outdated or inappropriate. Changes to ministerial conditions are dealt with under Section 46 of the Environmental Protection Act (1986) through a separate report to the Minister for the Environment.

Adherence to ministerial conditions and proponents' commitments is presently monitored by the DEP by the means of audit tables that are negotiated with the proponents. This process was not followed for the conditions and commitments originally set in 1989, but did occur for those added in 1993, which were essentially concerned with impacts associated with the construction of the Dawesville Channel rather than those due to its opening. The DEP plans to carry out a full audit in June/July 1998.

10.2.3 Post-Dawesville Channel

In view of public interest likely to be expressed over the changes to the ministerial conditions proposed by the three proponents of the Peel Inlet and Harvey Estuary Management Strategy, a public discussion paper on these matters was released in July 1994 for public review (EPA 1994). Changes to the present ministerial conditions and management commitments have yet to be formalised.

The overall aim of the Peel-Harvey Management Strategy was revised for a fourth time by the three proponent agencies in 1994. The present aim of the strategy which is not dissimilar to that formulated in 1986, reads:

'to restore the estuary to health and resilience' (WWC, DoT & WADA 1994).

10.3 Management Agencies

10.3.1 Pre-Dawesville Channel

Prior to construction of the Dawesville Channel there were thirteen different agencies involved in implementing the Peel Inlet and Harvey Estuary Management Strategy. These were:

- Department of Marine and Harbours (DMH), responsible for managing construction of the Dawesville Channel and the reclamation associated with it;

- Western Australian Department of Agriculture (WADA), responsible for implementation of the catchment management strategy;
- Waterways Commission (WWC) and the Peel Inlet Management Authority (PIMA), responsible for management of the PHES, for much of the catchment monitoring and for the weed-harvesting program;
- Environmental Protection Authority (EPA), responsible for assessing the performance of the above three agencies, pollution control and the environmental assessment of new developments;
- Department of Planning and Urban Development (DPUD), responsible for land-use planning, development control and the development of a policy statement and the Peel Region Plan;
- Western Australian Water Authority (WAWA), responsible for water management in the catchment (including the drainage system), the licensing of point-source polluters, the installation and operation of gauging stations and the treatment and disposal of sewage;
- Health Department of Western Australia (HDWA), responsible for the coordination of mosquito control activities and research in relation to mosquitoes;
- Peel Development Commission (PDC), responsible for the coordination of regional planning and development;
- Department of Conservation and Land Management (CALM), responsible for afforestation program in the catchment and management of public lands and reserves adjoining the PHES;
- Fisheries Department of Western Australia (DoF), responsible for management and monitoring of the PHES as a commercial and recreational fishery;
- local government authorities (LGAs) that is, various shires and city councils, responsible for the development and implementation of town-planning schemes and for facilitating community action.

10.3.2 Post-Dawesville Channel

On 1 January 1996 the Water and Rivers Commission (WRC) was created under an Act of Parliament to manage the State's surface water and groundwater resources, including rivers and estuaries. The WRC was formed by merging:

- the Western Australian Water Resources Council;
- the Water Resources Division of WAWA (i.e. its regulatory portion);
- the Hydrogeology and Groundwater Resources Branch of the Department of Minerals and Energy;
- the Waterways Commission.

The WRC now answers to both the Minister for Water Resources and the Minister for the Environment. A number of other name changes have also occurred in the agencies responsible for implementation of the Peel Inlet and Harvey Estuary Management Strategy since the opening of the Dawesville Channel:

- the utilities portion of WAWA has become the Water Corporation (WC);
- the Department of Planning and Urban Development (DPUD) has become the Ministry for Planning (MFP);
- the Western Australian Department of Agriculture (WADA) has become Agriculture Western Australia (AgWA);
- the Department of Marine and Harbours (DMH) has become the Department of Transport (DoT);
- local government authorities (LGAs) are now known as local governments (LGs).

Insofar as the PHES is concerned, as from 1 January 1996 the WRC assumed responsibility for water management in the PHES catchment area, for the PHES itself, for groundwater-well licensing, for land capability assessment, for the collection of water quality data, the operation of gauging stations and for the collection of stream-flow data in the catchment. The WC has remained responsible for the operation of the drainage system, the supply of potable water and the treatment and disposal of sewage to urban areas.

The Ministries of Transport and Agriculture and the Waterways Commission are still regarded as the proponents of the Peel Inlet Harvey Estuary Management Strategy, and are legally bound to carry out the management commitments (i.e. the ministerial conditions) that were set in 1994 to the satisfaction of the EPA.

The interrelationships between the agencies presently involved in implementation of the Peel Inlet and Harvey Estuary Management Strategy, together with the roles of the Senior Officer Group (SOG) and the Peel-Harvey Project Managers Group (PHPMG), are shown in Figure 10.1.

10.4 Management Policy

10.4.1 Pre-Dawesville Channel

The first guiding principles for planning and management of the PHES were contained in the Statement of Planning Policy No. 2 produced by the DPUD in February 1992 (Government of Western Australia 1992b) for the Peel-Harvey coastal plain catchment. The overall purpose of the Statement of Planning Policy was 'to ensure that the land use changes within the PHES, likely to cause damage to the Estuary, are brought under planning control and prevented' (Government of Western Australia 1992b).

The objectives of the Statement of Planning Policy were:

- to improve the social, economic, ecological, aesthetic and recreational potential of the Peel-Harvey Coastal Plain Catchment;
- to ensure that changes to land use within the catchment to the PHES are controlled so as to minimise environmental damage;
- to balance environmental protection with the economic viability of the primary sector;
- to increase high-water-using vegetation cover within the Peel-Harvey Coastal Plain Catchment;
- to reflect the environmental objectives in the draft Environmental Protection Policy;
- to prevent land uses likely to result in excessive nutrient export into the drainage system.

The Environmental Protection (Peel-Harvey Estuary) Policy was then published in December 1992; it applies to 193,400 ha of the PHES catchment (Government of Western Australia 1992a). The protection policies formulated have the full force of the law, as if they were part of the Environment Protection Act of 1986 (see Section 1.2.2), and were to be reviewed every seven years. The objectives of the Environmental Protection Policy were:

- to set out environmental quality objectives for the PHES which, if achieved, would rehabilitate it and protect it from further degradation;
- to outline the means by which the environmental quality objectives for the PHES were to be achieved and maintained.

The two policies made provision for the protection of vital areas such as those essential to protecting the quality of run-off (freshwater wetlands), those that are essential to preserving the integrity of the shoreline (fringing wetlands) and areas where estuarine species gather for feeding, breeding and refuge purposes (for example, tidal flats and shallows covered in submerged macrophytes).

The Environmental Protection Policy established acceptable phosphorus loads for the PHES and for the rivers flowing into it (see Section 1.2.2). The Statement of Planning Policy gives direction for land-use management to reduce phosphorus run-off from urban, rural and industrial areas. Finally, the controls to support the Statement of Planning Policy goal apply to all residential, commercial, industrial, rural and recreational land uses and public sector undertakings in the policy area. They include approval procedures for sewage disposal systems, vegetation clearance, intensive agriculture and the grazing of livestock.

10.4.2 Post-Dawesville Channel

Since the opening of the Dawesville Channel in April 1994 the Peel Regional Strategy — a strategic policy statement and land-use plan — was published in September 1994 by the MFP. Although subservient to the Statement of Planning Policy and the Environment Protection Policy, the significance of the Peel Regional Strategy lies in the emphasis placed on the whole catchment rather than just the coastal plain catchment. The Peel Regional Strategy highlights the need for relevant authorities and public groups to develop mechanisms 'to manage salinity, siltation and other impacts on the whole Peel-Harvey catchment area'. It reinforces the range of strategies adopted in 1992 as the Environment Protection Policy 'to ensure that the Peel-Harvey Estuary is restored to health and resilience' and that ìadequate resources for management are made available on an on-going basis to agencies responsible for the total Peel-Harvey catchment'.

As the concept of "policy" becomes meaningful only where control is feasible, the success of the Peel Regional Strategy will rely heavily on the degree of cooperation achieved between numerous state and local government agencies, local community groups and private enterprise. At present, however, the Peel Regional Strategy represents a type of partnership agreement designed to capitalise on the management capabilities of each participant and the widely accepted need to develop a more holistic approach to protection of the PHES. It is important, therefore, where inconsistencies currently exist at a policy level over matters such as drainage and the clearing of remnant vegetation in urban versus rural areas, that, for the sake of equity, these are eliminated. For example, at present the clearing of remnant vegetation can occur on land zoned urban or industrial but not at all in rural areas. Similarly, as landowners and developers are encouraged by the government to use 'best management practices' for drainage in urban or industrial areas, no new drains of any form can be dug in rural areas using similar techniques.

10.5 Community Involvement

10.5.1 Pre-Dawesville Channel

Ever since PIMA formed in 1977 a considerable effort has been made to maintain contact and involve the core groups of people affected by the proposed Peel-Harvey Management Strategy (WWC, DoT & WADA 1994). The extent of community involvement is discussed in some detail in Appendix 9, and is therefore not repeated here.

10.5.2 Post-Dawesville Channel

After the opening of the Dawesville Channel in April 1994 a program designed to involve the community in monitoring the environmental changes in and around the PHES was to be initiated (WWC, DoT & WADA 1994). There is some involvement of high-school students in summer monitoring of benthic invertebrates, fish and birds (see Appendix 7), but otherwise this action does not seem to have been followed through.

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Plate 3: The Creery wetlands.

Plate 4: Fringing vegetation at Goegrup Lake.