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Report prepared on behalf of
UNSW Global Pty Limited

Conceptual Models of Potential Ecological Impacts of Plankton Entrainment in the Port Kembla Steelworks Cogeneration Plant

for

CH2M HILL Australia Pty Ltd

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28 March 2008

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Acronyms

CLT Cardno Lawson Treloar Pty Ltd

ICP Illawarra Cogeneration Plant

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Executive Summary

This report has been commissioned by BlueScope Steel Limited (BlueScope Steel) to detail potential ecological issues associated with the proposed modification to the Illawarra Cogeneration Plant (ICP). Specifically, this report addresses points 4a-c in the Department of Environment and Climate Change letter from the 26 October 2007 to BlueScope Steel.

BlueScope Steel is proposing to use a once through salt water cooling system utilising salt water from Port Kembla Harbour to cool the cogeneration plant's steam turbine generators. The ICP will draw salt water from Port Kembla Harbour via the existing salt water channel utilising the spare capacity in the existing lift pumps at the entrance to the Port Kembla Inner Harbour (the Cut).

This report is based on a conservative premise that the extraction of seawater will result in a 100% mortality rate of plankton entrained in the ICP cooling system. Based on this premise and the proposed extraction rate of seawater, this report will consider the potential impact upon the ecology of Port Kembla Harbour associated with a 17-32% extraction rate of plankton during one residence time of seawater in the harbour. Plankton are an important component of the ecology of the harbour as they supply recruits (i.e. larvae) for many fish and invertebrate species inhabiting the harbour and plankton are also a source of food for many fish and invertebrates.

From a review of the ecological literature it is clear that whilst there has been extensive toxicological research examining plankton mortality within cooling systems, few studies have examined the ecological impacts of this mortality beyond the point of discharge. The few studies that have been conducted have yielded variable results which range from no detectable ecological impacts, to reductions in plankton abundance up to 200 m from the discharge point. Observations also suggest organisms such as sessile filter feeders and fish which feed upon plankton may congregate around cooling water discharges to feed upon plankton concentrated there. Thus, despite a general lack of research, it is known that industrial cooling systems can potentially alter the composition and abundance of marine communities in receiving systems.

This report also proposes simple conceptual models of impact, based upon ecological principles, and a basic understanding of the circulation patterns within Port Kembla Harbour. These models suggest that the severity and extent of ecological impacts of plankton entrainment in Port Kembla Harbour are likely to be determined by patterns of water flow post-ICP operation. In particular, flows of plankton-rich waters from the Outer to the Inner Harbour are an important mode of replenishment of plankton stocks in the Inner Harbour. It would however, appear likely that an extraction of 17-32% of the plankton per residence time in Port Kembla Harbour may result in alterations to the abundance of plankton, benthic invertebrates and fish in waters adjacent to the discharge point in the Inner Harbour. Effects are expected to be much smaller in the Outer Harbour due to greater levels of tidal flow and replenishment of plankton from the open ocean. Also, it is unclear whether altering the depth of the intake would reduce any potential effects as more data are required to determine whether stratification of the plankton occurs within the harbour. These models will assist in assessing the worst case scenarios of ecological impact

1. Introduction

This report has been commissioned by BlueScope Steel Limited (BlueScope Steel) to detail potential ecological issues associated with the proposed modification to the Illawara Cogeneration Plant (ICP) Project. Specifically, this report addresses points 4a-c in the Department of Environment and Climate Change (DECC) letter from the 26 October 2007 to BlueScope Steel –

> ***4. Further literature evaluation must be undertaken to assess:***
>
> ***a) the consequences of the loss of Pm proportions of plankton and larvae on Port Kembla Harbour. This should distinguish the potential impacts for the Inner and Outer Harbours, assuming that discharge will create a net outflow from Inner to Outer Harbours and thus is likely to limit recruitment and food in the Inner Harbour*** (addressed in Section 3 and 4)***.***
>
> ***b) the importance of planktonic components to the ecology of Port Kembla Harbour, both as a food source and as a source of recruits*** (addressed in Section 2 and 3)***.***
>
> ***c) whether plankton show vertical stratification in the water column and whether measures such as depth selective inlets would minimise entrainment*** (addressed in Section 4.3.2).

1.2. Background

BlueScope Steel is proposing to use a once through salt water cooling system utilising salt water from Port Kembla Harbour to cool the ICP's steam turbine generators. The ICP will draw salt water from Port Kembla Harbour via the existing salt water channel utilising the spare capacity in the existing lift pumps at the entrance to the Port Kembla Inner Harbour (the Cut, Figure 1).

This report is in addition to two previous desktop studies:

- Johnston, Carey & Knott (2006): outlined the potential ecological issues and effects of the operation of the ICP;
- Knott & Johnston (2007): reviewed the available data on plankton in Port Kembla Harbour and the existing ecological literature regarding mortality rates of plankton entrained in industrial cooling systems; and outlined the potential effects of the ICP on plankton.

It is expected that the increased seawater extraction from Port Kembla Harbour may result in an extraction of 32% of the plankton every 6 days in winter and 17 % every 3 days in summer from Port Kembla Harbour (CLT, Sept 2006). Therefore, an assessment regarding the potential ecological effects of this plankton extraction and mortality upon the ecology of Port Kembla Harbour has been undertaken.

This report will conduct an ***a priori*** literature review to assist in predicting potential ecological effects. Conceptual models based upon an understanding of plankton ecology and prevailing water circulation patterns in Port Kembla Harbour will also be proposed which outline scenarios under which ecological effects may be realised, and may assist in predicting maximum probable scales of impacts across which these ecological effects may occur. Thus the major aims of this report are:

1. To review and summarise existing research which has considered the ecological effects of seawater extraction for cooling purposes on marine communities in recipient ecosystems;
2. To propose conceptual models which may assist in predicting putative ecological effects of plankton extraction under various environmental conditions upon the ecology of Port Kembla Harbour ***beyond the point of discharge*** (i.e. from the opening of Allan's Creek to the oceanic entrance to the Outer Harbour).

This review and the conceptual models will provide a guide to potential effects of the cooling water extraction based on several assumptions.

2. Literature review: The ecological effects of plankton entrainment in industrial cooling systems on marine ecosystems

Since the 1970s there has been increasing awareness in the general public with respect to environmental issues, and one issue attracting increasing attention is the ecological impact of using seawater as a coolant in industrial plants. Industrial cooling systems require water which invariably contains large amounts of plankton which are pumped into, and circulated around, cooling systems before being discharged to the marine environment (Enright, 1977). During this entrainment plankton are exposed to mechanical, thermal and chemical stresses (such as biocides), each of which may reduce the survival of entrained plankton (Mayhew et al., 2000).

The vast majority of research to date has focused upon the acute and immediate effects of these stresses upon plankton survival. Such studies have generally taken the form of collecting seawater samples at the intake zone, and in the outlet canal to compare plankton abundance and determine expected mortality rates (Carpenter et al., 1974). Alternatively, laboratory based experiments have been conducted which simulate the conditions experienced during entrainment under controlled conditions (Taylor, 2006). There is however, a lack of consistency in the ecological literature regarding the predicted survival of entrained plankton once discharged into the marine environment.

Historically, it has been assumed that plankton mortality was approximately 100% (Enright, 1977; Mayhew et al., 2000). Furthermore, the small proportion of plankton that do survive entrainment were thought to experience relatively high latent mortality over several days following discharge, thus further reducing survival expectancy (Enright, 1977). However, with improvements to sampling techniques, more recent syntheses of ecological experiments suggest survival of plankton, taking into account latent mortality, may be as great as 90% (Mayhew et al., 2000). Furthermore, recent reviews of studies undertaken at power plants have found temperature to be the greatest predictor of plankton survival following entrainment (Mayhew et al., 2000; Taylor, 2006). For example, Mayhew (2000) found good survival of plankton if entrained water remained below 30ºC however, at temperatures exceeding 32ºC some species experienced 100% mortality. Thus, estimates of plankton survival following entrainment in industrial coolant systems vary greatly from absolute mortality to greater than 90% survival. This variance is probably due to operational conditions of individual coolant systems, particularly the proportional change in the temperature of the coolant water as it passes through the cooling system (Mayhew et al., 2000; Taylor, 2006). It should be highlighted however, that there appear to be few studies which consider sublethal effects of entrainment upon factors such as mobility which may also influence survival of entrained plankton following discharge (Enright, 1977).

A detailed assessment of the potential ecological impacts of plankton entrainment for Port Kembla Harbour is reliant upon estimates of plankton survival following entrainment. However, such information is not readily available for the current Port Kembla cooling system. Currently, the outflow pipework becomes fouled by sessile invertebrates and requires the uses of anti-fouling agents periodically to remove the invertebrates. This fouling clearly suggests that some plankton survive the entrainment process as they are able to colonise the outflow pipes of the one-way cooling system. Nevertheless, in a conservative approach to the initial assessment of the effects of the ICP on the plankton of Port Kembla Harbour it has been assumed (although unlikely) that the cooling water emanating from Allan’s Creek contains no live plankton (i.e. it is effectively “sterile”). Hence, the remainder of this report will focus on potential ecological effects of 100% entrainment mortality which results in a reduction in total plankton abundance of 6% daily (or 32% every 6 days in winter and 17%

every 3 days in summer; CLT September 2006), ***beyond the discharge point*** upon the Inner and Outer Harbour.

Box 1: Plankton mortality following entrainment

- Estimates of plankton mortality due to entrainment vary from 10-100%
- One factor which strongly influences survival rates is the increase in temperature of seawater during passage through the cooling system
- Entrained plankton that do survive often experience delayed mortality and sublethal effects which increase mortality rates over longer periods of time
- In this report a conservative approach is taken and it is assumed that plankton mortality is 100% following entrainment into the ICP cooling system
- This is a conservative assumption

2.1. Ecological effects of the use of seawater in industrial cooling systems on marine ecosystems

There has been a relatively large amount of research considering the immediate effects of entrainment upon plankton survival. Fewer studies, however, have considered the ecological effects of plankton entrainment upon marine systems from which cooling water is taken, and into which it is discharged. The vast majority of research has considered effects on plankton only until the discharge point. This is an important point of distinction, as the ultimate aim of most environmental management strategies is the protection of entire ecosystems (ANZECC 2000), rather than a single component of an ecosystem (such as plankton entrained into the cooling systems).

Cooling systems of coastal power plants cannot be considered closed systems and there is the potential for plankton mortality within these systems to have flow on effects upon the coastal environment in which the plant operates. Planktonic organisms fill key roles in marine ecosystems as primary producers (phytoplankton) and as a source of food for higher trophic level organisms such as fish (plankton and zooplankton). Furthermore, many marine organisms spend at least part of their life-cycle as planktonic larvae before they settle and become sessile. Thus, enhanced extraction of plankton in Port Kembla has the potential to impact upon various components of the marine ecosystem. Unfortunately, a review of the available ecological literature highlights that very few studies have considered such ecological effects and this is an area requiring much closer attention than has been the case to date.

Any disturbance, be it anthropogenic or natural, has the potential to have two broad types of ecological effects in marine systems. These two types of effects are referred to in the ecological literature as direct and indirect ecological effects. In the case of plankton entrainment, the direct ecological effects may include plankton mortality (which is well established), and a reduction in the abundance and/or diversity of plankton in marine waters surrounding the discharge point (which has not been extensively studied). Indirect ecological effects are those which are a result of “flow on” effects which occur as a result of decreased plankton abundance. For example, there may be alterations to the number of fish which are reliant on plankton for food around the discharge point post-ICP.

Furthermore, if plankton species show differing sensitivities to the physical and chemical stresses associated with entrainment, one may also find alterations to the composition of plankton communities in waters around the discharge point. Specifically, species which are tolerant of the chemical, mechanical and thermal stresses associated with entrainment would be expected to comprise a greater proportion of plankton communities around the discharge point. Thus, a power plant cooling system can effectively be considered as a “selective predator”, which has the potential to remove some species of plankton, but not others (Enright, 1977).

In reality however, the potential for these direct and indirect effects have been rarely studied beyond the actual discharge canal. Thus, the ecological effects of plankton entrainment for the ecology of the wider ecosystems in which power plants occur are quite poorly understood. Of the few studies that have been conducted, variable effects of plankton entrainment in cooling water systems have been found upon the ecology of receiving systems (summarised in Table 1).

Several studies have found no detectable effects of cooling water discharge upon the abundance of plankton beyond the actual discharge point (Carpenter et al., 1974; Jordan et al., 1983; Poornima et al., 2005). In these cases, while mortality of plankton in cooling systems ranged from 25 to 100% (Table 1), no detectable reductions in plankton abundance were found in receiving waters. Generally, the authors considered the lack of effects were a result of rapid mixing of the discharge with “natural” seawater which was relatively rich in plankton, and the ability of plankton surviving the entrainment to recover and regenerate which replenished depleted stocks relatively quickly (Carpenter et al., 1974; Jordan et al., 1983; Poornima et al., 2005). Thus, in wave and current dominated coastal marine ecosystems, and estuarine environments with good tidal or river flushing, effects of cooling water discharges may be quite minor.

Some studies have however, identified reductions in zooplankton biomass and primary production up to 200 m from the discharge of industrial cooling systems (Fox and Moyer, 1975; Shiah et al., 2006; Youngbluth, 1976). In these studies, ecological impacts took the form of reduced plankton abundance which recovered over several hundred metres from the discharge point as discharged waters mixed with “natural” seawater. The study which identified the largest impact of an industrial cooling system examined a plant which discharged cooling water into a coastal embayment (Youngbluth, 1976). It would appear likely that embayments which have slow turnover with coastal waters would have the largest possibility of ecological effects. Thus, it is clear that under certain operational conditions and in some marine environments there is the potential for plankton entrainment to alter the abundance of plankton in receiving systems.

It is interesting to note from Table 1, that the likelihood of ecological effects is not easily predicted by plankton mortality following entrainment. Studies which found no effects examined the ecological effects of cooling systems which resulted in high plankton mortality (Table 1). Those studies which did find ecological effects were not necessarily those which found the greatest mortality of plankton during entrainment (Table 1). Such a finding suggests that the potential for ecological impacts of cooling water discharges is not simply determined by the mortality rates of plankton, but the environment into which cooling waters are discharged (Enright, 1977). In the following section of this report is a discussion of conceptual models of ecological impacts which have been developed by considering a range of water flow conditions post-ICP as a means of predicting the scale and intensity of potential ecological impacts.

In addition to these direct effects there may be indirect ecological effects which manifest later. For example, many sessile organisms, fish and algae disperse as planktonic larvae before they settle to the seafloor and assume a benthic existence. If these planktonic larvae are entrained in cooling systems this may result in a reduced pool of potential larval recruits of benthic organisms (e.g. barnacles, sponges and ascidians) around the discharge point. Such ecological effects would be seen in reduced recruitment of sessile invertebrate communities around cooling water discharge points and may not be immediately apparent, but rather take some time to become obvious. These types of studies were called for in the late 1970s (Enright, 1977) and this still remains an area which requires research as no studies were identified which considered the effects of plankton entrainment upon the recruitment of benthic invertebrates around the discharge of a cooling system. One study was identified which described conceptual models which may be of assistance in predicting potential ecological effects of larval entrainment upon sessile invertebrate populations (Enright, 1977). These models were not based upon ecological data, but rather predictions generated from ecological theory. These models will be discussed in the following section where we outline conceptual models describing potential ecological effects of the cooling discharge.

There is also the potential for indirect effects upon filter feeding organisms and higher trophic level organisms such as small fish which are reliant upon plankton as a source of food. These effects may be negative (i.e. act to reduce abundances) if filter feeders and fish require live plankton. Alternatively, effects may be positive (i.e. act to increase abundances) if the discharge behaves as a delivery vector, concentrating food particles in a small area, and in a form still available to filter feeders and fish. For example, Schroeter et al (1993) found that the abundance of gorgonian corals and sponges were significantly greater near the discharge of cooling water from a power plant. While many factors may explain this observation, one possible explanation is that the cooling discharge acts to concentrate plankton (albeit dead) in a relatively small area around the discharge point, which would be beneficial for these organisms which feed upon suspended organic matter (Schroeter et al., 1993). It is interesting to note in this case that plankton entrainment did not reduce the available pool of larval recruits substantially enough to affect recruitment of corals and sponges which have planktonic larval stages. Similarly, congregation of fish around the discharge of industrial cooling systems has been noted (Simpson and Dudaitis, 1981). This may be due to the attraction of fish to warmer waters emanating from these discharges, or alternatively the increased plankton numbers available in those areas.

Box 2. Ecological effects of plankton entrainment in receiving systems

- Few studies consider the ecological effects of plankton entrainment upon recipient ecosystems beyond the discharge point of cooling systems.
- Potential effects may be direct (reduced abundance and diversity of plankton) or indirect (reduced recruitment of invertebrates and changes to the abundance of organisms reliant on plankton for food).
- In well flushed coastal environments where “natural” seawater mixes rapidly with cooling water, effects of cooling water discharge may be relatively small. Enclosed waterways with limited or slow water turnover are more likely to experience deleterious ecological effects of plankton entrainment.
- In cases where reduced plankton abundance has been identified in recipient systems, these effects have occurred within 200 m of the discharge point.
- Indirect effects of plankton entrainment are rarely considered and remain poorly understood.

3. Potential effects of plankton entrainment in Port Kembla Harbour

In the following section, specific communities or functional groups of organisms are highlighted which may potentially be affected by plankton entrainment. The following section is considered an initial assessment or indication of potential ecological impacts.

3.1. Specific taxa and functional groups likely to be affected by entrainment

3.1.1. Plankton currently found in Port Kembla Harbour

Table 2 summarises the plankton which are commonly found in the Inner and Outer Harbours. This table has previously been described in detail (Knott & Johnston (2006). Each of these organisms has the potential to be entrained in the ICP cooling system, however by considering the length of time each of these taxa spend in planktonic forms, it has been determined that the taxa most likely to be entrained into the ICP cooling system are jellyfish, copepods, penaid shrimp and barnacle, crab, crayfish and fish larvae.

3.1.2. Sessile invertebrate communities dispersing with planktonic larvae

Many of the taxa identified in Table 2 have planktonic larval stages. Enright (1977) proposes conceptual models which predict potential effects of plankton entrainment by considering population dynamics of organisms which are dependent upon recruitment by planktonic larvae. Essentially, Enright (1977) considers the potential for ecological effects under two broad, but different scenarios:

1. The recruitment success of planktonic larvae is solely a function of the number of larvae available;
2. The recruitment success of planktonic larvae is a function of interactions between adult populations of sessile invertebrates which act to liberate space for new larvae to recruit.

If the success of larval recruitment of sessile invertebrates is simply determined by the abundance of larvae then a reduction in the available larvae by a given percentage would be expected to lead to an equivalent reduction in the size of the adult population. For example, in the case of Port Kembla the additional extraction of seawater is predicted to result in an entrainment of between 17% of the plankton every 3 days (= residence time) in summer and 32% every 6 days in winter (CLT, Sept 2006). Thus, according to models proposed by Enright (1977), the worst case scenario assuming 100% mortality of entrained plankton is that the additional extractions will affect recruitment to adult populations of benthic invertebrates by a maximum of 32% during the residence time.

This is however, a simplistic scenario and in many cases the success of planktonic larval recruits is determined by many interacting factors. For example, the success of recruitment may be controlled by adult density (such as when adults have colonised most or all of the available space for recruitment), or post-recruitment mortality, such as when recruits compete for resources and experience high mortality rates after they have settled (Dayton, 1971). Under these conditions, the population of adults in an area will probably be less defined by the availability of larval recruits than it is by post-larval processes and thus, a reduction in the availability of larvae would be expected to have lesser effects upon adult population sizes (Enright, 1977). Furthermore, it is possible that plankton communities are subject to density dependent processes. If this is the case, removal of plankton may act to liberate resources which could paradoxically enhance growth and reproduction rates in remaining planktonic community. Thus, the ecological impacts of plankton entrainment are likely to be complex. In addition to sessile invertebrates, a great range of other organisms include a planktonic larval stage or propagule stage in their life history. These organisms include fish and macroalgae. As with sessile invertebrates the worst case scenario for these organisms is a decrease in adult populations which is directly proportional to the larval of propagule mortality.

3.1.3. Planktivorous organisms and benthic detritivores

Dead plankton emanating from the cooling water discharge in the Inner Harbour may have one of three fates:

1. They may remain suspended in the water column in which case they will be available to filter feeders and fish for consumption;
2. They may sink and be deposited in surficial sediments; in which case they will be incorporated into benthic food webs and become available to detritivores (organisms that feed on organic detritus);
3. As plankton pass through the cooling system, mechanical stresses may destroy the organisms, in which case they may be discharged in a form more available to micro-organisms.

Thus, the discharge of dead plankton may have variable impacts upon the ecology of Port Kembla Harbour depending upon its fate. For example, if plankton remains suspended in the water column in a form available to the feeding apparatus of planktivorous organisms, one may predict positive effects (increased abundances) upon filter feeders such as sponges and ascidians. Similarly, small fish may benefit from the discharge and be expected to congregate around the outlet in order to feed upon plankton as has been observed in other instances (Simpson and Dudaitis, 1981). Alternatively if plankton sinks immediately to the seafloor benthic deposit feeders such as amphipods and polychaetes which consume dead organic matter in surface sediments would be expected to increase in abundance. If however, mechanical stresses are sufficient to destroy plankton, this food source may not be available to any macro-organism, and thus a valuable resource would be lost from the system. If this is the case, a decrease in the abundance of filter feeders, fish and detritivores may be observed in the region influenced by the discharge. An increase in bacterial abundance might also be predicted. It should be highlighted that the terms “positive” and “negative” are used by ecologists to indicate direction of change (i.e. increased and reduced abundances of organisms respectively). The terms do not imply benefit or detriment to the ecosystem (e.g. “positive” or “negative” ecological outcomes).

3.1.4. Sessile invertebrate communities outside of Port Kembla Harbour

Planktonic organisms are typically passive in their dispersal and their movement is largely controlled by water currents. Adult populations of benthic invertebrates which have larval stages that persist for long periods of time (days to months) may be maintained by larvae produced by adult populations elsewhere (i.e. metapopulations). This complicates predictions of potential ecological effects of plankton mortality upon Port Kembla Harbour as removal of plankton in Port Kembla may in fact be realised outside the harbour in nearby coastal regions dependant upon external propagule supply (e.g. supply side ecology: Underwood and Keough 2001). An assessment of such ecological effects is beyond the scope of this report.

4. Potential scales of impact

As plankton are at least partly passive dispersers which drift on ocean currents, any meaningful predictions of ecological impacts beyond the discharge point require some knowledge of plankton distribution and the near shore circulation of the discharge (Jordan et al., 1983). In particular it is important to know the influence of the discharge on the natural circulation of the discharge environment (Carpenter et al., 1974). These factors will assist in a determination of the proportion of plankton removed from the system by the intake and the rate of external supply and replenishment of plankton from outside the zone of impact.

Without these specific data from Port Kembla, predictions of potential ecological effects will be limited to conceptual models based on simple scenarios which may logically be expected to occur post-ICP. These conceptual models should not be considered to be precise predictions of the scales across which ecological impacts will occur, but as a simplistic basis which aims to provide an indication of a range of potential outcomes which may assist in the assessment of potential impacts of the ICP. In the following section, several assumptions are made regarding the nature of plankton entrainment:

1. 100% mortality of plankton entrained in the cooling system;
2. Plankton are evenly distributed across Port Kembla Harbour, such that the diversity of plankton entrained in the cooling system is a general representation of plankton present in the Outer Harbour;
3. All planktonic species are passive dispersers which are unable to actively avoid entrainment by swimming away from the inlet currents.

4.1. Pre-ICP circulation models for Port Kembla

Water circulation patterns within the Inner and Outer Harbours of Port Kembla were determined in a report by MSE & CEC (1991). This study found two major inputs of water into Port Kembla which have an influence over the circulation of water in the harbour (Figure 2a, 3a). These inputs are:

1. Tidal exchange between the Outer Harbour and the ocean (saline input);
2. Inputs from Allan's Creek into the Inner Harbour (comprised of , freshwater runoff, heated seawater from the ICP coolant system, No.2 Blower Station Drain, Main Drain and contaminants from steelworks, mining, mixed industry and urban activities).

The combined water inputs from Allan's Creek create a thermal plume which under calm conditions flows from the Inner to the Outer Harbour through the Cut. This thermal plume flows along the surface of the water and generates a counter-current which flows beneath the plume from the Cut back towards Allan's Creek. This counter-current which runs along the seafloor brings water from the Outer Harbour towards Allan's Creek and is therefore believed to be responsible for most of the turnover of water between the Inner and Outer Harbours (MSE and CEC, 1991). This counter-current also carries relatively plankton-rich waters from the Outer Harbour, towards Allan's Creek. Water entering the Outer Harbour as a result of tidal exchange circulates in a clockwise direction within the Outer Harbour, some is entrained in the seafloor counter current flowing towards Allan's Creek whilst the remainder exits the Outer Harbour after a residence time of 3-6 d depending upon season (MSE & CEC, 1991; residence times as per CLT, Sept 2006)

4.2. Potential circulation scenarios post-ICP

4.2.1 Outer Harbour

The additional intake of seawater for the purposes of cooling the ICP may have variable impacts upon plankton abundances in Port Kembla Harbour depending upon flow conditions within the harbour post-ICP. It would appear to be relatively unlikely that an increased extraction of plankton of 32% by the intake at the Cut would have appreciable impacts upon plankton abundance in the Outer Harbour as plankton removed in cooling water is likely to be replaced by plankton entering the harbour during tidal exchange relatively quickly. It should be noted however, that this may result in Port Kembla Harbour becoming a plankton sink, with plankton rich waters entering and depauperate waters leaving, with potential impacts outside the harbour as discussed earlier (Knott and Johnston, 2006).

4.2.2 Inner Harbour

Ecological impacts of plankton entrainment are most likely to be realised within the Inner Harbour adjacent to the discharge point, and the likelihood, or scale of impacts will probably be largely determined by circulation patterns within the Inner Harbour post-ICP. Below we consider three possible scenarios which may occur post-ICP and the likely ecological impacts under each of those scenarios.

SCENARIO 1: Additional extraction does not appreciably influence pre-ICP circulation patterns - No detectable, or slight ecological impacts

Under this scenario, it is assumed that the additional extraction of seawater for cooling purposes from the Cut does not alter the pre-ICP water circulation pattern (Figures 2b, 3b). A thermal plume dominates circulation within the Inner Harbour, proceeding from Allan's Creek to the Cut, with a counter current running from the Outer Harbour to the Inner Harbour along the seafloor. This counter current carries water from the Outer the Inner Harbour which would be expected to be relatively rich in plankton due to tidal exchanges, thus replenishing communities in the Inner Harbour. Under this scenario any deleterious ecological effects of the outflow would probably be confined to a relatively small area surrounding the mouth of Allan's Creek, and be similar to those effects previously identified in the region (MSE & CEC 1991 identified a trend towards reduced abundance and species richness of plankton in the Inner Harbour than the Outer Harbour).

SCENARIO 2: Additional extraction increases flow rates in thermal plume, and underlying counter current - Moderate impacts

The additional extraction of seawater from the Cut may act to intensify the pre-ICP circulation model for the Inner Harbour. Under this scenario, the additional extraction of seawater from the Cut would result in an appreciable extension of the thermal plume emanating from the mouth of Allan's Creek. Associated with this is an increase in the velocity of the counter current which flows beneath the thermal plume which would again bring relatively plankton rich waters from the Outer Harbour to replenish communities in the Inner Harbour (Figure 2c). However, the increased flow emanating from Allan's Creek, in combination with a 32% increase in plankton extraction from the Outer Harbour may slow the rate at which replenishment occurs, resulting in a larger area of the Inner Harbour being affected by the outflow of cooling water. Thus, the increased volume of discharge would be expected to impact upon a greater proportion of the Inner Harbour.

The thermal plume would be expected to flow across the surface of the Inner Harbour as is currently the case. Thus, cooling effluent which is depauperate in plankton would presumably be found to concentrate within the upper few metres of the water column (Figure 3c).

SCENARIO 3: Additional extraction dominates circulation patterns within Port Kembla Harbour - Large impacts

If the increased extraction of seawater at the Cut is sufficiently large to result in an outflow which dominates the circulation of water from the Outer to the Inner Harbour, and back again this would result in a “worst case scenario” for ecology of the system. Under this scenario, circulation would be controlled by a large volume of water extracted from the Outer Harbour, matched by a large outflow from Allan’s Creek towards the Cut which would effectively generate a uni-directional flow of water across most depths within Port Kembla Harbour, limiting the degree to which plankton communities would be replenished by Outer Harbour waters (Figure 2d). Such a scenario has the potential to impact upon the entire Inner Harbour which extends horizontally and vertically to the seafloor. As the replenishing counter-current ceases to exist under this scenario, it would be predicted that the entire depth of the water column would be characterised by plankton-poor waters (Figure 3d). Such a scenario would appear to be relatively unlikely due to the volume of discharge water that would be necessary to overcome the counter current and tidal flushing of the Inner Harbour. Thus, the most likely outcomes are those proposed in scenarios 1 and 2.

4.3. Potential modifications to predictions if assumptions do not hold

While assumptions are necessary to define the bounds of conceptual models, it is prudent to consider the potential implications of the assumptions not being held in the real world. As stated earlier, three main assumptions were made when producing the above ecological models and in the following section we discuss potential modification to predictions if these assumptions are erroneous.

4.3.1. 100% mortality of plankton

As highlighted in the literature review, this assumption is likely to be quite conservative as estimates of plankton mortality in cooling systems vary greatly from 10-100% depending upon operational conditions. The consistent fouling of existing cooling water systems at BlueScope Steel from plankton and other species also suggests that a 100% mortality rate is quite conservative. If plankton mortality is less than 100% (taking into consideration latent mortality and the importance of sub-lethal impacts) then the ecological impacts of the cooling discharge will presumably be reduced in severity and spatial extent.

Furthermore, there is the potential for selective effects upon plankton populations as more tolerant species survive entrainment. If this is the case then impacts may not be seen solely in terms of reductions in the abundance of plankton, but also in terms of changes to the structure and species richness of plankton communities. If this is the case, indirect ecological effects of plankton entrainment would probably be seen in a reduction in the diversity of plankton and sessile invertebrate communities within the Inner Harbour, with these communities becoming increasingly dominated by robust species which are insensitive to thermal, mechanical and chemical stresses. By considering the length of time each of these taxa spend in planktonic forms, we can also predict which taxa most likely to be entrained into the ICP cooling system during their larval life. On the basis of larval life span we predict that jellyfish, crustaceans and fish larvae are the most vulnerable to entrainment (Table 2).

4.3.2. Plankton are evenly distributed

If plankton are not evenly distributed within the Outer Harbour, the intake may target certain species or groups, rather than representing an average sample of all plankton species in the harbour. For example, plankton often shows vertical zonation, with a greater diversity of plankton in the surface or middle depths, than at the seafloor (although there is a daily migration of plankton from deeper depths to the sea surface during night time hours). Depending upon where the intake is located, only a sub-set of the plankton species may be taken into the cooling system. Nevertheless, only one study has assessed (MSE and CEC 1991) whether there was any variation in plankton with depth in Port Kembla Harbour. As this study had very little replication, it is unclear whether there were any differences between planktonic communities at the surface and at 6m except for Gobidae larvae (a specific family of benthic fish) which appeared to be more abundant at 6m. Again, if the assumption of even distribution of plankton does not hold, the ecological effects of entrainment would probably be reduced in severity and would take the form of alterations to species richness of plankton and sessile invertebrates around the discharge point.

4.3.3. Plankton cannot avoid entrainment by swimming away from intake

Some plankton may indeed be capable of avoiding entrainment by swimming away from the intake. In particular larval fish may have better swimming capabilities than smaller plankton such as copepods. Any species which are capable of actively avoiding entrainment would be less likely to be impacted by the cooling system.

4.3.4. Seasonal differences in plankton extraction

Throughout this report we have adopted a conservative approach so as to predict maximum probable impacts under a worst-case scenario. However, there is the potential for the amount of plankton entrained in the cooling system to vary seasonally. Current predictions of the amount of plankton entrained in the cooling system range from 17% loss of plankton for every residence time in summer, and 32% loss of plankton each residence time in winter (CLT, Sept 2006). This appears to be due to different residence times in each season (3 d in summer, 6 d in winter). As tidal flushing increases, residence times of water in the harbour will decrease and replenishment of plankton populations by seawater outside the harbour will increase. Thus it would appear that deleterious ecological impacts of the cooling system will be greatest in spatial extent and severity during winter, when residence times are longest and extraction estimates greatest.

Box 3: Conceptual models of potential ecological impacts

- Plankton entrainment may have ecological impacts upon planktonic organisms, sessile invertebrates, benthic and pelagic planktivores and detrivores.
- According to Enright (1977), the worst case scenario of ecological impact would occur when plankton abundance and recruitment to sessile invertebrate communities are directly proportionate.
- Using this scenario, a reduction of plankton abundance by up to 32% can be expected to result in an equivalent reduction in the abundance of organisms with planktonic larvae such as invertebrates, algae and fish post-ICP.
- The scale and intensity of actual impacts will also depend upon circulation patterns post-ICP in the harbour.
- Conceptual models suggest that the area of the harbour affected will be determined by turnover rates of water between the Outer Harbour and the ocean, and the Outer Harbour and the Inner Harbour.

5. Conclusions

The additional extraction of cooling water for the ICP has the potential to impact upon several aspects of the Port Kembla marine ecosystem. An initial examination of the ecological literature suggests functional groups which may experience ecological impacts include plankton communities, sessile invertebrate assemblages and organisms reliant upon plankton for food (such as fish and filter feeders, as well as benthic detritivores).

Simple models of population dynamics suggest that the worst case scenario of ecological impact is a reduction in plankton abundance which equals the extraction of plankton in cooling waters. According to modeling by Cardno Lawson Treloar, this worst case scenario would be a 32% reduction in plankton abundance and larval recruitment during winter, which decreases to approximately 17% during the summer months for each residence time. However, several key factors may interact to reduce these predicted effects. Actual observed ecological impacts will be a combination of actual mortality rates of plankton following entrainment and replenishment of plankton communities via tidal exchanges. Hence, it is unlikely that there will be substantial effects in the Outer Harbour due to reasonable tidal flushing and the subsequent replenishment of plankton from the ocean. The location of the discharge of the ICP deep within the Inner Harbour can be expected to greatly reduce the rate of flushing. The only study which could be found from a similar environment (i.e. an enclosed coastal embayment) found detectable alterations to plankton communities within approximately 200 m of the discharge point. A similar scenario is therefore likely to occur in the Inner Harbour of Port Kembla (i.e. Scenario 2).

The scale of these ecological impacts in the Inner Harbour is likely to be determined by the patterns of water circulation post-ICP. Generally, as the influence of the discharge of the cooling water upon the circulation of water in Port Kembla Harbour increases, so too do the predictions of the amount of the Inner Harbour that will be negatively affected by the plankton extraction. Turnover of seawater through tidal flushing of the Outer Harbour, and the sub-surface thermal counter current between the Outer and Inner Harbours are important factors which will interact with the thermal plume to determine the precise scale of ecological impact. It would however, appear likely that an extraction of 17-32% of the plankton in Port Kembla Harbour will result in detectable alterations to the abundance of plankton in the surface waters adjacent to the discharge point (i.e. Scenario 1 and 2) based on an assumed mortality rate of 100% of all plankton entrained.

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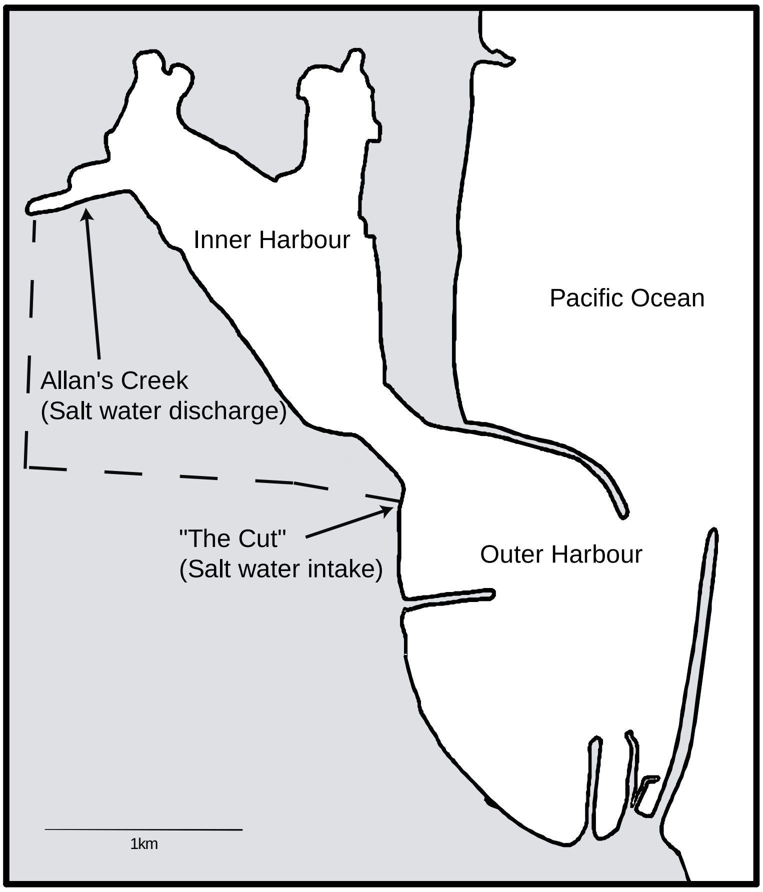

Figure 1.

Map showing Inner and Outer Port Kembla Harbour. The dashed line indicates the approximate position of the cooling system intake and discharge. Light grey shaded areas indicate land (☐) un-shaded areas indicate water (☐)

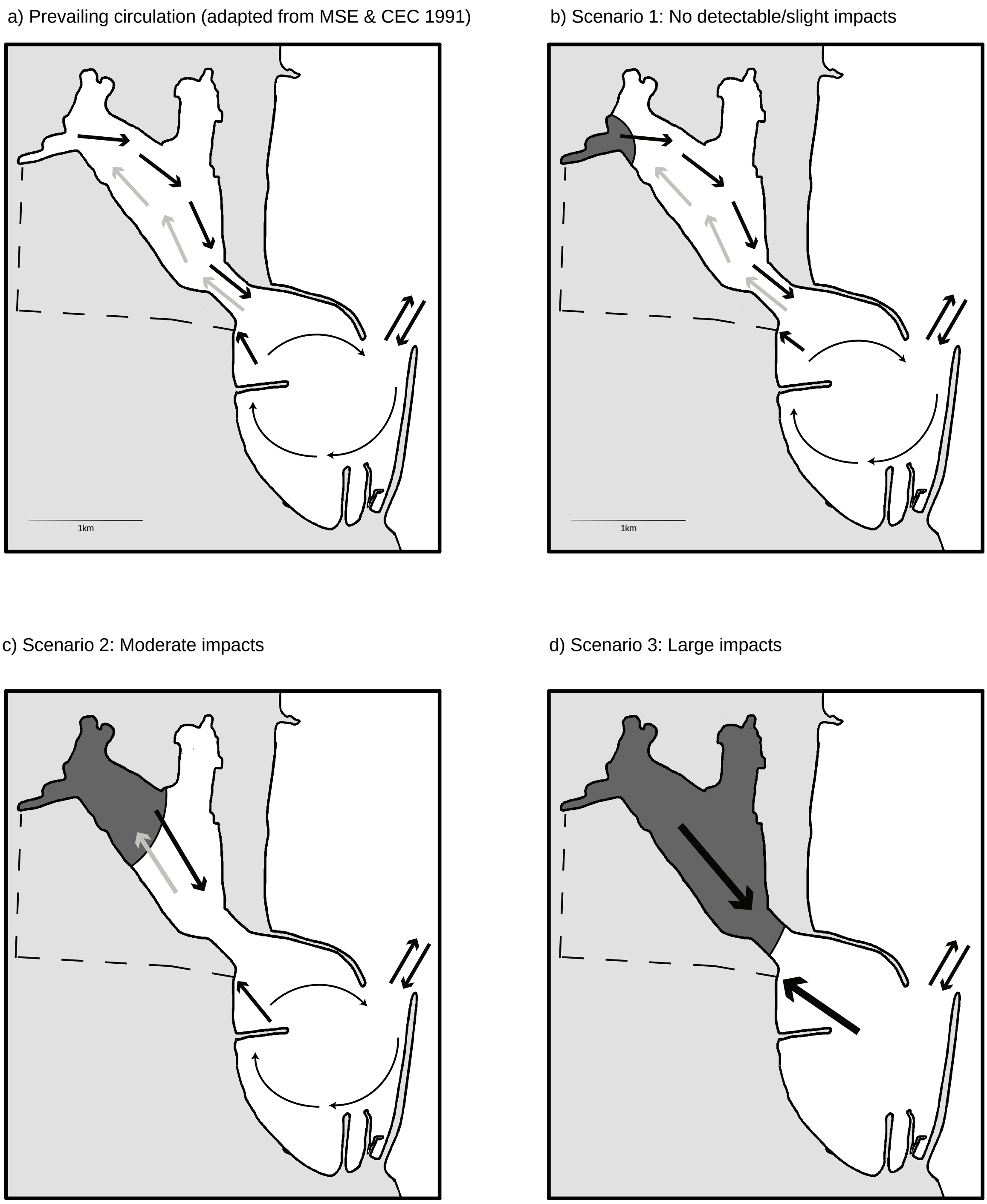

Figure 2. Prevailing and potential horizontal circulation patterns post-ICP and approximate scales of ecological impact which may occur under those conditions. Black arrows indicate surface flows, grey arrows indicate water flows along the seafloor (i.e. the counter-current beneath the thermal plume). Dark grey shading indicates the potential scale of ecological impact under each scenario. Light grey shaded areas indicate land (□), un-shaded areas indicate water (□)

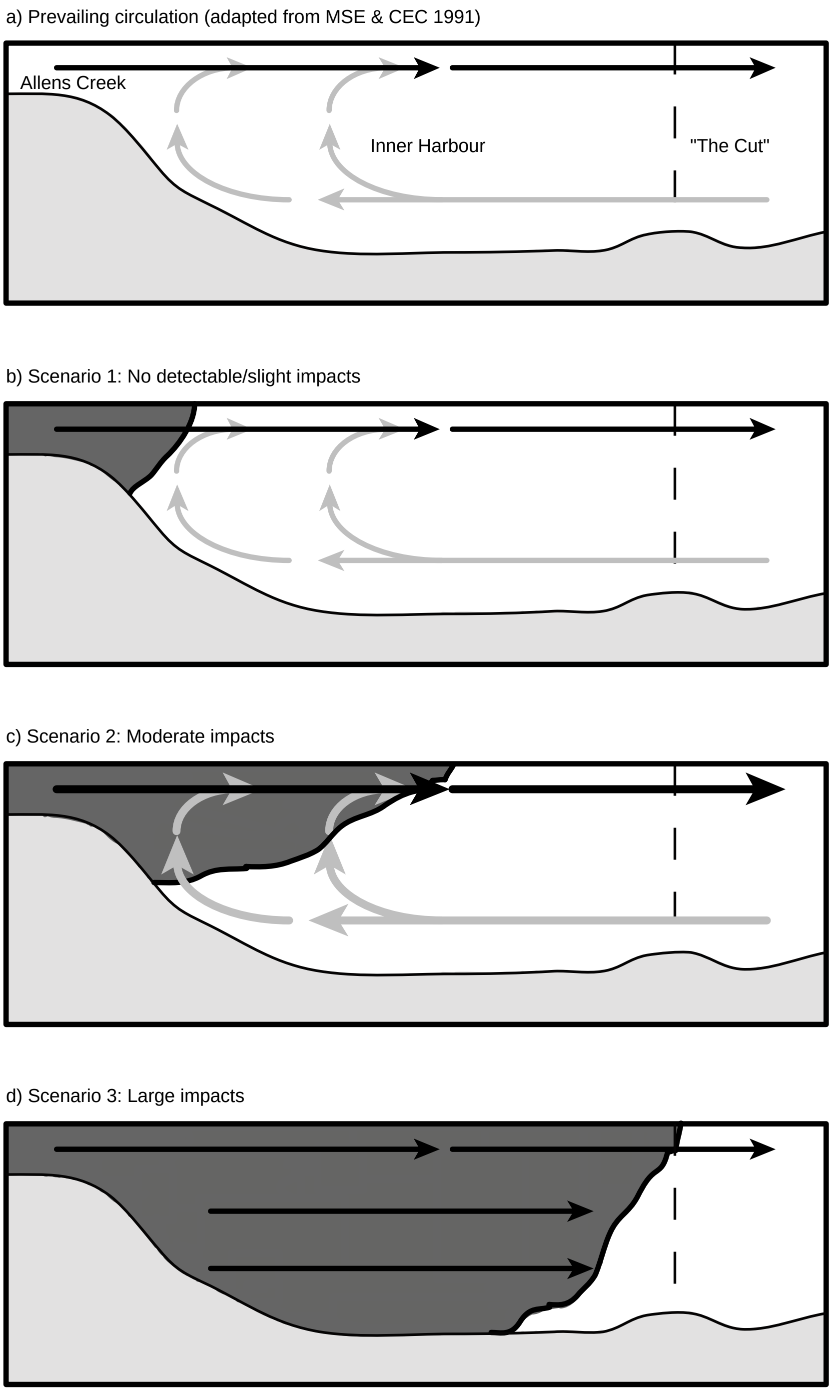

Figure 3. Prevailing and potential vertical water circulation patterns post-ICP and approximate scales of ecological impact which may occur under those conditions. Black arrows indicate surface flows emanating from Allan's Creek (i.e. the thermal plume). Grey arrows indicate water flows along the seafloor (i.e. the counter-current beneath the thermal plume). Dark grey shading indicates the extent of predicted impacts. Light grey shaded areas indicate land ( ), un-shaded areas indicate water ( )

Table 1. Review of ecological effects of industrial cooling plants detected in marine ecosystems.

Reference	Location	Receiving environment	Volume (m^3s^{-1})	Passage time (min)	Plankton mortality	Observed ecological effects on receiving waters	Summary
Jordan et al (1983)	Virginia, USA	Estuarine	106	61	25-80%	No detectable alterations to planktonic communities beyond immediate discharge point	***No detectable effects***
Carpenter et al (1974)	Long Island Sound, USA	Open coast	26	n.s.	70-100%	No detectable alterations to planktonic communities in receiving waters	
Poornima et al (2005)	Kalpakkam, India	Open coast	35	n.s.	35-70%	Rapid mixing of discharge water with 'natural' seawater, no detectable alterations to primary production or phytoplankton abundance within 10s m of discharge point	
Fox & Moyer (1975)	Florida, USA	Open coast	405	8	57%	Reduced primary production found at discharge mixing point due to phytoplankton mortality, not detectable at 1 mile from discharge	***Negative direct effects***
Youngbluth (1976)	Guayanilla Bay, Puerto Rico	Coastal embayment	38	3	95%	Reduced abundance and diversity of zooplankton within ~ 200 m of the discharge, reductions not evident at locations several kilometers from the discharge	
Shiah et al (2006)	Taiwan	Open coast	n.s.	n.s.	100%	Bacterial biomass and primary production ~ 40% lower at discharge mixing point, recovered over a distance of ~ 200 m from outlet	
Schroeter et al (2003)	California, USA	Open coast	52	n.s.	n.s.	Found increased abundances of corals and sponges near the cooling water outfall, possibly due to a concentration of dead plankton in the area which served as food	***Positive indirect effects***

n.s. = not specified

Table 2. The ratio of life or larval span of common or commercially important planktonic organisms and the residency time (Ti) of water in Port Kembla Harbour. A ratio greater than 1 indicates that the taxon will be likely to be entrained into the cooling water system during its life or larval span (life and larval spans may vary for many taxa so lower and upper estimates are presented). Predicted indexes are presented for summer (average and peak loads) and winter (average loads) both before and after the commissioning of the ICP. Adapted from Knott & Johnston (2006), continued over page.

Taxa	***Life or larval span (d)***	***Summer-Pre-Ave (Ti = 28.5 d)***		***Summer-Post-Ave (Ti = 18.4 d)***		***Winter-Pre-Ave (Ti = 29.6 d)***	
		Lower	Upper	Lower	Upper	Lower	Upper
Diatoms	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Dinoflagellates	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Jellyfish	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Copepods	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Penaid prawns	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Bryozoan larvae	0.05 - 5	0.00	0.18	0.00	0.27	0.00	0.19
Barnacle larvae	14 - 21	0.49	0.74	0.76	1.14	0.52	0.78
Crab larvae	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Crayfish larvae	90 - 180	3.16	12.81	4.89	19.84	3.35	13.57
Mussel larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Oyster larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Abalone larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Urchin larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Ascidian larvae	0.05 - 7	0.00	0.25	0.00	0.38	0.00	0.26
Fish larvae	90 - 730	3.16	25.61	4.89	39.67	3.35	27.14

Table 2. (Continued)

Taxa	*Life or larval span (d)*	*Winter -Post-Ave (Ti = 18.4 d)*		*Summer-Pre-Peak (Ti =*		*Summer-Post-Peak (Ti = 17.9 d)*	
		Lower	Upper	Lower	Upper	Lower	Upper
Diatoms	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Dinoflagellates	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Jellyfish	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Copepods	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Penaid prawns	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Bryozoan larvae	0.05 - 5	0.00	0.18	0.00	0.27	0.00	0.19
Barnacle larvae	14 - 21	0.49	0.74	0.76	1.14	0.52	0.78
Crab larvae	90 - 365	3.16	12.81	4.89	19.84	3.35	13.57
Crayfish larvae	90 - 180	3.16	12.81	4.89	19.84	3.35	13.57
Mussel larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Oyster larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Abalone larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Urchin larvae	3 - 7	0.11	0.25	0.16	0.38	0.11	0.26
Ascidian larvae	0.05 - 7	0.00	0.25	0.00	0.38	0.00	0.26
Fish larvae	90 - 730	3.16	25.61	4.89	39.67	3.35	27.14