Derwent Estuary Water Quality Improvement Plan Stage 2:

Heavy Metals & Nutrients

SYNTHESIS REPORT

A project supported under the Australian Government Coastal Catchments Initiative

Tasmania
Explore the possibilities

Derwent Estuary Program

Australian Government

DERWENT ESTUARY

WATER QUALITY IMPROVEMENT PLAN STAGE 2:

SYNTHESIS REPORT AND RECOMMENDATIONS

Management of heavy metals and nutrients

July 2010

EXECUTIVE SUMMARY

The *Derwent Estuary Water Quality Improvement Plan* (WQIP) was carried out in two stages, supported through grants from the Australian Government's *Coastal Catchments Initiative* program. Stage 1 focused primarily on heavy metal contamination, while Stage 2 included a major focus on nutrient enrichment. Over 20 scientists have contributed to this WQIP, primarily through partnerships with CSIRO and Tasmanian Aquaculture and Fisheries Institute. Key elements of the WQIP for both heavy metal and nutrients included:

- an assessment of heavy metal and nutrient sources, sinks and cycling within the estuary;
- monitoring of water, sediments and biota;
- investigations of sediment processes, toxicity and bioaccumulation;
- implementation of a suite of high-resolution system models (hydrodynamics, sediment transport, toxicants and nutrient-response);
- use of these models to test a range of management scenarios;
- development of proposed targets for heavy metals and nutrients;
- management recommendations.

Key Findings – Heavy Metals

Zinc was selected as the primary indicator of heavy metal contamination as it is by far the most abundant heavy metal in the Derwent and can be readily measured in water, sediments and biota, thus enabling the development of calibrated estuary models. Furthermore levels of most other heavy metals (e.g. cadmium, copper and lead) showed a strong correlation with zinc levels, and it was anticipated that management actions proposed to address zinc contamination would address most other metals as well.

An assessment of heavy metal loads discharged to the estuary was carried out, including major industries, sewage treatment plants, urban stormwater, tips and landfills and the Derwent River catchment. The single largest source (>80%) was found to be the zinc smelter, in particular the groundwater contamination at the site which contributed the majority of the current load. The second largest source was identified as urban stormwater run-off.

The large area of contaminated sediments in the Derwent estuary raised a number of important questions for future management. Analysis of short cores indicates that the most contaminated middle reaches of the estuary are undergoing some degree of natural recovery, with highest heavy metal levels now occurring at a depth of about 20-30 cm below the surface. While surface sediments are still highly contaminated, the majority of these metals are relatively inert and/or tightly bound to sediments and do not appear to leach readily to the overlying waters under current conditions. However, should the current situation change (e.g. oxygen depletion, physical disturbance) there is the potential that sediments could become a significant source of heavy metals. Sediment incubation experiments demonstrated a clear link between dissolved oxygen levels and heavy metal mobility, with a very rapid response to reduced oxygen levels (i.e. within 24 hours).

Investigations into heavy metal toxicity yielded varying results, depending on the specific sites and test organisms used. A comparative survey of benthic invertebrate communities in the Derwent and Huon estuaries documented an unexpectedly abundant and diverse benthic community in most areas of the Derwent, and indicated that heavy metal contamination was not the overriding factor controlling benthic infaunal community composition for the estuary as a whole. A series of experiments using the native brittlestar (*Amphiura elandiformis*) suggested that this could be a useful native indicator of sediment quality/toxicity in the Derwent, particularly as it can be readily observed using video survey methods. Surveys of Derwent estuary biota confirmed high levels of heavy metal bioaccumulation, with the highest levels recorded in fish and shellfish from the middle estuary and from Ralphs Bay. A pilot survey of a broader range of functional groups also documented generally higher levels of metals in biota collected from the middle estuary but did not find a consistent pattern between trophic levels. Based on the investigations carried out to date, it appears that the issue of bioaccumulation rather than toxicity may be a more significant concern in the Derwent, warranting further investigation, particularly with respect to mercury.

As part of the target-setting process, an interim water column target of 15 µg/L total zinc was selected, corresponding to the ANZECC trigger level to protect 95% of species (i.e. slightly- to-moderately disturbed system). A series of modeling runs suggested that this would correspond to a reduction in the annual load by approximately 30 to 95 tonnes of zinc/year, and that this could potentially be achieved through a combination of remediation works at the zinc smelter site and improved stormwater management.

Key Findings – Nutrients

An assessment of nutrient loads discharged to the estuary was carried out, with a focus on nitrogen which is the limiting factor for algal growth in most marine systems. The majority of nitrogen was found to be derived from marine sources (44%), followed by inputs from the River Derwent catchment (29%) and sewage treatment plants (18%). Aquaculture wastes associated with fish farms in the D'Entrecasteaux Channel and Huon are likely to be a component of marine inputs, particularly during summer months.

A detailed biogeochemical model for the Derwent estuary was successfully implemented and validated against observations, providing a good understanding of the interplay between estuarine morphology, hydrodynamics and nutrient processing. The model indicates that the majority of nutrients within the estuary are retained within the system, with elevated levels of dissolved nitrogen, phosphorous and chlorophyll *a* predicted (and observed) in the middle reaches of the estuary and at depth.

The model was used to evaluate three alternative management scenarios:

- a near pristine scenario which removed all anthropogenic inputs but retained the existing (modified) flow regime of the River Derwent;
- an 'Active Management' scenario for 2015 that assumed reduced anthropogenic inputs as compared to 2003, and:
- a 'Business-as-Usual' scenario for 2015 that assumed increased anthropogenic inputs as compared to 2003, as well as low river flows.

These model runs highlighted the critical role played by denitrification in maintaining the overall health of the estuary, in that an estimated 40 to 60% of the nitrogen load to the estuary is removed through this process. Without this denitrification capacity, nutrients could accumulate to high levels in the Derwent, resulting in poor water quality. This highlights the need to identify and protect areas with high nutrient removal capacity.

The model runs also indicate that freshwater flows from the River Derwent play a major role in nutrient and chlorophyll dynamics throughout the estuary. Low river flows affect the estuary in several important ways, particularly through increased penetration of nutrient-rich water from the Channel and Storm Bay into the lower estuary, as well as through reduced discharge of highly coloured river water, resulting in greater water clarity in the upper estuary.

Further work is needed to develop robust nutrient indicators and targets for the Derwent estuary, particularly in light of the critical role played by river flows. It is recommended that additional model scenarios be tested to evaluate future management scenarios under a range of different river flows to determine under what conditions and in which areas the estuary is most vulnerable. Using this information, targets can be set to protect against a 'worst case scenario'. In the interim, the 2015 'active management' scenario is clearly a preferred management direction, in comparison to either the 2003 or 2015 'business-as-usual scenario'. This would suggest a maximum annual nitrogen load of about 2600 tonnes, and certainly no more than 2900 tonnes (2003 load) if the current trophic status and oxygen levels of the Derwent are to be maintained or improved. It will be particularly important to set dissolved oxygen targets that both protect benthic communities and maintain sediment processes, particularly with respect to the remobilisation of heavy metals.

Management Recommendations and Implementation

The following management actions are recommended to further reduce heavy metal loads to the Derwent, manage nutrient inputs, limit risks associated with contaminated sediments and manage seafood safety risks. A number of actions have recently been completed or are currently underway to implement these recommendations, as described below.

1. ***Continue to reduce heavy metal inputs*** from external sources, particularly through remediation of contaminated groundwater and stormwater at the zinc smelter site and improved management of urban stormwater. Recent actions to implement this recommendation include:
   - Major groundwater and stormwater remediation projects at the Nyrstar Hobart Smelter, covering and/or reprocessing of stockpiles, and improvements to process controls.
   - Stormwater management projects, including a number of Water Sensitive Urban Design initiatives by regional councils
2. ***Minimise disturbance of heavy-metal contaminated sediments*** by limiting and carefully managing dredging and reclamation activities. Recent actions to implement this recommendation include:
   - development of Derwent-specific dredging and reclamation guidelines (in progress).
3. ***Improve seafood safety monitoring and public reporting*** to minimize potential risks associated with recreational fishing in the Derwent estuary. Recent actions to implement this recommendation include:
   - Extended surveys of mercury levels in recreationally-targeted fish and other biota in the Derwent estuary;
   - Updated seafood safety brochure and community service announcement providing precautionary health advice.
4. ***Manage nutrient and organic inputs*** from marine, catchment, sewage treatment and industrial sources to prevent further eutrophication. Recent actions to implement this recommendation include:
   - implementation of major sewage effluent reuse schemes in Clarence and Brighton;
   - tertiary treatment at Selfs Point and Rokeby sewage treatment plants;
   - construction of new secondary treatment system at Norske Skog paper mill (removal of organic matter).
5. ***Manage freshwater flows*** to enhance water quality, wetlands and macrophytes.
6. ***Conserve areas with high nutrient-removal capacity*** including wetlands, tidal flats and seagrass/macrophyte beds. Recent actions to implement this recommendation include:
   - Expansion of the Ralphs Bay Conservation Area.
7. ***Enhance and integrate monitoring and reporting.*** Recent actions that will support this recommendation include:
   - Continued ambient water quality monitoring in the Derwent estuary (monthly) and preparation of annual Report Cards;
   - Commencement of monthly water quality monitoring programs in Storm Bay (TAFI) and the D'Entrecasteaux Channel;
8. ***Improve understanding through targeted investigations*** Recent actions that will support this recommendation include:
   - investigations into Derwent estuary sediment processes, including denitrification rates;
   - mapping and investigations of upper estuary wetland and macrophyte communities;
9. ***Extend and integrate system models to refine targets and guide management***. Recent actions that will support this recommendation include:

- Development of integrated models, sensors and information systems through the INFORMD project, TasMAN project and other initiatives.

Acknowledgements

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- The Tasmanian State Government (EPA Division, Department of Primary Industries, Parks, Water and the Environment);
- Councils border on the Derwent (Brighton, Clarence City, Derwent valley, Glenorchy City, Hobart City and Kingborough);
- The DEP's industry and business partners (Nyrstar Hobart, Norske Skog, Southern Water, TasPorts and Hydro Tasmania)

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1. Introduction

The Derwent estuary lies at the heart of the Hobart metropolitan area and is an asset of great natural beauty and diversity. Named for the Celtic word 'clear water' in 1794, the Derwent is an integral part of Tasmania's cultural, economic and natural heritage. The estuary is an important and productive ecosystem and supports a wide range of habitats and species. Approximately 40% of Tasmania's population – nearly 200,000 people – live around the estuary's margins. The Derwent is widely used for recreation, boating, fishing, marine transportation and industry. Further upstream, the Derwent River supplies the majority of the region's drinking water supply and is a major source of hydro-electric power.

A number of environmental issues affect the Derwent estuary, in particular:

- heavy metal contamination of water, sediments and biota;
- elevated nutrient concentrations;
- organically-enriched sediments and locally depressed oxygen levels;
- intermittent faecal contamination of recreational waters;
- altered environmental flows and physical barriers to fish migration;
- infestation by a variety of introduced marine pests and weeds;
- loss and degradation of estuarine habitat and species.

Between 2004 and 2006, the Australian Government's *Coastal Catchment Initiative* funded a Water Quality Improvement Plan (WQIP) for the Derwent estuary that focussed primarily on heavy metal contamination, with a minor emphasis on environmental flows. An overview of heavy metal contamination and a summary of the Stage 1 WQIP report findings are provided in Section 2. The full report can be accessed on the Derwent Estuary Program website at www.derwentestuary.org.au.

The Stage 1 WQIP highlighted several key areas where further information and understanding of heavy metal processes in the Derwent was needed, and also recommended that the estuarine models be extended to incorporate nutrients and organic matter enrichment, as these could potentially influence the stability of sediment-bound metals. See Section 3 for a discussion of nutrients and potential eutrophication effects in the Derwent.

Furthermore, a review of data collected over the past 5 years reveals a number of indications of increasing nutrient stress, including increased water column nutrient concentrations and decreased DO levels in localised areas, as well as reported increases in attached and filamentous algae in shallow bays and intertidal areas.

In 2007, the Australian Government supported a second stage Water Quality Improvement Plan (WQIP-2) for the Derwent estuary to address these issues. This report summarises the findings of the heavy metal investigations and the nutrient modelling. Investigations into heavy metal sediment chemistry, bioaccumulation and toxicity were carried out by scientists at the University of Tasmania/Tasmanian Aquaculture & Fisheries Institute. A summary of these studies is provided in Section 4, with full reports included as Annexes A, B, and C.

A detailed biogeochemical model addressing nutrient and organic matter enrichment was developed by scientists at CSIRO, and this model was used to evaluate the predicted impacts of several alternative management scenarios, as summarised in Section 5. Detailed reports on the biogeochemical model and scenario-testing are provided in Annexes 5 and 6. Section 6 reviews estuarine indicators and targets for the Derwent estuary, while sections 7 and 8 summarise key findings and management recommendations.

1.1 Consultation process used in developing the updated plan

The Stage 2 WQIP was developed in consultation with key regional stakeholders including the state government, councils, major industries (including Nyrstar Hobart smelter and Norske Skog Boyer), research organisations and conservation groups.

Stakeholders were regularly briefed through DEP Steering Committee, Technical Working Group and Monitoring Task Force meetings. Key project findings were presented to the wider community at the Derwent Science – Management Symposium in November 2009, and will be further disseminated *via* the State of the Derwent Report, newsletters, the internet and presentations.

2 Managing heavy metal contamination

The Derwent estuary is affected by elevated levels of heavy metals in water, sediments and biota, which are largely the legacy of past industrial practices. While there have been significant reductions in loads and gradual improvements in estuarine condition, further action is needed to reduce loads and to manage risks associated with contaminated sediments and seafood.

2.1 Stage 1 Water Quality Improvement Plan

The Stage 1 WQIP report reviewed heavy metal sources and loads, set environmental targets and recommended actions to reduce and manage heavy metals in the Derwent. Detailed estuarine models were developed by CSIRO scientists to support the WQIP and extensive sediment investigations were carried out by DEP, TAFI and CSIRO scientists.

Zinc was selected as the primary indicator of heavy metal contamination as it is by far the most abundant heavy metal in the Derwent and can be readily measured in water, sediments and biota, thus enabling the development of calibrated estuary models. Furthermore levels of most other heavy metals (e.g. cadmium, copper and lead) showed a strong correlation with zinc levels, and it was anticipated that management actions proposed to address zinc contamination would address most other metals as well. An interim water column target of 15 µg/L total zinc was selected, corresponding to the ANZECC trigger level to protect 95% of species (i.e. slightly- to-moderately disturbed system).

An assessment of heavy metal loads discharged to the estuary was carried out, including major industries, sewage treatment plants, urban stormwater, tips and landfills and the Derwent River catchment. The single largest source was found to be the zinc smelter, in particular the groundwater contamination at the site which contributed the majority of the current load. The second largest source was identified as urban stormwater run-off.

The large area of contaminated sediments in the Derwent estuary raised a number of important questions for future management. In general, heavy metals were found to be tightly bound to estuarine sediments and did not appear to leach readily to the overlying waters under current conditions. However, should the current situation change (e.g. oxygen depletion, physical disturbance), there is the potential that sediments could become a significant source.

Several pilot studies and baseline surveys into heavy metal toxicity, bioaccumulation and benthic community health were carried out with mixed findings. This area was identified as an important knowledge gap, in need of further investigation.

The WQIP recommended a range of management actions to further reduce heavy metal loads to the Derwent, manage contaminated sediments and reduce seafood safety risks. These include:

- further capture and remediation of contaminated groundwater and stormwater at the zinc smelter site;
- development of dredging and reclamation guidelines and protocols to avoid disturbing contaminated sediments;
- management of nutrient and organic loads so as to prevent low oxygen levels (which could cause sediments to release heavy metals);
- more detailed studies of heavy metals in fish and biota, with a greater emphasis on mercury;
- improved community information and awareness about seafood safety.

2.2 Follow-up actions to implement recommendations

Since the heavy metals WQIP was completed in 2007, a number of follow-up actions have been initiated in line with the recommendations above. These include:

- Construction of a 10 MG stormwater system at the zinc smelter site to capture and treat contaminated runoff from the most highly contaminated areas of the site (Nyrstar: completed 2008);
- Installation of additional groundwater collection infrastructure at the zinc smelter site (Nyrstar: new horizontal finger bore system installed in 2009; additional extraction bore planned in 2010);
- Preparation of draft dredging and reclamation guidelines for the Derwent estuary (DEP: in preparation);
- Derwent estuary seafood safety brochure printed and distributed (DEP: completed 2007 and updated in 2009)
- Studies of mercury levels in recreationally-targeted Derwent estuary fish (University of Tasmania/TAFI: pilot survey completed 2008; more extensive surveys underway)
- Surveys of heavy metal levels in Derwent estuary flathead and shellfish (Nyrstar: completed 2007, 2008, 2009)

3. Managing nutrients, carbon and dissolved oxygen

Preventing eutrophication is a key management goal of the Derwent Estuary Program. Eutrophication of aquatic systems occurs when inputs of nutrients and organic matter increase over time, resulting in ‘blooms’ of nuisance and toxic algal species, nuisance weed growth, loss of seagrass beds, low dissolved oxygen levels, fish kills and odours. In the Derwent, this could potentially be compounded by the release of sediment-bound heavy metals during low oxygen events.

3.1 Nutrient cycling and primary production in the Derwent estuary

Nitrogen is considered to be the primary nutrient that drives plant growth in most marine and estuarine systems, although phosphorus may be an important influence in the upper/fresher reaches.

An initial study in 1993/94 demonstrated that the Derwent experiences elevated nutrient levels, particularly in the middle reaches of the estuary and at depth, where the majority of sewage outfalls are located (Coughanowr, 1995). This study and subsequent work also showed that the estuary experiences strong natural variations in nutrient levels, with seasonally elevated nutrient levels entering the estuary from both the ocean and upper catchment during winter months.

Large inputs of organic matter can stimulate bacterial production, resulting in low dissolved oxygen levels as the carbon is consumed. Organic matter also has a strong affinity for metals, hydrocarbons, pesticides, and many other contaminants, and may scavenge these substances from the water column, transferring them through the food chain or sequestering them in sediments. At higher loading rates, organic matter may accumulate as organic-enriched sediments, characterised by low oxygen levels and impoverished benthic fauna and flora. In extreme cases, organic matter may accumulate as sludge deposits, accompanied by anoxia, death of benthic organisms and production of unpleasant/toxic gases such as methane and hydrogen sulphide.

The Derwent does not have a history of severe nuisance phytoplankton blooms. While chlorophyll levels are periodically elevated in some areas, wetlands, seagrasses, macroalgae and microscopic sediment algae also undoubtedly play an important role in primary production, and some of these species (particularly seagrasses) are sensitive to nutrient enrichment. Significant losses of seagrasses – particularly in Ralphs Bay – have been reported in the past (Rees, 1993).

3.2 Nutrient enrichment – current conditions and trends

A review of nutrient and chlorophyll data collected through the DEP's ambient water quality monitoring program between 2003 and 2009, suggests that the estuary may be experiencing some symptoms of increasing eutrophication, probably exacerbated by unusually low Derwent River flows in recent years.

A review of ambient water quality data collected between Jan 2003 and December 2009 suggests the following trends:

- Extended periods of low dissolved oxygen (DO) in the upper estuary (summer and autumn) and occasional episodes of low DO at sites in the middle and lower estuary;
- Elevated levels of dissolved inorganic nitrogen (DIN, particularly ammonia) and dissolved reactive phosphorus (DRP) at depth, particularly in the upper estuary;
- An increase in ammonia levels near the seaward boundary of the estuary, possibly associated with aquaculture expansion in the channel (Wild-Allen et al, 2009).

Furthermore, a number of other signs of potential eutrophication have been reported in recent years, including:

- Occasional reports of toxic blue-green algae species in the lower Derwent River (probably related to blooms in upstream tributaries)
- Dense beds of intertidal macroalgae (*Ulva*) at middle estuary sites, filamentous and epiphytic algal growth on seagrasses (State of Derwent, 2009) and widespread filamentous algal growth to depths of 7 m in Ralphs Bay (Aquenal, 2008).

Note: further work is needed to confirm and quantify some of these trends.

3.3 Nutrient sources and trends

Nutrients entering the Derwent are derived from a variety of point and diffuse sources. This section reviews the major nutrient sources, including estimated loads and trends from 2003 through 2008.

Sewage treatment plants

Nutrient inputs from sewage treatment plants (STPs) contribute an estimated 18 to 20% of the annual nitrogen load to the system. STP loads are calculated each year by the DEP, based on monitoring data previously provided by councils (and now by Southern Water) to the EPA.

In 2003, 10 STPs discharged treated wastewater to the Derwent estuary, accounting for a combined total nitrogen load of 519 tonnes. The majority of this nitrogen is in dissolved form, predominantly as ammonia. Since 2003, nutrient loads have declined, as a result of advanced treatment and/or effluent reuse at a number of plants. For example, DIN loads have declined by an estimated 28% (138 tonnes) during this 5-year period. Future nutrient loads from sewage plants are anticipated to decrease further, in response to planned effluent reuse (at Rokeby) and tertiary treatment (Blackmans Bay).

Industries

Only a few industries discharge treated wastewater directly to the Derwent estuary – specifically the Norske Skog Boyer paper mill, the Nyrstar Hobart Smelter and Impact Fertilisers. Wastewater from other industries is treated at regional sewage treatment plants prior to discharge, and these emissions have been accounted for as part of the sewage plant loads described above. Estimated nitrogen loads associated with industrial sources are relatively low, accounting for about 3 to 4%.

In 2003, industrial wastewater discharges accounted for a combined total nitrogen load of 83 tonnes. Since 2003, industry-derived nutrient loads have increased slightly due to additional nutrient inputs required to run the secondary treatment process at Norske Skog, which commenced in 2007.

In contrast to nitrogen, industry-derived organic loads have been relatively high until recently, primarily associated with Australia's largest paper mill, which is located on the upper estuary at Boyer. Historically, the Boyer paper mill has been the major source of organic matter to the Derwent contributing over 90% of the anthropogenic Biochemical Oxygen Demand (BOD) load, with the remainder sourced from sewage treatment plants and urban runoff. In October 2007, Norske Skog commissioned a secondary treatment system at the plant that reduced the BOD load by over 80% in 2008. Future organic loads from the mill are anticipated to reduce further, in response to process changes implemented in late 2009 (cessation of eucalypt processing).

Stormwater (Greater Hobart area catchment)

Nutrient inputs from stormwater associated with the greater Hobart metropolitan area were estimated on the basis of stormwater monitoring and catchment modelling, and contribute an estimated 5 to 7% of the annual nitrogen load to the system. Future trends depend to a large degree on the level of new construction and whether urban stormwater management controls such as Water Sensitive Urban Design (WSUD) are utilised.

Catchment sources (River Derwent catchment)

During an average flow year, nutrients associated with catchment run-off contribute an estimated 29% (847 tonnes/year) of the annual nitrogen load to the system. During a low flow year (e.g. 2007) this contribution may drop to 7% (202 tonnes/year). Nutrients are derived from a combination of agricultural run-off (fertilizers and animal wastes), forestry run-off, fish hatcheries, small-scale sewage treatment plants and natural sources. Catchment loads were estimated on the basis of monitoring data collected at New Norfolk, combined with river flow data. Nutrient concentrations vary both seasonally (e.g. nitrates) and with events (particulates). Future trends are difficult to predict, and would depend on how land uses change within the catchment.

Marine sources, including aquaculture

Marine sources contribute an estimated 44% (1258 tonnes/year) to 62% (1665 tonnes/year) of the annual nitrogen load to the Derwent estuary, derived from a combination of natural sources – particularly nutrient-rich Southern Ocean waters – as well as nutrients associated with aquaculture activities in the D'Entrecasteaux Channel/Huon estuary. Marine inputs were estimated based on observations used to set boundary conditions for the calibrated Derwent biogeochemical model.

Southern Ocean inputs are greater during winter months, when the nutrient-rich Zeehan Current dominates the region, while aquaculture inputs may be more significant during summer months. Nutrient dynamics associated with aquaculture production have been recently been investigated as the focus of a multi-year Aquafin CRC project: *A whole-of-ecosystem assessment of environmental issues for salmonid aquaculture* (Volkman et al, 2009). This project included a wide range of investigations, including the development of detailed hydrodynamic and biogeochemical models for the Huon/Channel area.

A finding of particular relevance to the Derwent estuary is that the net transportation of water between the two systems is from the Channel northwards into the Derwent, carrying with it nutrients derived from the increasing numbers of salmon farms. This effect has been observed at DEP monitoring stations B1, B3 and B5 – situated across the mouth of the Derwent estuary – where ammonia levels have doubled between 2003 and 2008(Wild-Allen et al 2009).

It is difficult to partition marine nitrogen inputs between natural and aquaculture related sources, as it is unclear how much of the Channel-derived nutrients are processed within the Channel and/or entrained within the Derwent vs Storm Bay. However, the Aquafin CRC report indicates that fish farm wastes accounted for an estimated 843 tonnes of nitrogen in 2002 and were projected to reach 1747 tonnes in 2009, based on planned aquaculture expansion. It is also estimated that 86% of this nitrogen is in soluble form – primarily as ammonia. Fish farm wastes tend to have the largest impact on marine ecosystems during summer and autumn months, when they augment naturally depleted surface nutrient concentrations, enabling additional phytoplankton growth (Volkman et al, 2009).

Further work is needed to establish the significance of inputs from aquaculture to the Derwent system.

4. Addressing key gaps and uncertainties in heavy metals WQIP

4.1 Sediment chemistry

Stage 1 WQIP studies

The Stage 1 WQIP included a number of studies into the chemistry of Derwent estuary sediments, as described in Section 5.2 and Annex 2 of the heavy metals WQIP report (DEP, 2007). These included:

- designation of contamination 'zones' based on the degree of metal contamination, sediment grain size and organic content;
- analyses of bulk sediment and porewater characteristics within each zone;
- elutriate tests (salt water and weak acid) and sediment resuspension experiments to determine how strongly metals were bound to sediments;

- summer and winter sediment redox surveys to determine sediment oxygenation states.

These studies found that despite the high levels of heavy metals found in bulk sediments throughout much of the estuary, concentrations in pore waters were relatively low and were not well-correlated to the levels found in bulk sediments. Saltwater elutriate tests and sediment resuspension experiments indicated that only a small fraction of the metals in sediments were water soluble and these were readily reabsorbed onto particulates as they settled. The weak acid elutriate tests suggested that over 20% of the zinc and lead in sediments appeared to be associated with iron and manganese oxi-hydroxides, and could be liberated under acidic conditions. However, the remaining zinc, lead and other metals such as copper and nickel did not appear to be acid available, probably occurring as sulphides, which comprise up to one weight percent of the most metal-rich sediments.

The report concluded that heavy metals in most Derwent estuary sediments seem to be tightly bound, particularly where there are elevated level of organic matter, and do not appear to leach readily into the overlying water column under current conditions. However, should these conditions change (e.g. oxygen depletion, physical disturbance), sediments could potentially become a significant source of heavy metals.

The report also found that sedimentation rates within the Derwent appear to be relatively high and that – as industrial emissions have been reduced - the most heavily contaminated sediments are now found at a depth of approximately 10 to 20 centimetres below the surface. Given this on-going burial of the most contaminated sediments and the potential for widespread transportation of sediment-bound metals by tides and currents, a cautionary approach to dredging or other large-scale disturbance was recommended.

Stage 2 WQIP studies

From sink to source: how changing oxygen conditions can remobilise heavy metals from contaminated sediments (Banks and Ross, 2009)

A key objective of the Stage 2 WQIP was an improved understanding of sediment processes, in particular how dissolved oxygen levels may affect the mobility and bioavailability of sediment-bound metals, and the degree to which sediments may act as a source or sink of heavy metals under current and potential future conditions. This was achieved through a series of innovative field and laboratory experiments described below, with the full report provided in Annex 1.

Laboratory incubations were conducted on sediment cores collected from a contaminated site in the middle reaches of the Derwent estuary (mouth of Geilston Bay). The dissolved oxygen (DO) content of the overlying water was manipulated in three treatments – 75%, 20% and 5% oxygen saturation. A DO of 75% represents the ambient bottom water saturation level on the day the sediment was collected, DO of 20% represents an oxygen depletion event and mild hypoxia and a DO of 5% represents severe hypoxia such as can occur in eutrophication events. Metal mobilisation was measured using diffusive gradient thin-film (DGT) probes and conventional pore water extraction techniques. To assist with a mechanistic interpretation of the metal reactions a suite of geochemical techniques such as microsensor profiling, sediment characterisation and sulphide analyses were also employed. (Note: mercury was not included in these experiments due to funding constraints.)

Results show that reductions in bottom water dissolved oxygen saturation can lead to significant increases in the aqueous fraction of zinc, copper and cadmium rendering these metals potentially more bioavailable.

See Figure 1a for an example of how zinc concentrations in porewaters are influenced by varying DO levels. The experiments also suggested some net flux of zinc from sediments to the overlying water column under low DO conditions (Figure 1b), but noted that this may be influenced by a relatively low diffusion gradient.

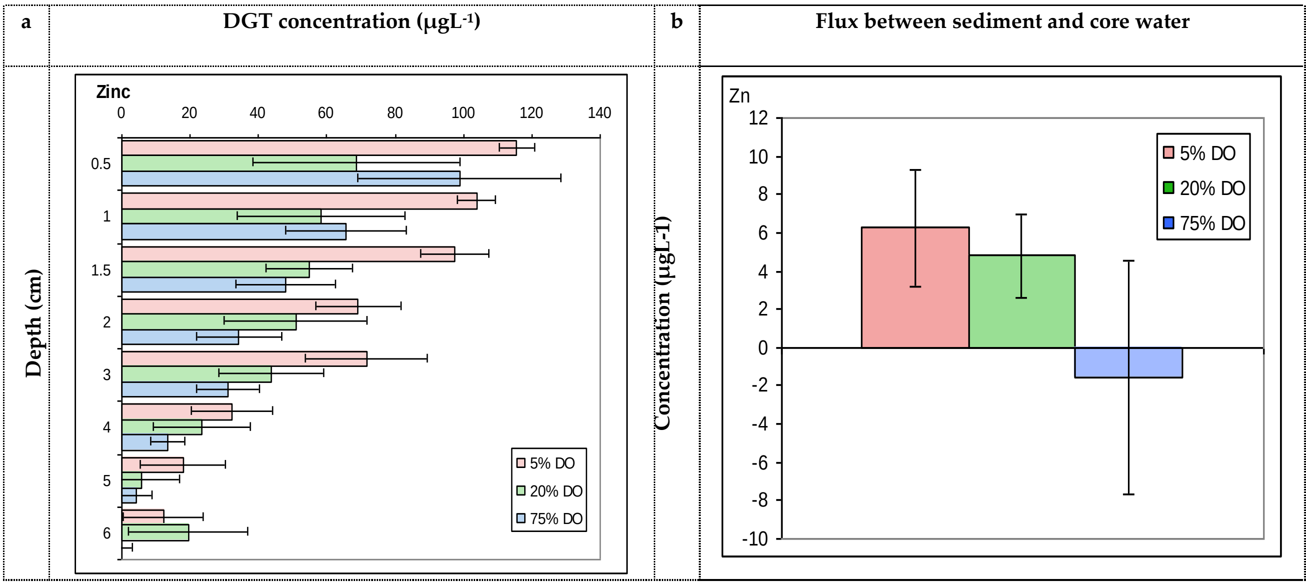


Figure 1. Effects of changing the DO saturation (5%, 20% and 75%) of overlying water on zinc flux from sediments to a) ***pore waters:*** *chart shows depth profiles of zinc concentrations as measured by DGTs after 24 hrs deployment, and b)* ***water column:*** *chart shows the difference in metal concentration detected in samples withdrawn from the flux chamber at the start and finish of the 4 hr incubation. (Error bars = standard error of mean, n=5).*

Another interesting result was the relatively rapid rate of response between water column and near-surface sediment DO levels, with sediment DO levels showing a rapid depletion within 4 hours, as demonstrated in Figure 2. This is likely due to the relatively high porosity of the surface sediments.

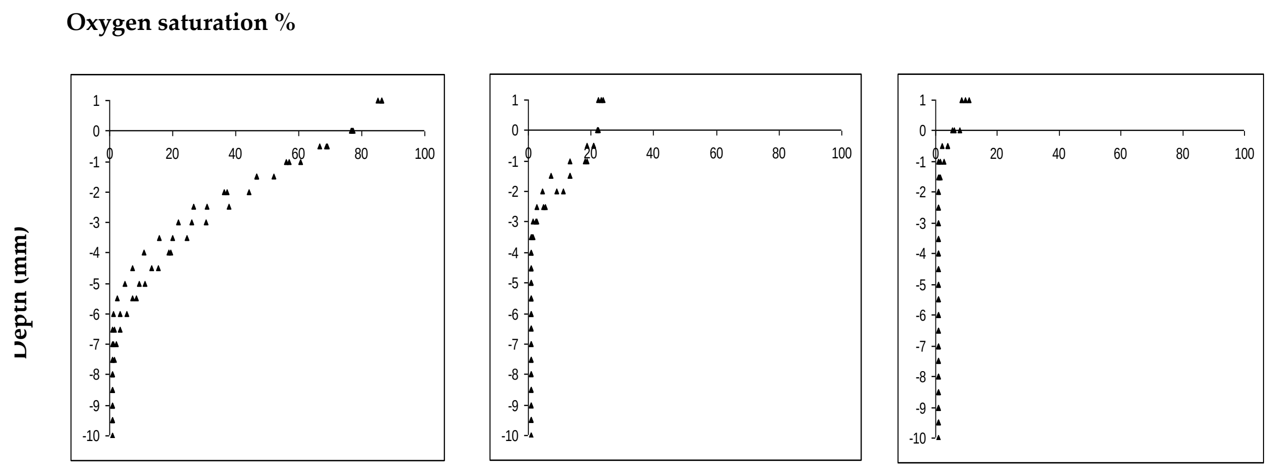


Figure 2: Oxygen penetration depth profiles of test sediments incubated for 4 hours with three different DO saturations in the overlying waters a) 75%, b) 20% and c) 5% (strongly hypoxic).

This study also found that although sediments collected from the study site in the middle of the Derwent estuary had very high concentrations of heavy metals – particularly zinc, copper and lead – the greater proportion (90%) of the zinc and copper load remained insoluble in a weak acid solution (1M HCL) and would therefore most likely be biologically unavailable to organisms. Lead was found to be somewhat more acid-soluble, with up to 30% released. Measured porewater concentrations were in keeping with these results, and suggest that under steady state conditions toxicity levels for most metals, excluding zinc, are within recommended targets. There was no relationship between the concentration of bioavailable metals, as measured by DGTs or conventional extraction technique, and the total or weak acid extracted sediment load. These results indicate that the bulk of the total metals in the sediment are not presently bioavailable and as such, it is only the remainder that has the potential to become available under certain conditions.

Table 1: Metal loads within sediments: comparing partial and total metal extractions.

		0-3 cm			3-6 cm		
Metal	**ANZECC Trigger - High**	**Weak acid extraction (mg/Kg)**	**Total Metals (mg/Kg)**	**%**	**Weak acid extraction (mg/Kg)**	**Total Metals (mg/Kg)**	**%**
Al	-	1556 (± 231)	38200 (± 500)	**4.1**	2074 (± 163)	38350 (± 450)	**5.4**
Cd	10	0.9 (± 0.12)	30 (± 1)	**3**	1.35 (± 0.1)	46.5 (± 1.5)	**2.9**
Co	-	1.4 (± 0.2)	20 (± 0)	**6.8**	1.93 (± 0.17)	23 (± 0)	**8.4**
Cr	370	3.5 (± 0.54)	62.5 (± 0.5)	**5.6**	4.54 (± 0.35)	62 (± 0)	**7.3**
Cu	270	27.4 (± 4.4)	238 (± 8.5)	**11.5**	12.86 (± 2.95)	309.5 (± 7.5)	**4.2**
Fe	-	5285 (± 760)	44950 (± 550)	**11.8**	6522 (± 500)	45250 (± 1050)	**14.4**
Mn	-	21.2 (± 2.7)	520 (± 3.5)	**4.1**	25.38 (± 1.85)	627 (± 4.5)	**4.1**
Ni	52	0.83 (± 0.2)	26.5 (± 0.5)	**3.2**	1.05 (± 0.1)	26.5 (± 0.5)	**4**
Pb	220	355 (± 56)	1155 (± 45)	**30.8**	460 (± 26)	1425 (± 25)	**32.3**
Zn	410	462 (± 64)	5975 (± 255)	**7.7**	686 (± 57)	8450 (± 210)	**8.1**

(numbers shown in red are values that exceed the ANZECC trigger values)

The manipulative experiments demonstrated that altering the geochemistry of the sediment, in this case by lowering the dissolved oxygen saturation of the overlying water, significantly affected the availability of the remaining metals. Reducing the DO led to an increase in pore water concentrations of zinc, copper and cadmium, most likely as a result of the solubilisation of solid phase metals. The pattern of metal release was similar to that of manganese supporting the hypothesis that the increased concentration of these metals within pore waters was a result of the reductive dissolution of manganese oxides and the concomitant release of bound zinc, copper and cadmium.

It should be noted that the oxygen manipulations conducted in this experiment were far greater than the range of bottom water saturations commonly recorded within the environs of the middle estuary. However, the potential for such low oxygen conditions to occur should not be disregarded, particularly as the Derwent waters are subjected to potentially lower flows (drought, water extractions), increased nutrification (STPs, industries and aquaculture) and changing organic loads (both in composition and quantity). Moreover, hypoxia in bottom waters can occur on both temporal and spatial microscales undetected by routine sampling efforts. DO levels fluctuate diurnally; photosynthesis ceases at night but organisms continue to respire, so DO saturation tends to be lowest at dawn. However, most monitoring of estuarine DO conditions occurs by taking a limited number of "point-in-time" measurements during daylight hours. Long-term continuous monitoring would be a more appropriate method to capture low DO events.

This study also highlights the importance of utilising multiple techniques in monitoring threats from contaminated sediments as conventional pore water extraction techniques were less sensitive than DGTs in detecting short term fluxes of metals such as copper into aqueous states within the experimental sediments.

4.2 Biological impacts: toxicity and bioaccumulation

Previous and associated studies

Stage 1 WQIP studies

The Stage 1 WQIP included several preliminary investigations into the biological effects of heavy metal contamination in the Derwent related to toxicity and bioaccumulation, with mixed findings. Initial toxicity screening studies suggested that sediments and pore waters were not highly toxic, however, more definitive tests using more sensitive species indicated significant sediment toxicity in some areas.

A detailed survey of benthic invertebrate communities in the Derwent and Huon estuaries found a surprisingly diverse and abundant fauna living in sediments throughout the Derwent (Macleod and Helidoniotis, 2006). Contrary to expectations, heavy metal contamination was not determined to be the overriding factor controlling benthic community structure in the estuary as a whole. Areas with high levels of heavy metals sustained abundant but modified faunal populations, suggesting either that the bioavailability of metals was low, or that the organisms were not highly sensitive to the contaminants.

The issue of bioaccumulation (the potential for heavy metal accumulation up the food chain), rather than toxicity or direct metal fluxes, was identified as a potentially more significant concern in the Derwent estuary. To assess this, it was recommended that a wider range of marine species be collected and analysed as part of a study considering a range of different trophic levels.

Since the Stage 1 WQIP was completed, there have been a number of follow-up biological investigations, as outlined below.

Nyrstar Hobart Smelter: shellfish and finfish monitoring

Metal levels in seafood (oysters, mussels and flathead) have been monitored annually by the Nyrstar Hobart zinc smelter for many years as a requirement of their license conditions with the EPA. Starting in 2003, the monitoring frequency for shellfish was reduced to a triennial basis, as there had been little consistent change and further resources have been put into a series of caged oyster experiments. Monitoring of flathead (annually) and shellfish (3-yearly) is carried out at sites throughout the estuary, with a control site in the D’Entrecasteaux Channel (Mickeys Bay).

In 2008, mean zinc levels in wild oysters sampled from different regions of the estuary ranged from around 2000 to 4500 mg/kg, while mean lead levels in mussels ranged from 4 to 20 mg/kg. These levels are above the recommended guidelines for human consumption set by Food Safety Australia and New Zealand (FSANZ), which set a Generally Expected Level of up to 130 mg/kg for zinc in oysters and a maximum permitted level of 2 mg/kg for lead in mussels.

Mercury levels in wild finfish (flathead) were compared to the FSANZ guideline of 0.5 mg/kg. Over the past five years (2003 – 2008), median mercury levels in Derwent-caught flathead have been 0.58 mg/kg as compared with the recommended standard of 0.50 mg/kg. Larger flathead, and flathead caught north of the Tasman Bridge or in Ralphs Bay tend to have somewhat higher levels.

Nyrstar Hobart Smelter: caged oyster experiments

During 2007 and 2008, caged oyster trials were conducted using oysters sourced from a clean environment, which were then deployed at 13 locations in the middle and upper estuary. The effect of position in the water column, and length of deployment was studied by conducting staged retrievals from 3 depths. Accumulation of zinc, lead and cadmium in oysters was substantial at most locations. Zinc concentrations after 6 weeks exposure ranged from 200 to 1500 mg/kg - well in excess of FSANZ Generally Expected Levels criterion for Zn of 130 mg/kg. See Whitehead et al, 2010 for details.

Tasmanian Aquaculture & Fisheries Institute: bioaccumulation Honours projects

In 2007/8, a pilot study of heavy metal contamination in recreationally-targeted finfish species from the Derwent estuary was carried out as an Honour's project At TAFI (Verdouw, 2008). This study measured levels of mercury, arsenic, cobalt, chromium, copper, iron, manganese, nickel, lead, selenium and zinc in the muscle tissue of four key recreational fish species; yellow-eye mullet (*Aldrichetta forsteri),* black bream (*Acanthopagrus butcheri),* sand flathead (*Platycephalus bassensis)* and sea-run trout *(Salmo trutta*) from the Derwent Estuary. Results indicated that mercury levels in bream were three times the limit set by the national Food Standards code, while levels in flathead and trout were slightly above this limit. Mercury levels in mullet were generally low. The findings from this study resulted in the precautionary advice being issued by the Director of Public Health against the human consumption of black bream caught from the Derwent estuary.

A second Honours project investigated the relationship between diet and heavy metal concentrations in the sand flathead (*Platycephalus bassensis*) (Hunt, 2008). Heavy metals concentrations were measured in muscle, liver and gonad tissues of sand flathead (*Platycephalus bassensis*), as well as in two major prey groups of flathead (crabs and fish), from four different regions within the Derwent estuary. Metal concentrations in flathead organs showed positive relationships with prevalence of certain prey groups in the diet (based on fish stomach contents analysis). Of the regions studied in the Derwent, Ralphs Bay had the highest heavy metal contamination level in flathead; however, a relationship between prey and total sediment heavy metal contamination was not apparent (Hunt, 2008).

Stage 2 WQIP Studies: toxicity and bioaccumulation

Two investigations focusing on heavy metal toxicity and bioaccumulation were carried out with support from the Stage 2 WQIP, to address key information gaps associated with a) heavy metal bioaccumulation in a wider range of marine species and b) improved understanding of heavy metal toxicity on benthic fauna. These are summarized below, with full reports provided in Annexes 2 and 3.

a) Baseline metal levels in selected faunal species from the Derwent estuary and surrounding areas (Dr Kerrie Swadling and Dr Catriona Macleod)

A pilot study was undertaken into the baseline heavy metal levels in selected trophic groups from the Derwent estuary and surrounding areas. Samples were collected from three sites within the Derwent (Geilston Bay, Ralphs Bay and Upper Derwent), as well as from reference sites in the Huon estuary and offshore from Bruny Island. Seventy-one samples were collected, processed and analysed for a range of heavy metals known to be of particular interest in the context of the Derwent estuary (Al, Pb, Mn, Fe, Ni, Cu, Zn and As). Unfortunately analysis of Hg was beyond the resources available for this study.

The analyses focused on the following trophic groups:

- Benthic deposit feeders (e.g. polychaetes, amphipods, ghost shrimp, molluscs)
- Epibenthic deposit feeders (e.g. crabs, seastars, molluscs/snails)

- Epibenthic filter feeders (e.g. oysters, mussels, tunicates)
- Predatory species (e.g. polychaetes, ribbon worms, skates and dogfish)
- Primary producers (e.g. phytoplankton, macroalgae, seagrass)
- Pelagic grazers (e.g. zooplankton)

This study provided a broad snapshot of the relative metal burdens associated with the main biotic groups in the Derwent estuary, providing useful baseline data with which to assess differences in metal loadings between regions, sites and species. While it was limited in both temporal and spatial representation, it highlighted some interesting differences between trophic levels and raised some significant questions. In particular:

- Heavy metal levels in benthic deposit feeders sampled from the more highly contaminated central reaches of the Derwent (Geilston Bay) were clearly higher than from other sites sampled.
- The metal loadings in the invertebrate species observed could not account for the high metal levels previously reported for common recreationally caught fish species in the Derwent.
- Levels were markedly higher in the sub-tidal epibenthic grazers than in intertidal species. This may be a reflection of differences in dietary composition associated with the organic material deposited in these areas, or the level of microphytobenthos or perhaps even species-specific physiological differences and further work is needed to clarify this.
- In the molluscs there were marked differences between the metal levels in the shell and in the flesh of the animals. Similarly, in tube-building polychaetes the metal levels associated with the tube were often higher. This has significant metal uptake implications for seabirds and other higher trophic order fauna that feed on the whole animal (shell and tube included) and those that remove the fleshy parts.
- How does age affect metal uptake rate/ loading? The ascidians sampled had very high levels for several metals, but it is unclear whether this is a function of their feeding process or their longevity. This leads to several other interesting questions i.e. how responsive are they to declining metal loads and would they be good remediation indicators?
- Heavy metal levels in seagrass sampled from the upper Derwent were found to be low.
- Metal levels in the phytoplankton collected from Ralphs Bay were relatively high. However, it was not clear whether this reflected specific taxonomic differences from this area or was indicative of particular accumulation pathways in this region?
- Metal levels in Geilston Bay zooplankton were 3 times higher than comparable samples from the Huon Estuary and Ralphs Bay. This has interesting implications for the levels in the rest of the estuary. Such a large difference over a small spatial scale might suggest that the zooplankton are responding to localised changes in the food (phytoplankton and organic material) in the water column. However, the phytoplankton results did not support and so there would appear to be some other mechanism driving the zooplankton loadings.

On the whole, the study suggested that environmental conditions (i.e. sediment loadings) do seem to provide a good indication of the infaunal/epifaunal loads for secondary trophic level organisms, however the picture is more complicated with the higher trophic levels. Furthermore, metal concentrations found in the lower order trophic levels did not provide a clear explanation for the metal levels in higher order species, and it is clear that further information is needed to put these results into context. In order to track bioaccumulation pathways, a comprehensive dietary analysis of key species, coupled with detailed ^{15}N analysis to assign trophic level, was recommended as a promising approach. The study confirmed that oysters are sensitive indicators for zinc contamination, and identified several other species that may also be suitable bio-indicators (e.g. ascidians).

b) Copper ecotoxicity studies – development of whole sediment toxicity tests for the Derwent (Eriksen, Macleod and Meyer, 2009)

This study was designed to address several key questions and information gaps identified in the Stage 1 WQIP, specifically:

- Can suitable benthic indicator species be identified as a measure of sediment 'health' in the Derwent estuary?
- How sensitive are these species to specific heavy metals present in Derwent estuary sediments and how does this compare to the national Interim Sediment Quality Guidelines (ISQGs)?
- How do the indicator species react when exposed to the full range of heavy metals present in Derwent estuary sediments?

Ideally, it would have been good to investigate the response of a broad range of indicator species to the full suite of heavy metals typically found in Derwent estuary sediments. However, given time and budget constraints, combined with the need to develop robust methods, this study was limited to a single indicator species, and with an initial focus on copper toxicity.

The native brittlestar, *Amphiura elandiformis,* is a Tasmanian ophiuroid species that has previously been identified as an indicator of sediment quality in key southeastern Tasmanian estuarine systems, where it is widespread in clean soft sediments. It is found in some parts of the Derwent estuary and is abundant in the nearby Huon estuary.

Two separate sediment toxicity assessments were conducted:

Experiment 1 – Involved spiking of clean reference sediments obtained from the Huon estuary at 3 levels (65, 270 and 1000 mg Cu/kg) and subsequent assessment of sediment toxicity for the brittlestar *Amphiura elandiformis*.

Copper was chosen as the reference toxicant for this study firstly because it is a significant contaminant in the Derwent and is known to be highly toxic to a range of marine organisms (hence its common use as an antifoulant). In addition, it is one of the most widely researched toxicants and as such toxicity data for a wide range of species are available. In addition it had a significantly shorter equilibration period for sediment spiking experiments than the other metals of interest in the Derwent estuary (i.e. nickel, zinc, lead or cadmium), and thus could be accommodated within the limited time frame of the study.

Experiment 1 adapted established protocols for sediment spiking to enable treatment and testing of larger sediment volumes for copper toxicity. Using these modified protocols standard 10-day whole sediment toxicity tests were conducted in purpose-built benthic mesocosms to evaluate the response of *Amphiura elandiformis* to varying levels of copper contamination.

The toxicity results clearly indicate that the local brittlestar *Amphiura elandiformis* is sensitive to elevated copper levels in sediments and is a useful environ mental indicator species. At concentrations greater than 270 mg Cu/kg there was a significant toxicity effect on these brittlestars and consequently it is extremely unlikely that this species would occur naturally under such conditions. Given that this species is mobile, it would remove itself from contaminated areas and therefore where brittlestars are observed it is likely that sediment copper concentrations will be less than 270 mg Cu/kg. The sediment spike test results confirmed the relevance of the ISQG for local Tasmanian conditions, with no sub-lethal effects observed where concentrations were at or below 65 mg/kg, whilst concentrations above 65 mg/kg clearly had the potential to cause significant behavioural effects, severe autonomy and mortality.

Experiment 2 – Involved collection of ’natural’ contaminated sediments from the Derwent (Elwick Bay) and clean sediments from the Huon, and subsequent assessment of sediment toxicity for *Amphiura elandiformis.* Copper levels in the Derwent sediments were 165 mg/kg, however these sediments also contained elevated levels of zinc, mercury, lead and cadmium.

Additional tests investigated the effect of sediment manipulations (sieving, defaunating) to evaluate whether different sediment treatment methodologies had an influence on toxic response.

The whole sediment tests comparing Derwent and Huon sediments indicated that there were significant behavioural effects at contamination levels lower than the high effect level for copper identified in the current ISQG, with effects evident at a total copper concentration of 165 mg/kg. However, it is likely that this increased response is due to the presence of other metal toxicants contributing to a synergistic effect.

In conclusion, this project significantly increased our general understanding of the environmental effects of heavy metals, both locally and in a broader Australia-wide context by:

- establishing experimental techniques for spiking and testing large volumes of sediments. This will enable future ecotoxicological studies to be undertaken on community responses to environmental contaminants rather than on individual species responses.
- providing basic metal toxicity data for the brittlestar species (*Amphiura elandiformis*).
- improving our ability to interpret the results of existing ecotoxicity data and community studies by providing a measure of reliability in comparing spiked sediments and real sediments with comparable contamination levels, which will in turn enable a comparison of real and test response characteristics.
- providing information to help managers evaluate change and recovery in urbanised estuaries throughout temperate Australia but specifically in the Derwent. The results of this project will help managers make informed decisions on metal toxicity and develop suitable and sustainable management strategies.

<u>Management implications:</u>

- The native brittle star appears to be a good indicator of sediment health in the Derwent.
- Derwent sediments from the middle estuary are clearly toxic to benthic species such as the native brittle star.
- The interim sediment quality guidelines for copper appear to be appropriate to southeastern Tasmanian waters (based on tests for a single species).
- The sediment spiking techniques developed through this project provide a promising approach for investigation of the toxicity of key heavy metals and comparison to recognised standards. However, a

more extensive and longer term approach is needed to assess toxicity of other heavy metals, as well as the effects of multiple contaminants and this may be done by exposing animals to the natural sediment 'cocktails'.

5. Nutrient response modelling

High resolution 3D biogeochemical models can be implemented in estuarine systems to simulate the seasonal dynamics of nutrients, phytoplankton and dissolved oxygen concentrations. Models validated against observations can be used to interpolate between observations and give valuable insight into the biogeochemical dynamics of coastal waters, including quantification of nutrient fluxes and simulated budgets. In addition, scenario simulations can be used to explore alternative possible futures, or past events, to inform resource managers.

The objective of this project was to implement a high resolution 3D biogeochemical model of the Derwent estuary from New Norfolk to Iron Pot, hindcast to the year 2003. The biogeochemical model is dynamically coupled to an existing calibrated hydrodynamic model (Herzfeld et al., 2005a) and sediment transport model (Margvelashvili 2005). The model was successfully calibrated against water quality observations taken throughout the estuary by the DEP monthly monitoring program estuary and – once validated - used to characterise the cycling of carbon, nitrogen, phosphorus and dissolved oxygen in the estuary. The calibrated biogeochemical model was then used for scenario simulation of alternative management strategies and to reconstruct former conditions in the estuary prior to urbanisation. The full modelling report is provided in Annex 4, and the model scenarios report in Annex 5. The following discussion is derived from these reports.

5.1 Biogeochemical model description and validation (Wild-Allen et al 2009)

The model was developed as part of the CSIRO Environmental Monitoring Suite (EMS), which includes 3D coupled hydrodynamic, sediment and biogeochemical models. The Derwent model is the latest in a series of case studies of temperate Australian estuaries starting with Port Phillip Bay, Gippsland Lakes, the Huon Estuary and D'Entrecasteaux Channel. In most of these previous studies, the BGC model was linked to a box model; the Derwent BGC model is only the second to be directly coupled to a 3D hydrodynamic model and the first in which sewage treatment plant and stormwater sources have been incorporated within the model.

The Derwent Estuary model is similar in design to the D'Entrecasteaux model (Wild-Allen et al., 2005) and has a modular form with a software core linked to a central library of ecological processes. With this structure the biogeochemical model is dynamically coupled to the high resolution 3D hydrodynamic model SHOC and multilayer sediment model (Margvelashvili et al., 2005) that were developed in support of the Stage 1 WQIP. The SHOC model parameter file, as used by Herzfeld et al (2005a) and Margvelashvili (2005) was augmented with biogeochemical model tracers, initial and boundary conditions, and point source loads from industry, sewage and stormwater sources. Additional biogeochemical model parameters were sourced from observations, previous modelling studies and literature studies appropriate for the estuary.

The Derwent model uses a high resolution horizontal grid, with 25 vertical layers, illustrated in Figure 3. The hydrodynamic model is nested in regional and intermediate scale models, forced with Derwent river flow and local meteorology and calibrated against mooring data. Above the Bridgewater Bridge, the model is coarsely resolved, relative to the convoluted channel bathymetry, and has limited capacity to resolve the complex hydrodynamics, sediment dynamics and biogeochemistry of the upper reaches of the estuary.

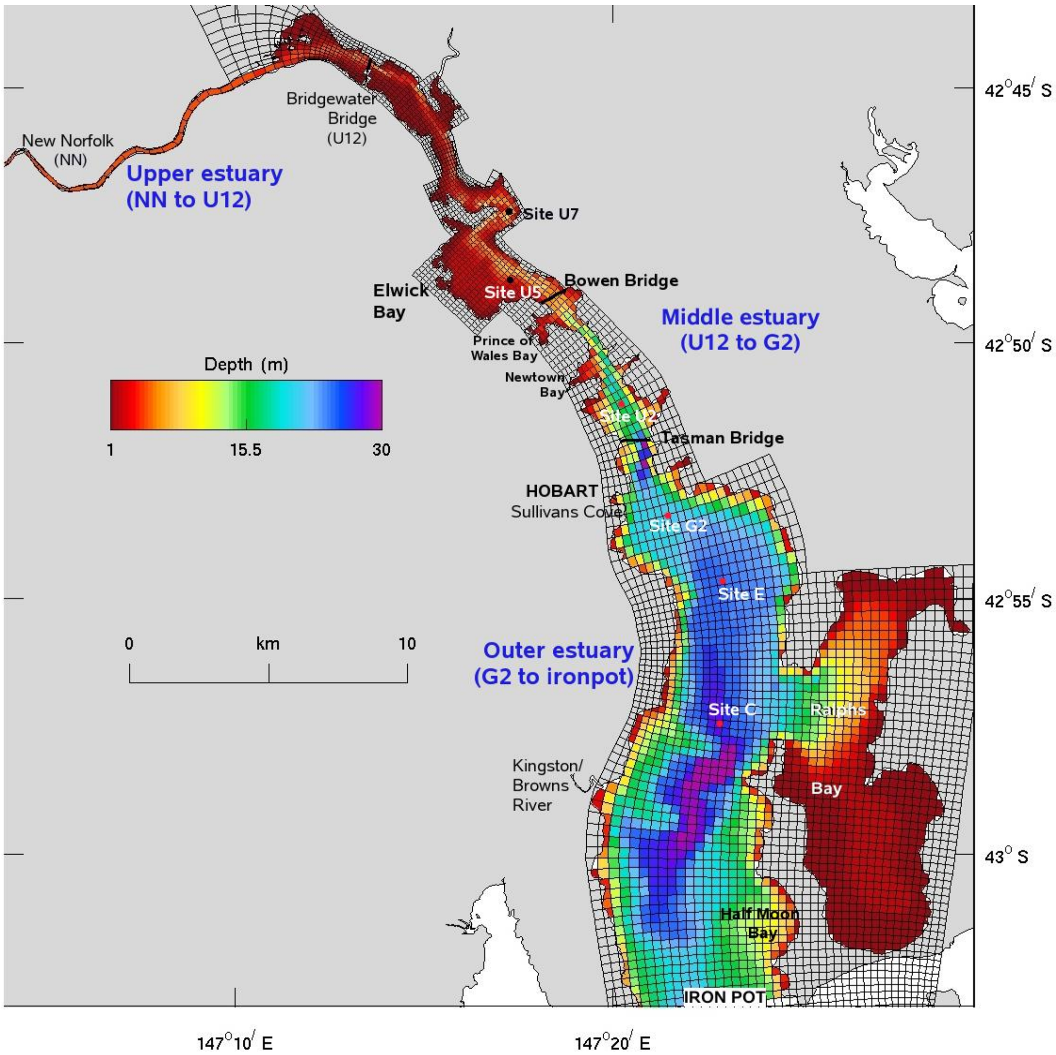


Figure 3 Map of the Derwent Estuary bathymetry showing the model grid and geographic locations. (source: Wild-Allen et al, 2009)

The biogeochemical model simulates the cycling of carbon, nitrogen, phosphorus and associated dissolved oxygen, through dissolved and particulate organic and inorganic phases. The model includes 4 phytoplankton, 2 macrophytes, 2 zooplankton and 4 groups of particulate detritus. The ecological model is organised into 3 'zones': pelagic, epibenthic and sediment, as shown in Figure 4. Pelagic processes include phytoplankton and zooplankton growth and mortality, detritus remineralisation and fluxes of dissolved oxygen, nitrogen and phosphorus. Macroalgae and seagrass growth and mortality are included in the epibenthic zone, whilst further phytoplankton mortality, microphytobenthos (benthic diatom) growth, detrital remineralisation and fluxes of dissolved substances are included in the sediment layer.

Biogeochemical dissolved tracers are advected and diffused in an identical fashion to physical tracers such as temperature and salinity and ecological particulate tracers sink and are resuspended by the same formulation as sediment particles. At each ecological time step, non-conservative ecological rate processes such as growth, nutrient uptake, grazing and mortality are integrated within the ecological module which returns updated tracer concentrations to the hydrodynamic and sediment models via an interface routine.

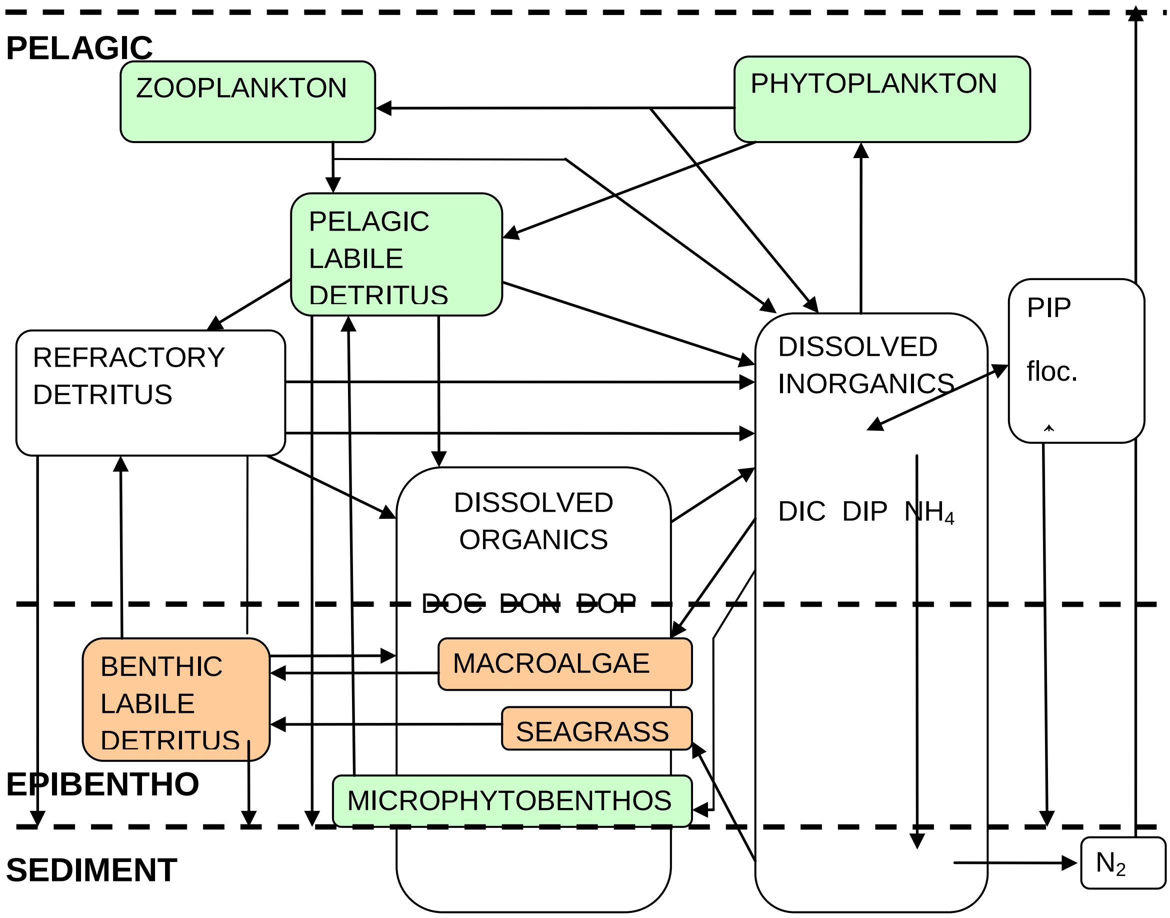


Figure 4 Schematic diagram of the biogeochemical model compartments, links and vertical layers. Green compartments have fixed nutrient content at Redfield ratio (106C:16N:1P); brown compartments are fixed at Atkinson ratio (550C:30N:1P). (source: Wild-Allen et al, 2009)

Model parameters were derived from observations, literature values and previous model simulations. The model ran from January 2003 for 14 months and was initialised with tracer concentrations derived from observations for nutrients, phytoplankton and dissolved oxygen; other model variables were initialised with uniform low concentration. The hydrodynamic model was forced with River Derwent flow, local meteorology and incident irradiation. For the biogeochemical model, boundaries at New Norfolk and across the estuary at Iron Pot were implemented. The northern river end of the model was forced using River Derwent flow data (derived from Meadowbank) together with a time series of inflowing concentrations of model tracers derived from observations. At the southern marine end of the model, tracer concentrations were specified with an upstream condition such that out-flowing concentrations were determined by the model whilst in-flowing concentrations were derived from observations.

Point source nutrient loads into the estuary in 2003 from industry, sewage treatment plants and stormwater sources were parameterised from data supplied by the Derwent Estuary Program (DEP), local industry and councils. Stormwater loads from the greater Hobart catchment were calculated by the DEP on the basis of stormwater modelling (MUSIC version 2), with the model outputs calibrated on the basis of a limited number of field observations. As discussed in Section 3, the majority of nutrients entering the Derwent estuary are derived from external marine and River Derwent catchment sources, however with respect to internal point sources, STPs supplied the largest quantity of nitrogen and phosphorus into the estuary whilst industry loads provided most carbon.

The model was validated against observations made throughout the estuary in 2003 obtained from the DEP database. Observations of nitrate, ammonia, dissolved inorganic phosphorus (DIP), chlorophyll and dissolved oxygen, in surface and bottom waters were directly comparable with model output. There were no observations of macrophytes, phytoplankton assemblages or zooplankton for 2003, although some information on broad patterns was gathered. Validation criteria were set for the conservation of mass and reproduction of the observed timing and amplitude of the seasonal cycle in dissolved nutrients, chlorophyll and dissolved oxygen. Poorly constrained parameters were varied within known ranges during calibration to optimise the simulation of observed biogeochemical substances.

The model achieved all validation criteria and simulated the observed estuarine dynamics of nitrate, ammonia, DIP, chlorophyll, DOC and dissolved oxygen in most parts of the estuary very well. In the upper estuary, the complex channel bathymetry was not well resolved by the relatively coarse model grid and model results should be treated with more caution. In some side bays with very high nutrient loads (e.g. Prince of Wales Bay) the model was not able to reproduce the full range of observed values possibly due to sub-grid scale gradients in observed concentrations and/or under-estimation of actual nutrient inputs. The modeled succession of plankton species, zooplankton abundance and distribution of macrophytes broadly agreed with ancillary data except that favourable conditions for seagrass growth were simulated in Ralphs Bay, where none is currently found.

5.2 Model results and key findings (Wild-Allen et al 2009)

Water column

Model results show a persistent salt wedge structure in the upper estuary which intersects the sea bed upstream of Elwick Bay (near DEP station U7). Nutrient concentrations were greatest in the bottom waters of the mid estuary adjacent to the salt wedge front. Nutrients appear to accumulate in this area from point source loads and remineralisation of organic material that re-circulates in the estuarine currents. Simulated nutrient concentrations were elevated in winter and reduced in surface waters in other seasons due to phytoplankton assimilation. DIP concentrations exceed Redfield ratio in summer indicating that modelled primary production in the estuary is controlled by access to nitrogen and irradiance for photosynthesis. During 2003 the model simulated a number of high rainfall events. In March 2003 the model results show the formation and dispersal of long plumes of nitrate originating from STP and stormwater discharge into Elwick Bay over a 10 day period.

Modelled chlorophyll concentrations were highest in the mid-estuary and along the shoreline in regions of elevated nutrient supply. Sustained periods of high chlorophyll occur in all seasons in sub-regions of the estuary depending on the modelled availability of light and nutrients. In the upper estuary coloured dissolved organic matter (CDOM) and opaque industry effluent limit the propagation of light and photosynthesis through the water column and chlorophyll concentrations are generally low. Simulated phytoplankton biomass showed seasonal succession with dinoflagellates dominating in summer and autumn, large phytoplankton in winter and mixed populations in spring, throughout much of the estuary. In the model, grazing by small zooplankton was tightly coupled with production by small phytoplankton whilst large zooplankton grazing responded more slowly to increases in large phytoplankton and dinoflagellates.

Modelled dissolved oxygen levels were reduced in bottom waters in the upper estuary and the mid and lower reaches of the estuary, particularly in autumn. Regions of low dissolved oxygen saturation were simulated adjacent to the salt wedge front, similar to the distribution of elevated nutrient concentration and likely associated with local remineralisation of organic material.

Benthos

Modelled photosynthetically active radiation reaching the epi-benthos was greatest in the shallow waters of the lower estuary and Ralphs Bay, Elwick Bay and in shallow waters of the upper estuary. The model favoured macrophyte growth in these areas, however it does not resolve gradients in substrate type, disturbance or recruitment and results should be interpreted as potential rather than actual areas of macrophyte growth. The model simulated potentially favourable conditions for seagrass growth in Ralphs

Bay, whilst there was the potential for epiphytic macroalgae to dominate in the mid and upper estuary due to elevated water column nutrients. With access to more detailed observations of species present, typical biomass levels, substrate type, growth, disturbance and recruitment rates, the model could be improved to resolve macrophyte dynamics more accurately.

Modelled surface sediment dissolved oxygen concentrations were lowest in the mid and lower reaches with 10 percentile monthly concentrations falling below 40% saturation in autumn and spring. In March 2003 simulated surface sediment concentrations fell to 20% saturation for 3 days in a small area close to the Tasman Bridge. Modelled denitrification flux was highest in the upper estuary and mid estuary corresponding to regions with high sediment ammonia and low dissolved oxygen saturation. In the vicinity of Bridgewater Bridge and Ralphs Bay the simulated denitrification flux was low due to higher dissolved oxygen saturation resulting in part from the shallow bathymetry and in part from photosynthesis of local macrophytes. There were no observations of sediment properties in 2003-4 to validate the simulated sediment biogeochemistry and these results should be treated only as a hypothesis of possible conditions. Recent observations in 2008 have shown high spatial and temporal variability in local sediment conditions due in part to bioturbation and bio-irrigation of sediment by in-fauna. The impact of sediment in-fauna on porewater biogeochemistry is poorly constrained in the model, due to lack of observations and parameterisation of these processes, and is a priority area for future model improvement.

Nitrogen budget and trophic status

The modelled nitrogen budget for the estuary showed that in 2003 the depth-integrated daily flux of nitrogen across the marine boundary was the largest flux into the region (44%), followed by the Derwent River (29%), STP inputs (18%), stormwater (6%) and industrial loads (3%). See Section 3 for a discussion of these nutrient sources. The largest loss term from the estuary was denitrification (59%) with depth-integrated daily flux of nitrogen across the marine boundary accounting for 41% of export. During 2003 the net accumulation of nitrogen in the estuary was a minor ~44 tN/y which suggests the estuary was in near steady state.

Modelled annual mean chlorophyll concentrations in the top 0-11 m were used to classify the estuary by area as 18 % mesotrophic and 82 % eutrophic. The modelled mesotrophic areas (with annual mean chlorophyll 1-3 mg/m^3) include the upper estuary where light limits phytoplankton growth, and the lower estuary and southern Ralphs Bay, where near-surface nutrient concentrations were depleted for much of the year. The modelled eutrophic region (with annual mean chlorophyll > 3 mg/m^3) included the mid- and lower estuary and the remainder of Ralphs Bay.

Recommendation for future work

Recommendations for future work include utilising modern instrumentation in the estuary to collect biogeochemical observations over a greater diversity of time and space scales. In addition, observations of phytoplankton, zooplankton and macrophyte properties would allow these aspects of the model to be better constrained. This study suggests that denitrification plays a key role in maintaining the ‘health’ of the ecosystem and it would be good to validate the algorithms and parameterisations used in the model with detailed observations of these (as yet unvalidated) processes. As the current modelling study is limited to a specific year and set of environmental conditions, it would be wise to extend the simulated period to place it in the context of natural inter-annual variability. This could be efficiently achieved through the implementation of a near real time operational biogeochemical model that is routinely updated with the most recent advances in scientific understanding.

5.3 Management scenarios

The 2003 calibrated Derwent estuary biogeochemical model (Wild-Allen et al 2009) was used to simulate several hypothetical management scenarios for the Derwent estuary. Three scenarios were selected in consultation with the Derwent Estuary Program, EPA Division, local industries, councils and conservation groups, as described below. These scenario simulations are hypothetical projections of plausible conditions in the estuary (in 2003) given alternative point source loads and river forcing.

1) A 'near pristine' scenario, removing all known anthropogenic inputs, but retaining the 2003 River Derwent flow conditions;
2) a 2015 'active management' scenario assuming improved treatment of industrial effluent and sewage, with marine nutrient inputs constrained to 2003 concentrations, and assuming levels of river flow similar to 2003;
3) a 2015 'business as usual' scenario assuming improved treatment of industrial effluent but increased sewage loads, marine nutrient inputs increased to 2008 concentrations, and reduced River Derwent flow (similar to 2007);

Near-pristine scenario

This scenario was designed to simulate plausible pre-European conditions in the estuary. Compared to 2003, the following changes were made:

- All (10) sewage treatment plant (STP) inputs omitted.
- All (3) industry inputs (nutrients, DOC, POC and effluent colour) omitted.
- No change to Derwent River flow (uses 2003 flow and current management regime).
- 96 stormwater inputs reduced to 12 forested catchments.
- No change to 2003 marine boundary conditions derived from observations.

'Active management' scenario (2015)

This scenario was designed to simulate conditions in the estuary under projected management practices achievable in about 2015, assuming similar levels of Derwent River flow. Compared to 2003, the following changes were made:

- overall reduction in STP inputs based on recent (2008) and proposed Council improvements, effluent re-use schemes, and taking into account projected increased urbanisation.
- 2 Industry (Nystar zinc refinery; Impact fertiliser) inputs remain at 2003 levels; Norske Skog effluent colour removed, carbon load decreased and nutrient input increased to Best Available Techniques (BAT) guidelines associated with effluent processing plant upgrades in 2007-10.
- No change to Derwent River flow (uses 2003 flow and current management regime).
- No change to stormwater inputs (uses 2003 flow and catchment loads).
- No change to 2003 marine boundary conditions derived from observations.

'Business as usual' management scenario (2015)

This scenario was designed to simulate conditions in the estuary in the absence of active nutrient management practices, and assuming a reduction in Derwent river flow. Compared to 2003, the following changes were made:

- overall increase in STP inputs, based on present (2008) Council loads and projected increased load from increased urbanisation.
- Industry inputs: same as for 2015 best case management.
- Derwent River flow reduced to low flow year (uses 2007 flow and current management regime).
- Stormwater inputs use 2003 flow and catchment loads except for 19 catchments in greater Hobart which have increased catchment urbanisation.
- 2003 Marine boundary condition for ammonium increased to levels observed in 2008 to account for increased aquaculture adjacent to the estuary.

Scenario results

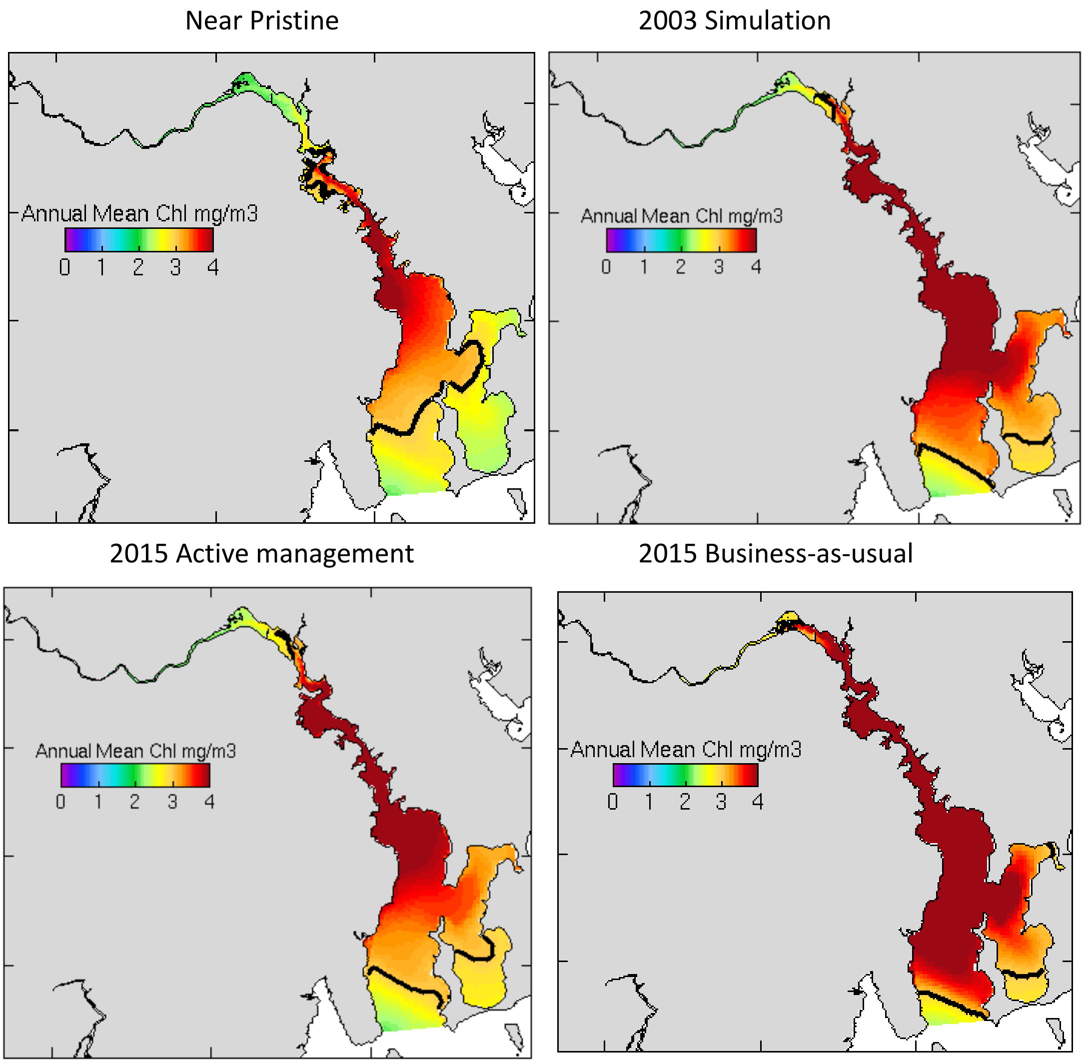
The *Derwent estuary biogoechemical model: scenario report* presents results of the three scenarios described above as compared to the 2003 baseline condition for a variety of parameters, including salinity, dissolved oxygen, light attenuation, nutrients, chlorophyll, phytoplankton/zooplankton, and seagrass/macroalgae. Some of the key findings are summarised below, with the full report provided in Annex 5.

All model simulations demonstrated broad similarities in seasonal nutrient characteristics and phytoplankton succession, with highest biological productivity and nutrients simulated in the middle reaches of the estuary. There appears to be natural accumulation of nitrogen in the upper and mid estuary in winter and persistent elevated chlorophyll concentrations in the middle reaches associated with the dynamics of the salt wedge front. There was also lower dissolved oxygen saturation in bottom waters and surface sediments (seasonal mean saturation 40-60%) in the deeper parts of the mid to lower estuary, particularly in autumn, but also in spring for all scenarios.

Modelled annual mean near surface chlorophyll concentrations show that the estuary under the current flow management regime and without any anthropogenic loads (i.e. near-pristine scenario) would be predominantly mesotrophic (54%) and partially eutrophic (46%) [although it is very likely that for a pristine scenario where river flow was unmanaged the results of this classification would be different]. In 2003 eutrophic conditions occurred over 82% of the region and this increased to 87% in the 2015 business-as-usual scenario. In the 2015 active management scenario the eutrophic area of the estuary was reduced to 72% of the region, with the remaining area classified as mesotrophic.

The active management scenario simulation had lower dissolved inorganic nitrogen (DIN), dissolved inorganic phosphate (DIP) and chlorophyll concentrations and higher dissolved oxygen (DO) percent saturation in bottom water and surface sediment than the 2003 calibrated model. The acitve management scenario simulation demonstrated the greatest water quality improvement in the middle reaches of the estuary when compared to both the 2015 business-as-usual scenario and the 2003 calibrated model.

The business-as-usual scenario had higher DIN, DIP and chlorophyll concentrations and lower DO percent saturation in bottom water and sediment than the 2003 calibrated model. The lower river flow used in the 2015 business-as-usual scenario allowed excursion of the marine salt wedge upstream into the estuary and there was an enhanced influx of nutrients across the marine boundary. In this scenario, the model favoured seagrass and macroalgae growth in shallow parts of the upper and middle reaches and Ralph's Bay due to a combination of low attenuation (and increase propagation) and elevated sediment nutrient concentrations. The near-pristine scenario favoured less seagrass and macroalgae growth possibly due to nutrient limitation.

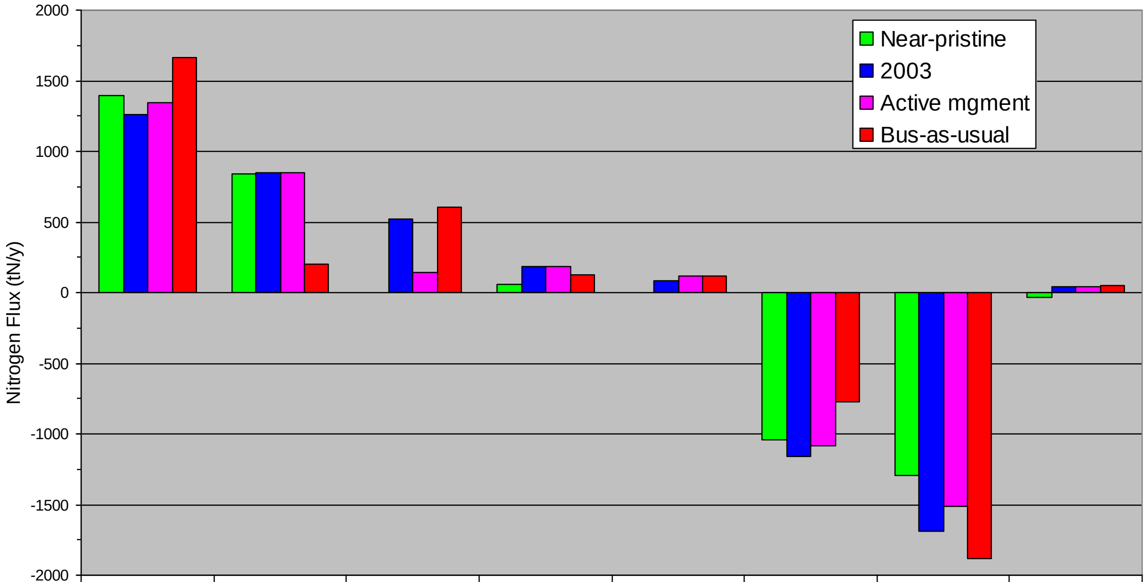


	Near pristine scenario	2003 simulation	2015 Active management	2015 Business-as-usual
Oligotrophic (<1mg Chl /m3)	0.0	0.0	0.0	0.0
Mesotrophic (1-3mg Chl /m3)	54.1	18.3	27.9	12.7
Eutrophic (>3mg Chl /m3)	45.9	81.7	72.1	87.3

Figure 5 Regional chlorophyll derived classification for three scenarios and the 2003 Derwent Estuary calibrated model simulation (summarized in table as % area) based on annual mean chlorophyll in near surface (0-11m) layer after Smith (1998). In the figure legend 1 is oligotrophic (purple) 2 is mesotrophic (green) 3 is eutrophic (dark red). (source: Wild-Allen et al, 2009)

Nutrient budgets and denitrification

Figure 6 shows the amount and relative proportion of nitrogen influx and export from the estuary. In all simulations the greatest influx of nitrogen to the estuary was across the marine boundary. Nitrogen budgets for all scenarios showed that contrasting nitrogen inputs from marine, river and point source loads were very nearly balanced by denitrification and marine export, and that the net accumulation of material within the estuary is negligible. Modelled dentritrification was found to be a key process in maintaining the health of the estuary, and whilst this component of the model is consistent with limited observations in the estuary, improved observation and validation of the modeled algorithms is a priority for future work. The modeled budgets suggests that a decline in denitrification efficiency could result in rapid accumulation of nitrogen and an associated decline in estuarine water quality. The simulations confirm the critical role that the River Derwent flow has in regulating water exchange throughout the estuary.



	+ Marine	+ Derwent River	+ Treated Sewage	+ Stormwater	+ Industry	- Marine	- Denitrification	Net Flux
Near-pristine	1394	844	0	57	0	-1039	-1292	-35.4
2003	1258	847	519	186	83	-1162	-1687	44.9
Active mgment	1346	847	140	186	119	-1082	-1515	40.3
Bus-as-usual	1665	202	601	124	119	-776	-1886	48.3

Figure 6 Annual nitrogen flux into and out of the estuary, including total denitrification and net flux, for the three model scenarios and the 2003 Derwent Estuary calibrated model simulation. (source Wild-Allen et al, 2009)

This study has shown that interactions between river flow, nutrient sources and water quality are complex but well simulated by the biogeochemical model. Low sediment dissolved oxygen saturation was found to vary with total nitrogen load to the estuary as indicated in Figure 7, provisionally by an exponential relationship. To achieve sediment DO concentrations in excess of 40% saturation over 95% of the region for 98% of the year then under average flow conditions nutrient loads to the estuary should be constrained to levels proposed in the 2015 active management scenario. Under low Derwent flow conditions, nutrient loads to the estuary would need to be reduced further to avoid extension of low sediment DO. This analysis could be improved by excluding the large refractory DON component of total nitrogen and repeating each scenario simulation for a range of river flows.

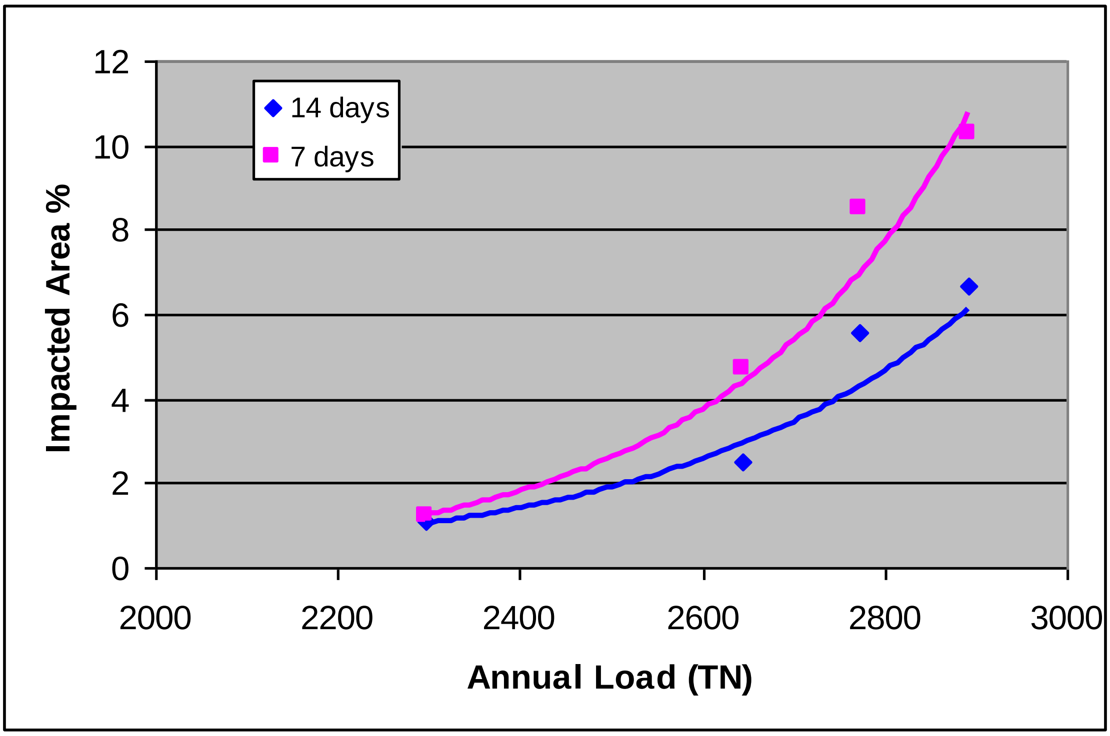


Figure 7 Annual total nitrogen input to the estuary and area of estuary with sediment DO saturation less than 40% for 7 and 14 days from the near-pristine, 2003, active management and business-as-usual model simulations. (source Wild-Allen et al, 2009

6. Review of heavy metal and nutrient indicators and targets

6.1 Heavy metal indicators and targets

At this point, no revision of the interim target proposed for zinc concentrations in water (i.e. 15 µg/L total zinc) is proposed. Several other potential heavy metal indicators have been identified through the studies carried out in the Stage 2 WQIP. In particular, maintaining adequate bottom water and surface sediment dissolved oxygen (DO) levels has been identified as a key management objective in order to limit the bioavailability of sediment-bound heavy metals. On the basis of the experimental work presented in Section 4, an interim bottom water target of 40% saturation may be appropriate to achieve this objective. This is based on the observed response of contaminated sediments exposed to 5% and 20% DO levels, and incorporates a Margin of Safety.

However, it is strongly recommended that further investigations be carried out to refine and support this target, including experiments carried out on a broader range of sediment types and a wider spectrum of DO levels for the full range of heavy metals, including mercury. As discussed in Section 6.2 below, a bottom water DO target of more than 40% may be required to support benthic ecosystem health. It is also noted that a DO target of 40% may not be achievable for some areas of the upper estuary between New Norfolk and Bridgewater, where summer DO levels are frequently well below 40% saturation (even under a 'near pristine' scenario. In this area, enhanced monitoring and investigations are recommended to better quantify bottom water DO levels and their effects on sediment processes/benthic communities, and to set achievable targets.

The bioaccumulation studies described in Section 4.2 confirmed the value of shellfish as bio-indicators of heavy metal contamination, and identified several other potential faunal groups that may also be useful. Studies of mercury levels in recreationally targeted finfish identified several species (i.e. bream, trout) that could pose a human health risk, and precautionary health advice was issued. The Stage 1 WQIP targets identified for heavy metal levels in seafood remain unchanged, as these are based on the national food safety standards.

The toxicity investigations described in Section 4.2 identified the native brittlestar *Amphiura elandiformis* as a good potential indicator of sediment quality, and quantified behavioural and toxic response to varying levels of copper through sediment spiking experiments. Exposure to a wider 'cocktail' of heavy metals found in Derwent estuary sediments confirmed this behavioural/toxic response, however further work is needed to clarify the role of other toxicants. It is proposed that future sediment monitoring activities document the distribution and abundance of this species as a potential indicator of benthic ecosystem health.

6.2 Eutrophication indicators and targets

Further work is needed to develop robust nutrient response indicators and targets for the Derwent estuary, particularly in light of the critical role played by river flows. It is recommended that additional model scenarios be tested to evaluate future management scenarios under a range of different river flows to determine under what conditions and in which areas the estuary is most vulnerable. Using this information, targets can be set to protect against a 'worst case scenario'.

In the interim, the 2015 active management scenario is clearly a preferred management direction, in comparison to either the 2003 or 2015 business-as-usual scenario. This would suggest a maximum annual nitrogen load of 2638 tonnes, and certainly no more than 2893 tonnes (2003 load) if the current trophic status of the Derwent is to be maintained or improved (assuming average flow conditions). Further discussion about potential indicators and targets is provided below.

Dissolved oxygen levels at depth

As discussed above, bottom water dissolved oxygen levels appear to play a major role in heavy metal bioavailability in the Derwent estuary. Furthermore, low bottom DO has been shown to have a deleterious effect on benthic fauna, and DO targets have been set in a number of other estuarine systems to maintain ecosystem health. For example, DO trigger levels of 5 to 6 ppm have been set for the bays and channel of the adjacent D'Entrecasteaux Channel (Thompson et al 2008). In other systems (e.g. Chesapeake Bay), biologically based reference curves have been used to set DO criteria (USEPA, 2010). It is recommended that DO targets be set for the Derwent that take into account both the frequency and duration of low DO events, with a focus on regions and times of year when DO risks may be highest.

Dissolved inorganic nitrogen concentrations

Dissolved inorganic nitrogen is known to stimulate algal growth in most marine ecosystems, including the Derwent, and ammonia levels in bottom water are also an indicator of nutrient flux from sediments, associated with low DO conditions. DIN targets have been set in a number of other estuarine systems to maintain ecosystem health. For example, ammonia trigger levels have recently been set for the bays and channel of the adjacent D'Entrecasteaux Channel, focussing on both annual and summer conditions (Thompson et al 2008). It is recommended that similar DIN targets be set for the Derwent.

Frequency and extent of algal blooms

Excessive nutrient enrichment typically results in an increase in the frequency and extent of algal blooms. These blooms may involve either phytoplankton, nuisance macroalgae such as *Ulva sp*. or filamentous and epiphytic algae. Where seagrass and macrophyte beds are present, phytoplankton blooms may reduce light clarity and epiphytic and filamentous algae may overgrow seagrass and macrophytes, resulting in the loss of these valuable habitats.

Phytoplankton targets have been set in a number of other estuarine systems to maintain ecosystem health. For example, chlorophyll *a* trigger levels have recently been set for the bays and channel of the adjacent D'Entrecasteaux Channel, focussing on annual and summer mean chl *a* levels, as well as setting triggers for bloom conditions (Thompson et al 2008). It is recommended that similar chl *a* targets be set for the Derwent. Nuisance macroalgae targets are more difficult to set, given the paucity of quantitative monitoring data for these species. It is recommended that the DEP monitoring program be reviewed to address this issue.

Extent and condition of seagrass and macrophyte beds

As noted above, seagrass and macrophyte mortality is a common result of eutrophication due to a combination of reduced water clarity and epiphytic algal overgrowth. It is recommended that indicators and targets be developed for Derwent seagrass/macrophyte beds to ensure – at a minimum – no net loss of existing habitat.

7. Key Findings

7.1 Heavy metals

A number of investigations were carried out through this project which have significantly improved our understanding of heavy metal sediment processes, toxicity and bioaccumulation.

Sediment incubation experiments demonstrated a clear relationship between dissolved oxygen levels and the bioavailability of heavy metals, with a very rapid response to reduced oxygen levels (i.e. within 24 hours). Although the majority of heavy metals in Derwent estuary sediments tend to be inert, the residual metals constitute an important reservoir of potential contamination under certain conditions. It is recommended that future sediment surveys incorporate more sophisticated techniques to assess heavy metal bioavailability (e.g. DGTs).

Investigations into benthic toxicity focused on a promising potential indicator of benthic health – the native brittlestar. A series of experiments confirmed that this common species is sensitive to heavy metals, with copper toxicity established within specific ranges using sediment spiking techniques. This indicator species also showed a clear toxic response when exposed to a broader range of heavy metals in sediments collected from the Derwent. Further work would be beneficial to confirm the sensitivity of this species to other sediment/heavy metal combinations and to investigate the current distribution of this indicator in Derwent estuary sediments.

Surveys of heavy metal concentrations in a wider range of biota collected from several sites in the Derwent (plus a control) documented generally higher concentrations of metals in biota collected from the middle estuary, but did not find a consistent pattern between trophic levels. Several organisms were identified as potential indicator species for future monitoring. Further investigations are recommended, but these should include mercury and should be designed to focus on food chain pathways.

7.2 Nutrients

In 2003, the majority of nutrients were derived from marine (44%) and catchment (29%) sources, followed by sewage treatment plants (18%), with limited nutrients associated with stormwater and industries. Since 2003, marine farming activities have expanded considerably in the adjacent D'Entrecasteaux Channel and Huon Estuary and nutrients associated with fish farms may now comprise a significant component of marine inputs, particularly during summer months.

A detailed biogeochemical model for the Derwent estuary was successfully implemented and validated against observations. This model provides a better understanding of the interplay between estuarine morphology, hydrodynamics and nutrient processing. In particular, the model demonstrates the build-up of elevated DIN, DIP and chlorophyll a in the middle estuary, and a persistent 'upwelling' feature in the vicinity of Site U7 (Dogshear Point). The model also indicates that the majority of nutrients within the estuary are retained within the system, and that denitrification is a critical process in removing excess nitrogen from the system.

While the model output compared well with most observations, there are several limitations that should be considered, and model output associated with these areas and variables should be interpreted with caution. In particular:

- The upper estuary (between Bridgewater and New Norfolk) is not as well resolved due to the complex bathymetry and hydrodynamics of this area;
- Some variables could not be fully validated against observations due to lack of observational data, particularly sediment DO, denitrification, seagrass/macrophyte distribution and phytoplankton/zooplankton population dynamics.

The biogeochemical model – calibrated for 2003 – was used to evaluate three alternative management scenarios: near pristine, active management 2015 and business-as-usual 2015 (low flow). Model simulations for these scenarios revealed a number of interesting findings, in particular:

- The near-pristine simulation suggests that the pre-European Derwent had many of the same characteristics we see today, including higher nutrient and chlorophyll levels in the middle estuary and at depth, and lower oxygen levels at depth.
- The near-pristine Derwent was a predominantly mesotrophic system, rather than the predominantly eutrophic system of 2003 and the 2015 scenarios.
- The 2015 business-as-usual scenario predicts considerably higher levels of nutrient and chlorophyll build up – particularly in the middle estuary – and lower dissolved oxygen levels, as compared to the 2015 active management scenario.
- Of particular interest is the interplay between river flow and nutrient and chlorophyll dynamics. Low river flows affect the estuary in several important ways, particularly through:
    - Increased penetration of nutrient-rich water from the Channel and Storm Bay into the lower estuary, and upstream movement of the salt-wedge into the upper estuary along with elevated nutrients, chlorophyll and low DO;
    - Reduced discharge of highly coloured river water, resulting in greater water clarity in the upper estuary and increased primary production.

The biogeochemical model also highlights the critical role played by denitrification in maintaining the overall health of the estuary. The scenarios suggest that the system has some capacity to increase denitrification in response to increase nutrient loading, however, studies of other systems (e.g. Port Phillip Bay) have shown that this capacity can only be maintained up to a point, after which the system may decline precipitously. Without this denitrification capacity, nutrients could accumulate to high levels in the Derwent, resulting in poor water quality. This highlights the need to identify and protect areas with high denitrification potential.

8. Management Recommendation

8.1 Continue to reduce heavy metal inputs

Further reduction of external heavy metal loads remains an important management objective, particularly with respect to historical soil and groundwater contamination at the Risdon zinc smelter site (currently managed by Nyrstar). Management of urban stormwater will also have multiple benefits, including capture/treatment of heavy metals generated within urban and industrial catchments. Specific management actions to achieve this recommendation include:

- Further extension of groundwater extraction systems and improved management of processing leaks at the Nyrstar Hobart smelter site to extract and treat contaminated groundwater
- Further extension of stormwater treatment systems at the smelter site to capture and treat contaminated surface water;

- Design and installation of stormwater treatment systems in other urban and industrial catchments as this represents the second largest source of heavy metal pollution to the estuary. Where possible, these systems should incorporate the principles of Water Sensitive Urban Design (WSUD).

8.2 Minimise disturbance of heavy metal contaminated sediments

Given the extremely high levels of contamination and the demonstrated natural recovery, dredging and other sediment disturbing activities should be undertaken only where absolutely necessary. Fortunately dredging is not routinely required to maintain shipping channels in the Derwent. However, to guide other proposed activities, Derwent-specific guidelines are being developed to identify potential risks associated with disturbance of contaminated sediments within the Derwent, including dredging, dredge spoil disposal and other construction activities. These guidelines include an identification of high-risk areas, sampling and assessment protocols, techniques and preventative measures to limit exposure and dispersion of contaminated sediments (e.g. low impact dredging technologies, siltation booms and curtains) and recommended monitoring systems (before, during and after dredging activities).

8.3 Improve seafood safety monitoring and public reporting

Further monitoring of fish, shellfish and other seafood is needed minimize potential risks associated with recreational fishing in the Derwent estuary. Some of this work is currently underway with support from the Australian Government and Tasmanian Aquaculture & Fisheries Institute, including a more extensive survey of bream, flounder, sea run trout, Australian salmon and eel. Additional studies are also underway or proposed to better understand the biological pathways by which heavy metals ae transferred up the food chain, with a particular focus on mercury contamination (TAFI/Nyrstar/DEP).

Public information on heavy metal levels in Derwent estuary fish and shellfish has recently been updated to provide precautionary health advice (September 2009) and televised community service announcements were also produced reiterating this information. This information will need to be updated when the current surveys are completed, and it is recommended that advisory signage also be developed.

8.4 Manage nutrient inputs to prevent further eutrophication

Given the importance of the Derwent estuary to the 200,000 people of the Hobart metropolitan area, prevention of eutrophication is clearly a high priority. In addition to the public amenity concerns associated with eutrophic ‘symptoms’ such as algal blooms, fish kills and odours, low oxygen levels could have severe implications in terms of remobilizing heavy metals from sediments. Increased bioavailability of heavy metals in Derwent sediments could result in public health concerns for both recreational and commercial fisheries, as well as aquaculture.

Given that marine and River Derwent catchment inputs are the largest nutrient inputs to the Derwent under both current and projected scenarios, there is a clear need to manage both marine and catchment activities to ensure the long-term health of the system. Sewage-derived nutrients also contribute a substantial proportion of the load, and there are measurable benefits to be gained from pursuing an active management approach, as indicated by the modelling results. Specific management actions to achieve this recommendation include:

- Monitor and quantify nutrient loads associated with catchment and marine-based activities;
- Implement catchment land-use and aquaculture practices as needed to minimise/reduce nutrient loads to the estuary;

- Minimise/reduce sewage loads to the estuary through beneficial reuse, improved process controls and/or advanced treatment.

8.5 Conserve areas with high nutrient-removal capacity

According to model simulations, denitrification removes an estimated 59% of nitrogen from the system under current conditions, and up to 71% under the Business-as-usual scenario – representing an essential safety valve. Without this, nutrients could rapidly accumulate, potentially causing severe eutrophication. While the model identifies deep areas in the middle/lower estuary as important areas for denitrification, some shallow water and wetland habitats may also be important, particularly where oxidizing and reducing zones are found in close proximity and there is a high density of large, burrowing macrofauna. Recent studies have also identified other habitat types with high densities of macrophytes (e.g. upper Derwent wetlands) and microphyobenthos (e.g. Ralphs Bay) that play a critical role in nutrient removal and cycling (Cook et al, 2007). It is important that we identify areas with high nutrient removal capacities and preserve/manage these to maintain this critical service. Specific management actions to achieve this recommendation include:

- Identify and map estuarine areas with high nutrient removal capacity;
- Quantify nutrient removal rates associated with dentrification and primary production;
- Adjust models to incorporate new process information.

8.6 Manage freshwater flows to enhance water quality and aquatic habitats

River Derwent flows are shown to play a critical role in maintaining the overall health of the estuarine system. Modelling has demonstrated that reduced river flows results in a substantial increase in the influence of nutrients associated with the D'Entrecasteaux Channel and Storm Bay. This effect needs to be fully considered if additional flows are to be diverted from the River Derwent for water development projects. There may be a need to balance the development goals of aquaculture and irrigated agriculture to avoid compromising estuarine health. Specific management actions to achieve this recommendation include:

- Improve monitoring of Derwent River flows entering the estuary at New Norfolk;
- Develop environmental flow criteria for the River Derwent to maintain estuarine water quality, wetlands, macrophytes, migratory fish and other key components of ecosystem health.

8.7 Enhance and integrate monitoring and reporting

A number of actions are recommended to enhance and improve monitoring and reporting, in particular:

- Improved monitoring of DO at depth in vulnerable areas;
- New/improved indicators for monitoring sediment health and heavy metal bioavailability;
- Further development of catchment and Channel monitoring, and integration of this with estuary monitoring;
- Development of an integrated 'catchment to coast' reporting system.

8.8. Improve understanding through targeted investigations

A number of actions are recommended to further improve our understanding of nutrient and heavy metal processing and impacts, including the following:

- Sediment processes: further investigations of oxygen impacts on heavy metal mobility and denitrification rates;
- Investigate other potential sources of heavy metal contamination (e.g. historic foreshore tips);

- Investigate potential sources of mercury contamination and identify areas with high rates of mercury methylation (existing and potential);
- Investigation of heavy metal food chain pathways, focussing particularly on mercury;
- Investigate the 'Ralphs Bay conundrum' (i.e. the apparent discrepanct between low heavy metal levels in sediments and high levels in biota);
- Investigation of environmental flows needed to maintain estuarine water quality, wetlands and other key habitats;

8.9 Extend and integrate system models and decision-support tools to support management

- Run additional Derwent scenario runs to evaluate broader range of inputs and activities, including river flows, aquaculture and projected climate change scenarios;
- Rerun model with latest nutrient inputs (2009) – compare model outputs with observations;
- Fine tune some of model assumptions based on updated process studies, habitat surveys, etc;
- Improve model predictive capacity for the upper estuary;
- Link Southeast regional models (Derwent, Channel, Huon & Storm Bay) to provide an integrated basis for management decisions;
- Develop/integrate catchment model(s).

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